A Dual-Parameter Approach to Environmental Air Monitoring

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***Abstract*— This research introduces a novel air quality monitoring apparatus designed to address the need for precise and reliable environmental assessments. Utilizing advanced sensor technology, the device can detect a wide range of pollutants, including particulate matter, volatile organic compounds, and gasses, while also measuring humidity and temperature with high accuracy. Rigorous calibration has ensured consistent performance across diverse conditions, making it particularly effective in regions with complex air quality challenges, such as Indonesia.**

During a monitoring period from 1 PM to 10 PM, the sensor recorded a notable decrease in temperature from 28.1°C to 23.9°C and an increase in humidity from 76% to 90%, with a slight drop to 87% by the end of the period. These data were accompanied by an improvement in air quality from 'Poor' to 'Very Good,' suggesting a correlation between higher humidity, lower temperatures, and improved air quality. The device's real-time data logging and wireless connectivity enable immediate monitoring and intervention, enhancing public health protection and environmental sustainability. User feedback confirmed its usability and reliability, ensuring its practicality in various contexts.

Comparative analysis with existing air monitoring systems highlighted the apparatus's superior performance in delivering comprehensive, real-time data. These insights guide future innovations in air quality monitoring technologies, emphasizing the importance of integrating advanced technology with user feedback. This research contributes significantly to global efforts in addressing air quality issues, promoting healthier and more sustainable living environments.

***Keywords*— Air Monitoring; Apparatus; Pollution; Health; Internet of Things; Device; Air Sensor; Indoor air quality; Air quality sensing; Gas sensors; Urban buildings; Human exposure; Low-cost instrument**

I. Introduction

Pollution is a major global issue with severe consequences for human health and development, especially in low- and middle-income countries.. Industrial activities, agriculture, and inadequate waste management contribute to air, water, and chemical pollution. As a result, excess deaths due to fine particulate and ozone air pollution are estimated at 8.34 million deaths per year. Most of the mortality burden is related to cardiometabolic conditions, particularly ischemic heart disease (Lelieveld, 2023). The economic costs are also staggering, because air pollution is estimated to cost the global economy over 8 trillion dollars a year.

Pollution is not only harming human health but also hinders economic growth and development. It creates unhealthy living conditions, destroys ecosystems, and disproportionately burdens the poor, who lack the resources to protect themselves. Addressing pollution is crucial to improve public health, boost economies, and create a more sustainable future. Thus, the need for accurate measurement and analysis of real-time air quality monitoring must be seriously considered.

The advancement and utilization of mobile platforms have significantly transformed air quality research by enabling real-time resolution of air pollutant concentrations (Brantley, Hagler, Kimbrough, Williams, Mukerjee, and Neas, 2014). The Internet of Things is now finding profound use in various sectors and plays a key role in our air quality monitoring system. (Rawal, 2019). Air quality sensors such as the MQ135 and MQ7 are great in detecting negative substances in the air that might cause health issues towards humans such as excessive carbon monoxide and sulfur dioxide which are emitted from vehicles (Sai, 2019).

Manufactured by D-Robotics UK, the DHT11 sensor is a cost-effective peripheral designed to measure relative humidity within a range of 20 to 90% RH and temperature between 0 to 50°C. It provides humidity readings with an accuracy of ±5% RH and temperature measurements with an accuracy of ±2°C, both with an 8-bit resolution (Warren, 2018).

With the increasing concerns about indoor and outdoor air quality, as well as the impact of humidity and temperature on human health and comfort, there is a growing demand for accurate and reliable monitoring solutions. In this research, we attempt to conduct an apparatus which could detect the air quality, humidity, temperature around a certain radius of area on buildings and in which real-time data can be displayed. Another author has concluded that there were some inaccuracies in the data collection of the monitoring system compared to the actual data (Novelan, 5, 2018). To avoid this issue, we ensure multiple trials to eliminate any inaccurate measurement as much as possible can be performed using.

This study also investigates an innovative apparatus to revolutionize air quality monitoring. The apparatus utilizes these sensors which are the DHT11 and the MQ135. This cutting-edge air monitoring system goes beyond conventional methods, as it offers the capability to detect a range of negative substances in the air, including ammonia (NH_3), sulfur dioxide (SO_2), and carbon monoxide (CO), readings of humidity and temperature. Through the development of this apparatus, we contribute to the enhancement of public health and the environment by providing accessible and reliable air quality data in real time.

II. Related Works

Integrating machine learning techniques with IoT sensor data to predict air pollution levels has become a prominent approach, particularly in smart city contexts. Recent studies have shifted from simple machine learning techniques to more advanced and sophisticated algorithms for more accurate predictions. Notably, China leads in case studies focusing on predicting particulate matter (PM2.5) levels, using open data sources and considering external factors like weather conditions and temporal features for efficient air quality prediction[1]. Building on these advancements, practical applications of IoT for air quality monitoring are now increasingly prevalent, employing various sensors to provide real-time data to the public.

Practical applications of IoT in air quality monitoring often use sensors such as the MQ135 for general air quality and the MQ7 for carbon monoxide detection.IoT platforms, such as ThingSpeak and Cayenne, have made air quality data accessible to the general public in real time. Additionally, proactive measures by governments, such as India's ban on high-emission vehicles, demonstrate how IoT can support regulatory efforts and public awareness[2]. While outdoor air quality monitoring through IoT technologies has become a crucial part of regulatory frameworks, indoor air quality monitoring also plays a vital role in protecting human health.

The increasing air pollution levels and their adverse effects on human health necessitate continuous and real-time monitoring systems. IoT facilitates real-time data collection and communication over the internet, addressing the impracticality of periodic manual sampling. This continuous monitoring is essential for mitigating health risks such as lung and heart diseases[3]. Recognizing the critical importance of maintaining air quality not only outdoors but also indoors, researchers have developed specialized systems for monitoring indoor air pollutants, ensuring comprehensive coverage for health and safety.

Indoor air quality (IAQ) is also a critical aspect of human health, given that people spend more than 90% of their time indoors. A study developed an Indoor Air Quality Detector (IAQD) to measure CO_2, PM 2.5, temperature, and humidity in residential buildings using IoT technology. Deployed in a residential building for a month, the system collected data every two minutes and transmitted it to a cloud server, making the information accessible through mobile apps and web browsers. Analysis revealed significant spikes in PM2.5 levels during cooking and increased CO_2 concentrations in closed-door environments, highlighting the importance of continuous indoor air quality monitoring for residential health and safety[4]. These findings underscore the necessity of integrating IoT solutions for both indoor and outdoor environments to provide a holistic approach to air quality monitoring and health protection.

Collectively, these studies underscore several key trends and conclusions in IoT-based air quality monitoring. One significant trend is the advancement in machine learning techniques, with a shift towards more sophisticated algorithms to enhance the accuracy and efficiency of air quality predictions. This progression highlights an ongoing commitment to improving the reliability of air pollution forecasts, crucial for effective environmental management and public health protection.

Another critical trend is the emphasis on real-time data accessibility. The proliferation of IoT platforms and public dashboards demonstrates a growing focus on transparency and public engagement in air quality issues. By making data readily available, these systems empower individuals to make informed decisions about their health and environmental impact, fostering a more informed and proactive community.

Advances in IoT technology have also led to improved precision and sensitivity in air quality monitoring systems. The integration of high-precision sensors and user-friendly applications addresses traditional monitoring limitations, providing more accurate and actionable data. This enhancement helps identify and mitigate pollution sources more effectively, contributing to better environmental and health outcomes.

Furthermore, the integration of IoT systems with regulatory measures supports efforts to monitor and control pollution levels. Real-time data and predictive capabilities enhance the effectiveness of environmental regulations and policies, reinforcing their role in managing pollution and protecting public health.

Overall, IoT plays a critical role in advancing air quality monitoring and prediction. The ability to provide accurate, real-time data and predictions enables more informed and effective pollution management strategies. As these technologies continue to evolve, they will likely play an increasingly vital role in safeguarding both the environment and public health, ensuring a healthier and more sustainable future.

III. Literature Review

3.1 Internet of Things

The concept of the Internet of Things (IoT) has its roots in the convergence of multiple technologies, including wireless communication, micro-electromechanical systems (MEMS), and the internet. Kevin Ashton coined the term 'Internet of Things' in 1999 during his work at Procter & Gamble, where he sought to enhance supply chain management using RFID (radio-frequency identification) technology. The last decade has seen exponential growth in IoT adoption, driven by advancements in sensor technology, cloud computing, and data analytics. The proliferation of smartphones and the expansion of high-speed internet access globally have further fueled this growth. Today, IoT technology is integrated into numerous aspects of daily life, from smart home devices and wearable technology to industrial IoT (IIoT) systems and environmental monitoring. The development of 5G networks promises to enhance IoT capabilities further by providing faster data transfer rates and more reliable connections.

In the context of environmental monitoring, IoT technology offers significant advancements. IoT-based systems utilize a variety of sensors to measure different environmental parameters, such as air quality, temperature, humidity, and pollutants like PM2.5, CO_2, and NO_x. These sensors transmit data wirelessly to central systems or cloud platforms, where it can be processed, analyzed, and visualized. The key benefits of IoT in environmental monitoring include real-time data collection, enhanced accuracy, scalability, and cost-effectiveness. IoT systems can provide continuous, real-time monitoring, allowing for immediate detection of changes in environmental conditions. This real-time capability is particularly valuable for air quality monitoring, where timely data can help mitigate health risks and inform policy decisions. Furthermore, IoT technology supports the deployment of numerous low-cost sensors across wide areas, making it feasible to create dense monitoring networks. This scalability and flexibility enable comprehensive environmental assessments and more informed decision-making.

3.2 Air Pollution

Air pollution is a critical global issue with severe consequences for human health and economic development, particularly in low- and middle-income countries. Lelieveld et al. (2023) estimate that air pollution, specifically fine particulate matter (PM2.5) and ozone (O_3), is responsible for approximately 8.34 million excess deaths annually, predominantly due to cardiometabolic conditions such as ischemic heart disease. The economic burden is also significant, with global costs estimated at over $8 trillion per year. Air pollution involves the release of chemicals, particulates, or biological materials into the atmosphere that cause discomfort, illness, or death in humans, as well as harm to other living organisms, such as crops, and damage to the natural or built environment. Substances in the air that can negatively impact humans and the environment are known as air pollutants. These pollutants can exist as solid particles, liquid droplets, or gasses and may originate from natural or anthropogenic sources.

Air pollution can stem from both human activities and natural phenomena. Natural events contributing to air pollution include forest fires, volcanic eruptions, wind erosion, pollen dispersion, evaporation of organic compounds, and natural radioactivity. Sources of air pollution encompass the different locations, activities, or factors responsible for the emission of pollutants into the atmosphere. Pollutants are categorized as either primary or secondary. Primary pollutants are those released directly from a source, such as ash from volcanic eruptions, carbon monoxide from vehicle exhausts, or sulfur dioxide from industrial emissions. In contrast, secondary pollutants are not emitted directly; instead, they form in the atmosphere through chemical reactions between primary pollutants. Ground-level ozone, a major component of photochemical smog, is a significant example of a secondary pollutant. Some pollutants can be both primary and secondary, meaning they are directly emitted and also formed from reactions involving primary pollutants.

Sulfur oxides (SO_x), notably sulfur dioxide (SO_2), are produced by both natural sources, like volcanoes, and various industrial processes. The combustion of coal and petroleum, which often contain sulfur compounds, generates sulfur dioxide. Further oxidation of SO_2, usually in the presence of a catalyst such as NO_2, forms H_2SO_4, resulting in acid rain. This environmental impact raises concerns over the use of these fuels as energy sources. Nitrogen oxides (NO_x), especially nitrogen dioxide (NO_2), are expelled from high-temperature combustion processes and naturally during thunderstorms by electric discharges. These pollutants are visible as the brown haze dome above cities or the plume downwind. Nitrogen dioxide, a chemical compound with the formula NO_2, is a reddish-brown toxic gas with a sharp, biting odor and is one of the most prominent air pollutants. Carbon monoxide (CO) is a colorless, odorless, non-irritating but highly poisonous gas produced by the incomplete combustion of fuels such as natural gas, coal, or wood. Vehicular exhaust is a major source of carbon monoxide.

Volatile organic compounds (VOCs) are important outdoor air pollutants divided into methane (CH4) and non-methane VOCs (NMVOCs). Methane is a highly efficient greenhouse gas contributing to global warming, while other hydrocarbon VOCs significantly impact greenhouse gas levels by creating ozone and prolonging methane's atmospheric life. Within NMVOCs, aromatic compounds like benzene, toluene, and xylene are suspected carcinogens and may cause leukemia with prolonged exposure. 1,3-butadiene, associated with industrial use, is another dangerous compound. Particulates, also known as particulate matter (PM), are tiny solid or liquid particles suspended in a gas. Aerosols refer to particles and gas together. Particulates can be natural, originating from sources such as volcanoes, dust storms, forest fires, and sea spray, or man-made, from burning fossil fuels in vehicles, power plants, and industrial processes. Human-made aerosols currently make up about 10 percent of the total atmospheric aerosols. Increased fine particle levels in the air are linked to health issues like heart disease, altered lung function, and lung cancer.

Persistent free radicals associated with airborne fine particles could cause cardiopulmonary disease. Toxic metals, such as lead and mercury, and their compounds are significant pollutants. Chlorofluorocarbons (CFCs), harmful to the ozone layer, have been emitted from products now banned. Ammonia (NH3), emitted from agricultural processes, is a gas with a pungent odor used in synthesizing many pharmaceuticals. Despite its wide use, ammonia is both caustic and hazardous. Odors from sources such as garbage, sewage, and industrial processes also contribute to air pollution. Radioactive pollutants are produced by nuclear explosions, events, war explosives, and natural processes like radon decay.

According to the WHO, air pollution is a major risk factor for various health conditions, including respiratory infections, heart disease, and lung cancer. Health effects from air pollution can include difficulty breathing, wheezing, coughing, asthma, and the worsening of existing respiratory and cardiac conditions. These health issues can lead to increased medication use, more frequent doctor or emergency room visits, higher hospital admissions, and premature death. Poor air quality primarily affects the respiratory and cardiovascular systems, with individual responses varying based on the pollutant type, exposure level, health status, and genetics. Common air pollutants include particulates, ozone, nitrogen dioxide, and sulfur dioxide. Both indoor and outdoor air pollution contribute to approximately 3.3 million deaths worldwide annually. Children under five in developing countries are particularly vulnerable to air pollution-related deaths. The WHO estimates that 2.4 million people die each year from causes directly related to air pollution, with 1.5 million of these deaths due to indoor air pollution.

Significant air pollution disasters include the 1984 Bhopal Disaster in India, where leaked industrial vapors from the Union Carbide factory killed over 25,000 people and injured hundreds of thousands more. The UK's worst air pollution event, the Great Smog of 1952 in London, resulted in over 4,000 immediate deaths and 8,000 more in the following months. In 1979, an accidental leak of anthrax spores from a Soviet biological warfare laboratory near Sverdlovsk caused hundreds of civilian deaths. Globally, children in cities with high air pollution levels face increased risks of asthma, pneumonia, and other respiratory infections. Due to more outdoor activities and higher minute ventilation, children are more susceptible to air pollution dangers. Additionally, low birth weight risks are heightened in heavily polluted cities.

Toxic air pollutants can lead to the formation of acid rain and dangerous ground-level ozone, which harm trees, crops, animals, and water bodies, making them unsafe for humans and wildlife. Air pollution negatively impacts the economy by reducing agricultural crop and commercial forest yields, costing billions each year. Additionally, health-related absences from work decrease productivity, further straining the economy. The economy thrives when people are healthy and businesses reliant on natural resources operate efficiently; air pollution undermines both. Traditional air quality monitoring has relied heavily on stationary monitoring stations that provide high-accuracy measurements of various pollutants. However, these methods have limitations in spatial resolution and flexibility. Stationary monitors are typically expensive and sparse, providing limited coverage and failing to capture the spatial variability of air pollutants in urban environments.

Recent advancements in the Internet of Things (IoT) and mobile technologies have revolutionized air quality monitoring. IoT-enabled sensors and mobile platforms allow for high-resolution, real-time monitoring of air pollutants, overcoming the limitations of traditional methods. Brantley et al. (2014) highlight the transformative impact of mobile sensor platforms in providing detailed spatial and temporal data on air quality. In recent years, technological advancements have significantly impacted the quality of air globally, leading to worsening conditions. To raise awareness about the severe and irreversible effects of air pollution on human health, particularly on children, the World Health Organization (WHO) organized its first global conference on "air pollution and health" in Switzerland at the end of October 2018.

On an international scale, PM2.5 has been identified as a high-risk carcinogen by the WHO. The United States adopted a new Air Quality Index (AQI) in 1999 to better represent air quality data. Previously, Taiwan's

Environmental Protection Administration (EPA) used the Pollution Standard Index (PSI). However, the PSI had a significant limitation: it did not account for PM2.5. Recognizing this gap, Taiwan launched a new AQI in July 2014. The updated AQI includes measurements for ozone (O3) and PM2.5, offering a more thorough evaluation of air pollution levels. For instance, when comparing air pollution days, the AQI identifies approximately 50 more days of pollution annually than the PSI, indicating its superior accuracy in assessing air quality.

3.3 Air Quality Index

The AQI categorizes the impacts of several pollutants, including carbon monoxide (CO), ozone (O3), fine particulate matter (PM2.5), particulate matter (PM10), sulfur dioxide (SO2), and nitrogen dioxide (NO2), based on daily data from the EPA. The health effects associated with these pollutants are detailed in various classifications. The AQI is calculated using a formula that considers the concentrations of different pollutants and their respective sub-indices, selecting the highest value to represent the day's air quality. This methodology is explained by specific equations for indoor air quality sub-indices. Indoor air quality indices (IAQI) for each pollutant are determined based on their concentration levels. These indices are calculated by comparing the pollutant concentration to set high and low benchmark values, then finding the corresponding sub-index values. The index is divided into six levels of hazard: good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous. Each level is represented by a specific color: green, yellow, orange, red, purple, and maroon, respectively. These colors indicate the potential health impacts, with levels above purple signifying dangerous air quality conditions.

IV. Hardware And Software Installations

To ensure the proper functionality and accuracy of the air quality monitoring apparatus, meticulous attention was given to both hardware and software installations. This section outlines the comprehensive setup process, including the selection and integration of sensors, the assembly of the hardware components, and the configuration of the software necessary for data acquisition and analysis.

An Internet of Things (IoT)-based air quality monitoring system that uses the DHT11 temperature/humidity sensor and the MQ135 gas sensor is shown in Figure 1 flowchart as its operational sequence. It starts with the system turning on and initializing the components. Next, it shows an OLED screen with a startup message. After that, the system reads the sensor data, converts it, and assesses it in relation to certain thresholds. The OLED panel shows the results for instantaneous user input. The system emphasizes its function in continuous air quality evaluation for environmental health by operating in a continuous loop that monitors and displays data until manually ended.

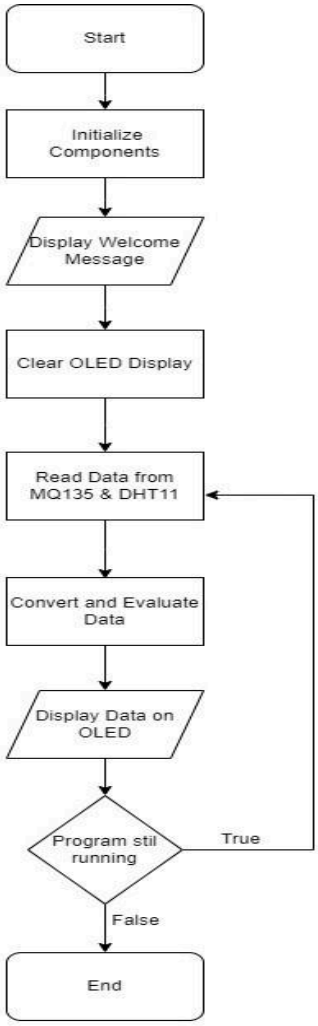

Figure 1. Flowchart

The schematic diagram shown in Figure 2 depicts an IoT configuration for monitoring environmental air quality. Its central processing unit is a microcontroller, which is an Arduino Nano. Crucial sensors are attached to the microcontroller: the MQ-135 gas sensor, which is adept at identifying a broad range of air contaminants like CO2, ammonia, and benzene, and the DHT11 for temperature and humidity readings. These sensors use their respective power and data ports to transmit important environmental data to the microcontroller. The system also includes an OLED display, which is linked to the microcontroller by conventional I2C lines. This configuration makes it possible to monitor and show temperature, humidity, and various air pollutant levels in real-time, which makes it a useful and practical Internet of things project for evaluating indoor air quality.

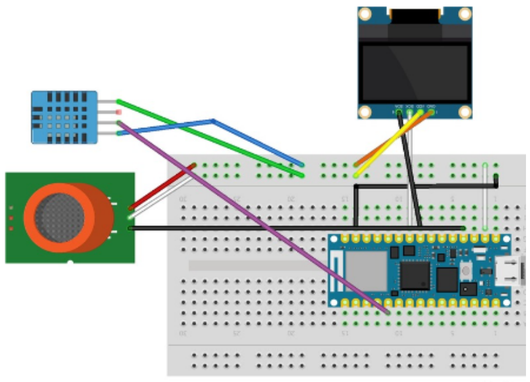

Figure 2. IoT Schematic

The main hardware used in this device consists of 4 important parts as shown in Figure 3 which are the arduino nano, DHT11, the 0.96-inch OLED display via an I2C interface and the MQ135.

The Arduino Nano is a compact, flexible microcontroller that is ideally suited for DIY and IoT projects due to its robust capabilities and small dimensions. This microcontroller is equipped with an ATmega328 processor, 14 digital I/O pins, 8 analog input pins, and an adequate amount of memory to manage a variety of sensor data processing duties. It is compatible with a diverse array of sensors and modules due to its capacity to operate at both 5V and 3.3V.

The microcontroller is connected to the 0.96-inch OLED display via an I2C interface, which necessitates only two ports (SCL and SDA) and has a resolution of 128x64 pixels. An OLED display is more energy-efficient due to its capacity to generate vibrant colors and high contrast without the necessity of a backlight. This display presents real-time sensor data, which offers a clear visual representation of the temperature, humidity, and gas levels in the immediate vicinity.

The DHT11 sensor is affordable and easy to use, measuring humidity with ±5% RH and temperature with ±2°C accuracy. It is ideal for basic air quality monitoring systems where cost is a concern[18].

Due to its versatility in assessing urban air pollution, the MQ135 sensor is preferred in air quality monitoring due to its capacity to detect a variety of dangerous gasses, including ammonia, sulfur dioxide, and carbon monoxide. In contrast to sensors such as MQ7 (specific to carbon monoxide) and MQ2 (smoke and combustible gasses), MQ135's wide detection range makes it more appropriate for thorough air quality assessments[11].

Numerous studies have shown that integrating IoT and sensor technology improves air quality monitoring by providing real-time data and increasing pollution detection accuracy[6]. However, there are obstacles, particularly when compared to conventional monitoring techniques, such as guaranteeing sensor data accuracy through exacting calibration and validation procedures. Notwithstanding these difficulties, sensors such as the DHT11 and MQ135 provide a favorable blend of low cost, simplicity of implementation, and adequate precision for efficient utilization in various environmental monitoring applications, supporting environmental management and public health programs.

Figure 3. Hardwares

V. Result and Discussion

The following section presents the findings from our air quality monitoring experiments, highlighting the performance of the apparatus under various conditions. Detailed analysis and discussion of the collected data are provided, offering insights into the effectiveness of the system and its potential implications for environmental monitoring and public health.

Time	Temperature (°C)	Humidity (%)	Quality
13:00	28.1	76	Poor
14:00	27.7	76	Poor
15:00	27.1	81	Good
16:00	26.5	82	Good
17:00	26.2	85	Good
18:00	26.2	87	Very Good
19:00	25.0	88	Good
20:00	24.9	89	Good

21:00	24.5	90	Good
22:00	23.9	87	Good

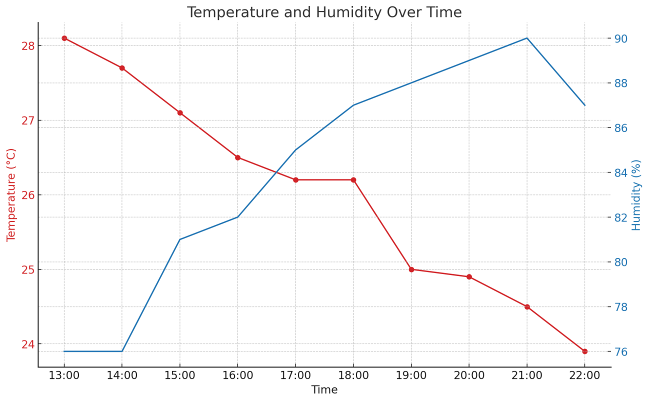

Figure 4. Graph

The graph displays the variation of temperature and humidity over time from 13:00 to 22:00. The red line represents the temperature, which starts at 28.1°C at 13:00 and shows a general decreasing trend, reaching its lowest point of 23.9°C at 22:00. The blue line represents the humidity, starting at 76% at 13:00. Initially, it remains constant until 14:00, then steadily increases from 15:00 onward, peaking at 90% at 21:00 before slightly dropping to 87% at 22:00.

The air quality, indicated in the data table but not depicted on the graph, shows that from 13:00 to 14:00, the air quality is "Poor." From 15:00 to 17:00, it improves to "Good," further enhancing to "Very Good" at 18:00, and remaining "Good" from 19:00 onwards. Generally, as the temperature decreases, the humidity increases, evident from the inverse relationship seen in the graph. This trend suggests that higher humidity and lower temperatures might correlate with improved air quality, as indicated by the transition from "Poor" to "Good" and "Very Good" ratings throughout the day.

The IoT air quality monitoring sensor, placed on a residential front porch, recorded notable environmental data from 1 PM to 10 PM. Throughout this period, the temperature exhibited a clear decreasing trend, starting from its peak at 1 PM and gradually cooling down by 10 PM. Correspondingly, humidity levels increased inversely with the temperature, reflecting the natural atmospheric changes as the day transitioned into night.

Significantly, air quality improved in the evening hours. This enhancement can be attributed to a reduction in human activities such as traffic and industrial operations, cooler temperatures reducing certain pollutants, and better atmospheric dispersion. These findings demonstrate the sensor's capability to effectively monitor real-time environmental conditions and highlight its potential role in improving air quality management and public health monitoring efforts.

VI. Conclusion and Future Works

6.1 Conclusion

This research introduces a groundbreaking air quality monitoring apparatus designed for accurate and reliable environmental monitoring. Utilizing advanced sensor technology, the device detects a wide range of pollutants and measures humidity and temperature with precision. Its rigorous calibration ensures consistent performance, making it particularly effective in complex air quality conditions like those in Indonesia.

The IoT air quality sensor recorded data from 1 PM to 10 PM, showing a decrease in temperature from 28.1°C to 23.9°C and an increase in humidity from 76% to 90%, before slightly dropping to 87%. Air quality improved from "Poor" to "Very Good" during this period, suggesting that higher humidity and lower temperatures correlate with better air quality. This data highlights the sensor's capability to monitor real-time environmental conditions effectively.

One of the key strengths of this apparatus is its real-time data logging and wireless connectivity, enabling immediate monitoring and analysis. This allows for prompt interventions when air quality standards are compromised, enhancing public health protection and environmental sustainability. User feedback has also provided valuable insights into the device's usability and reliability, ensuring practicality and adaptability in various contexts.

Comparing the new apparatus with existing air monitoring systems shows its superior performance in delivering comprehensive, real-time data. These insights guide future innovations in air quality monitoring technologies. The research underscores the importance of integrating advanced technology with user feedback to develop effective environmental tools, contributing to healthier and more sustainable living environments.

6.2 Future Works

To enhance the capabilities of our IoT air quality monitoring device, future developments should focus on integrating additional sensors to monitor a broader range of pollutants such as sulfur dioxide (SO_2) and volatile organic compounds (VOCs). This expansion would provide a more comprehensive assessment of air quality. Additionally, implementing machine learning algorithms could enable predictive analytics, allowing for real-time identification of pollution trends and potential sources, thus offering early warnings and contributing to proactive environmental management.

Another key area for future work involves improving the energy efficiency of the device by integrating renewable energy sources like solar panels. This would make the device more sustainable and suitable for long-term deployments, especially in remote areas. Enhancing user interfaces, such as through mobile applications and web platforms, will increase data accessibility and usability, enabling a broader audience to engage with and benefit from air quality information. Expanding the device's integration with smart city infrastructure and engaging in community and policy advocacy are also critical steps toward leveraging our technology for broader societal and environmental impacts.

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