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Wireless Sensor Network in Environment Monitoring: Advancements, Applications, and Challenges for Real-Time Data Collection and Analysis

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ABSTRACT
Wireless Sensor Networks (WSNs) are widely used in environmental monitoring due to their ability to collect data in remote or hazardous locations without requiring wired connections. These networks consist of distributed sensor nodes that gather data on various environmental parameters, such as temperature, humidity, air quality, and soil moisture. WSNs offer real-time monitoring, allowing for timely responses to environmental changes and potential threats. The collected data is transmitted wirelessly to a central server for analysis and decision-making. They help in detecting natural disasters, managing agricultural systems, and monitoring climate change. However, challenges such as energy efficiency, data security, and scalability must be addressed for optimal performance. The integration of WSNs with IoT (Internet of Things) enhances their functionality, enabling better automation and control. WSNs offer low-cost, high-efficiency solutions for continuous environmental surveillance. This paper explores the architecture, applications, challenges, and future directions of WSNs in environmental monitoring.

Keywords: Sensor-based wireless network, sink, and environmental data collection.

1. INTRODUCTION

With the fast growth of wireless communication, embedded systems, and sensor technology, Wireless Sensor Networks (WSNs) have emerged. Due to their low cost and low power usage, they are being used more and more in environmental monitoring..

A Wireless Sensor Network (WSN) is a self-organizing network made up of many small sensor nodes placed in a monitoring area. Figure 1 shows a typical WSN model, which includes four main parts: sensor nodes, a sink node, a communication network (CN), and a monitoring center.Their job is to observe the target, collect data from their surroundings, and process the information using built-in computing modules. The collected data is then sent to nearby nodes or sink nodes using a multi-hop method.

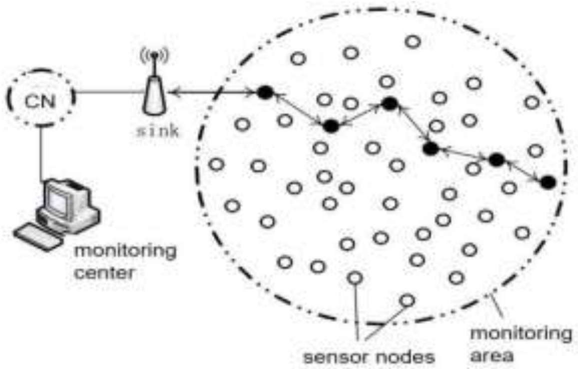

Figure 1: A standard WSN system includes sensor nodes deployed in a target environment,

The sink node acts like a gateway with strong processing, storage, and communication abilities. It connects the WSN to the communication network, allowing real-time data processing and control through the monitoring center.

A modern Wireless Sensor Network (WSN) is like a new type of distributed control system made up of many sensor nodes spread across a monitoring area. Unlike traditional sensor systems, WSNs do not rely on fixed network infrastructure. Instead, the sensor nodes create a self-organizing network based on specific transmission rules, sending data through multiple connected nodes.

These nodes can communicate with distant nodes using intermediate ones and can join or leave the network at any time without disrupting others. This makes WSNs highly flexible, resistant to failures, and capable of covering large areas.

Because of these benefits, WSNs are widely used and researched in various fields, including the military, industry, agriculture, environmental monitoring, healthcare, smart homes, and space and ocean exploration. They have gained strong interest from military organizations, industries, and researchers worldwide.

Environmental monitoring is one of the key applications of wireless sensor networks. As people become increasingly aware of environmental issues, the demand for advanced monitoring technologies continues to grow. Traditional methods of collecting environmental data are often challenging and inefficient. For instance, gathering raw data manually can be time-consuming and difficult.

Traditional atmospheric monitoring relies on manual sampling. Workers collect air samples over a set period and then analyze them in a laboratory. This method only provides average data for that time frame rather than real-time information, and results can be influenced by human factors. Additionally, exposure to toxic gases can pose serious health risks to the workers.

Wireless Sensor Networks (WSNs) offer an effective solution to these challenges. With their ability to communicate and operate through multiple sensor nodes, they can gather more data while minimizing human involvement. This improves accuracy, efficiency, and safety in environmental monitoring.

Because of these advantages, WSN-based environmental monitoring enhances traditional methods and has great potential for the future. Research on its applications—such as real-time data collection, monitoring, processing, analysis, and prediction—is crucial for improving both the effectiveness and safety of environmental monitoring systems.

2. CURRENT CHALLENGES AND CORE TECHNOLOGIES IN WIRELESS SENSOR NETWORK RESEARCH

Based on its function, the structure of a wireless sensor network can be divided into five layers: the basic layer, network layer, middleware layer, data management and processing layer, application development environment layer, and application layer. The tableillustrates this structure. Each layer has its own tasks and challenges. The following sections discuss the main components, important issues, and key technologies related to wireless sensor network research.

Table 1: The structure of a wireless sensor system consists of sensor nodes, communication modules, a sink node or gateway, and a central processing unit, working together to collect, transmit, and analyze data efficiently

Application Layer
Application Development Environment Layer
Data Management and Processing Layer
Network Layer
Basic Layer

2.1.Basic layer

The foundational layer is centered around the sensor set, encompassing each sensor's software and hardware resources. This layer's primary functions include object monitoring, information collection, and the initial processing and transmission of gathered data. A crucial aspect of research in this layer focuses on wireless sensor networks' software and hardware technologies.

2.2. Network layer

The network layer is focused on the communication network, including the hardware and software needed for communication. Its main functions are enabling communication between sensors, sensors and observers, and supporting cooperation between multiple sensors to complete larger tasks. Research in this area mainly focuses on communication protocols and wireless sensor network technologies.

2.3.Data managementandprocessinglayer

This layer handles the storage, analysis, and mining of data to support decision-making. The key focus is on managing and processing the data effectively to help users make informed decisions. The software used to manage, analyze, and process the data collected by the sensors.

2.4. Applicationdevelopmentenvironment layer

The main function of this layer provide the tools needed for programming and developing applications that use the wireless sensor networks.Key focus here is on programming languages, network applications, and decision-making support systems based on sensor data. The software development tools and environment that help users build sensor network systems.

2.5.Application layer

This layer's function includes software systems that help users apply sensor network data in real-world applications. The focus is on developing applications for various uses of the wireless sensor network, which are software applications that actually use the data from the sensor network.

3. APPLICATIONS OF WIRELESS SENSOR NETWORKS (WSNs) IN ENVIRONMENT MONITORING

Wireless Sensor Networks (WSNs) have become a crucial technology in environmental monitoring due to their ability to collect, analyze, and transmitreal-time data in remote and hard-to-reach research areas. These networks consist of specially distributed sensors that can gather various environmental parameters such as temperature, humidity, air quality, soil moisture, pollution level and more**.**

3.1 Atmospheric Environment Monitoring with Wireless Sensor Networks (WSNs)

Atmospheric environment monitoring using Wireless Sensor Networks (WSNs) is an important application for real-time tracking of atmospheric conditions. Traditional gas composition monitoring systems have several limitations, such as being large, difficult to install, and heavily reliant on wired communication. These systems often lack flexibility and efficiency in detecting changes in environmental parameters.

With the advent of WSNs, atmospheric conditions across large areas can now be monitored in real time. WSNs enable the detection of various gas compositions and allow for timely monitoring of toxic gas leaks, taking into account factors like wind direction, speed, and gas concentration—parameters that are collected by sensor nodes distributed across the environment.

"Wireless sensor networks (WSNs) heavily depend on
wireless communication. Using WSNs, atmospheric conditions can be monitored in real-time, the composition of gases can be detected with various sensor probes, and the leakage of harmful gases can be tracked effectively based on parameters like wind direction, wind speed, and gas concentration collected by the nodes.

J Geng, X Zhou, and B Zhang proposed a network setup foran atmospheric environment detection system based on WSN. They designed the hardware structure of wireless sensor network nodes for monitoring the environment.

For instance, J. Geng, X. Zhou, and B. Zhang proposed a network construction scheme for an atmospheric environment detection system based on WSNs, focusing on designing a wireless sensor network node hardware structure specifically for atmospheric monitoring. Z. Wu and colleagues developed a wireless sensor network system capable of monitoring harmful gases in living areas. This system can operate continuously for up to three weeks, with nodes transmitting data directly to a central sink node. The system boasts a maximum data transmission rate of 165 kb/s, with a transmission range of 75 meters between buildings and up to 320 meters in open areas.

Additionally, Y. Li, G. Ji, and J. Han designed a multi-greenhouse environmental monitoring system using WSNs, incorporating ZigBee technology, mesh topology, and 2.4 GHz RF transceiver modules. Their system provides a stable, scalable solution for monitoring various environmental parameters in a greenhouse setting, offering both hardware and software schemes for individual greenhouse applications. The system is simple in design, flexible in sensor placement, and enhances real-time monitoring capabilities.

3.2 Water resources monitoring

Wireless Sensor Network (WSN) technology offers significant advantages for water resources monitoring. The nodes in a WSN can measure various environmental parameters, including temperature, infrared light, visible light, and toxic substances. These networks are easy to deploy, requiring no infrastructure like cables, which makes them cost-effective and versatile. Furthermore, sensor nodes are inexpensive and can be densely deployed over large water bodies, facilitating the analysis of spatial correlations within the collected data to enhance environmental monitoring accuracy.

For instance, L. Zhao and J. Fan combined WSN with soft sensors and advanced information processing techniques to monitor wetland water quality in real-time, improving the detection accuracy of remote environmental monitoring systems. Similarly, W. Bi and H. Guo utilized the ZigBee protocol to establish a wireless sensor network designed to monitor the marine environment. This system integrates wireless sensing technology, embedded computing, modern networking, wireless communication, and distributed intelligent information processing. The result is a network that significantly enhances the sensors' capability to monitor various oceanic parameters. The system leverages medium- and short-range low-power wireless networks, which reduce radio frequency transmission costs and support flexible power supply options.

3.3 Geology monitoring

Wireless Sensor Networks (WSNs) are also increasingly applied in geology monitoring. For example, the University of Southampton's GlacsWeb system project aims to monitor and analyze glacier activity using WSN technology. Deployed on the Briksdalsbreen Glacier within the Jostedalsbreen Ice Sheet in Norway, sensors placed on, within, and beneath the glacier collect data and transmit it to base stations. The data gathered significantly contributes to the study of globalacier movement and its implications for global warming.

In another notable application, L. Luo and Y. Zhang designed a WSN specifically for monitoring glaciers in extreme environments. They outlined the network structure and data transmission paths for the sensor nodes. They also highlighted several challenges associated with WSNs, such as the operating system, sensor materials, energy consumption, and communication capabilities in sub-glacial environments. To address these challenges, they proposed strategies for constructing an all-weather observation network and real-time data display platform, utilizing tools like Google Earth and Google SketchUp to enhance data visualization.

3.4 Mineenvironmentmonitoring

Accidents in coal mines are common, and the safety of workers underground is a major concern. To improve safety, it's important to have effective monitoring technology. As coal production grows, mines are becoming more complex, making wired safety systems less effective. Wireless systems, like ZigBee technology, are a better solution. ZigBee is a wireless network that uses little power, is low cost, and can transmit data over short distances. It is very useful in creating sensor networks to monitor safety in mines. Researchers like Y. Zhang, G. Yuan, and L. Chen have developed a wireless positioning system using ZigBee to improve underground communication and safety.

3.5 Militaryenvironmentmonitoring

Wireless sensor networks are made up of many small, low-cost sensors that can be spread out and self-organize. This makes them more resilient because the system can still work even if some sensors are damaged or attacked. These networks are useful in military settings, especially for tasks like monitoring equipment, tracking enemy forces, and detecting biological or chemical threats. The US Army has launched several projects to explore how wireless sensor networks can improve battlefield operations. One project, called Sens IT, helps soldiers get real-time information from sensors scattered across the battlefield. Another project, called A Line in the Sand, uses wireless sensors to detect enemy vehicles. These systems are expected to revolutionize how military operations are conducted in the future.

Wireless sensor networks are made up of many low-cost, widely distributed nodes. These networks are self-organizing and fault-tolerant, which means they can continue to function even if some nodes are damaged in attacks. This makes them ideal for use in challenging military environments. They are a key part of systems like C4ISRT (Command, Control, Communication, Computing, Intelligence, Surveillance, Reconnaissance, and Targeting). WSNs can be used to monitor military equipment, assess enemy defenses, track attack targets, and detect nuclear, biological, and chemical threats.

The U.S. Army has launched several projects to explore how WSNs can be used in future warfare. One such project is SensIT, which enables soldiers to gather battlefield information quickly by deploying WSNs with different types of sensors. These networks are self-organizing, meaning they adapt to failures and aging equipment and can respond to changing needs. Another project, called "A Line in the Sand," involves deploying wireless sensor systems to detect enemy tanks and vehicles. These technologies are shaping the future of the battlefield, providing new ways to monitor and control military operations.

3.6 Applications of Wireless Sensor Networks

Wireless sensor networks also have many other uses, such as monitoring environments in mining, agriculture, forestry, animal husbandry, and pipeline transportation.Wireless Sensor Networks (WSNs) have various applications in environmental monitoring beyond the common uses like weather forecasting and pollution detection. Here are some other innovative uses:

1. Wildlife Tracking and Conservation
2. Forest Fire Detection
3. Landslide Prediction and Monitoring
4. Water Quality Monitoring
5. Glacier and Iceberg Monitoring
6. Soil and Agricultural Monitoring
7. Air Quality and Noise Pollution Monitoring
8. Coastal and Marine Ecosystem Monitoring
9. Volcanic Activity Monitoring
10. Radioactive and Hazardous Waste Monitoring

The Future of Wireless Sensor Networks

Although the field of wireless sensor networks is growing rapidly, there are still many challenges to overcome. Issues like power consumption, network reliability, environmental conditions, and network maintenance need to be addressed. For example, many sensor nodes rely on built-in batteries, so finding ways to conserve power and extend their lifespan is crucial. Also, remote sensor nodes, which are hard to access or maintain, often break down, creating challenges in network upkeep.

These problems can't be solved individually. The best approach is to balance these issues to make WSNs as effective as possible. As technology continues to improve, wireless sensor networks will become an essential part of daily life and be used in many more applications in the near future.

4 CONCLUSION

As the Internet of Things (IoT) and smart technology continue to grow, the demand for wireless sensor networks (WSNs) is increasing due to their low cost and low power consumption. Researchers are particularly interested in using WSNs for environmental monitoring. Several studies, such as those on atmospheric environment detection, marine water monitoring, and the GlacsWeb system project, show that WSNs offer significant benefits and a promising future in environmental monitoring. However, there are challenges to address, such as power consumption, network reliability, environmental conditions, system structure, cost, and fault tolerance. Despite these challenges, researchers are working hard to overcome them, and with time, these issues will be solved, making WSNs even more effective and widely used.

Wireless Sensor Networks (WSNs) offer versatile and powerful solutions for environmental monitoring across various domains. By enabling real-time data collection, analysis, and communication, these networks significantly enhance our ability to observe, manage, and protect the environment. With applications in air and water quality monitoring, agriculture, disaster management, and beyond, WSNs play a crucial role in promoting sustainable environmental practices, improving public health, and safeguarding natural resources for future generations.

REFERENCES

1. D. Gislason, T. Gillman. ZigBee wireless sensor networks [J]. Dr. Dobb’s Journal, 2004, 29(11): 38-40.
2. K. Martinez, J.K. Hart, R. Ong. Deploying a wireless sensor network in Iceland. In: N. Trigoni, A. Markham, S. Nawaz. Lecture Notes in Computer Sciences: Proceedings of the 3rd International Conference on GeoSensor Networks, Berlin, Springer, 2009, pp. 131-137.

3. L. Luo, Y. Zhang. Application research of wireless sensor networks in glacial environment monitoring[J]. Journal of Glaciology and Geocryology, 2008, 30(6): 1018-1023.
4. W. Bi, H. Guo. Design of ocean water environment monitoring system based on wireless sensing network [J]. Electronic Technology, 2010(8): 68-71.
5. F. Hong, H. Chu, Z. Jin, et al. Review of recent progress on wireless sensor network application[J]. Journal of Computer Research and Development, 2010, 47 (Supp.2): 81-87.
6. L. Zhao, J. Fan. Research on key technology of water resources monitoring system based on wireless sensor networks [J]. Computer and Modernization, 2010(8): 85-88.
7. Z. Wu, Z. Liu, J. Liu, et al. Wireless sensor networks for living environment monitoring. In: Proceedings of the 2009 WRI World Congress on Software Engineering, Xiamen, 2009, pp. 22-25.
8. T. Arampatzis, J. Lygeros, S. Manesis. A Survey of Applications of Wireless Sensors and Wireless Sensor Networks. In: Proceedings of the 2005 IEEE International Symposium on Mediterranean Conference on Control and Automation Intelligent Control, 2015, pp. 719-724.
9. Y. Li, G. Ji, J. Han. Application of the wireless sensor network in the environment monitoring system of a green house [J]. Process Automation Instrumentation, 2010, 31(10): 61-64.
10. F. Kiyoshi, T. Akira, Shigeru. ZigBee technology for low-cost and low-power radio communication systems[J]. Journal of the Institute of Electronics, Information and Communication Engineers, 2005, 88(1): 40-45.
11. Witrante, D. Innocenzo, A. Sandoug, et al. Wireless ventilation control for large-scale systems: The mining industrial case[J]. International Journal of Robust and Nonlinear Control, 2010, 20(2): 226-251.
12. X. Jing, W. Wang, L. Hei, et al. Application of wireless sensor network in coal mine safety intelligent monitoring system[J]. Coal Technology, 2009, 28(4): 93-97.
13. J. Geng, X. Zhou, B. Zhang. An atmosphere environment monitor system based on wireless sensor network[J]. Journal of Xi-hua University: Natural Science, 2007, 26(4): 44-46, 96.
14. I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, et al. Wireless sensor network: A survey[J]. Computer Networks, 2002, 38(4): 393-422.
15. Y. Kang, Y. Hu, C. Xie, et al. Application of WIFI in mine emergency WSN[J]. Journal of Henan Polytechnic University: Natural Science, 2010, 29(5): 635-638.
16. J. Jia. Coverage Control and Node Deployment Technologies in Wireless Sensor Networks[M]. Shenyang: Publisher of Dongbei University, 2013.
17. H. Chen. Overview of Wireless Sensor Network[J]. Software, 2016, 37(09): 105-108.
18. Z. Guo, H. Luo, F. Hong, et al. Current progress and research issues in underwater sensor networks[J]. Journal of Computer Research and Development, 2010, 47(3): 377-389.
19. W. Wang, T. Wang, Q. Wu, et al. Survey of delay-constrained data collection with mobile elements in WSN[J]. Journal of Computer Research and Development, 2016, 53(11): 1-19.
20. H. Wang, J. Elson, L. Girod, et al. Target classification and localization in habitat monitoring[J]. In: Proceedings of IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP 2003), Hong Kong, China, 2003.
21. P. Gong. Progress in recent environmental applications of wireless sensor networks[J]. Journal of Remote Sensing, 2010, 14(2): 387-395.
22. Hart, J. K., & Martinez, K. (2006). Environmental sensor networks: A revolution in the earth system science? *Earth-Science Reviews*, 78(3-4), 177-191.

23. Albaladejo, C., Sánchez, P., Iborra, A., Soto, F., López, J. A., & Torres, R. (2010). Wireless sensor networks for oceanographic monitoring: A systematic review. *Sensors*, 10(7), 6948-6968.
24. Lloret, J., Garcia, M., Bri, D., & Sendra, S. (2009). A wireless sensor network deployment for rural and forest fire detection and verification. *Sensors*, 9(11), 8722-8747.
25. Yick, J., Mukherjee, B., & Ghosal, D. (2008). Wireless sensor network survey. *Computer Networks*, 52(12), 2292-2330.
26. Wang, N., Zhang, N., & Wang, M. (2006). Wireless sensors in agriculture and food industry—Recent development and future perspective. *Computers and Electronics in Agriculture*, 50(1), 1-1
27. Mainwaring, A., Polastre, J., Szewczyk, R., Culler, D., & Anderson, J. (2002, June). Wireless sensor networks for habitat monitoring. *Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications*, 88-97.
28. Zhang, Y., & Zhao, Q. (2007). Sensor deployment algorithms for wireless sensor networks with mobile sinks. *IEEE Transactions on Mobile Computing*, 6(5), 543-556.
29. Dyo, V., et al. (2010). Wildlife and environmental monitoring using RFID and WSN technology. *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems*, 145–158.
30. Araujo, A., et al. (2012). Real-time environmental monitoring for oil spill detection using wireless sensor networks. *Sensors*, 12(1), 119-132.
31. Ahmed, A., & Rani, M. (2016). A review on WSN-based smart irrigation systems for precision agriculture. *International Journal of Engineering Research & Technology*, 5(10), 253–257.
32. Rawat, P., Singh, K. D., Chaouchi, H., & Bonnin, J. M. (2014). Wireless sensor networks: A survey on recent developments and potential synergies. *The Journal of Supercomputing*, 68(1), 1–48.
33. Chong, C. Y., & Kumar, S. P. (2003). Sensor networks: Evolution, opportunities, and challenges. *Proceedings of the IEEE*, 91(8), 1247–1256.
34. Sankara Subramaniam, Y., Akan, O. B., & Akyildiz, I. F. (2003). ESRT: Event-to-sink reliable transport in wireless sensor networks. *Proceedings of the 4th ACM International Symposium on Mobile Ad Hoc Networking & Computing*, 177–188.
35. Ahmed, M. T., et al. (2015). Wireless sensor network-based system for real-time flood monitoring and warning. *Procedia Computer Science*, 52, 382–389.
36. Kim, Y., Evans, R. G., & Iversen, W. M. (2008). Remote sensing and control of an irrigation system using a distributed wireless sensor network. *IEEE Transactions on Instrumentation and Measurement*, 57(7), 1379–1387.
37. Li, X., et al. (2012). A real-time monitoring system for landslide disaster using wireless sensor networks. *Environmental Earth Sciences*, 66(7), 1877–1886.
38. Sudevalayam, S., & Kulkarni, P. (2011). Energy harvesting sensor nodes: Survey and implications. *IEEE Communications Surveys & Tutorials*, 13(3), 443–461.
39. Iova, O., et al. (2016). Low-power wireless sensor networks for environmental monitoring: The LoRa way. *IEEE Conference on Wireless and Mobile Computing, Networking and Communications*, 1–8.
40. Gupta, H., et al. (2016). Real-time air quality monitoring using wireless sensor networks. *IEEE Sensors Journal*, 16(19), 7232–7244.
41. Gungor, V. C., & Hancke, G. P. (2009). Industrial wireless sensor networks: Challenges, design principles, and technical approaches. *IEEE Transactions on Industrial Electronics*, 56(10), 4258–4265.

42. Sudha, T., & Valarmathi, M. L. (2014). A comparative study of WSN protocols for precision agriculture. *Procedia Engineering*, 97, 345–352.
43. Zennaro, M., et al. (2009). On the design of a water quality wireless sensor network. *International Conference on Information and Communication Technologies and Development*, 1–12.
44. Lin, J., Yu, W., Zhang, N., Yang, X., & Zhao, W. (2017). A survey on Internet of Things: Architecture, enabling technologies, security and privacy, and applications. *IEEE Internet of Things Journal*, 4(5), 1125–1142.
45. Shaikh, F. K., Zeadally, S., & Exposito, E. (2015). Enabling technologies for green Internet of Things. *IEEE Systems Journal*, 11(2), 983–994.
46. Kumar, R., & Patel, D. R. (2014). A survey on Internet of Things: Security and privacy issues. *International Journal of Computer Applications*, 90(11), 20–26.
47. Atzori, L., Iera, A., & Morabito, G. (2010). The Internet of Things: A survey. *Computer Networks*, 54(15), 2787–2805
48. Saini, H., et al. (2015). Smart environment monitoring using wireless sensor networks. *Procedia Computer Science*, 70, 508–513.
49. Khedo, K. K., Perseedoss, R., & Mungur, A. (2010). A wireless sensor network air pollution monitoring system. *International Journal of Wireless & Mobile Networks (IJWMN)*, 2(2), 31–45.
50. Anastasi, G., Conti, M., Di Francesco, M., & Passarella, A. (2009). EnergyAnastasi, G., Conti, M., Di Francesco, M., &22.22 Conservation in wireless sensor networks: A survey. *Ad Hoc Networks*, 7(3), 537–568.
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