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Solar-Powered Intelligent Multi-Gas Air Quality Monitoring and Automated Ventilation Framework Based on Multi-Sensor Data Fusion and Real-Time Iot Alerts

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***Abstract*—This paper presents an innovative solar powered automated ventilating system and multi-gas air quality surveillance system to continuously monitor the environment. The system has many sensors constantly measuring the concentration of ammonia, carbon monoxide, methane, temperature, humidity, and volatile organic compounds. Through the start of automated ventilation and local alarms and supporting the early detection of hazardous conditions, a threshold-based decision system mitigates gas build-up. The system incorporates a cellular communication channel as opposed to a network since the cellular communication is more reliable during network outrages. The data and alert messages monitored are distributed through the use of IoT. The results of the experiment prove the reliability of sensors in terms of continuous operation, low energy consumption, and timely reaction to alerts. It offers a reliable, scalable and energy efficient approach to indoor air quality monitoring to apply in homes, workplaces and in intelligent environments.**

***Index Terms*—Air Quality Monitoring, Automated Ventilation, Energy-Efficient Embedded Systems, Environmental Monitoring, Hybrid Communication, Internet of Things (IoT), Multi-Gas Sensing, Solar-Powered Systems.**

I. INTRODUCTION

Air pollution and toxic gases in controlled and semi-controlled environment is a significant health and safety risk to human health. The disadvantages of the traditional air quality monitoring systems are the high cost, continuous infrastructure requirements, and dependency on grid power to monitor the air quality before incidence of a disastrous event.

A lot of the systems that are currently deployed require a manual process of data processing and response, or, are single-parameter sensors. These disadvantages render them less useful in a generalized sense, particularly, in the context of situations that involve the continuous, autonomous observation that are remote, resource-limited, or energy-intensive.

Developments in sensor technology and Internet of Things (IoT) platforms have made small and network-connected environmental monitoring devices viable. Situational awareness is significantly increased with the IoT-based solutions as they allow automated alarming, remote access, and data visualization in real time.

The power source is another major issue with long-term environmental monitoring systems, however, because many IoT air quality devices lack sufficient reliability to be used in safety-critical applications, they only have a single channel of communication and no inbuilt mitigating features.

Grid gadgets are also vulnerable to power cuts in contrast to battery-powered devices which require regular upkeep. One of the ways through which continual operation will always require minimum help of human beings is the use of sustainable sources of energy such as solar electricity.

Communication, lifespan of working, sensor accuracy has to be in a balance with energy-saving system design because as much as monitoring is important, acting fast in the situations that may be hazardous is important. Passive warning mechanisms may not be sufficient to reduce the risk in the short term. Like the controlled ventilation, automated actuation has the potential to minimally accumulate gas and improve the quality of indoor air, but without human intervention.

Complex decision-making algorithms are required to ensure such reactions are activated at the right time and in a consistent manner, the automatic ventilation system and solar-powered intelligent multi-gas air quality monitoring system that are under consideration in this paper are aimed at the constant monitoring of the environment.

The proposed architecture comprises of hybrid connection, multi-sensor data collection, autonomous power management and real-time warnings.

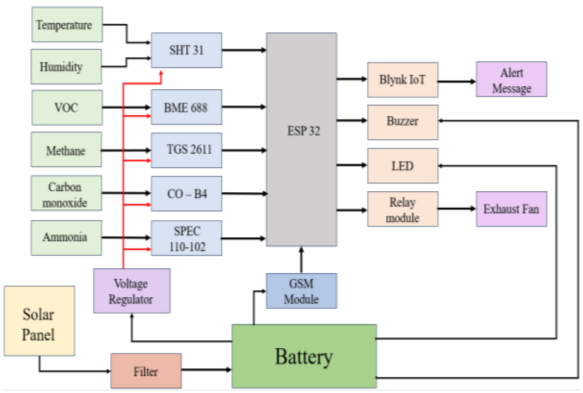

Figure 1. Illustrates the overall system architecture of the proposed solar-powered multi-gas air quality monitoring and automated ventilation system. The architecture comprises sensing, processing, communication, actuation, and power management modules, all coordinated to enable continuous monitoring and real-time alert generation.

II. SYSTEM ARCHITECTURE

The proposed system architecture has intelligent warning, automatic ventilation, ceaseless multi-gas air quality, and low power consumption features. The whole architecture incorporates sensor, energy management, actuation, compute and communication modules on one platform. Figure 1 illustrates the block scheme of the system, communication of the different modules and direction of data flow of what is monitored in the environment to the development of alarms and mitigation measures.

The sensing module collects the number of toxic components present in the sewage system. The analogy and digital outputs of these sensors give current information on the local air quality. The system will ensure a comprehensive environmental monitoring by use of heterogeneous sensors to detect flammable and hazardous gases in diverse indoor and semi-enclosed settings. The primary control unit, which is called the processing module, is responsible to the collection, selection, and preprocessing of sensor data. Sensor data is collected, filtered, and checked against safety requirements by software on a regular basis.

The processing unit provides deterministic and reliable system operation by orchestrating all systems functions such as data transmission, power, ventilation, and alerting. The communication module makes it possible to monitor remotely and distribute the alarms using hybrid networking technology. The status of the system and the environmental data are transmitted by a wireless network to an IoT platform that is hosted on the cloud to record and monitor in real-time. A cellular communication interface can be used to add a level of redundancy to the system, which can be used to send alert signals in the case of a network outage or other major threat. The alarm and actuation module responds instantly on a local basis when there are dangerous air quality conditions.

Automated ventilation system is activated through a relay connection in order to dilute the gas level and warn the neighbours through the visual and auditory signals. The energy management module allows the IT system to operate autonomously and implement immediate mitigation of any hazards detected by the system based on the power source available to run the system and the presence of a battery backup. The system runs every element using solar energy which has been managed and stored. The design is suitable in the long-term application in remote and energy-constrained environments since load management and power distribution ensures continued operation even in low-light conditions.

III. HARDWARE DESIGN AND IMPLEMENTATION

The hardware architecture of the suggested system is characterized by low power consumption, strong connection, and certain multi-gas detection. Some of the subsystems that are interdependent include actuators, sensors, power management, computing, and communication. In choosing every piece of hardware, parameters such as precision, energy usage, and the ability to operate long-term autonomously in an indoor or semi-enclosed setting are considered.

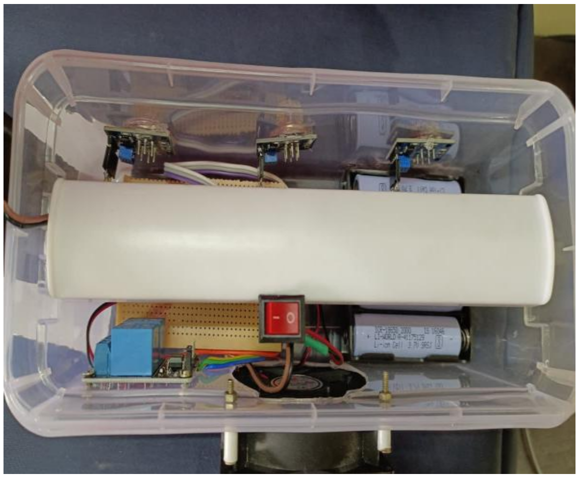

Figure 2. Hardware implementation of the Proposed System.

The sensors of the environmental sensing subsystem detect temperature, humidity, ammonia, carbon monoxide, methane, and volatile organic compounds. These sensors have combined detection abilities whereby they can detect hazardous and flammable gases. The analogy and digital signal of gas sensors should be properly connected with the processing unit and this can modify and enhance the accuracy of gas concentration data. The proper voltage scaling and filtering circuitry of conditioning analogy outputs enable making an analogy-to-digital conversion accurately. There are gas sensors that are fitted with heating elements which are energized through controlled electricity in order to maintain their operating temperatures at a constant level.

To reduce the amount of power used in continuous monitoring without significantly affecting the sensing accuracy, the processing unit performs hardware-level duty-cycling, and the processing unit is also the main controller. This system provides a reliable communication with analogy, digitals and multiple sensors at the same time. The CPU hardware option supports real-time operation, low power modes, and reliable peripheral management. The communication equipment provides information in a hybrid approach with cellular modules and wireless networking. Wireless connectivity makes it possible to transfer data continuously to a cloud-based platform and the cellular module ensures delivery of alerts in case of a network outage.

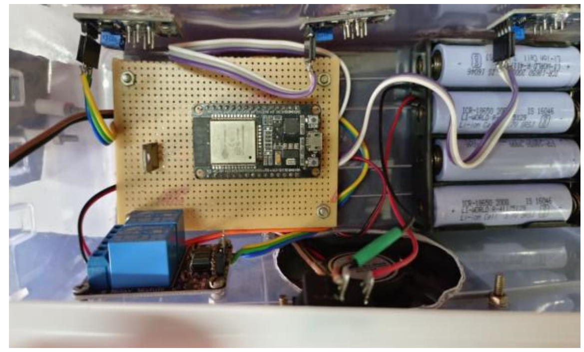

Figure 3. Internal hardware components and connections.

Decoupling capacitors and dedicated power channels handle the momentary current demand during transfer of data, the actuation subsystem is comprised of visual indications, a ventilation system, which is operated by a relay, and an aural alarm system. Relay connectors provide stable and safe use, since they electrically isolate high power load circuits and low power circuitry.

This subsystem allows a local response in time in case the sensor module senses the dangerous air quality conditions. Rechargeable batteries and solar energy-gathering gadgets are used to regulate power. In order to reduce noise and avoid voltage dips, sensitive and high-power devices are put on dedicated regulated rails. The entire hardware system is packaged into a small platform to simplify the process of deployment and maintenance. The modular structure of the hardware can be extended in the future, sensors can be swapped, and be scaled to suit various objectives of air quality monitoring.

Unless the operating conditions are regulated, semiconductor and electrochemical gas sensors cannot be operated with reliability of any kind. The noise and transient oscillation due to changes in the environment or sensor warm-up behaviour are eliminated by signal stabilization techniques.

IV. SOFTWARE AND FIRMWARE IMPLEMENTATION

The software architecture of the proposed system is to allow the minimum of power consumption, prompt decision-making, and reliable data collection. The modular functional blocks are managed by the firmware and are in control of the communication, data processing, sensor interface, alarm management and system monitoring. This modular approach allows scalable system expansion and increases regard to maintainability. This modular approach establishes predetermined sample intervals of sensor data to collect.

After the analogy and digital sensors have been started, the data is collected on a periodical basis. To remove noise and transient changes and give the sensor values a steady contribution to the next phases of decision-making, simple filtering methods are employed on the raw sensor values to remove two factors in the environment that may change the results of the decision-making process, namely temperature and humidity. The decision-making reasoning is performed by the threshold-based assessment method employing pre-established calibration factors and correction coefficients to pre-normalize sensor data and then making a comparison against threshold values. Any parameter that passes beyond an appropriate threshold trigger both local and remote reaction mechanisms and places the system in an alert state.

All the visual cues, aural alarms and ventilation actuation are all controlled by alert management protocols. Firmware avoids repetitive triggering by making sure that such outputs are turned on at the same time by use of timing control and state management. This minimizes unwanted vibrations in the long-term abnormal situations and enhances user experience. Communication protocols regulate the data flow through wireless connection to a cloud-based IoT platform.

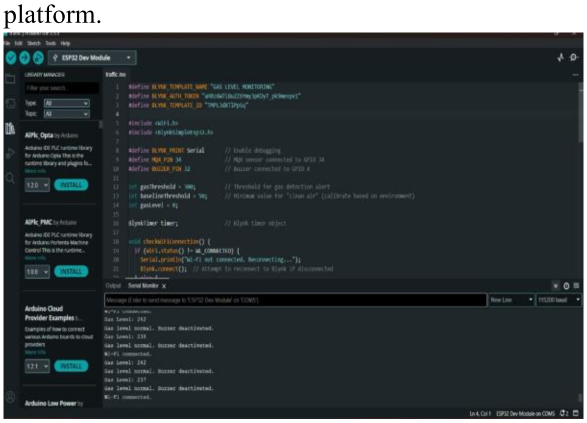

Figure 4. Master code for the ESP – 32 modules.

Power efficiency is also the purpose of firmware-level power management techniques in ensuring that the messages are received reliably in case of network disruption or other critical situations. Unnecessary peripherals are switched off when idle and operating in low power modes are applied. The activity and power consumption are adjusted to reach reactivity and power consumption respectively, with the change of transmission frequency and intervals between samples. The status of sensors, their availability and the level of power is also monitored through system supervision.

Fault detection systems identify when something strange is going on like a sensor or a communication error. The entire firmware design can also guarantee the robustness of warning generation, deterministic behaviour, and environmental monitoring. Its modular architecture that does not necessitate major architectural modifications allows future extension by adding more sensors, more complicated algorithms and better communication.

V. DECISION ALGORITHM AND ALERT LOGIC

Due to the versatility of software design, it is suitable to a variety of monitoring situations. The stability and reliability of the system is increased by integrating the process of error handling methods. Automated task recovery methods, exception management and watchdog clocks are utilized in order to maintain constant service and avoid system lock up. These characteristics enhance the reliability and the strength of the monitoring system under unattended deployments. The decision system aims at reducing false alarms and correctly detecting risky air quality conditions. It constantly gathers information of various sensors and real time analysis of the environment. Since the method is deterministic, there is also consistency in the performance of the system when using both typical and abnormal operating environments.

Data collecting module gives validated sensor values with every monitoring cycle. All of the monitored and displayed parameters include temperature, humidity, volatile organic chemicals, ammonia, carbon monoxide, and methane. All metrics are standardized using preset calibration factors which are then represented by threshold values which are stored in the system memory representing the safe operating limitations. The threshold values for each of the sensors are calculated by safety rules and specifications of the sensors.

The program will compare the measured values against the relevant criteria at the end of every cycle to ensure that there are no violations. The conceptual processing of all the parameters simultaneously by the evaluation technique can be done in a sequential manner even though the firmware may execute them in a sequential manner. Response time is enhanced by ensuring that only one detrimental condition is used to instigate an alert condition without further comparisons.

The use of temporal validation enhances the method. An alarm cannot be verified until a breach of threshold is maintained in consecutive samples over a certain number of samples. This eliminates the effect of spikes and sensor noise in the behaviour of the system. The system is placed in active reactive condition by the technique when an alarm situation is verified. In order to reduce gas build-up, the automated ventilation system is triggered whenever there were visual and audible signals surrounding the area.

The alert state is maintained until the sensor values reach a steady point. Ammonia and carbon monoxide have been classified as priorities of essential gases. Such parameters will eliminate the long delays of validation as they will activate the alarm when the limits are overshot. This will ensure that in case of looming health hazards, there will be timely action. Also, the program regulates behavioural recovery and alert repetition. Hysteresis is employed to ensure that warnings do not exceed rapidly.

The system has a few prerequisites that it needs to satisfy before returning to normal monitoring mode. The decision algorithm after consideration of all the relevant variables comes up with a compromise between sensitivity and reliability. The logical system of this system is its primary intelligence and it allows to properly estimate hazards, respond in time and operate in a stable manner.

The data flow along the threshold limit for each sensor is shown in Figure 3. When the actual value measured by the sensors exceeds the set value, the alert system will be activated, All the sensors output are in parallel system, so even any one the actual value exceeds the set value the alert system will be activated.

Table 1. Description of Flow chart variables.

Flow Chart Description	
X1	Set Temperature
X2	Set Humidity level
X3	Set VOC level
X4	Set Methane level
X5	Set Carbon Monoxide level
X6	Set Ammonia level
A1	Actual Temperature
A2	Actual Humidity level
A3	Actual VOC level
A4	Actual Methane level
A5	Actual Carbon Monoxide level
A6	Actual Ammonia level

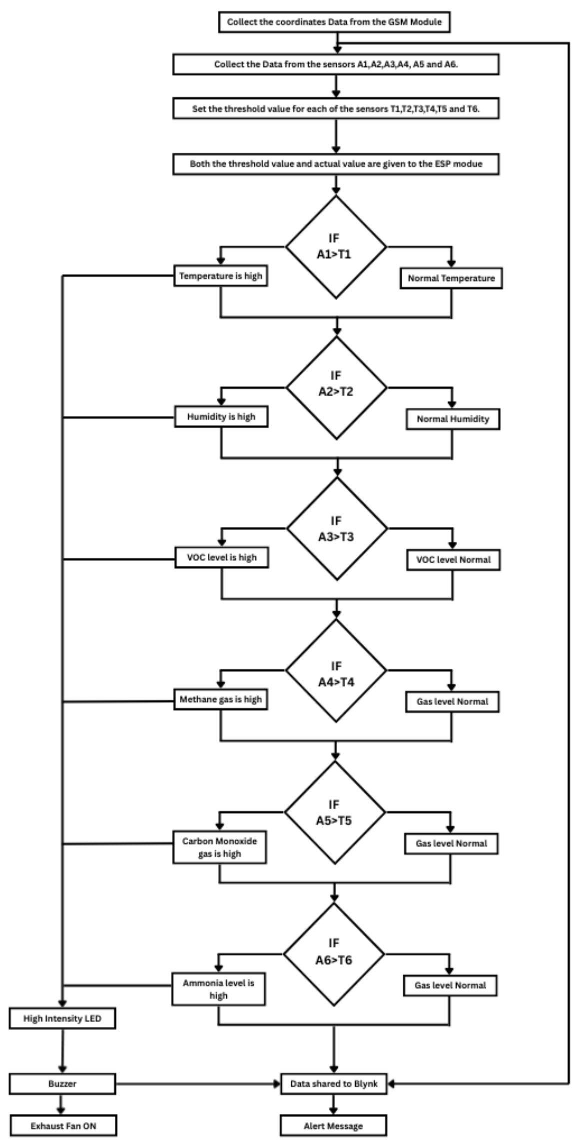

Figure 5. Data Flow diagram of the Proposed System.

VI. EXPERIMENTAL SETUP

The rationale of the experimental arrangement was to evaluate the performance, reliability and responsiveness of proposed multi-gas air quality monitoring system. The device was tested in indoor conditions to replicate the climatic variation and the gas exposure conditions that are available in the real world. A hybrid of solar and battery technologies was used to ensure an independent work of every hardware module. Before experimentation, the sensor had been calibrated to ascertain the accuracy of measurements.
Standard reference devices were used in the calibration of temperature and humidity environmental sensors. The sensors have been calibrated, according to the recommendations of the manufacturer, by stabilizing the sensor numerical values and exposing the sensor to known sources of known concentrations. This process ensured good performance of the systems over a significant period of time. Gas exposure tests of each gas sensor were carried out in isolation.

Figure 6. Experimental setup for static condition testing.

Sensitivity, reaction time and recovery behaviour properties of a sensor response were tested by adding small and controlled volumes of test gases. These experiments proved that such a system is able to identify threshold violation. The decision system was tested on a variety of test scenarios, such as individual and multiple gas threshold exceedances. Ventilation triggering sequence, alarm activation sequence and system reaction time were all recorded and looked into. This showed that the warning mechanism that was in place was legitimate and precise.
The communication performance with the IoT platform was observed during the normal and degraded state of a network to provide the data flow. Cellular alert transmission was also experimented in the case of simulated wireless network failures, so that to achieve the reliability and redundancy of distant warnings. The consumption of power was determined in various operating conditions like alert, active sensing, and idle monitoring. Constant running functionality was verified with the help of monitoring the behaviour of the solar charger and battery aging.

Figure 7. Field experimental setup.

The stability tests were done in the long term. The system was run over long durations of time to identify any issues, communication hitch or sensor drift. The findings verified the stable operation to be used in unsupervised deployment. The experimental analysis indicates that the suggested system is suitable to real-life operating conditions of the operating conditions, including a high level of reliability in monitoring multi-gases, timely alarms, and low-cost energy usage.

VII. RESULTS AND DISCUSSION

The experimental findings indicate how accurate the proposed system is in monitoring a number of air quality indicators in real-time. The increase in the concentration of gases led to the sensor outputs changing significantly, which is normally stable. This is an example of how the sensing unit can detect the change in the gas and the environment. The temperature and humidity measurements remained also constant throughout the test and they acted as good reference to set up gas sensors. These factors enhanced the stability of the gas measurements in the presence of varying external conditions by minimizing the drift of measurements and false triggering.
The response analysis of the gas sensor was used to find threshold exceedances very fast. Since they wanted to be sensitive, it was logical that the reaction time of combustible gas sensors would be delayed in

comparison with carbon monoxide and ammonia sensors. Following the removal of the gas, the recovery times came down into levels that were not acceptable in applications that demanded continuous observation.

The algorithm used to decide on the detection of dangerous situations had very few false alarms and correctly detected dangerous situations. The hysteresis and the temporal validation methods reduced transient spikes induced by short-term disturbances of the environment or noise on the sensor. This enhanced long-term reliability of the system. Outputs of alerts and actuations confirm a timely response of the system.

The automated ventilation system was successful to reduce the levels of gas and visual and auditory messages were also emitted when threshold violations were detected. The closed-loop approach ensured better security by eliminating risks that did not need human intervention. The results of communication show that under normal network conditions, the data transfer to the IoT platform should be reliable. There was very little latency in real-time data capture and viewing.

The power performance of the hybrid communication method demonstrates effective energy utilization. The effectiveness of the hybrid communication method to relay cellular messages during simulated network outages is proven across a variety of operating conditions. The device was solar powered and included a backup battery which ensured that it worked even when the light was insufficient. When alert levels increased, power consumption also increased, but within limits which was still below acceptable level to continue with deployment.

The system worked all the time, and long-term stability testing did not indicate any problems with the communication or sensor drift.

VIII. FUTURE SCOPE

Machine learning and other data analytics can help to further improve the recommended method. Predictive algorithms can be developed by using historical air quality data to predict when hazardous conditions are going to be experienced before the threshold is broken. This would enhance proactive alarms and proactive safety protocols in the industrial and the indoor environments.

Mesh networking and centralized data management platforms can allow the system architecture to scale to large scale deployments. Integration with smart building management systems would provide a better energy optimization and coordinated ventilation control of many monitoring nodes, ruggedized enclosures, support of different environmental conditions and adherence to relevant air quality standards.

The system with these improvements would be better applicable in applications that required industrial safety, regulatory compliance, and external monitoring which could be the scope of the future studies to focus on sensor fusion and adaptive calibration methods to enhance sensing accuracy.

IX. CONSLUSION

This paper suggested the use of solar powered intelligent multi-gas air quality monitoring system and automatic ventilation system in order to ensure effective and consistent monitoring of the environment. A combination of multi-sensor data gathering, decision algorithm, hybrid communication, and autonomous power management are proposed to work with the system and detect dangerous air quality conditions and take necessary mitigation actions in a timely manner. Under the conditions of actual operation in the field, the results of the experiments indicate stable sensor behaviour, accurate warning creation, and effective use of energy. It solves the key flaws of traditional air quality monitoring systems through allowing continuous use with renewable energy, offering local and remote alarms, and automatic response with no human intervention. It has a flexibility and scalability in various application environments, which can be made possible by its modular hardware and firmware architecture.

REFERENCES

[1] Phadatare, R., Pokharkar, E., Puri, S., & Bhosale, S. (2025). IoT-Based Solar-Powered Air Quality Purification and Monitoring Systems. *International Journal of Electronics and Computer Applications*, 2(1), 136–142. https://doi.org/10.70968/ijeaca.v2i1.E1008

[2] Ramadan, M. N. A., et al. (2026). Intelligent multi-pollutant prediction for indoor air quality

management in industrial buildings using adaptive sensor fusion. *Journal of Building Engineering*, 118, 115048. https://doi.org/10.1016/j.jobe.2025.115048

[3] Kushwaha, S. & Durga Reddy, K. P. C. (2025). An integrated IoT-Based framework for real-time urban air quality monitoring and predictive analytics. *Frontiers in Digital Twin Urban Ecosystems*, 1(1), 26–36. https://doi.org/10.64229/atgbs834

[4] Kondeti, A. R., Rudraksha, L., Chinnaiahgari, S., & Bujunuru, A. (2025). Real-Time Air Quality and Weather Monitoring System Utilizing IoT for Sustainable Urban Development. *Eng. Proc.*, 118(1), 56. https://doi.org/10.3390/ECSA-12-26599

[5] Yildiz, O. & Sucuoglu, H. S. (2025). Development of Real-Time IoT-Based Air Quality Forecasting System Using Machine Learning Approach. *Sustainability*, 17(19), 8531. https://doi.org/10.3390/su17198531

[6] Soemphol, C., Thongsan, T., Ninkaew, S., & Panmuang, P. (2025). Design and implementation of a solar-powered IoT-based real-time air quality monitoring system. *Bulletin of Electrical Engineering and Informatics*, 14(5), 4150–4160. https://doi.org/10.11591/eei.v14i5.10473

[7] Abubeker, K. M., Prajitha, C., Rinesh, S., Arun, M., & Senthil Kumar, A. P. (2025). Internet of Things and LoRaWAN-assisted real-time indoor air quality monitoring and automation system for enhancing passenger safety. *International Journal of Low-Carbon Technologies* (2025).

[8] Afrial, M., Rauf, M., Nouman, M., Talal Khan, M., Arslan Rizwan, M., & Ahmad, N. (2025). Multi-Sensor Indoor Air Quality Monitoring with Real-Time Logging and Air Purifier Integration. *Mater. Proc.*, 23(1), 12. https://doi.org/10.3390/materproc2025023012.

[9] Mule, S. N., Mundhe, A. V., Muntode, S. R., Nagare, T. B., Nagpure, S. S., & Bhaskar, T. (2025). IoT-Based Smart Ventilation and Air Quality Monitoring System. *Journal of Computer Based Parallel Programming* (2025).

[10] Solar Air Purifier and Air Quality Monitoring System integrating IoT and solar energy (Solar-powered, automated exhaust/ventilation). *IJEDR*, 13(4), 2025.

[11] Ram Kondeti et al. (2025). Real-Time Air Quality and Weather Monitoring System Utilizing IoT (includes real-time IoT data and environmental controls). *Eng. Proc.*, 118(1).