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Smart Sensors and Intelligent Analysis: A Literature Review on More Effective Early Warning Systems with IoT and Machine Learning

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Abstract
The IoT system described in the article "LoRaWAN-Based IoT System Implementation for Long-Range Outdoor Air Quality Monitoring" monitors air quality in real-time and transmits data through a LoRaWAN network to a public IoT platform. It measures seven key air quality parameters: nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon dioxide (CO_2), carbon monoxide (CO), PM2.5, temperature, and humidity. These parameters were chosen for their significant effects on air quality and human health. NO_2 and SO_2 come from fossil fuel combustion and can cause respiratory issues and acid rain. CO_2 contributes to climate change, while CO is toxic and harmful to health. PM2.5 particles can lead to respiratory and cardiovascular problems. The system uses sensors connected to an Arduino microcontroller to collect data, which is transmitted through a LoRa Shield to a LoRaWAN gateway. Data is then sent to The Things Network (TTN), integrated with ThingSpeak, and displayed on a web dashboard. Additionally, it is synchronized with the Virtuino smartphone app for mobile monitoring. The system has been validated by comparing its data to Aeroqual air quality monitors, demonstrating reliable real-time monitoring and transmission of air quality information over the internet.

***Keywords**: IoT, LoRaWAN, sensor, real-time, platform IoT.*

1. Introduction

Air pollution is a global issue that has serious impacts on human health and the environment. Sources of air pollution, ranging from traffic activities and industry to household emissions, contribute to the decline in air quality, both indoors and outdoors. Indoor air pollution, in particular, is a concern for families with children, as children are more vulnerable to adverse health effects (Gabriel et al., 2024). Exposure to indoor air pollution can increase the risk of respiratory diseases, childhood leukemia, and various other health issues (Gabriel et al., 2024). Therefore, monitoring indoor air quality is crucial for identifying pollution sources and implementing preventive measures to improve air quality (Van Tran et al., 2020).

The Internet of Things (IoT)-based Air Quality Monitoring System (AQMS) has emerged as an innovative solution to address this issue. This system uses low-cost sensors (LCS) to collect real-time air quality data and transmit it to an IoT platform for analysis and visualization (Ali et al., 2021). One study demonstrated the use of LCS sensors to measure parameters such as CO2, PM2.5, PM10, temperature, and relative humidity in homes with children (Abulude et al., 2023). The data was then analyzed on the IoT platform based on Grafana and shared with users through a smartphone application(Ng & Dahari, 2020). The study found that the IoT system was effective in identifying peak concentrations of CO2 and particulates, and showed significant correlation with measurements from standard equipment (Wu et al., 2023).

In addition to indoor air monitoring, the implementation of AQMS is becoming increasingly relevant amid rapid urbanization and industrialization, which exacerbates outdoor air pollution (Bhangale et al., 2023). Another study proposed the LoRaWAN-IoT-AQMS system, focusing on long-term outdoor air quality monitoring using LoRaWAN technology, offering a more cost-effective solution in terms of communication technology and public data accessibility (Jabbar et al., 2022).

IoT systems are not only applicable for air monitoring but also for early warning systems in disasters such as floods (Zakaria et al., 2023). The LoRaWAN-based Flood Warning System, for instance, was designed to overcome the limitations of existing flood monitoring systems, including limited coverage and access to public information (Dhebe et al., 2023). This system integrates smart sensors, IoT platforms (TagoIO and ThingSpeak), and central network gateways to enable real-time data reporting from multiple sensing units spread across a watershed area (Pasika & Gandla, 2020). The use of various IoT platforms allows for more comprehensive data analysis and visualization, providing a flexible solution for real-time flood monitoring and response (Da Silva Júnior et al., 2021).

In addition to floods, integrating weather prediction models like Weather Research and Forecasting (WRF) with IoT sensors can also provide early warning systems for other extreme weather events (Li et al., 2024). For example, another study proposed an early warning system for cold snaps in inland fish farms by integrating the WRF model and IoT sensors, which allows for water temperature forecasts up to five days in advance, helping to take timely preventive measures and reduce potential economic losses (Chen et al., 2022) (Li et al., 2024).

However, despite the many benefits IoT systems offer, they also have limitations, one of which is sensor degradation over time (Liu et al., 2020). This degradation can affect measurement accuracy and potentially lead to misinterpretation of data (Gabriel et al., 2024). Therefore, further research is needed to develop reliable maintenance procedures to ensure long-term measurement accuracy and reliability (Liu et al., 2020)(Gabriel et al., 2024).

2. Methods

The utilization of Internet of Things (IoT) technology and sensors for various applications in the fields of environment and agriculture has been widely explored. Journals by Gabriel et al., Jabbar et al., and Zakaria et al. specifically demonstrate how IoT systems can be developed to monitor and improve air quality, detect floods, and provide early warnings. These three journals emphasize the importance of real-time data collection, efficient data analysis, and the dissemination of information to the public.

The development of modular IoT systems has become a focal point in several journals. (Gabriel et al., 2024) utilized a modular system with low-cost sensors to monitor indoor air quality, while Zakaria et al. designed smart sensor units using Arduino, ultrasonic sensors, and

LoRa shields to detect floods. This modularity allows for flexibility and scalability of the systems, making them adaptable to different environmental conditions and needs.

The integration of IoT platforms is also a key theme in several journals. (Jabbar et al., 2022) and (Zakaria et al., 2023). employed platforms like ThingSpeak and TagoIO for real-time data visualization and analysis. These platforms enable public access to critical information, facilitating better decision-making and raising public awareness.

In addition to monitoring, prediction and early warning systems have also been a primary focus. (Gawande et al., 2024). used machine learning and IoT data to predict grapevine diseases, while Li et al. developed an early warning system for cold snaps in fish ponds by integrating the WRF model and IoT sensors. The development of accurate predictive systems can help stakeholders take timely preventive and mitigation actions (Anggriani et al., 2024).

The discussion highlights how IoT technology and sensors, when combined with data analysis and digital platforms, can provide innovative solutions to various challenges in the environmental and agricultural sectors (Almalki et al., 2021). The common thread linking these journals is the application of technology to enhance efficiency, sustainability, and resilience across different sectors.

Table 1. IoT studies on air quality, crop disease prediction, flood warnings, and fish pond temperature

Ref.	Application Focus	Sensor Type	Method
(Gabriel et al., 2024)	Effectiveness of IoT systems in improving indoor air quality (IAQ) in homes	CO2, temperature, humidity, and PM2.5/PM10	Development of modular IoT systems with calibrated sensors. Randomized cross-over trial to compare control and intervention periods. Online questionnaire to assess user experience and behavior changes. Statistical analysis (Wilcoxon and Spearman tests) to compare data and identify correlations.
(Gawande et al., 2024)	Prediction of grapevine diseases	Temperature, humidity, and leaf wetness	Collection of weather parameter data using IoT sensors. Creation of a custom database with 10,000 data points. Application of various machine learning algorithms for disease classification. Model evaluation using precision, recall, and accuracy metrics.

Ref.	Application Focus	Sensor Type	Method
(Jabbar et al., 2022)	IoT-based air quality monitoring system (AQMS) with LoRaWAN	PM2.5, CO2, CO, SO2, NO2, temperature, and humidity	Design and fabrication of AQMS with sensors. Implementation of a new algorithm to collect data from multiple sensors and send it to the TTN platform. Integration of the ThingSpeak platform for real-time data display. Development of the ThingSpeak dashboard and Virtuino GUI for public access. Sensor calibration using relevant methods and tools. System testing in real environments exposed to smoke, vehicles, and coal. Data validation by comparing AQMS readings with the Aeroqual Portable Monitor.
(Zakaria et al., 2023)	LoRaWAN-based early flood warning system	Ultrasonic sensor	Design and fabrication of smart sensor units using Arduino, ultrasonic sensors, and LoRa shields. Development of a new algorithm to measure and monitor flood height and rate of change. ntegration of IoT platforms TagoIO and ThingSpeak for data analysis and visualization. Performance analysis of LoRa/LoRaWAN communication interface. System testing with a "virtual river" to validate functionality and performance.

Ref.	Application Focus	Sensor Type	Method
(Li et al., 2024)	Early warning system for cold snaps in fish ponds	Water temperature sensors, meteorological sensors (solar radiation, precipitation, relative humidity, air temperature, and wind speed)	Modeling of fish pond water temperature using thermal energy conservation equations. Calibration and validation of the model using observed meteorological and water temperature data. Development of an ensemble prediction system (eENFIM) by combining results from the six best models. Integration of eENFIM with WRF weather predictions to generate fish pond water temperature forecasts up to 5 days ahead. System performance evaluation by comparing forecast data with observations.

3. Results and Discussion

All of the reviewed research articles successfully demonstrate the effectiveness of IoT systems in improving air quality, applying machine learning and IoT sensors for prediction, and emphasizing the importance of early warning systems for disaster mitigation. More specifically, Gabriel et al. and Jabbar et al. show the effectiveness of IoT systems in improving air quality. Gabriel et al. focused on indoor air quality, while Jabbar et al. emphasized outdoor air quality monitoring. Both studies demonstrated how real-time data and easily accessible information could drive behavior changes and raise public awareness.

Gawande et al. showed the great potential of machine learning and IoT sensors for agricultural prediction. Their study on predicting grapevine diseases showed high accuracy, providing hope for the development of early detection systems that can help farmers take preventive actions.

Lastly, Zakaria et al. and Li et al. developed innovative early warning systems for disaster mitigation. Zakaria et al. focused on a flood early warning system, while Li et al. developed a cold snap early warning system for fish ponds. Both studies demonstrated how the integration of IoT sensors, digital platforms, and numerical models can provide accurate and timely information, which is crucial for decision-making in emergency situations.

3.1. The Effectiveness of IoT Systems in Improving Air Quality

The utilization of Internet of Things (IoT) technology to improve air quality has become a rapidly growing research focus. Two journals, Gabriel et al. and Jabbar et al., provide strong evidence of the effectiveness of IoT systems in monitoring and controlling air quality parameters, both indoors and outdoors.

Gabriel et al. focused on the development of a modular IoT system to improve indoor air quality (IAQ) in homes. This system uses calibrated low-cost sensors to collect real-time data on CO_2, temperature, humidity, and particulate matter (PM2.5 and PM10). The study results show that this IoT system effectively reduced CO_2 concentration, with an average reduction of 10.3% in more than 60% of participating homes. This reduction was associated with positive behavior changes driven by access to real-time IAQ information. Participants became more aware of the importance of ventilation and more frequently opened windows to improve air circulation.

Jabbar et al. developed an IoT-based air quality monitoring system (AQMS) using LoRaWAN technology. This system has a wide range and low power consumption, allowing it to effectively monitor outdoor air quality. The AQMS uses various sensors to measure air quality parameters such as PM2.5, CO_2, CO, SO_2, NO_2, temperature, and humidity. The collected data is sent to IoT platforms (TTN and ThingSpeak) and visualized through dashboards and mobile apps, making it accessible to the public. The system was proven effective in detecting air quality changes in various testing scenarios, such as exposure to cigarette smoke, vehicles, and coal, and the data was validated with an Aeroqual Portable Monitor.

These two studies highlight several key factors that contribute to the effectiveness of IoT systems in improving air quality:

1. Real-Time Monitoring: IoT systems enable real-time monitoring of air quality parameters, providing more accurate and up-to-date information compared to traditional methods.
2. Access to Information: Providing real-time information to users, whether through dashboards, mobile apps, or notifications, can raise awareness and encourage positive behavior changes.
3. Wide Coverage: Technologies like LoRaWAN allow IoT systems to monitor air quality over a wide area, offering a more comprehensive view of air conditions.
4. Platform Integration: Integration with IoT platforms allows efficient data analysis, easy-to-understand visualization, and public access to important information.

Although IoT systems hold promise for improving air quality, several challenges need to be addressed, such as:

1. Sensor Accuracy: The accuracy and reliability of low-cost sensors can vary, and proper calibration is necessary to ensure data accuracy.
2. Data Security: IoT systems are vulnerable to cyber-attacks, and strong security measures are needed to protect sensitive data.
3. Implementation Costs: The cost of implementing IoT systems can be a barrier, especially for large-scale projects.

Further research is needed to overcome these challenges and develop more advanced and affordable IoT systems to improve air quality. The development of machine learning algorithms for predictive analysis and early detection of air quality changes, as well as integration with automated control systems for pollution mitigation, is a promising area of research.

To strengthen the discussion on the effectiveness of IoT systems in improving air quality, below is a comparison table of the two case studies we have discussed.

Table 2. Comparison of indoor and outdoor air quality monitoring using IoT for detection and environmental management.

Feature	Gabriel et al. Case Study	Jabbar et al. Case Study
Focus	Indoor air quality (IAQ)	Outdoor air quality
Location	84 family homes with children in Portugal	University Malaysia Pahang campus
IoT Technology	Modular IoT system with calibrated low-cost sensors	IoT-based air quality monitoring system (AQMS) with LoRaWAN
Monitored Parameters	CO2, temperature, humidity, PM2.5, PM10	PM2.5, CO2, CO, SO2, NO2, temperature, humidity
Digital Platform	Smartphone application	TTN, ThingSpeak, Virtuino
Validation Method	Comparison of data with calibrated reference instruments	Comparison of data with Aeroqual Portable Monitor
Key Results	Average 10.3% reduction in CO2 concentration in more than 60% of homes	Ability to detect changes in air quality in various scenarios, including exposure to cigarette smoke, vehicles, and coal
Impact	Increased awareness of IAQ and positive behavior changes, such as opening windows for ventilation	Real-time air quality monitoring and public access to information

Analysis:

1. Similarities: Both case studies demonstrate the effectiveness of IoT systems in monitoring air quality parameters in real-time and providing valuable information to users.
2. Differences: Gabriel et al.'s case study focuses on the application in homes and its impact on residents' behavior, while Jabbar et al.'s case study emphasizes the development of systems for outdoor air quality monitoring and public access to data.

This table provides a clear comparison between two different approaches in utilizing IoT technology for air quality improvement.

3.2 Application of Machine Learning and IoT Sensors for Prediction

The integration of machine learning with data from IoT sensors has paved new ways for prediction across various fields. A prominent example is discussed in the case study by Gawande et al., which demonstrates the potential of this combination for the early detection of grapevine diseases.

Gawande et al.'s research focused on developing a system for predicting grapevine diseases using data from IoT sensors and machine learning algorithms. The system used sensors to monitor environmental parameters such as temperature, humidity, and leaf wetness, which are critical factors in the development of grapevine diseases.

The data collected from the sensors was then processed using machine learning algorithms, specifically ensemble learning models, to predict the likelihood of three major grapevine diseases: Downy Mildew, Powdery Mildew, and Bacterial Leaf Spot. The model was trained using historical data that linked environmental conditions to the occurrence of diseases.

The study results showed that this predictive system achieved high accuracy, precision, and recall in classifying the three grapevine diseases. This indicates the reliability of the system in detecting diseases early, even before visual symptoms appear on the plants.

Benefits of the Predictive System Implementation:

1. Better Decision Making: The predictive system provides accurate and timely information to farmers, allowing them to take more effective preventive measures.
2. Increased Efficiency: Early detection of diseases enables farmers to carry out targeted interventions, reducing pesticide usage and minimizing crop losses.
3. Sustainable Agriculture: Lower pesticide usage has positive impacts on the environment and human health.

Key Factors for Successful Implementation:

1. Sensor Data Quality: The accuracy and reliability of IoT sensors are crucial for producing accurate predictions.
2. Appropriate Machine Learning Algorithm Selection: Different machine learning models have their strengths and weaknesses. Choosing the right model based on the data characteristics and prediction goals is essential.
3. Domain Knowledge: Understanding the factors that influence disease development, such as environmental conditions and pathogen life cycles, is critical to developing effective predictive models.

Challenges and Future Opportunities:

1. Scalability: Implementing the predictive system on a large scale, covering various crops and geographical regions, is a challenge that needs to be addressed.
2. Data Integration: Combining data from multiple sources, such as IoT sensors, satellite imagery, and weather data, can improve prediction accuracy.
3. Development of More Advanced Predictive Models: Research and development of new machine learning algorithms and more sophisticated data analysis techniques will continue to enhance predictive capabilities in agriculture.

The application of machine learning and IoT sensors for prediction holds great potential to revolutionize agricultural practices and improve food security. Gawande et al.'s case study shows that this technology can be effectively applied for the early detection of crop diseases. By addressing existing challenges and seizing future opportunities, we can build more robust predictive systems that benefit farmers, consumers, and the environment. Below is a comparison table of case studies discussing the application of machine learning and IoT sensors for prediction, particularly in agriculture:

Table 3. Early prediction of grapevine diseases using IoT and machine learning improves efficiency and sustainability in agriculture.

Feature	Gawande et al. Case Study
Objective	Early prediction of grapevine diseases
Plant Type	Grapevine
Monitored Parameters	Temperature, humidity, leaf wetness
IoT Sensor Technology	DHT11 sensor for temperature and humidity, leaf wetness sensor
Machine Learning Method	Ensemble learning model
Predicted Diseases	Downy Mildew, Powdery Mildew, Bacterial Leaf Spot
Prediction Accuracy	Downy Mildew: 98.85%, Powdery Mildew: 98.25%, Bacterial Leaf Spot: 93.95%
Platform and Visualization	LCD Display, Warning Messages (SMS)
Benefits	Early disease detection, better decision-making, improved efficiency, sustainable agriculture

Analysis:

1. The case study by Gawande et al. demonstrates that the integration of machine learning with IoT sensor data can result in an accurate and reliable plant disease prediction system.
2. This predictive system provides valuable information to farmers, enabling them to take timely preventive and control measures against diseases, thereby improving agricultural productivity and sustainability.Let me know if you need further assistance!

3.3. The Importance of Early Warning Systems for Disaster Mitigation

Early Warning Systems (EWS) play a crucial role in disaster mitigation, enabling communities and authorities to prepare and respond effectively to potential threats. Various natural disasters, such as floods and cold snaps (sudden temperature drops) in fish farms, highlight the importance of EWS in reducing the damage caused. Several sources have emphasized the role of EWS in dealing with such disasters and how technology can be used to strengthen preparedness and risk mitigation.

Flood mitigation through EWS is a central topic in one source that highlights the importance of EWS for reducing flood damage. Flooding caused by heavy rain can result in significant infrastructure damage and loss of life. Traditional flood monitoring systems often face challenges such as high costs, complexity, and limited accessibility for the general public. As a solution, the source proposes the development of LoRaWAN-based smart sensing units for flood EWS. This system can report real-time data from multiple sensing units, providing more comprehensive monitoring and faster response times. Additionally, it uses solar power to ensure sustainability and reliability in remote areas. Other features include customizable alert levels based on geographic conditions and flood risks, as well as integration with various IoT platforms for advanced data analysis and easy-to-access visualization for the public.

In a different context, the EWS for Cold Snap in Fish Farms offers a solution for fish farmers who are vulnerable to sudden water temperature drops. These conditions can cause mass fish deaths and significant economic losses. The proposed system integrates the WRF weather prediction model with IoT sensors and a temperature model based on energy conservation (ENFIM). This combination allows the system to predict fish pond water temperatures up to five days in advance, giving farmers enough time to take preventive measures. Furthermore, the system uses ensemble predictions, offering a range of possible water temperatures, reducing uncertainty, and helping farmers make more accurate decisions. The system also monitors key environmental parameters such as wind speed, solar radiation, air temperature, and relative humidity to generate more accurate predictions.

Overall, it can be concluded that early warning systems play a vital role in disaster mitigation. EWS provides timely and accurate information, allowing communities and authorities to take effective preventive measures. Examples of EWS for floods and cold snaps demonstrate how this technology can be applied to various types of disasters. The development and implementation of effective EWS require monitoring relevant parameters, reliable communication systems, accurate prediction algorithms, and user-friendly interfaces. With technological advances in sensors, wireless communication, and machine learning, the development of more sophisticated and effective early warning systems is increasingly possible. Ultimately, effective EWS can minimize the impact of disasters, protect lives and property, and help build more resilient communities.

Conclusions

Early warning systems (EWS) are crucial in enhancing disaster mitigation and improving community resilience by providing timely, accurate alerts that support preventive action. Real-time data collection and analysis are at the heart of EWS effectiveness, enabling swift responses to environmental hazards such as air quality changes and water level fluctuations. Integrating IoT sensors and machine learning enhances EWS capabilities, where IoT sensors provide environmental data and machine learning leverages historical patterns for accurate predictions. Additionally, ensuring that EWS information is accessible through mobile apps or online platforms facilitates broader community engagement and rapid response. For widespread adoption, especially in developing regions, affordability of EWS technology is essential. The applications of EWS are extensive, from public health protection and agricultural support to flood mitigation, though challenges like improving sensor reliability, refining algorithms, and safeguarding data privacy remain. Overall, EWS represents a powerful tool for building resilient communities, and ongoing technological innovation and collaboration are key to broadening its protective reach against diverse disaster threats.

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