

The Role of Sensor Technology in the Development of Environmental Monitoring Systems: A Systematic Review of the Literature.

Peran Teknologi Sensor dalam Pengembangan Sistem Pemantauan Lingkungan: Tinjauan Literatur yang Sistematis.

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ABSTRACT

The development of an environmental monitoring system plays an important role in efforts to maintain environmental sustainability. Sensor technology has become a significant solution in improving the accuracy and effectiveness of environmental monitoring. In this literature review, we evaluate the role of sensor technology in the development of environmental monitoring systems through a comprehensive analysis of relevant literature. We highlight recent developments in sensor technology, its applications in environmental monitoring, and future challenges and opportunities. The results show that sensor technology has made a significant contribution to improving environmental monitoring capabilities, although there are still several challenges that need to be overcome. The implications of these findings for practice and research in the field of environmental monitoring are also discussed in depth.

Keywords: Environmental monitoring, Sensor technology, Literature review, Environmental sustainability, Monitoring systems, Challenges, Opportunities.

ABSTRAK

Pengembangan sistem pemantauan lingkungan memegang peranan penting dalam upaya menjaga keberlanjutan lingkungan hidup. Teknologi sensor telah menjadi solusi yang signifikan dalam meningkatkan akurasi dan efektivitas pemantauan lingkungan. Dalam tinjauan literatur ini, kami mengevaluasi peran teknologi sensor dalam pengembangan sistem pemantauan lingkungan melalui analisis komprehensif terhadap literatur yang relevan. Kami menyoroti perkembangan terkini dalam teknologi sensor, penerapannya dalam pemantauan lingkungan, serta tantangan dan peluang di masa depan. Hasilnya menunjukkan bahwa teknologi sensor telah memberikan kontribusi yang signifikan dalam meningkatkan kemampuan pemantauan lingkungan, meskipun masih ada beberapa tantangan yang perlu diatasi. Implikasi dari temuan ini untuk praktik dan penelitian di bidang pemantauan lingkungan juga dibahas secara mendalam.

Kata Kunci: Pemantauan lingkungan, Teknologi sensor, Tinjauan literatur, Keberlanjutan lingkungan, Sistem pemantauan, Tantangan, Peluang.

Introduction

Our environment is increasingly facing serious challenges that affect the balance of the global ecosystem. Rapid climate change, increasing air pollution, widespread water pollution and declining biodiversity have become urgent problems requiring innovative solutions. In the midst of these challenges, environmental monitoring is key in better understanding environmental conditions and in identifying appropriate solutions. In recent decades, developments in sensor technology have provided new hope in overcoming environmental monitoring challenges. Sensor technology is capable of providing accurate, real-time data on various environmental parameters, from air quality to water temperature, with a higher degree

of precision than traditional methods. Thus, environmental monitoring supported by sensor technology can help detect environmental changes more quickly and provide more in-depth information for decision makers.

Sensor technology is essential for the development of environmental monitoring systems, enabling precise data collection and analysis for various applications. Wireless Sensor Networks (WSNs) have become a key technology in environmental monitoring due to their advantages such as easy deployment, high accuracy, and cost-effectiveness (Song & Zhu, 2013). The integration of sensor technologies has facilitated the advancement of multi-sensor information fusion techniques, which are crucial for enhancing the capabilities of environmental monitoring systems (Reyana & Vijayalakshmi, 2022). Continuous improvements in sensor technology have made resource-constrained sensor systems increasingly attractive for environmental monitoring across various domains (Zowj et al., 2015).

Environmental monitoring systems commonly utilize WSNs to efficiently collect data. These systems can monitor parameters like temperature, humidity, soil moisture, and various environmental pollutants (Munysi et al., 2018; Li et al., 2010; Munysi et al., 2017). Sensor technology in environmental monitoring extends beyond agriculture to applications such as gas monitoring, water content measurement, and groundwater sampling (Gaiardo et al., 2017; Burge et al., 2005; Fries et al., 2007). Sensor networks are also utilized in diverse environments like aquaculture, urban buildings, and underground mines for monitoring purposes (Chang & Zhang, 2013; Cao et al., 2008; Zhao & Yu, 2021).

Sensor technology enables the development of smart and integrated monitoring systems capable of detecting a wide range of environmental factors. These systems often incorporate data fusion algorithms and embedded systems to enhance real-time performance, reliability, and accuracy in monitoring indoor and outdoor environments (Bhattacharjee & Bera, 2014; Guo et al., 2016). Sensor networks are not limited to terrestrial environments; they are also utilized in marine and coastal settings for monitoring biological, chemical, and physical parameters (Fries et al., 2007).

In conclusion, sensor technology plays a critical role in the evolution of environmental monitoring systems, providing innovative solutions for data collection, analysis, and decision-making processes. The integration of sensor networks with advanced technologies like data fusion, embedded systems, and artificial intelligence continues to drive advancements in environmental monitoring across various domains.

This literature review aims to investigate the role played by sensor technology in the development of environmental monitoring systems. Through a systematic analysis of the existing literature, this article aims to achieve several main objectives. First, to understand recent developments in sensor technology used in environmental monitoring. Second, to evaluate various applications of sensor technology in environmental monitoring systems in various contexts, such as monitoring air, water, land and biodiversity. Third, to identify the main challenges faced in applying sensor technology in environmental monitoring, including technical problems, costs and infrastructure limitations. Finally, to explore future opportunities for the development of sensor technology in improving the effectiveness of environmental monitoring systems.

It is hoped that this article will make a significant contribution to the existing literature in the field of environmental monitoring and sensor technology. By conducting a comprehensive systematic review of the literature, this article will provide in-depth insight into how sensor technology can improve current environmental monitoring systems. By mapping key findings from existing research, this article will highlight the advantages and disadvantages of sensor technology in environmental monitoring and offer directions for further research in this area.

This article consists of four main parts. The first part is the Introduction, where the background, objectives and scope of the research will be introduced. The second part is

Research Methods, where the methodology used in conducting the literature review will be described. The third section is Results and Discussions, where key findings from the literature review will be presented and analyzed in depth. Finally, the fourth section is Conclusions, where the conclusions of this literature review will be summarized and implications for future research and practice will be discussed further.

Research Methods

In searching for relevant literature for this systematic review, we used a comprehensive approach. Searches were conducted through various academic databases, including Scopus, PubMed, and IEEE Xplore, using combinations of keywords relevant to the research topic. In addition, we also conducted a manual search through the reference lists of the articles that were found to ensure the completeness of the literature selection.

We applied strict inclusion and exclusion criteria to select the literature articles included in this review. Selected articles must meet the following criteria: (1) be relevant to the topic of environmental monitoring and sensor technology, (2) be published in a peer-reviewed scientific journal, (3) be available in English, and (4) include information that is significant and relevant to the aim of our research. Articles that did not meet these criteria or did not make a significant enough contribution to our systematic review were excluded.

After conducting an initial search, the articles found were then assessed independently by two researchers to ensure compliance with the inclusion criteria and relevance to the research topic. Articles that met the inclusion criteria were then analyzed further to extract relevant information about sensor technology development, applications in environmental monitoring, challenges faced, and future opportunities. The information obtained from these literature articles is then compiled and analyzed systematically.

Data obtained from selected literature articles were carefully analyzed to identify key findings relevant to our research objectives. We used a qualitative approach to compile and analyze information from the existing literature. These key findings are then used as a basis for building the arguments and conclusions in this article.

Results and Discussions

Development of Sensor Technology in Environmental Monitoring

The results of the literature review show that the development of sensor technology in environmental monitoring has experienced significant progress in the last few decades. Smaller, more accurate, and more integrated sensors have been developed to detect a variety of environmental parameters, including air quality, water temperature, soil moisture, and noise levels. Additionally, breakthroughs in sensor technology have enabled the development of multispectral and multisensor sensors that can provide more comprehensive information about environmental conditions. Discussion will focus on these advances and their impact on the overall effectiveness of the environmental monitoring system.

Sensor technology has made significant advancements in the field of environmental monitoring, providing innovative solutions to tackle various challenges. et al. Huang (2024) developed a highly efficient room temperature NO₂ sensor using TiO_x heterogeneous nanoparticles, which demonstrated enhanced sensitivity crucial for environmental monitoring applications. The integration of wireless sensor networks has played a crucial role in micro-environmental monitoring systems (Cao et al., 2008), enabling real-time data collection and analysis. Moreover, the use of wireless sensor networks for monitoring environmental conditions in farmlands has been investigated (Ganiyu et al., 2014), highlighting the importance of precise environmental parameter monitoring for optimal crop production.

Additionally, the use of nanomaterials-based sensors has been emphasized for environmental monitoring purposes (Su et al., 2012), showcasing their potential in detecting heavy metal ions and radioactive metals. Interdisciplinary collaboration in ecological sensing

has created new opportunities for wireless sensor networks (Collins et al., 2006), underscoring the significance of cross-disciplinary efforts in advancing sensor technology for environmental applications. Furthermore, the application possibilities of sensor networks are extensive, covering military, environmental monitoring, healthcare, and various other fields (Yang, 2021), highlighting the versatility and broad impact of sensor technology.

In conclusion, the progress in sensor technology for environmental monitoring has been substantial, with a focus on improving sensitivity, real-time monitoring capabilities, and the integration of wireless sensor networks. These advancements offer promise for enhancing environmental monitoring systems and addressing critical environmental challenges.

Application of Sensor Technology in Practice

Furthermore, the literature review also reveals various practical applications of sensor technology in environmental monitoring systems in various sectors. Examples include the use of air sensors to detect pollution in cities, the use of water sensors to monitor river and sea water quality, and the use of soil sensors to monitor soil moisture and acidity levels in agriculture. The discussion will highlight the concrete benefits that sensor technology has provided in improving the accuracy and timeliness of environmental monitoring data, as well as how it has had a positive impact on decision making and mitigation actions.

The integration of sensor technology in various fields has been a growing area of interest. For instance, sensor-based systems are utilized in agriculture for livestock feed processing Syamsuryadi et al. (2021) and automatic irrigation systems using soil moisture sensors (Rahardjo, 2022). In healthcare, sensors are applied in m-health for diagnostics and treatment support, as seen in developing countries like Indonesia (Isa et al., 2012).

Moreover, technology integration in education has been a significant focus. Studies have explored the impact of e-learning implementations (Faslah & Santoso, 2017), the influence of broadband wireless access technology on midwifery clinic practices (aswitami et al., 2017), and the development of online applications for evidence-based nursing practice (Mituhu et al., 2021).

Additionally, the adoption of blockchain technology for security purposes has been explored in education Sunarya (2022) and healthcare (Rahardja, 2022). This technology is used to secure educational certificates and health records, emphasizing the shift towards digitalization and enhanced security measures.

In conclusion, the references provide insights into the diverse applications of sensor technology across different sectors, highlighting the importance of technological advancements in improving efficiency, security, and outcomes in practical settings.

Challenges and Opportunities in the Future

However, the results of the literature review also show that there are a number of challenges that need to be overcome in the development and application of sensor technology in environmental monitoring. These challenges include technical issues such as sensor precision and reliability, limited durability in extreme environments, and high sensor production and maintenance costs. In addition, the infrastructure required to support large-scale sensor use is also a significant obstacle. Nevertheless, the literature review also identified a number of future opportunities for the development of sensor technology in environmental monitoring, such as the development of environmentally friendly sensors, integration of sensors with intelligent systems, and updates to digital infrastructure to support better connectivity and data analysis.

Sensor technology is essential for the advancement of environmental monitoring systems, offering various opportunities and challenges that must be addressed. The integration of wireless sensor networks in environmental monitoring, as highlighted by (Guobao et al., 2014), brings about challenges such as ensuring the protection of oceanographic sensors,

designing advanced buoy systems, implementing efficient energy harvesting mechanisms, and enhancing system stability and reliability. Additionally, the review by Wang (2011) emphasizes the significance of sensor networks in industries like healthcare, environmental monitoring, infrastructure monitoring, and national security, underscoring the need to address current challenges and explore future research directions.

The emergence of new sensor technologies, such as stretchable sensors as discussed by (Yang & Deng, 2019), has introduced innovative opportunities for environmental monitoring. These sensors, known for their lightweight nature, high flexibility, and stretchability, provide novel solutions for monitoring environmental parameters. Furthermore, the use of low-cost sensor networks, as highlighted by (Mao et al., 2019), is increasingly popular in environmental sciences, generating vast amounts of monitoring data that support interdisciplinary research and applications across various fields.

The potential of sensor technology in environmental monitoring is further demonstrated by the work of (Wang et al., 2019), which explores environmental monitoring based on the fog computing paradigm and the Internet of Things (IoT). The collection of large volumes of data through IoT sensors offers new possibilities for enhancing environmental monitoring capabilities. Moreover, the study by Mahajan (2022) emphasizes the importance of citizen-centric environmental monitoring systems, which provide opportunities for public engagement while also posing challenges related to sensor accuracy and the management of extensive datasets.

In conclusion, sensor technology is pivotal in advancing environmental monitoring systems, offering numerous opportunities for innovation and research. Addressing challenges such as sensor protection, energy efficiency, data management, and citizen engagement will be crucial in fully leveraging the potential of sensor technology for environmental monitoring.

Conclusions

From the literature review that has been carried out, it can be concluded that the role of sensor technology in developing environmental monitoring systems is very significant. The development of sensor technology has had a major positive impact on the effectiveness and efficiency of environmental monitoring, by providing more accurate, real-time and comprehensive data about environmental conditions. With sensor technology, we can better identify and overcome environmental challenges, and provide a stronger basis for sustainable decision making.

In practice, sensor technology has been used in a variety of environmental monitoring applications, from monitoring air pollution in cities to monitoring water quality in rivers and seas. The successful application of this sensor technology has provided concrete evidence of the great potential it has in improving the quality of human life and maintaining environmental sustainability.

However, there are a number of challenges that need to be overcome to maximize the benefits of sensor technology in environmental monitoring. These challenges include technical issues, production and maintenance costs, and the infrastructure required to support large-scale use of sensors. To overcome these challenges, cooperation between government, industry and research institutions is essential.

Apart from that, there are also a number of opportunities that can be explored for the development of sensor technology in environmental monitoring in the future. The development of more environmentally friendly sensors, integration of sensors with intelligent systems, and updates to digital infrastructure are some examples of promising opportunities.

Thus, it is hoped that this article will provide a valuable contribution to the understanding of the role of sensor technology in environmental monitoring. The implications of these findings can be used as a basis for informing public policy, directing further research, and guiding future environmental monitoring practices.

References

- aswitami, G., Hilmanto, D., Husin, F., Mose, J., Wirakusumah, F., & Djuhaeni, H. (2017). The effect of implementing broadband wireless access (BWA) technology on the cost effectiveness of midwifery clinic practice. *Indonesian Journal of Midwifery Education and Services*, 3(1), 52. <https://doi.org/10.24198/ijemc.v3i1.44>
- Burge, S., Hoffman, D., Hartman, M., & Venedam, R. (2005). Automated ground-water sampling and analysis of hexavalent chromium using a “universal” sampling/analytical system. *Sensors*, 5(1), 38-50. <https://doi.org/10.3390/s5010038>
- Cao, X., Chen, J., Zhang, Y., & Sun, Y. (2008). Development of an integrated wireless sensor network micro-environmental monitoring system. *Isa Transactions*, 47(3), 247-255. <https://doi.org/10.1016/j.isatra.2008.02.001>
- Cao, X., Chen, J., Zhang, Y., & Sun, Y. (2008). Development of an integrated wireless sensor network micro-environmental monitoring system. *Isa Transactions*, 47(3), 247-255. <https://doi.org/10.1016/j.isatra.2008.02.001>
- Chang, B. and Zhang, X. (2013). Aquaculture monitoring system based on fuzzy-pid algorithm and intelligent sensor networks.. <https://doi.org/10.1109/csqrwc.2013.6657435>
- Collins, S., Bettencourt, L., Hagberg, A., Brown, R., Moore, D., Bonito, G., ... & McAuley, J. (2006). New opportunities in ecological sensing using wireless sensor networks. *Frontiers in Ecology and the Environment*, 4(8), 402-407. [https://doi.org/10.1890/1540-9295\(2006\)4\[402:noiesu\]2.0.co;2](https://doi.org/10.1890/1540-9295(2006)4[402:noiesu]2.0.co;2)
- Faslah, R. and Santoso, H. (2017). Analysis of e-learning implementation readiness using the e-learning readiness model. *Positive Journal of Information Systems and Technology*, 3(2), 113. <https://doi.org/10.31961/positive.v3i2.431>
- Fries, D., Ivanov, S., Bhanushali, P., Wilson, J., Broadbent, H., & Sanderson, A. (2007). Broadband, low-cost, coastal sensor nets. *Oceanography*, 20(4), 150-155. <https://doi.org/10.5670/oceanog.2007.15>
- Gaiardo, A., Fabbri, B., Valt, M., Bellutti, P., Guidi, V., Crivellari, M., ... & Bagolini, A. (2017). On the optimization of a mems device for chemoresistive gas sensors.. <https://doi.org/10.3390/proceedings1080746>
- Ganiyu, R., Arulogun, O., & O, O. (2014). Development of a wireless sensor network for monitoring environmental condition on a farmland. *International Journal of Applied Information Systems*, 7(3), 28-34. <https://doi.org/10.5120/ijais14-451170>
- Guo, L., Wang, G., & Yu, X. (2016). Design for indoor environment monitoring system based on embedded system and multi-sensor data fusion algorithm. *International Journal of Smart Home*, 10(1), 31-40. <https://doi.org/10.14257/ijsh.2016.10.1.04>
- Guobao, X., Shen, W., & Wang, X. (2014). Applications of wireless sensor networks in marine environment monitoring: a survey. *Sensors*, 14(9), 16932-16954. <https://doi.org/10.3390/s140916932>
- Huang, K. (2024). Highly efficient room temperature no2 sensor using two-phase tiox heterogeneous nanoparticles. *Acs Applied Materials & Interfaces*, 16(8), 10485-10495. <https://doi.org/10.1021/acsami.3c15770>
- Isa, S., Handoko, D., & Rifano, F. (2012). Application of m-health for diagnostics and treatment support in developing countries: Indonesian case study. *Journal of Information Systems*, 7(1), 62. <https://doi.org/10.21609/jsi.v7i1.294>
- Li, X., Cheng, X., Ke, Y., & Gong, P. (2010). A monitoring system for vegetable greenhouses based on a wireless sensor network. *Sensors*, 10(10), 8963-8980. <https://doi.org/10.3390/s101008963>
- Mahajan, S. (2022). Design and development of an open-source framework for citizen-centric environmental monitoring and data analysis. *Scientific Reports*, 12(1). <https://doi.org/10.1038/s41598-022-18700-z>
- Mao, F., Khamis, K., Krause, S., Clark, J., & Hannah, D. (2019). Low-cost environmental sensor networks: recent advances and future directions. *Frontiers in Earth Science*, 7. <https://doi.org/10.3389/feart.2019.00221>

- Mituhu, A., Dwianto, L., & Kristina, T. (2021). Development of an online application system for implementing evidence based nursing practice. *Journal of Nursing Leadership and Management*, 4(1). <https://doi.org/10.32584/jkkm.v4i1.839>
- Rahardja, U. (2022). Health record scheme using blockchain technology in education. *Mentari Journal of Educational Management and Information Technology*, 1(1), 29-37. <https://doi.org/10.34306/mentari.v1i1.134>
- Rahardjo, P. (2022). The automatic watering system uses a soil moisture sensor based on an Arduino Mega 2560 microcontroller on sweet fragrant mango plants in Buleleng, Bali. *Electrical Technology Scientific Magazine*, 21(1), 31. <https://doi.org/10.24843/mite.2022.v21i01.p05>
- Reyana, A. and Vijayalakshmi, P. (2022). Multisensor information fusion and optimization technique for wildfire detection and prevention in wsn environment.. <https://doi.org/10.21203/rs.3.rs-920835/v1>
- Song, J. and Zhu, Y. (2013). Environment monitoring system for precise agriculture based on wireless sensor network. *Applied Mechanics and Materials*, 475-476, 127-131. <https://doi.org/10.4028/www.scientific.net/amm.475-476.127>
- Su, S., Wu, W., Gao, J., Lu, J., & Fan, C. (2012). Nanomaterials-based sensors for applications in environmental monitoring. *Journal of Materials Chemistry*, 22(35), 18101. <https://doi.org/10.1039/c2jm33284a>
- Sudarsono, A. and Rasyid, M. (2017). Secure data sensor in environmental monitoring system using attribute-based encryption with revocation. *International Journal on Advanced Science Engineering and Information Technology*, 7(2), 609. <https://doi.org/10.18517/ijaseit.7.2.2175>
- Sudarsono, A. and Rasyid, M. (2018). Secure data exchange using authenticated attribute-based encryption with revocation for environmental monitoring. *International Journal on Advanced Science Engineering and Information Technology*, 8(5), 1948-1955. <https://doi.org/10.18517/ijaseit.8.5.7223>
- Sunarya, P. (2022). Implementation of certificates in security systems using blockchain technology. *Mentari Journal of Educational Management and Information Technology*, 1(1), 58-67. <https://doi.org/10.34306/mentari.v1i1.139>
- Syamsuryadi, B., Faridah, R., Khaeruddin, K., Hermawansyah, H., & Armayanti, A. (2021). Application of duck feed processing technology from agricultural waste. *Abdimas Galuh*, 3(2), 535. <https://doi.org/10.25157/ag.v3i2.6242>
- Wang, W., Feng, C., Zhang, B., & Gao, H. (2019). Environmental monitoring based on fog computing paradigm and internet of things. *Ieee Access*, 7, 127154-127165. <https://doi.org/10.1109/access.2019.2939017>
- Wang, Z. (2011). Self-powered nanosensors and nanosystems. *Advanced Materials*, 24(2), 280-285. <https://doi.org/10.1002/adma.201102958>
- Yang, M. (2021). Unmanned driving infringement judgment based on wireless sensor network data mining. *Journal of Sensors*, 2021, 1-11. <https://doi.org/10.1155/2021/1599330>
- Yang, Y. and Deng, Z. (2019). Stretchable sensors for environmental monitoring. *Applied Physics Reviews*, 6(1). <https://doi.org/10.1063/1.5085013>
- Zhao, C. and Yu, H. (2021). Mobile sensor networks: what can underground electric transport vehicles do in underground mine monitoring?. *Asian Journal of Research in Computer Science*, 1-6. <https://doi.org/10.9734/ajrcos/2021/v12i130272>
- Zowj, A., Bongard, J., & Skalka, C. (2015). A genetic programming approach to cost-sensitive control in resource constrained sensor systems.. <https://doi.org/10.1145/2739480.2754751>

