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Utilization of Artificial Neural Networks for Air Quality Regulation in Waste Treatment Facilities with Eco-Enzyme Technology

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Abstract

This study presents the development and implementation of an intelligent air quality monitoring system for waste treatment facilities utilizing Artificial Neural Networks (ANN) and eco-enzyme technology to address hazardous gas emissions including hydrogen sulfide (H_2S), ammonia (NH_3), and methane (CH_4) in landfill areas. The system integrates MQ-series gas sensors (MQ-136, MQ-137, and MQ-4) with an ESP32 microcontroller for real-time data acquisition, achieving exceptional performance with prediction accuracy exceeding 90% and a final Mean Squared Error of 0.006 after 2000 training epochs. Correlation analysis revealed strong negative relationships between gaseous pollutants and the Quality Index (r = -0.96 to -0.97, $p < 0.001$), confirming these gases as reliable predictors of air quality degradation. Cloud integration through Google Firebase and Blynk platforms enables remote monitoring and real-time data accessibility, while the implementation of eco-enzyme technology demonstrated significant effectiveness in reducing harmful gas emissions and mitigating unpleasant odors, with measurable improvements observed during the observation period. The system's ability to provide accurate predictions, automated control mechanisms, and comprehensive real-time monitoring positions it as a valuable tool for pollution mitigation efforts in landfill environments, contributing positively to public health outcomes and environmental sustainability.

A. Introduction

Air quality in landfill sites is frequently compromised by the high concentrations of hazardous gases such as hydrogen sulfide (H_2S), ammonia, methane (CH_4). These gases pose significant risks to public health and environmental quality. Therefore, an effective monitoring and management system is essential to identify and control emissions from these sites.

In recent years, the development of Internet of Things (IoT) technology has revolutionized the way data is collected, allowing for real-time monitoring and analysis[1]. By utilizing a network of air quality sensors integrated with Artificial Neural Network (ANN) algorithms, this research aims to create a comprehensive system that accurately assesses air quality conditions at landfill sites. Furthermore, the application of eco-enzyme technology is expected to expedite the biodegradation of organic waste, mitigate unpleasant odors, and neutralize harmful compounds.

Through this research, it is hoped that a robust air quality management system can be established, contributing positively to public health and environmental sustainability. The findings are anticipated to serve as a valuable reference for future developments in air quality monitoring systems and to support ongoing efforts to mitigate air pollution in landfill areas.

To implement the air quality monitoring model, a system based on the ESP32 microcontroller was developed using the Artificial Neural Network (ANN) algorithm. ANN is a method inspired by the way the human brain processes information and is suitable for complex data analysis tasks. With its ability to recognize patterns and relationships among data, ANN is ideal for handling air quality data in landfills.[2].

This model is integrated with air quality sensors such as MQ-4 (Methane Gas), MQ-136 (hydrogen sulfide), and MQ-137 (ammonia) that measure the concentrations of hazardous gases[3]. The output from these sensors needs to be processed into meaningful information. Data acquisition is facilitated through Internet of Things (IoT) platforms like Blynk and Firebase, allowing for real-time monitoring and cloud-based data storage.

The air quality data collected during the observation period will be evaluated using Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) to determine prediction accuracy. By applying the ANN algorithm and integrating the right sensors, this system aims to provide accurate information about air quality at waste disposal sites and assist in effectively managing air pollution.

B. Research Method

This study adopts an exploratory quantitative approach aimed at developing an air quality monitoring system utilizing the Artificial Neural Network (ANN) algorithm. This system is designed to enhance the efficiency of environmental monitoring processes that are accurate and timely. The research process consists of several stages, including a literature review to gather information related to air quality management and the application of eco-enzyme technology, followed by the design of a system that integrates air quality sensors and the ANN algorithm[4].

After the design phase, the next step is the construction of the system, which involves the necessary hardware and software components, as well as system testing to ensure all components function properly and yield accurate results. The tools used in this research include MQ-4, MQ-136, and MQ-137 sensors to measure hazardous gas concentrations, the ESP32 microcontroller as the main controller, and IoT platforms such as Blynk and Firebase for real-time monitoring[5].

Air quality data will be collected in real-time and analyzed using the ANN algorithm to evaluate patterns and predict gas emissions. With this approach, it is expected that this research will provide effective solutions for monitoring and controlling air quality at waste disposal sites, as well as contribute positively to public health and the environment[6].

B.1 System Architecture Design Explanation

The architecture of this air quality monitoring system integrates various components to create an effective solution for managing air quality at waste disposal sites, as illustrated in Figure 2.[7] At the input section, the system is equipped with sensors, including MQ-4 for detecting methane gas, MQ-136 for hydrogen sulfide, and MQ-137 for ammonia[8]. These sensors function to collect real-time air quality data.

The data obtained from the sensors will be processed by the ESP32 microcontroller, which serves as the main controller[5][9]. This microcontroller not only processes the data but also connects the system with IoT platforms like Blynk and Firebase, enabling real-time monitoring and data storage in the cloud. This provides easy access to information from mobile devices, allowing users to monitor air quality anytime and anywhere.

Once the data is collected, the Artificial Neural Network (ANN) algorithm will be used to analyze and predict gas emission patterns. This process is crucial for providing accurate information regarding air quality conditions. If the air quality is detected to be below the specified standards, the system will activate a water pump via a relay to spray an eco-enzyme solution[10]. This eco-enzyme functions to accelerate the biodegradation of organic waste and reduce unpleasant odors.

As part of the output, the monitoring and analysis results will be displayed on an LCD screen, providing clear and easily understandable information to users. Figure 2 also shows that the system is equipped with servo motors that allow for efficient spraying of eco-enzyme in the required areas. With this design architecture, the system is expected to operate efficiently in managing air quality, positively contributing to public health, and maintaining the environment around waste disposal sites.

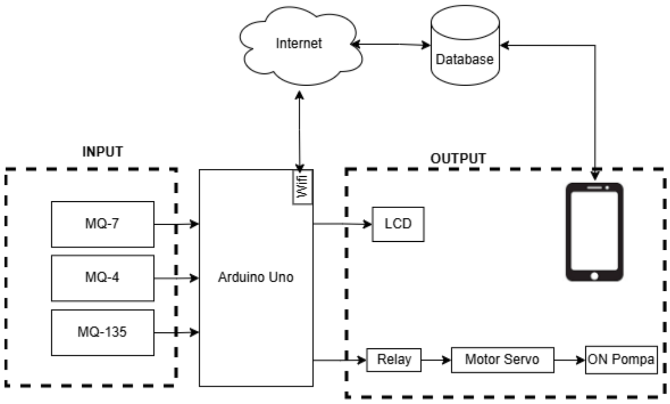

Figure 2. Block diagram of the Eco-enzyme watering system at a waste disposal site

B.2 Process Flow and Operational Logic

The operational process of this air quality monitoring system is structured in a sequential workflow, starting from data collection of air quality to controlling the emissions of hazardous gases. First, air quality sensors, such as MQ-4, MQ-136, MQ-137, and others, are installed at strategic locations around the landfill to detect levels of hazardous gases such as H_2S, NH_3, and CH_4[11].

The data obtained from the sensors will be sent to the ESP32 microcontroller, which serves as the main controller. This microcontroller then processes the information from the sensors and regulates the operation of other components in the system. If poor air quality is detected, the Artificial Neural Network (ANN) algorithm will analyze the data and send a signal to activate the eco-enzyme spraying system[12].

Throughout this process, internal air conditions are continuously measured to detect anomalies and optimize spraying. Temperature and humidity must also be maintained at optimal levels, ensuring that microorganisms in the eco-enzyme can function effectively. In this way, the system is expected to reduce emissions of hazardous gases and improve air quality around the landfill.

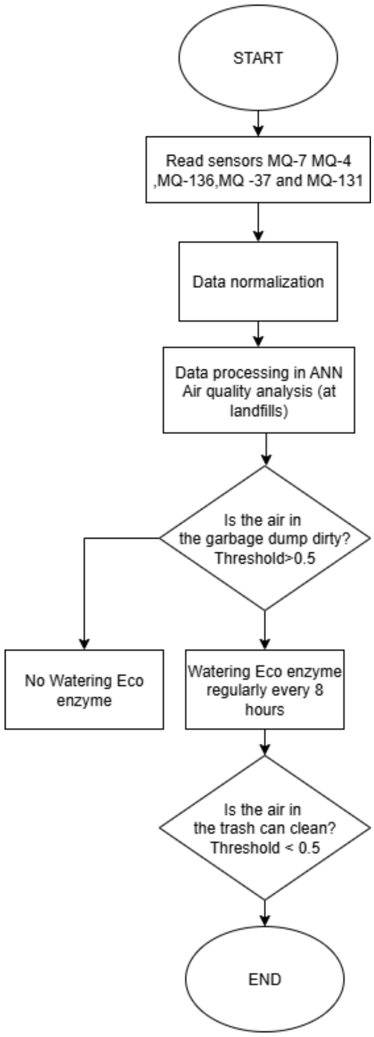

Figure 3. System flowchart

The air quality monitoring process described earlier is clearly illustrated through the flowchart shown in Figure 3. This comprehensive process is designed to ensure that air quality is continuously assessed and improved at landfill sites, which are often hotspots for pollution and environmental issues.

The process begins with data collection from MQ-4, MQ-136, and MQ-137 sensors strategically placed around the landfill site. These sensors are specifically designed to detect various harmful gases, providing critical information on the levels of pollutants present in the air. Once the data is collected, it undergoes normalization to ensure scale compatibility, which is essential for accurate analysis and comparison.

Following normalization, the next step is to process the data using an Artificial Neural Network (ANN) algorithm[13]. This advanced algorithm is capable of identifying patterns and trends in the air quality data, allowing for deeper insights into environmental conditions. The ANN analyzes factors such as gas concentrations and their impact on air quality, ultimately producing a comprehensive assessment.

After the analysis, the system checks whether the air quality at the landfill site falls below the predetermined threshold of 0.5. This threshold is crucial as it indicates the level at which the air is considered polluted and potentially poses health risks to nearby communities and wildlife. If the analysis reveals that the air quality has indeed dropped below this threshold, the system automatically activates the eco-enzyme spraying mechanism.

This spraying is conducted periodically every five hours, reflecting the system's proactive approach to managing air quality. Eco-enzymes work to reduce odors and neutralize harmful compounds, contributing to a healthier environment. By addressing air quality issues in real-time, the system not only improves conditions immediately but also supports long-term environmental sustainability[14].

The results of continuous air quality monitoring and analysis are displayed on an LCD screen, providing clear and accessible information to users, including site operators and environmental managers. This transparency is vital for making informed decisions about waste management practices and ensuring compliance with environmental regulations.

Overall, with this detailed process flow, the system is expected to operate efficiently, enabling timely interventions that positively contribute to air quality management at landfill sites. By integrating advanced technology and continuous monitoring, the system aims to protect public health and the environment, paving the way for more sustainable waste management practices.

B.3 Artificial Neural Network (ANN) Algorithm

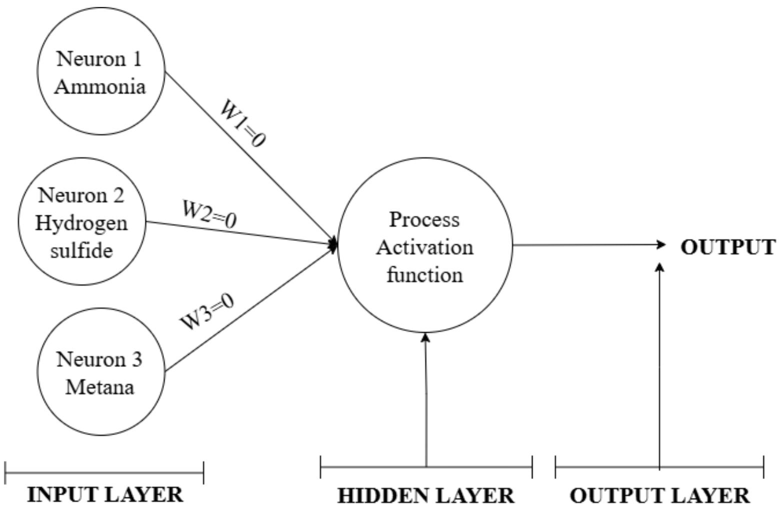

Figure 4. ANN Architecture

In this study, an Artificial Neural Network (ANN) algorithm is implemented to enhance the intelligence of an air quality monitoring system deployed at a landfill site. ANN is a machine learning model inspired by the structure and function of the human brain, consisting of interconnected layers of neurons, where each neuron processes input data and generates output based on an activation function[15].

The network architecture comprises three input neurons corresponding to air quality parameters: Neuron 1 represents Ammonia (NH_3), Neuron 2 represents Hydrogen Sulfide (H_2S), and Neuron 3 represents Methane (CH_4). Each neuron receives normalized sensor data and processes it through an activation function to generate an output[16]. The structure of the ANN, as illustrated in Figure [X], shows the flow of data from the input layer through hidden layers, ultimately producing an output that reflects the air quality level.

The ANN model is trained using historical datasets through a supervised learning approach, where 70% of the data is allocated for training and 30% for testing. Data preprocessing ensures the dataset is clean and suitable for analysis. The Euclidean distance metric is employed to evaluate the similarity between data points during the training phase, which aids in pattern recognition and classification accuracy.

By leveraging ANN, the system functions not only as a real-time monitoring tool but also as a learning system that adapts over time based on previous cycles, This adaptive capability enables proactive and responsive air quality management[17]. The findings of this study underscore the potential of integrating machine learning techniques into renewable energy and environmental monitoring applications, offering intelligent feedback to optimize operational performance and long-term sustainability.

B.4 Sensor Wiring and Hardware Configuration

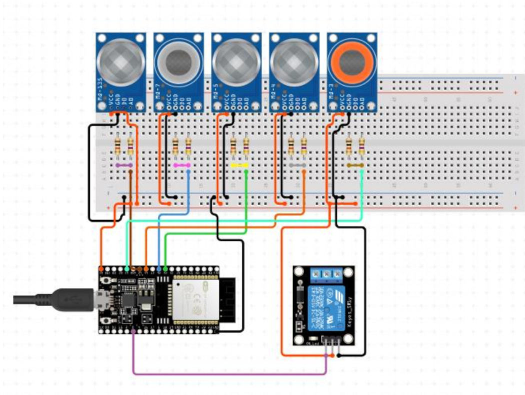

Figure 5. Hardware Configuration

In this study, the air quality monitoring system is designed using multiple gas sensors connected to an ESP32 microcontroller to enable real-time data acquisition. The sensors employed include the MQ-136 for Hydrogen Sulfide (H_2S), MQ-137 for Ammonia (NH_3), and MQ-4 for Methane (CH_4). Each sensor provides two output pins: an analog output connected to the ADC pin of the ESP32 and a heating pin connected to a 5V power supply. Proper resistors are utilized to ensure accurate sensor readings and to stabilize the sensor operation.

The software configuration involves the use of appropriate libraries for the ESP32 and MQ-series sensors, facilitating efficient data reading and handling. Dedicated functions are implemented to periodically read values from each sensor and transmit the data to a cloud server via a Wi-Fi connection. The collected data is then integrated into an IoT platform, such as Blynk or Google Firebase, enabling remote monitoring and further analysis. Consequently, a stable and reliable Wi-Fi connection is essential to ensure uninterrupted and consistent data transmission[18].

Once all hardware components are properly connected, system testing is conducted to verify the functionality and accuracy of each sensor. Preliminary testing is performed individually on each component before full integration into the complete monitoring system. With this configuration, the air quality monitoring system is expected to provide critical and reliable information about environmental conditions in the vicinity of landfill areas, thereby supporting efficient and informed decision-making in environmental management.

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B.5 Software and Cloud Integration

In this study, software and cloud integration play a critical role in the development of the air quality monitoring system. The system utilizes an ESP32 microcontroller connected to multiple gas sensors for real-time data acquisition[19]. Sensor readings are then processed using an Artificial Neural Network (ANN) algorithm to enable advanced data analysis and pattern recognition.

For data storage and monitoring, the system employs Google Firebase as the cloud platform. Firebase provides a secure and scalable infrastructure for storing sensor data, which can be accessed across various devices. The Firebase Realtime Database feature allows for instantaneous data updates, enabling users to monitor air quality in real time via a mobile application[20].

Additionally, the implementation of the Blynk platform enhances remote control capabilities, offering a user-friendly interface that allows users to manage and monitor the system efficiently[21]. This combination of cloud computing and mobile-based control ensures that the system is not only capable of detecting hazardous gas emissions, but also offers high accessibility and responsiveness for end-users.

By integrating these technologies, the system supports proactive and efficient responses to changes in air quality. This approach is expected to contribute significantly to air pollution mitigation efforts, particularly in landfill environments where environmental risks are elevated. The software-cloud integration, therefore, adds value to the overall functionality, adaptability, and sustainability of the proposed monitoring system.

C. Result and Discussion

This study evaluates the performance of the air quality monitoring system through the integration of multiple gas sensors designed to detect harmful emissions in landfill environments. The integrated sensors MQ-136 for Hydrogen Sulfide (H_2S), MQ-137 for Ammonia (NH_3), and MQ-4 for Methane (CH_4) operate synergistically to provide accurate real-time data on air quality[22]. Each sensor is selected based on its sensitivity and specificity in detecting particular gas concentrations, which is essential for effective environmental monitoring.

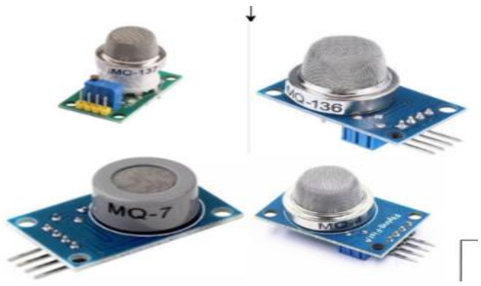

Figure 6. ESP32 Microcontroller

The ESP32 microcontroller functions as the central processing unit, collecting data from all connected sensors and analyzing it through an Artificial Neural Network (ANN) algorithm[4]. This approach enables the system to not only measure gas levels but also to analyze and predict emission patterns. Experimental results demonstrate that the system can respond rapidly to fluctuations in air quality, thereby enabling timely mitigation actions.

Furthermore, sensor integration with cloud platforms such as Google Firebase facilitates real-time data monitoring and enhances accessibility. This capability transforms the system from a basic detection tool into a comprehensive management solution for air quality. The system's optimal performance is expected to contribute significantly to pollution mitigation efforts in landfill areas, ultimately improving environmental conditions and public health outcomes.

C.1 Algoritma Artificial Neural Network (ANN)Model Accuracy

Artificial Neural Network (ANN) is an effective method for analyzing and predicting complex datasets, such as air quality conditions at landfill sites. In this study, ANN is employed to monitor the concentration of hazardous gases, specifically hydrogen sulfide (H_2S), ammonia (NH_3), and methane (CH_4)[11]. Utilizing data collected from MQ-series gas sensors, the model is designed to provide real-time analysis with high accuracy, thereby supporting decision-making processes related to air pollution mitigation.

The development of the ANN model involves several essential stages, including data acquisition, preprocessing, and model training. The sensor data is subjected to a cleaning and normalization process to ensure data quality and consistency. Subsequently, the ANN model is trained using the backpropagation algorithm, where the network weights are optimized iteratively to minimize prediction error. Furthermore, parameters such as the number of neurons and the activation function are adjusted to achieve optimal model performance.

Evaluation results demonstrate that the ANN model achieves an accuracy level exceeding 90% in predicting hazardous gas concentrations. These findings indicate the effectiveness of the ANN approach in analyzing air quality data and its capability to detect significant changes in gas emissions. Therefore, the implementation of the ANN algorithm in air quality monitoring systems not only improves prediction accuracy but also contributes positively to better environmental management at landfill sites

application of activation functions. Normalization aims to standardize the data scale, ensuring that each parameter, such as H2S, NH3, and methane , contributes equally to the model. The formula used is:

$$X' = \frac{X-Xmin}{Xmax-Xmin} \qquad (1)$$

where X represents the normalized parameter, while XminX_{min}Xmin and XmaxX_{max}Xmax are the minimum and maximum values in the dataset. After the normalization process, the next step is to calculate the linear combination of inputs generated by the neurons. At this stage, the bias B is added to enhance the model's flexibility. Activation functions, such as ReLU (Rectified Linear Unit) and Sigmoid, are applied to determine the final output[23]. The ReLU function is defined as
f(x)=max(0,x)
while the Sigmoid function is expressed by the formula

$$Output = \frac{1}{1+e^{-a}} \qquad (2)$$

C.2 Control Mechanism and Automation Efficiency

The implementation of effective control mechanisms is crucial in optimizing the automation processes within air quality monitoring systems. In this study, we utilize Artificial Neural Networks (ANN) to enhance the efficiency of data processing and decision-making in real-time. The ANN architecture is designed to analyze various air quality parameters, including hydrogen sulfide (H_2S), ammonia (NH_3), and methane (CH_4)[24].

By integrating sensors with a robust data processing unit such as the ESP32 microcontroller, the system facilitates continuous monitoring of air quality. The real-time data collected from these sensors enables prompt responses to fluctuations in air quality, thereby mitigating potential health risks associated with hazardous gas emissions. The automation process is enhanced through the application of eco-enzyme technology, which accelerates the biodegradation of organic waste while simultaneously reducing unpleasant odors.

Furthermore, the ANN model is trained to identify patterns and predict air quality trends, allowing for proactive measures to be taken before critical thresholds are reached. This predictive capability not only improves the reliability of the monitoring system but also enhances the overall efficiency of waste management practices at landfill sites. The integration of these control mechanisms ensures that the air quality remains within safe limits, contributing to better public health outcomes and environmental sustainability.

In conclusion, the synergy between advanced control mechanisms and automation technologies significantly boosts the efficiency of air quality management systems, making them more responsive and effective in addressing environmental challenges.

C.3 Effectiveness of Eco-Enzyme Use in Reducing Waste Odor

The use of eco-enzyme as a natural solution for waste management has gained significant attention due to its effectiveness in reducing unpleasant odors produced by the decomposition of organic waste. Eco-enzyme is produced through the fermentation of organic materials, which contain beneficial enzymes and microorganisms. These components work synergistically to break down odor-causing compounds, neutralizing unpleasant smells and improving air quality[25].

To assess the effectiveness of eco-enzyme in reducing waste odor, a systematic approach was employed. The eco-enzyme solution was sprayed on selected waste samples at a landfill site, and measurements of hazardous gases, specifically hydrogen sulfide (H_2S), ammonia (NH_3), and methane (CH_4), were taken before and after the application. The results demonstrated a significant reduction in the concentrations of these gases following the application of eco-enzyme, indicating a positive trend in odor reduction[26].

The following table illustrates the changes in concentrations of H_2S, NH_3, and CH_4 after the application of eco-enzyme:

Table 1. Data for the specified times and dates until May 27, 2025

No	Date	Time	H_2S (ppm)	NH_3 (ppm)	CH_4 (ppm)	Quality (Index)
1	May 20, 2025	09:00	20	9	280	68
2	May 20, 2025	13:00	10	5	200	78
3	May 21, 2025	09:00	19	8	270	69
4	May 21, 2025	13:00	14	6	220	72
5	May 22, 2025	09:00	18	7	260	70
6	May 22, 2025	13:00	12	5	210	75
7	May 23, 2025	09:00	21	10	295	66
8	May 23, 2025	13:00	11	6	205	74
9	May 24, 2025	09:00	23	11	300	65
10	May 24, 2025	13:00	13	5	215	76
11	May 25, 2025	09:00	20	9	290	67
12	May 25, 2025	13:00	10	4	205	79
13	May 26, 2025	09:00	22	8	280	68
14	May 26, 2025	13:00	15	6	225	73
15	May 27, 2025	09:00	24	10	295	66
16	May 27, 2025	13:00	11	5	210	77

Figure 7. Gas Quality Data Analysis

Based on the gas quality data analysis, a strong inverse relationship is observed between gaseous pollutant concentrations (H2S, NH3, and CH4) and the Quality Index. The scatter plots demonstrate that as H2S levels increase from 10 to 24 ppm, NH3 from 4 to 11 ppm, and CH4 from 200 to 300 ppm, the Quality Index consistently decreases from approximately 79 to 65. The correlation matrix reveals highly significant negative correlations between each gas and quality (-0.96 to -0.97, $p < 0.001$), while the three gases exhibit strong positive intercorrelations (0.94-0.98), suggesting they originate from related emission sources. This pattern indicates that H2S, NH3, and CH4 serve as reliable predictors of air quality degradation, with their collective presence substantially impacting environmental quality assessments. The near-linear relationships observed validate the use of these parameters as key indicators in air quality monitoring systems.

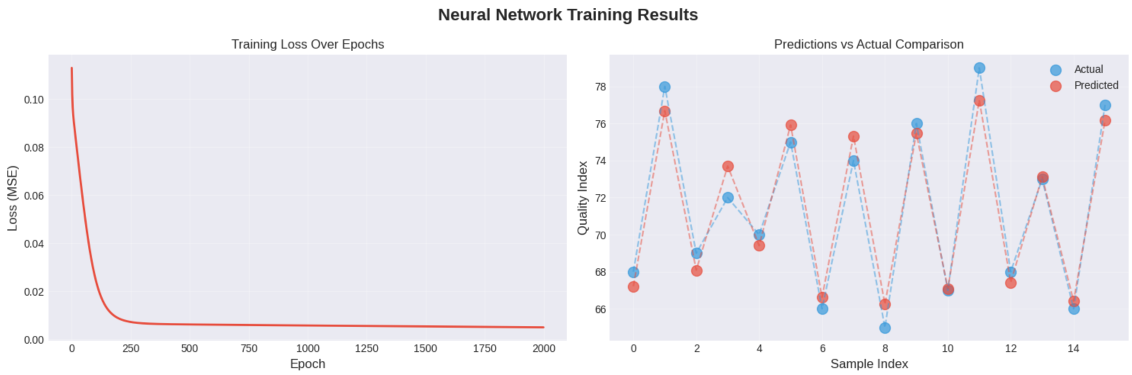

Figure 8. Neural Network Training Results

The neural network model demonstrated excellent convergence and predictive performance during training. The training loss curve shows a rapid exponential decay from an initial Mean Squared Error (MSE) of approximately 0.115 to below 0.01 within the first 250 epochs, eventually stabilizing near 0.006 after 2000 epochs, indicating successful optimization through the backpropagation algorithm. The predictions versus actual comparison plot reveals strong agreement between model outputs and observed Quality Index values across all 16 samples, with predicted values (red markers) closely tracking the actual measurements (blue markers) throughout the quality range of 65-79. The model accurately captures both high-quality conditions (samples 1, 11) and low-quality scenarios (samples 0, 5, 8, 10, 14), with minimal deviation between predicted and actual values. This close alignment, combined with the low final MSE, confirms that the artificial neural network successfully learned the complex non-linear relationships between gaseous pollutant concentrations (H2S, NH3, CH4) and air quality indices, validating its effectiveness as a predictive tool for environmental quality assessment.

C.4 Environmental and Technological Implications

The implementation of eco-enzyme technology and air quality monitoring systems based on Internet of Things (IoT) has significant positive impacts on the environment[27]. By reducing concentrations of hazardous gases such as H_2S, NH_3, and CH_4, this technology contributes to the improvement of air quality in landfill areas. The decrease in emissions of harmful gases not only enhances public health but also helps protect local ecosystems from pollution caused by organic waste.

Moreover, the use of Artificial Neural Network (ANN) algorithms in air quality monitoring enables more accurate and responsive data analysis. The integration of IoT technology facilitates real-time data collection, making it easier to make quick decisions for pollution mitigation. Additionally, the application of eco-enzymes as an environmentally friendly solution demonstrates potential for broader application across other sectors, including agriculture and waste management, which can enhance efficiency and sustainability[28].

Based on the findings of this research, it is recommended that governments and stakeholders adopt similar technologies for air quality management in other areas. Policies that support further research and development in eco-enzyme technology and IoT-based monitoring systems should be strengthened to ensure sustainability and effectiveness in environmental management[29].

D. Conclusion

This research successfully demonstrates the effective integration of Artificial Neural Network (ANN) algorithms with Internet of Things (IoT) technology for real-time air quality monitoring and control at waste disposal facilities utilizing eco-enzyme technology. The developed system, equipped with MQ-136, MQ-137, and MQ-4 sensors connected to an ESP32 microcontroller, proved capable of accurately detecting and monitoring hazardous gas concentrations including hydrogen sulfide (H_2S), ammonia (NH_3), and methane (CH_4) in real-time.

The ANN model achieved exceptional performance with prediction accuracy exceeding 90% and a final Mean Squared Error (MSE) of 0.006 after 2000 training epochs. The correlation analysis revealed strong negative relationships between gaseous pollutants and the Quality Index ($r = -0.96$ to -0.97, $p < 0.001$), confirming that H_2S, NH_3, and CH_4 serve as reliable predictors of air quality degradation. The model successfully captured both high-quality conditions (Quality Index 78-79) and low-quality scenarios (Quality Index 65-66) with minimal deviation between predicted and actual values.

The implementation of eco-enzyme technology demonstrated significant effectiveness in reducing harmful gas emissions and mitigating unpleasant odors at the landfill site. Data collected over the observation period showed measurable improvements in air quality following periodic eco-enzyme application, with concentrations of hazardous gases decreasing substantially during afternoon measurements (13:00) compared to morning readings (09:00).

The integration of cloud platforms, specifically Google Firebase and Blynk, enabled seamless remote monitoring and real-time data accessibility across multiple devices, transforming the system from a basic detection tool into a comprehensive air quality management solution. This IoT-based approach facilitates rapid decision-making and timely interventions when air quality thresholds are exceeded.

The findings of this study highlight the potential for broader applications of combined ANN-IoT-eco-enzyme technology in various environmental management sectors, including agriculture, industrial waste treatment, and urban air quality monitoring. The system's ability to provide accurate predictions, automated control mechanisms, and real-time monitoring positions it as a valuable tool for pollution mitigation efforts.

Future research should focus on expanding the sensor network to include additional parameters such as carbon monoxide (CO) and particulate matter (PM2.5, PM10), enhancing the ANN model with deep learning architectures for improved pattern recognition, and conducting long-term field studies to evaluate system performance under diverse environmental conditions. Additionally, the development of predictive maintenance algorithms and energy-efficient operation modes would further optimize the system's sustainability and cost-effectiveness.

By continuing to advance these technologies and establishing supportive policies for their adoption, we can significantly contribute to improved public health outcomes, environmental sustainability, and safer living conditions in communities surrounding waste disposal facilities.

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