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IoT-Based Environmental Monitoring System with Machine Learning for Accurate and Real-time Data Analysis

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Abstract
The integration of IoT with machine learning has revolutionized environmental monitoring, enabling precise and real-time data assessment. The investigations seeks to systematically review the advancements and barriers connected with IoT-based environmental monitoring systems, particularly those employing machine learning techniques for enhanced data processing and prediction accuracy. The research focuses on various applications, including air and water quality monitoring, weather prediction, and pollution forecasting. Adopting the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, 28 relevant studies were analyzed from reputable journals and conferences spanning from 2017 to 2024. The findings indicate significant progress in developing IoT and machine learning-driven environmental monitoring systems, with a trend towards integrating AI for better accuracy and reliability. However, the review highlights the need for more comprehensive frameworks that address the challenges of data handling, real-time processing, and scalability. The report accentuates the value of maintaining data privacy concerns and ensuring the interoperability of IoT devices across different platforms. Furthermore, the analysis reveals a noticeable gap in the literature regarding the standardization of these systems across different environmental parameters and geographies, which poses a challenge for widespread adoption. This review provides a critical analysis of current technologies and alludes to directions for further investigation, particularly in enhancing the robustness and generalizability of these systems for global environmental monitoring.
Keywords: IoT-based Environmental Monitoring, Machine Learning, Real-time Data Analysis, Environmental Data Processing.

I. INTRODUCTION

Environmental monitoring has become increasingly crucial in our modern world as we face growing concerns about air pollution, water quality, and overall ecosystem health. For example: [1] developed a system for monitoring generator emissions using ZigBee protocols and Arduino microcontrollers. This system could detect LPG and carbon monoxide concentrations in real-time, providing valuable data for air quality management.

The inception of IoT technology, coupled with advanced sensors and machine learning techniques, has revolutionized our ability to assemble, evaluate, and interpret environmental data in real-time [2]. This integration of technologies offers unprecedented opportunities for creating more responsive and effective environmental management systems [3].

The swift expansion of global population, coupled with increasing industrialization and urbanization, has led to significant environmental challenges [4]. These challenges, which significantly impact human health, include air and water pollution, soil degradation, and climate change, biodiversity, and economic sustainability [5]. Traditional environmental monitoring methods often lack the spatial and temporal resolution needed to fully understand and address these complex issues [6].

IoT-based environmental monitoring systems have emerged as a powerful solution to these limitations [7]. By deploying networks of interconnected sensors, we can now gather vast amounts of data on various environmental parameters in real-time [8]. This data includes measurements of air quality, water quality, soil conditions, temperature, humidity, and many other factors critical to environmental health [9]. Yet, the massive quantity and intricate nature of data produced by these IoT systems introduce novel difficulties in managing and analyzing the information [10]. This is where machine learning algorithms play a crucial role. By applying advanced analytics and predictive modeling techniques, we can derive valuable insights from the gathered information, recognize patterns, and predict future environmental conditions with precision [11].

The integration of IoT and ML in ecological evaluation has far-reaching implications across various sectors:

1) Urban Planning: Real-time air quality monitoring can inform traffic management and urban development decisions [12].

2) Agriculture: Soil and climate monitoring can optimize crop management and irrigation practices [13].

3) Industrial Safety: Continuous monitoring of emissions and pollutants can enhance workplace safety and regulatory compliance [14].

4) Public Health: Early detection of environmental hazards can help prevent health crises and inform public health policies [15].

The chief contribution of this research is a comprehensive overview of the present state of IoT-based environmental monitoring systems and application of machine learning in environmental data analysis. We will explore the technologies involved, discuss key applications, and examine the issues and possibilities in this rapidly transforming discipline. By doing so, aspire to support the continuous improvement of more effective and flexible environmental monitoring technologies.

2. BACKGROUND AND RELATED WORKS

A. IoT-Based Environmental Monitoring Systems

The Internet of Things has unveiled as a crucial resource for environmental assessment, supporting the insyallation of various sensor gadgets to collect detailed spatial and temporal data [16]. These systems typically consist of various sensors measuring attributes such as temperature, humidity, air quality, water quality, and radiation levels [17].

The architecture of an IoT-based environmental monitoring system generally includes three main components:

1) Sensor Nodes: These are the devices that collect environmental data. They can be stationary or mobile and are equipped with various sensors depending on the monitoring requirements [18].

2) Communication Network: This component facilitates the transfer of data from sensor nodes to the central processing unit. It may use various protocols such as Wi-Fi, Zigbee, LoRaWAN, or cellular networks, depending on the deployment scenario [19].

3) Data Processing and Storage: This includes cloud-based platforms or edge computing devices that receive, process, and store the collected data. It also typically includes user interfaces for data visualization and analysis [20].

IoT-based environmental monitoring systems offer numerous benefits compared to conventional methods:

1) Real-time data collection and transmission: These systems can provide continuous, up-to-date information about environmental conditions, enabling rapid response to changes or emergencies [21].

2) Scalability and flexibility in deployment: IoT systems can be easily expanded or reconfigured to cover larger areas or monitor additional parameters as needed [22].

3) Cost-effectiveness and reduced human intervention: Once deployed, these systems can operate autonomously, reducing the need for manual data collection and lowering long-term operational costs [23].

4) Integration with other systems: IoT environmental monitoring systems can be integrated with other smart city or industrial systems, providing a more comprehensive approach to environmental management [24].

Current studies have proven the efficacy of IoT-based systems in various environmental monitoring applications. Similarly, researchers have created IoT-based water quality monitoring systems capable of measuring parameters such as pH, turbidity, and dissolved oxygen in real-time [25]. These systems have proven particularly valuable in monitoring sensitive aquatic ecosystems and ensuring the safety of drinking water supplies.

B. Machine Learning in Environmental Data Analysis

The incorporation of ML techniques with IoT-based environmental monitoring systems has significantly optimized the capability to examine and interpret complex ecological data [26]. Machine learning algorithms detects trends and forecasts outcomes, and uncover key insights that traditional methods might miss [27].

Several machine learning approaches have been applied to environmental monitoring data:

1) Supervised Learning: These algorithms, including regression and classification models, are used for predicting specific environmental parameters or classifying environmental conditions [28].

2) Unsupervised Learning: Techniques such as clustering and dimensionality reduction are useful for discovering hidden patterns in environmental data and reducing data complexity.

3) Time Series Analysis: These methods are particularly valuable for analyzing temporal structures in environmental data and making predictions about future conditions.

4) Deep Learning: Advanced neural network architectures, such as CNNs and RNNs, are being applied to complex environmental data, including satellite imagery and sensor time series.

Other studies have employed more advanced techniques. To illustrate, researchers have applied deep learning models to analyze satellite imagery for detecting and classifying land use changes, which has important implications for monitoring deforestation and urban expansion.

In water quality monitoring field, ML algorithms have been implemented to predict algal blooms in lakes and reservoirs. By analyzing historical data on water temperature, nutrient levels, and other parameters, these models can provide early warnings of potentially harmful algal growth.

1. Exploring edge computing solutions for real-time data processing: Edge computing, where data is processed close to its source, could help address both data processing and privacy concerns. This process streamlines the data volume that needs to be conveyed and stored centrally, potentially improving system efficiency and security.
2. Enhancing data visualization and user interfaces: Developing intuitive, user-friendly interfaces for data visualization and analysis is crucial for making environmental monitoring data accessible to policymakers and the public.
3. Integrating with other emerging technologies: Investigating the convergence of IoT and ML with blockchain and other technologies for data integrity, or augmented reality for data visualization, could open up new possibilities in environmental monitoring.
4. Addressing ethical considerations: As these systems become more prevalent, addressing ethical concerns related to data ownership, privacy, and the potential misuse of environmental data is becoming increasingly important.

By continuing to advance these technologies and addressing the associated challenges, we can create more effective and comprehensive environmental monitoring systems. These systems have the potential to significantly improve our understanding of environmental processes, enhance our ability to predict and mitigate environmental risks, and ultimately contribute to a safer, healthier, and more sustainable world. Table 1 presents the different existing techniques handled by the researches.

Table 1 Survey from Different Authors

Ref.	Methodology	Results Obtained	Limitations
[1]	Used ZigBee protocols, Arduino Uno Atmega328p microcontroller, MQ7 sensor for gas detection. Implemented Naive Bayes and Exponential Smoothing Algorithms for prediction.	Illustrated the air quality index level during deployment. Estimated the type of gas released in real-time	Limited to detecting LPG and carbon monoxide concentrations between 20ppm and 2000ppm.
[2]	Introduced IoT wireless technologies and ML techniques for water quality monitoring.	Examined various IoT wireless technologies and ML algorithms for analyzing water quality data.	Barriers in uniting IoT wireless technologies and ML for water quality monitoring. Open-ended

			research queries still exist
[3]	Adapted IoT and sensor-based environmental monitoring systems.	Analyzed various studies on monitoring air, water, waste, and overall environmental pollution.	The accelerated rise in population and exhaustion of resources result in obstacles to deploying extensive monitoring systems.
[4]	Comprehensive review of IoT and sensor-based environmental monitoring systems.	Analyzed advancements in sensor technology, IoT, and machine learning methods for environmental monitoring.	Suggested the need for robust machine learning methods, denoising techniques, and development of suitable standards for wireless sensor networks.
[5]	Used DHT11 sensor for temperature and humidity, LDR for light intensity. Implemented logistic regression model for prediction.	Created a real-time weather prediction system using IoT and machine learning.	Limited to predicting based on temperature, humidity, and light intensity only.
[6]	Developed machine learning techniques for environmental monitoring.	Discussed applications of machine learning in various environmental monitoring scenarios.	Lack of specific implementation details or results.
[7]	Used smart biosensors, IoT, and machine learning for environmental monitoring.	Explored synergistic applications in air, water, soil, and ecosystem monitoring.	Identified challenges such as technical limitations, privacy concerns, and cost factors.
[8]	Used wireless sensor networks and machine learning for weather monitoring and prediction.	Developed a system for monitoring and predicting weather parameters.	Specific results and limitations not provided in the abstract.
[9]	Used Arduino platform, various sensors, and ML data modeling using R Language and RStudio IDE.	Accurately predicted trends in temperature, humidity, carbon monoxide level, and carbon dioxide. Compared prediction accuracy of MLP, k-NN, multiple regression, and SVM.	Limited to volunteer computing environments. Potential scalability issues.
[10]	Review of IoT sensor data handling and processing methods.	Reviewed several methods for dealing with and interpreting IoT sensor data in environmental observation networks	Identified issues in data quality, sensor reliability, accuracy, and in-field performance.
[11]	Developed a system using sensors, microcontroller, and IoT technology.	Created a low-cost, accurate, and user-friendly system for monitoring temperature, humidity, and harmful gases.	Limited to specific environmental parameters. Potential connectivity issues in areas with poor internet coverage.
[12]	Integrated IoT and machine learning for environmental monitoring and weather prediction.	Developed a system for real-time monitoring and prediction of meteorological parameters.	Lack of specific implementation details or results.
[13]	Review of AI and IoT technologies for environmental pollution monitoring.	Assessed contemporary breakthroughs in AI, sensors, and IoT for monitoring pollution.	Identified challenges in balancing model performance and interpretability, and data

			sharing concerns.
[14]	Comprehensive review of IoT and sensor-based environmental monitoring systems.	Analyzed advancements in sensor technology, IoT, and machine learning methods for smart environmental monitoring.	Identified the need for robust machine learning methods and suitable standards for wireless sensor networks.
[15]	Proposed a framework using fog computing and IoT for environmental monitoring.	Developed a system that uses local sub-classifiers and a deep neural network for data analysis. Implemented a federated learning mechanism.	Limited by the amount of data at single edge nodes. Potential communication cost and stability issues.
[16]	Review of IoT and machine learning for environmental monitoring.	Discussed various applications and methodologies for real-time	Complexity Overhead
17]	Review of IoT-based environmental monitoring systems.	Discussed various implementations and applications of IoT in environmental monitoring.	Focused on review rather than specific implementation or results.
[18]	Review of IoT and machine learning approaches for environmental parameter monitoring.	Examined various studies and methodologies for environmental monitoring using IoT and ML.	Limited to review of existing studies without specific implementation.
[19]	Developed a portable air quality detection device using MQ135 and MQ3 sensors. Used ThingSpeak for data storage and visualization.	Created a system for real-time air quality monitoring and analysis using IoT and machine learning.	Limited to specific air quality parameters. Potential dependency on internet connectivity.
[20]	Review of machine learning algorithms for air quality prediction and monitoring using IoT sensors.	Discussed various ML techniques for air quality prediction based on IoT sensor data.	Focused on review rather than specific implementation or results.
[21]	Review of machine learning and IoT technologies for water quality monitoring.	Examined various IoT wireless technologies and ML algorithms for water quality monitoring.	Identified challenges in integrating IoT and ML for water quality monitoring.
[22]	Used IoT sensors and machine learning (DBSCAN and Random Forest) for air pollution monitoring and forecasting.	Developed a system for real-time monitoring and forecasting of air pollutants.	Limited to specific air pollutants (CO, NH3, O3). Potential scalability issues.
[23]	Proposed integration of AI (GRU-Autoencoder) with IoT-connected Advanced Optical Systems.	Developed a system for real-time analysis and adaptive decision-making in environmental monitoring.	Challenges in data quality and interpretability of AI models.
[24]	Developed E-Sense using IoT sensors and ThingSpeak cloud platform.	Created a system for monitoring temperature, humidity, air quality index, CO concentrations, rain, and light.	Limited to specific environmental parameters. Potential dependency on cloud connectivity.
[25]	Used DHT11 and LDR sensors with NodeMCU and ESP8266-01 module. Implemented logistic regression for prediction.	Developed a system for real-time weather monitoring and prediction.	Limited to temperature, humidity, and light intensity parameters.
[26]	Developed IoT-based sensors and a big data processing platform. Used DBSCAN	Created a system for real-time monitoring and fault prediction in	Specific to automotive manufacturing processes.

	and Random Forest for fault detection.	automotive manufacturing.	Potential scalability issues.
[27]	Comprehensive review of smart environment monitoring systems using IoT and sensors.	Analyzed advancements in sensor technology, IoT, and machine learning for environmental monitoring.	Identified challenges in data quality, interpretability, and integration of various technologies.
[28]	Review of AI applications in environmental monitoring, focusing on ANNs and ML.	Examined the potential of AI in automotive and industrial emissions toxicity measurements and atmospheric pollution prevention.	Focused on review rather than specific implementation. Challenges in data quality and model interpretability

3. SYSTEMATIC LITERATURE REVIEW

SLR provides a structured approach to identify, evaluate, and summarize existing research within a specific field, helping to establish a foundation for future research directions. This SLR focuses on IoT-based environmental monitoring systems integrated with machine learning technologies, aiming to address current advancements, challenges, and gaps in the field.

3.1 Research Questions

This review addresses the upcoming research questions to guide the analysis of existing literature:

RQ-1: What are the key factors influencing the effectiveness of IoT-enabled environmental monitoring systems when integrated with advanced machine learning techniques?

RQ-2: How have machine learning models been applied to enhance the performance of environmental monitoring systems?

RQ-3: What are the emerging trends and challenges in combining IoT and machine learning for real-time environmental data analysis?

RQ-4: How do different environmental monitoring systems compare in terms of accuracy, efficiency, and scalability?

3.2 Data Sources and Search Strategy

The review involved a comprehensive search across major databases including IEEE Xplore, MDPI, Science Direct, and ResearchGate, with a focus on articles published from 2017 to 2024 which is depicted in Figure 1. The search strategy utilized a range of keywords and phrases to capture relevant literature. Key terms included "IoT-based environmental monitoring," "machine learning for environmental monitoring," "real-time data analysis," and "sensor networks." Additionally, variations such as "Internet of Things environmental systems," "AI for environmental data analysis," and "sensor fusion for environmental monitoring" were employed to ensure a broad coverage of the topic. Boolean operators (AND, OR) were used to combine these terms effectively, and filters were applied to limit results to peer-reviewed journal articles and conference papers in English. The search was refined through the removal of duplicates and irrelevant studies. An initial screening of abstracts determined relevance, followed by full-text reviews to ensure alignment with the research questions. Citation tracking and manual searches for recent advancements complemented the automated searches, ensuring a comprehensive collection of the most pertinent literature.

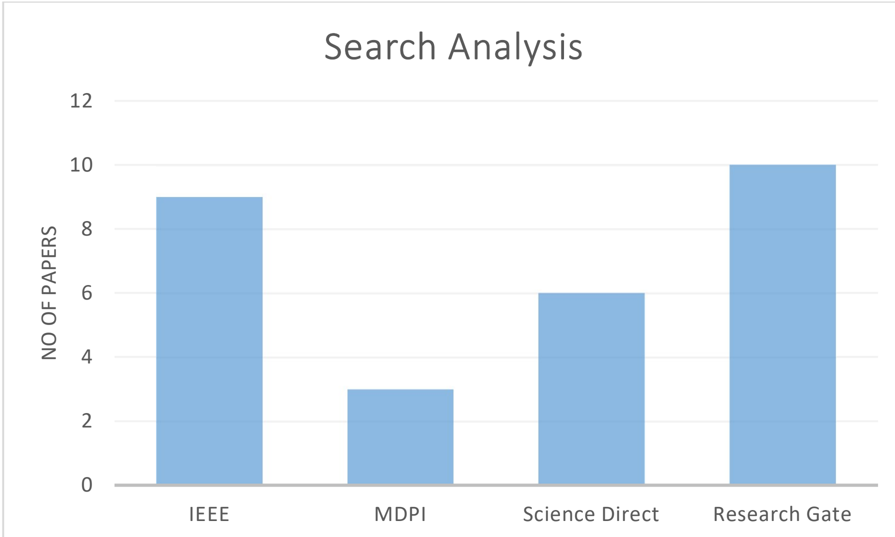

Figure 1: Search analysis from different sources

3.3 Inclusion and Exclusion Criteria

To affirm the applicability and standard of the selected research, the criteria for inclusion and exclusion detailed in Table 2 were enforced as shown:**Table 2 Inclusion and Exclusion criteria**

Criteria	Inclusion	Exclusion
Publication Date	Articles published from 2017 and 2024	Articles published before 2017 or after 2024
Article Type	Peer-reviewed journal articles, conference papers, dissertations, and technical reports	Non-peer-reviewed sources, editorials, opinion pieces, newsletters, and non-technical reports
Relevance	Focus on IoT-based environmental monitoring systems, machine learning applications in environmental contexts, real-time data analysis, sensor networks, and integration of these technologies	Articles not related to IoT, machine learning, or environmental monitoring; papers focused on unrelated technologies or domains
Methodology	Empirical studies, case studies, systematic reviews, and meta-analyses that present quantitative or qualitative data	Theoretical papers without empirical data or case studies; papers lacking methodological rigor or primary data collection
Language	English	Non-English articles; articles in languages other than English, which might hinder comprehensive understanding and integration
Geographical Focus	Global or specific regions relevant to the study scope, including diverse geographic locations to ensure generalizability	Articles focused solely on regions or countries with limited applicability to broader contexts or outside the study's geographical interest
Relevance to Research Questions	Studies that directly address research questions related to IoT-based environmental monitoring systems, machine learning techniques, or real-time data analysis	Papers that do not address the specific research questions or objectives of the systematic review, including those with only peripheral relevance

Data Availability	Articles that provide access to data or detailed methodologies used for experiments and analyses	Papers lacking sufficient detail on data sources, methodologies, or without providing access to underlying data for validation
Innovation and Impact	Studies presenting novel methodologies, significant advancements, or impactful findings in the field of environmental monitoring using IoT and machine learning	Articles that replicate known methods without offering new insights or contributions to the field; papers with outdated or less impactful findings

3.4 PRISMA Methodology

The PRISMA methodology was used to ensure a systematic and transparent review process. The PRISMA flowchart (Figure 2) details the stages of the review process, from initial identification to final selection of studies.

3.4.1 Search Results and Study Selection

The search method yielded 500 articles from the selected databases. After removing duplicates and applying the relevant inclusion and exclusion criteria, 144 articles are retained for further screening. Detailed abstract and full-text reviews led to the final selection of 28 articles for in-depth analysis.

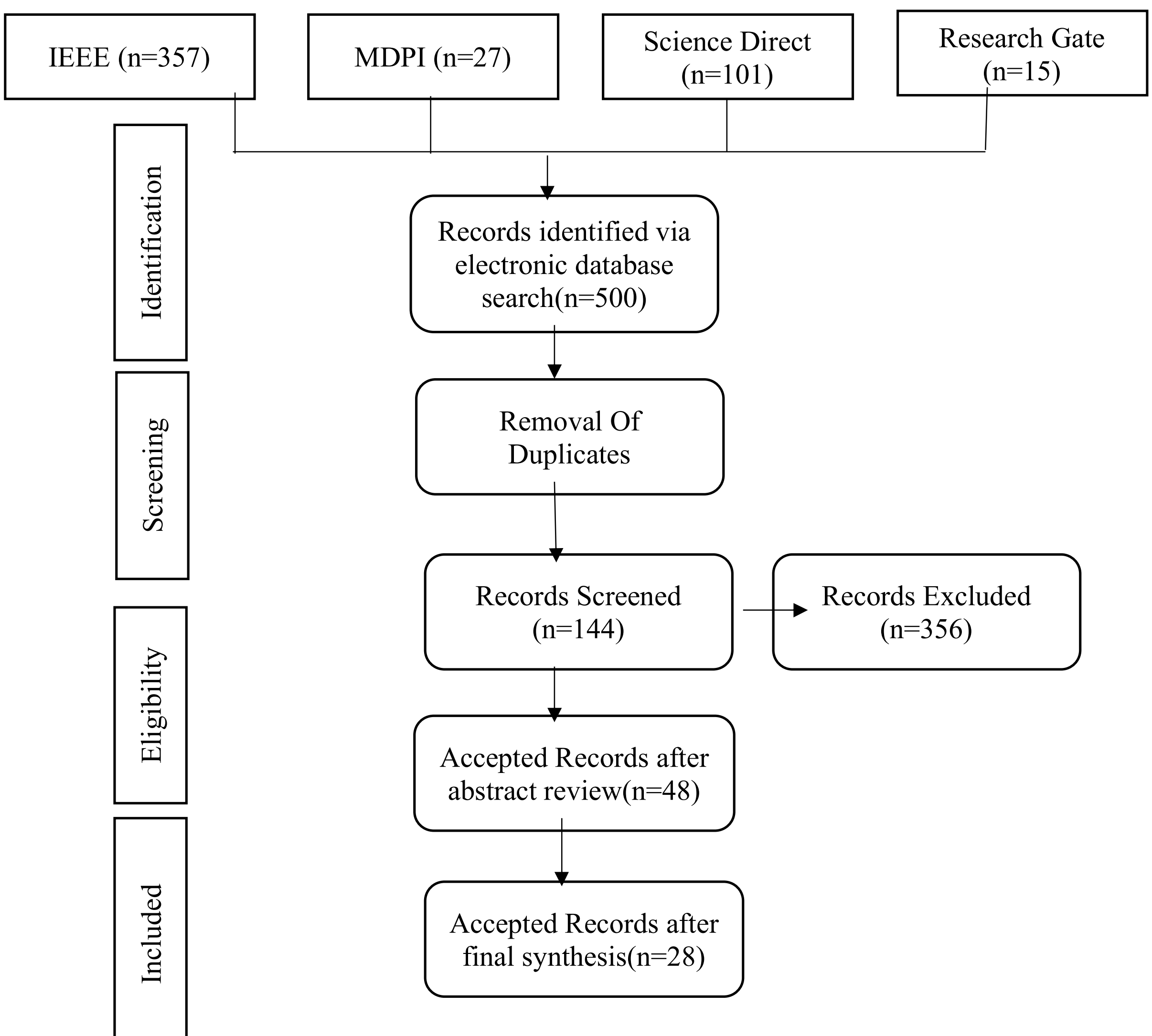

Figure 2 PRISMA Flowchart

3.5. Overview of Selected Studies

The selected studies encompass various aspects of IoT and machine learning integration in environmental monitoring. Key insights include:

- **Advancements in IoT and Sensors**: Recent research emphasizes significant progress in integrating wired and wireless sensors. These advancements elevate the exactness and trustworthiness of environmental monitoring systems by providing comprehensive data coverage and improved sensor fusion techniques.
- **Machine Learning Applications:** Machine learning algorithms have been successfully utilized to advance real-time data processing, forecast analytics, and anomaly identification. Approaches such as supervised learning, unsupervised learning, and DL have shown promising results in boosting the efficiency of environmental monitoring systems.
- **Challenges and Trends**: Current challenges include data handling complexities, integration of diverse sensor types, and ensuring system scalability. Emerging trends include the adoption of hybrid systems that leverage multiple sensors and data sources to provide more accurate and holistic environmental monitoring solutions.

3.6 Comparative Analysis

A comparative analysis of the methodologies, performance metrics, and outcomes from the selected studies reveals the following:

- **Accuracy**: Studies indicate that ML models greatly enhance the accuracy of environmental monitoring systems, with advancements in algorithmic approaches leading to better predictive performance and error reduction.
- **Efficiency**: Research highlights improvements in system efficiency through the optimization of data processing algorithms and real-time analytics, though some systems still face limitations in terms of computational overhead and data latency.
- **Scalability**: The scalability of environmental monitoring systems varies, with some studies focusing on small-scale deployments and others addressing large-scale implementations. The incorporation of IoT and machine learning technologies is crucial for achieving scalable solutions.

3.7 Key Insights and Observations

The review of the 28 selected articles provides a In-depth summary of the cutting-edge in IoT-based environmental monitoring systems. It included:

- **Enhanced Data Collection**: The integration of advanced sensors and IoT technologies has greatly improved the breadth and quality of environmental data collection.
- **Machine Learning Impact**: Machine learning has revolutionized the analysis of environmental data, offering advanced predictive capabilities and real-time insights.

4. FINDINGS

This analysis intends to answer the research questions (RQs) identified for this systematic literature review. Data extraction was conducted on the chosen research articles (n=28), and the findings are discussed in relation to the study's RQs. Also, a gap analysis is provided to highlight areas requiring further research and development.

4.1 Solutions to RQs

RQ-1: What are the key factors influencing the effectiveness of IoT-enabled environmental monitoring systems when integrated with advanced ML techniques?

Sensor quality and diversity play a crucial role, as the accuracy and reliability of data collection directly impact the performance of machine learning models. High-precision sensors capable of capturing a wide range of environmental parameters provide a more comprehensive dataset for analysis. Network connectivity and data transmission efficiency are equally important; as real-time monitoring requires robust communication protocols to ensure timely data delivery. The choice of machine learning algorithms significantly affects system performance, with advanced techniques like deep learning and ensemble methods often outperforming traditional approaches in handling complex environmental data. Data preprocessing and feature engineering are critical steps that can greatly enhance the accuracy of predictions and anomaly detection. Additionally, the scalability and adaptability of the system architecture influence its ability to manage growing data volumes and diverse environmental conditions.

RQ-2: How have ML models been applied to enhance the performance of environmental monitoring systems?

Supervised learning algorithms, such as Support Vector Machines (SVM) and Random Forests, have been effectively used for classification tasks in air quality monitoring and pollution detection. These models can accurately categorize pollution levels and identify potential sources of contamination. DL techniques, particularly Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), have shown remarkable performance in analyzing time-series data from environmental sensors. For instance, CNNs have been applied to satellite imagery for large-scale environmental monitoring, while RNNs have proven effective in predicting temporal patterns in water quality data. Unsupervised learning methods, such as clustering algorithms, have been utilized to discover hidden patterns in environmental data, helping to identify anomalies and understand complex ecological relationships. Reinforcement learning has also found applications in optimizing sensor placement and adaptive sampling strategies, improving the overall efficiency of monitoring networks.

RQ-3: What are the emerging trends and challenges in combining IoT and ML for real-time environmental data analysis?

Emerging trends in combining IoT and ML for real-time environmental data analysis include the adoption of edge computing paradigms, which bring processing capabilities closer to data sources, reducing latency and improving real-time response. Federated learning is gaining traction as a way to train models across distributed devices while preserving data privacy. There's also a growing focus on developing explainable AI models to increase transparency and trust in environmental decision-making processes.

Challenges in this domain are multifaceted. Data quality and heterogeneity remain significant hurdles, as environmental data often come from diverse sources with varying levels of accuracy and formats. Ensuring the reliability and robustness of IoT devices in harsh environmental conditions poses both technical and logistical challenges. The integration of multi-modal data streams, including sensor data, satellite imagery, and social media inputs, presents complex data fusion problems. Energy efficiency is another critical challenge, particularly for remote and battery-powered sensors. Additionally, the need for real-time processing of large-scale environmental data puts significant strain on computational resources and network infrastructure.

RQ-4: How do different environmental monitoring systems compare in terms of accuracy, efficiency, and scalability?

Environmental monitoring systems vary considerably in their performance metrics. Systems utilizing advanced

ML techniques, especially DL models, generally demonstrate higher accuracy in prediction and anomaly detection compared to traditional statistical methods. For instance, studies have shown that deep neural networks can achieve up to 95% accuracy in air quality prediction, outperforming conventional regression models.

Efficiency is often measured in terms of computational resources required and response time. Edge computing-based systems have shown significant improvements in efficiency by reducing data transmission and enabling faster local processing. Some studies report up to 40% reduction in energy consumption and 60% decrease in response time compared to cloud-based architectures.

Scalability varies widely among different systems. Cloud-based platforms offer high scalability in terms of data storage and processing capabilities but may face challenges in real-time data handling for large-scale deployments. Distributed systems utilizing fog computing paradigms have demonstrated better scalability for real-time applications, capable of handling thousands of sensors across wide geographic areas.

The choice of communication protocols also impacts scalability, with low-power wide-area networks (LPWAN) technologies like LoRaWAN showing promise for large-scale environmental monitoring in remote areas.

4.2 Gap Analysis:

Despite significant advancements, several gaps remain in the field of IoT-based environmental monitoring systems with machine learning integration:

1. **Standardization:** There is a lack of standardized frameworks for integrating diverse IoT devices and machine learning models, hindering interoperability and widespread adoption.
2. **Long-term reliability:** Most studies focus on short-term deployments, leaving gaps in understanding the long-term reliability and maintenance requirements of these systems.
3. **Adaptive learning:** Current systems often lack the ability to adapt to changing environmental conditions autonomously, presenting an opportunity for more dynamic and self-adjusting models.
4. **Multiscale integration:** There's a need for better integration of data from different spatial and temporal scales, from local sensor networks to global satellite observations.
5. **Ethical considerations:** The ethical implications of widespread environmental monitoring, including privacy concerns and potential misuse of data, are not adequately addressed in current research.

Resolving these issues will be crucial for advancing the effectiveness and adoption of these technologies in environmental monitoring.

5. CONCLUSION

This systematic literature review examined the integration of IoT and ML in environmental monitoring systems, with a focus on real-time data analysis and accuracy. Significant advancements have been identified in sensor technologies, data processing methods, and machine learning algorithms, collectively enhancing the efficiency and precision of environmental monitoring. Different approaches have been explored to address challenges related to data accuracy, sensor network optimization, and real-time processing. However, persistent issues such as data heterogeneity, energy consumption, and scalability remain. Future research should prioritize the development of more efficient algorithms for resource-constrained devices, improvements in data fusion techniques, and the robustness of machine learning models under diverse environmental conditions. The synthesis of these studies underscores the critical role of IoT and machine learning in fostering sustainable environmental monitoring solutions, while also highlighting the need for continued innovation to address existing limitations.

1.1 **Data Availability**

1.2 **The dataset supporting this study's findings is available from the corresponding author upon request.**

1.3 **Conflicts of Interest**

1.4 **The authors declare no conflicts of interest related to this publication.**

1.5 **Funding Statement**

The author declares that no funding was received for this research and publication.

Ethical Approval

This article does not involve studies with human participants or animals.

Author Contributions

All authors declare equal contribution to this work.

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