

Original Article

IoT System for Monitoring and Controlling Air Quality in Industrial Environments with Local Alerts

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Abstract - This article presents the development of an IoT system for real-time monitoring and control of air quality in industrial environments, focused on protecting the health and reducing risks to operators caused by pollutants generated in everyday production or chemical processes. The system is based on an electronic card with an ESP32 microcontroller using ESP-NOW for wireless communication between the control card that integrates the LoRa SX1278 module and control devices such as relays, integrating high-performance sensors for measuring CO₂, H₂, CO, PM_{2.5}, and PM₁₀ particulate matter, volatile organic compounds, toxic gases of electrochemical origin, as well as ambient temperature and humidity. The measurements are processed through this system to generate a standardized risk index on a scale of 0 to 100, shown in digits on a large numerical display, and sent to the cloud via the Adafruit IO platform for cloud monitoring, as well as enabling the automatic activation of visual alerts through a color-coded signaling system and audible alarms. A 60% to 68% reduction in the level of exposure of operators to critical pollutants is estimated after its implementation, as well as the ease of collecting data in the cloud for further analysis, making it a useful tool for the traceability of industrial risks that pose an environmental risk to the atmosphere and occupational health, providing support for industrial safety audits such as ISO 45001 as a prevention system and the sustained improvement of working conditions in industrial environments.

Keywords - Industrial Air Quality Monitoring, Internet of Things (IoT), Real-Time Environmental Monitoring, Occupational Health and Safety, LoRa-Based Sensor Networks

1. Introduction

Currently, industrial plants engaged in electrochemical production or treatment emit critical pollutants as a result of production processes or electrochemical reactions such as electrolysis, which pose health risks to workers and remain one of the main challenges in occupational safety and health. Despite advances in environmental pollutant mitigation, risk management, and the use of complex devices, many industries still rely on manual inspections, sporadic measurements, and conventional alarm systems that do not allow for continuous monitoring or automated real-time response due to the high cost of implementing these new technologies. This situation increases the likelihood of respiratory diseases, workplace incidents, and unscheduled production downtime due to high pollution levels that directly affect workers' health, highlighting the need for more precise and autonomous technological solutions that enable continuous monitoring of air quality in industrial environments.

This paper presents an IoT system based on an electronic board that integrates the ESP32 microcontroller and wireless communication via LoRa SX1278, for the acquisition, processing, and transmission of data to assess pollution levels

in a specific area. The system uses industrial sensors such as the SCD41 carbon dioxide sensor for detecting CO₂ concentrations, the SPS30 sensor for measuring PM_{2.5} and PM₁₀ particulate matter, the SGP41 sensor for detecting volatile organic compounds, the MQ7 and MQ137 sensors for detecting specific toxic gases from electrochemical processes, and the SHT31 sensor for monitoring temperature and relative humidity. The detection procedure is based on the continuous acquisition of real-time signals and the calculation of a risk index through the system's logic, which are sent to the Adafruit IO platform for a graphical interface. This data is displayed locally on a large 7-segment display and transmitted to a cloud-based data platform monitored by supervisors for storage and analysis, and to control the activation of exhaust fans in the area for the dissipation of contaminants.

The primary objective of this system is to provide real-time industrial environmental monitoring capable of detecting high pollution levels via sensors, issuing visual and audible alerts, and automatically mitigating hazardous air pollution conditions in various industrial areas by activating exhaust fans, thereby reducing workers' exposure to pollutants and improving the ability to respond to critical incidents. Expected



benefits include the optimization of air extraction systems, the reduction of incidents related to occupational health or lung diseases, with additional uses for strengthening audit processes under standards such as ISO 45001, and the sustainable improvement of working conditions through a scalable, reliable, and low-cost-to-implement solution.

2. Related Works

Similar models of the proposed design are obtained, highlighting protection for workers in spaces with high levels of atmospheric pollution caused by industrial productivity. In [1], an example is given of a comprehensive IoT-based solution for air monitoring in classrooms, designed with a structure that allows for easy replacement and updating of sensors and connectivity modules, favoring its adaptability in different scenarios. Its platform is geared towards improving scalability, facilitating the incorporation of new devices. Its implementation in a real environment, specifically in classrooms at the Industrial University of Hanoi, demonstrates that it is applicable in any environment and improves continuous indoor air monitoring. In [2], an IoT and Big Data system is proposed for real-time monitoring and prediction of air quality. The design seeks to identify pollution patterns and predict environmental variables using low-cost sensors, ensuring a scalable and sustainable solution. Its objective is to demonstrate significant improvements in predictive forecasting for industrial regulation, community health, and urban planning. Similarly, in [3], the objective is to design and implement a low-cost IoT system for monitoring Indoor Air Quality (IAQ) on a 24-hour average basis. It seeks to overcome the limitations of traditional metrics by detecting, quantifying, and predicting short- and long-term pollutants within 24 hours using IoT sensors and machine learning models. The result is automated ventilation control and real-time alerts, confirming that its approach after implementation demonstrates viability in terms of predictive risk management. Also in [4], where the IoT system and air management in hospital environments are crucial for monitoring critical parameters in a variety of spaces according to patient requirements, where parameters such as air quality, dust concentration, temperature, and humidity are monitored, as well as generating automatic alerts and notifications in the event of abnormal conditions. The system incorporates predictive analysis based on temporal models to anticipate environmental variations and enable preventive actions, validating the proposed solution in improving well-being, safety, and air quality efficiency in medical facilities. For [5], the similarity of the article is shown by designing and validating an autonomous, solar-powered IoT system. Air quality monitoring is focused on outdoor environments, oriented towards urban and industrial settings. The proposal seeks to guarantee operation without dependent connectivity, such as electrical power, in addition to the use of low-cost sensors that are integrated into the ESP32 microcontroller, with wireless data transmission to a cloud platform for historical visualization and analysis, thus validating the

portable and scalable solution, demonstrating the reliability, accuracy, and viability of the system in real conditions in environmental air quality management. In [6], a BIM, IoT structure is proposed for monitoring indoor air quality in healthcare environments, seeking to enable real-time data-driven decision-making by integrating IoT sensors to provide air quality for medical care, improving CO₂ levels, and recirculating the temperature of the environment to be controlled. The following application in [7] seeks to monitor and predict industrial air quality in manufacturing or production environments, addressing the comparison of traditional systems that lack predictive capabilities. Real-time data on multiple pollutants is collected and analyzed using IoT sensors and nodes, based on LSTM self-learning to forecast and rate air quality. The study enables environmental management, allowing industries to anticipate risks, optimize ventilation, and protect the health of their employees. In [8], the design of a comprehensive IoT structure for monitoring air quality in industrial environments is presented, adaptable to the requirements of each industry and integrable into existing systems. The system is developed with a database of environmental variables and location, applying machine learning techniques. It also has a high-precision prediction system for high-risk conditions, thus contributing to quality air management and protection for personnel and the environment. Similarly, [9] aims to analyze and quantify PM_{2.5} concentrations in urban areas with high population densities, using dedicated sensors and an autonomous learning model to identify key urban factors that determine seasonal variability in PM_{2.5} concentration levels. The purpose of the study is to provide practical, data-driven information to support urban planning and air quality management, demonstrating its viability in urban environments with high pedestrian traffic. Similarly, [10] develops an IoT system for real-time monitoring of air quality, temperature, and noise in six areas of high traffic congestion in Malang, Indonesia. The system integrates several sensors to measure atmospheric variables such as CO₂, CO, and suspended particles, temperature and humidity, and noise levels, with these variables displayed in the cloud via a web platform. The results show that vehicle emissions influence air quality, with high concentrations of CO₂ and particulate matter above normal safety limits. The system highlights the urban pollution mitigation strategy and proposes improvements in sensor calibration and communication methods to increase variable readings and system accuracy for environmental management and protection of the general public. In [11], a low-cost air quality monitoring station is developed using IoT and blockchain technology to improve the reliability and accessibility of environmental data. The system uses DHT11, MQ7, and MQ135 sensors to measure temperature, humidity, carbon monoxide, and carbon dioxide, allowing real-time air quality assessment. The data is collected and shared through the cloud with blockchain backup, facilitating access for researchers and the general public. This study enables sustainable development and offers a solution to strengthen

environmental monitoring and promote the use of technologies in cities. Finally, [12] presents real-time air quality monitoring capable of measuring pollutants such as NO₂, SO₂, CO₂, CO, PM_{2.5}, and PM₁₀, with long-distance transmission via the Lora network in mesh topology. A point-to-point Lora repeater was designed to obtain a greater range, allowing data transmission coverage to be extended to 1.7 km under normal conditions. As a result, RSSI measurements demonstrate stable and reliable transmission, validating the viability of the system for long-distance IoT environmental monitoring applications.

3. Methodology

The proposed system ensures continuous, reliable, and automated monitoring of exposure risks to volatile pollutants in industrial environments, optimizing decision-making, reducing response times to hazardous events, and strengthening occupational risk prevention through the use of IoT technologies, offering the following features:

- Electronic card for monitoring and controlling devices, equipment, and indicators.
- Implementation of dedicated, high-precision sensors.
- Graphical interface to the cloud for data collection.
- Visual and audible alarm system.
- Automated activation of adjacent processes to reduce atmospheric risk, such as extractors.
- Values are shown on a digital display from 0 to 100 to visualize the level of environmental pollution.
- Robust system design, resistant to electrical noise effects.
- High reliability, monitoring, and control of equipment depending on current environmental conditions.
- Unification of IoT nodes to a master for sending respective data to the cloud via an ESP32 by ESP-NOW.

Table 1. Components to be used

TYPE	MODEL	QUANTITY
CO2 sensor	SCD41	01
PM sensor	SPS30	01
VOC sensor	SGP41	01
C° and H% sensor	SHT31	01
H2 sensor	MQ-7	01
NH3 sensor	MQ-137	01
Electronic card	PCB Interlock	01
Electronic card	PCB control	01
Electronic card	PCB Display	01
Communication	Wire USB a C	01
Power supply	SR24V2A	02
Line filter	CW1B-6A-L040	01

The system is based on the Interlock, Control, and Display cards created in the EAGLE 9.6 program. The Interlock card integrates components such as the SCD41, SPS30, SGP41, SHT31, MQ-137, and MQ-7 sensors, the Lora

SX1278 module configured for sending variables, and an ESP32. The Control card has the LoRa SX1278 module and the ESP32 for receiving variables. Both electronic cards have a power supply with electrical noise protection, obtaining an industrial voltage of 24V as the main voltage, and the ESP32 microcontroller, logic that is programmed through the ARDUINO IDE software, and output devices such as 5-amp relays for handling external loads such as alarms, indicator lights, contactors, etc. The simulations were performed in PROTEUS 8 software. Similarly, for the initial calibration, a scan is performed with the physical devices to verify the correct collection of initial condition data by its control logic and subsequent programming.

The electronic card case was designed using AUTOCAD 3D software. This design provides a correct distribution of space, as it contains several built-in sensors, as well as the creation of large 7-segment displays, in order to obtain a compact space and provide robustness in environmental conditions for proper sensor reading and opacity due to contamination on the displays.

A diagram of the stages of the proposed system is shown (see Figure 1), beginning with the identification of risks in terms of industrial contamination, where the objectives of the system's scope and its main functions are established in terms of operator safety and critical parameters to be monitored. After that, research and selection of hardware (dedicated sensors) is carried out, seeking compatibility with voltages, appropriate communication, and selection in terms of accuracy, stability, measurement range, industrial reliability, and easy electronic integration, in addition to the appropriate selection of a microcontroller for the required program logic that offers robustness. The design of the IoT system architecture includes LoRa communication and a cloud platform. At this stage, the data flow, communication protocols such as ESP-NOW, and system firmware interaction are established.

In terms of the electronic design stage, the cards integrate the ESP32, power supply selection, signal conditioning with passive filters, electrical protection, and power outputs with relays, considering criteria of robustness, isolation, and compatibility between devices in industrial use in their design. For the system implementation stage, local visualization is developed using a numerical display and green, yellow, and red indicator lights, which represent detected levels of air pollution, as well as audible alarms in different areas. The condition evaluates the programmed logic using operating ranges for data collection in the cloud to the Adafruit IO platform and automatic activation conditions, such as extractors or alarms. Data collection to the cloud for storage, analysis, and historical traceability is based on the detection of sensors on the interlock PCB card to the control PCB card, which is used as a controller module that allows data to be sent to the IoT platform. These records are made daily, weekly, and

while the SPS30 sensor measures the concentration of PM2.5 and PM10 particles using laser scattering to provide accurate data that allows the detection of metallic dust, paint residues, and suspended particles. The SGP41 sensor is used to detect VOC organic compounds, generating air quality indices using the I2C communication interface for the aforementioned sensors. Likewise, the MQ-7 and MQ-136 sensors are used to detect toxic gases generated by electrochemical processes or reactive mixtures, providing analog signals through the ESP32's ADC. Finally, the SHT31 sensor provides information on the ambient temperature and relative humidity of the monitored space. The following diagram provides a better understanding of its operation and application (see Figure 3).

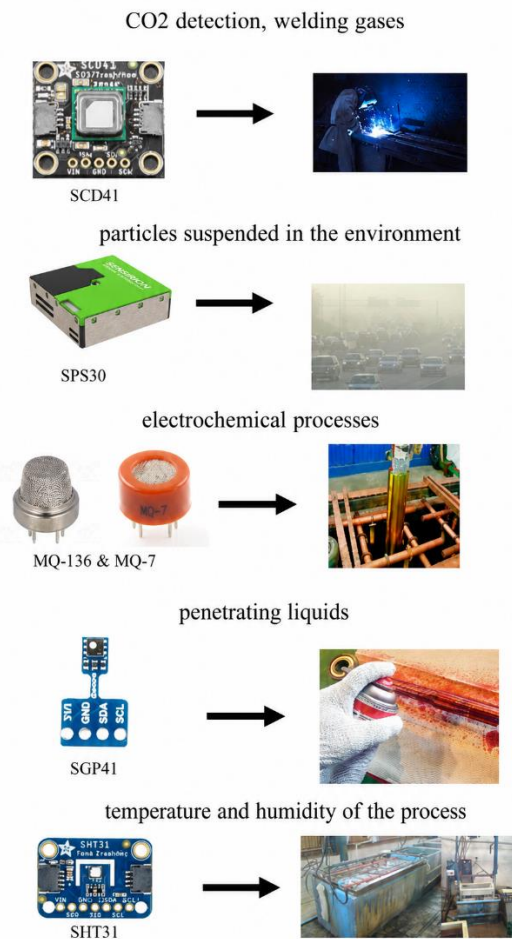


Fig. 3 Application of sensors used

The system's electronic design begins with the filtering of the mains voltage through selected EMI filters. Two mini power supplies are used, both of which reduce the voltage from 220VAC to 24VDC. The first will be used to power the control stage with regulation through a 3.3V linear regulator, the AMS1117 - 3.3 and the 7805 for 5VDC voltages. The second is responsible for powering external devices such as the display, light alerts, and sirens. Both power supplies are 2

amps and have fuse protection (see Figure 4). Likewise, the voltage to power the activation relays for the automatic system, if extractors are available, the design is based on the location of the ESP32's GPIOs for device acquisition and control. The electronic card is robust in terms of component selection, as it separates the control and power stages using PC817 optocouplers with their respective circuits, using 2N3904 transistors to activate relays that support a 5-amp load. For data acquisition, the microcontroller's I2C interface is used for communication with the SCD41, SPS30, SGP41, and SHT31 sensors, and the use of the MQ-136 and MQ-7 sensors via the ADC. Filtering these sensors prevents reading delays, which are performed electronically through semiconductors and passive components such as diodes, capacitors, resistors, etc.

All system communication is based on the LoRa SX1278 module, which performs intercommunication between the interlock PCB (a) and the control PCB (b) to send data to the cloud, known as the master module (see Figure 6). communication takes place in a specific area, since if more areas need to be covered, the system must behave as a network node, depending on how extensive the system needs to be. In this way, data would be sent between the interlock PCB card and the control PCB card, which receives all the relevant data from the sensors. The purpose of the control PCB card is to send data through its UART port, variables that are displayed on the Adafruit IO platform every 30 seconds (see Figure 5), a time set to provide statistics and subsequent analysis of the respective environmental conditions, obtaining traceability and engineering control to minimize or mitigate the risk of respiratory diseases over time or excessive air pollution. The sensor reading ranges are set according to their data sheet, with a maximum and minimum range that will allow for subsequent calibration.

The system case design offers robustness in terms of splash resistance, dust accumulation, and easy maintenance. It measures 40x10x15cm and incorporates an interlock card, which is divided into two parts: one containing the display, traffic light-type alert, and audible alert (a), and another containing sensors (b) (see Figure 7). According to the evaluation conditions, this module will be located 3 meters above the ground to cover a greater range of detection and atmospheric evaluation. It will also be located near an electrical distribution branch through industrial EMT pipes, which will contain 220VAC voltage to power the module. The control card will be located near the SSOMA supervisor's office for monitoring and data acquisition, which will act as the master and can be connected to more interlock cards if Lora communication is desired for data acquisition. This module will measure 20x10x10cm and will feature ESP-NOW communication via Wi-Fi built into the microcontroller through a user and API KEY for connection to the interlock card and its display, if it needs to be moved to another area with a connection no greater than 10 meters.

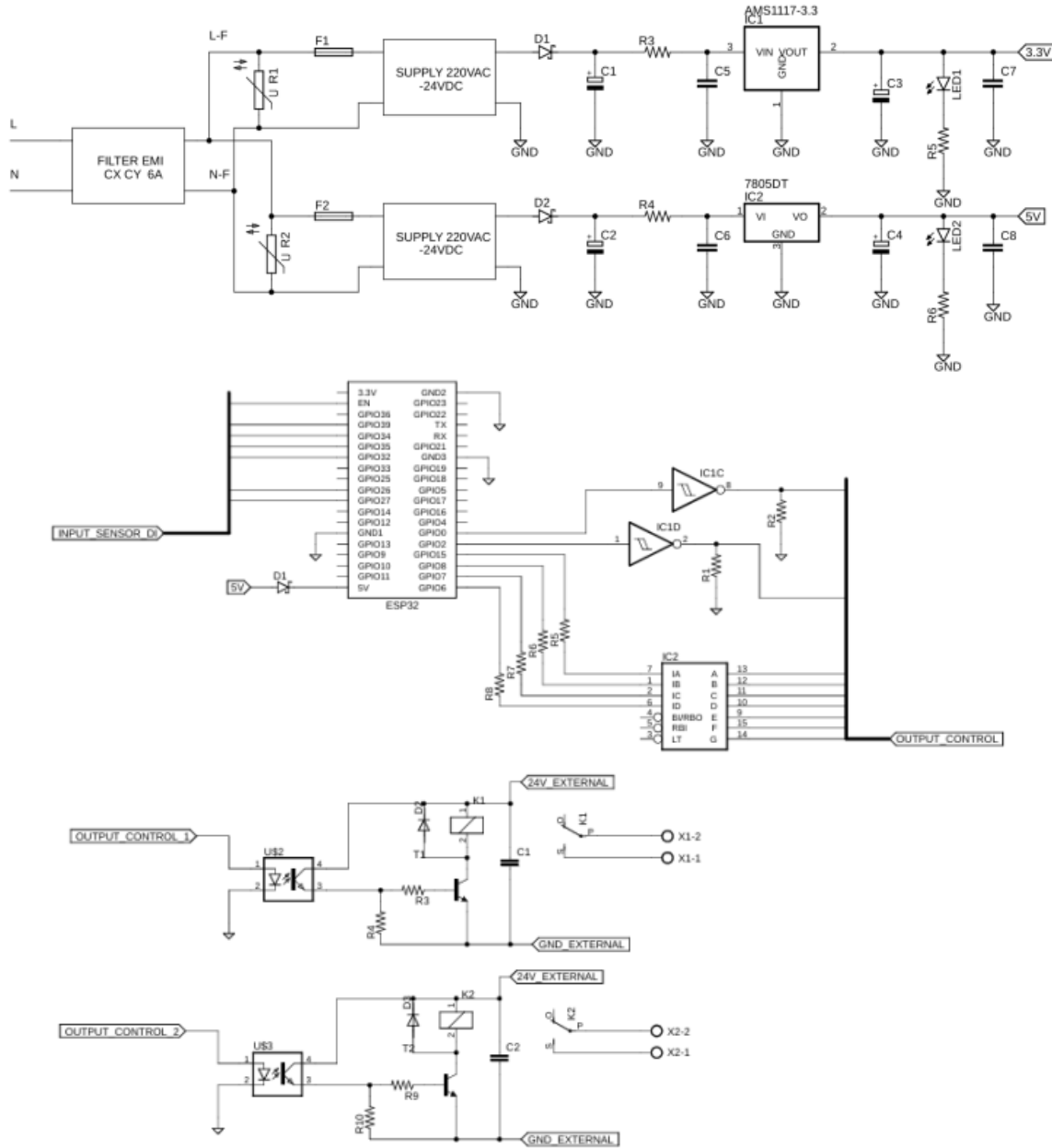


Fig. 4 Interlock power supply and control

Table 2. Range of sensors to be used

SENSOR	VARIABLE	READING RANGE
SCD41	CO2	0 – 40 000 ppm
SPS30	PM2.5/PM10	0 – 1000 ug/m3
MQ-136	Toxic gases	1 – 200 ppm
MQ-7	Toxic gases	1 – 150 ppm
SGP41	VOC	0 – 500 ug/m3
SHT31	Temperature	-40 a +125°C
SHT31	Humidity	0 – 100% HR

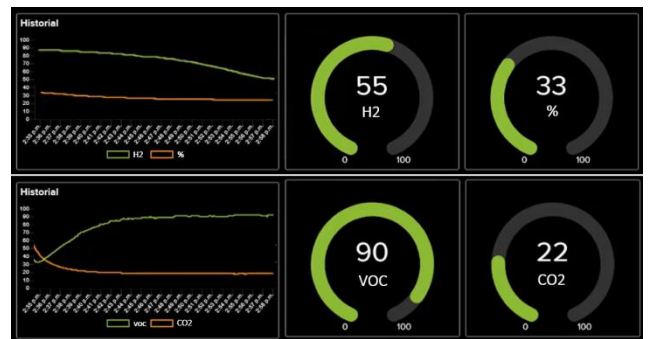


Fig. 5 Pollution levels in the area with Adafruit IO

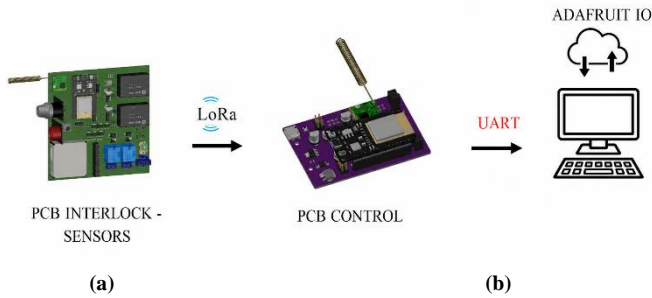


Fig. 6 Main module and system communication graphics between cards

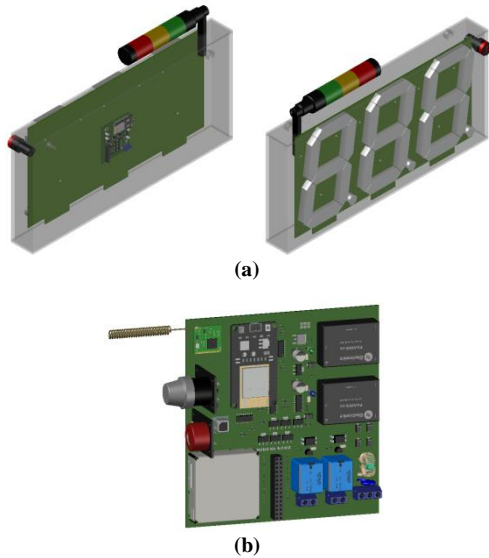


Fig. 7 Interlock card

The system contains several stages of operation, which validate safe working conditions. The first stage evaluates the atmospheric level from 0 to 10, which will have a message on the platform of “Safe Environment,” considered a minimum risk in terms of operation without protection based on respirators, turning on a green light. For the second stage, the condition is evaluated from 10 to 50, sending a message of “Caution: Use of EPPS,” considering opting for a type of control to mitigate this operation, such as the use of EPPS with corresponding filters for the application. The system turns on a yellow light. Similarly, for the third stage, the system evaluates the atmospheric condition, providing values from 50 to 70 on its display and sending a “High Pollution” message, allowing external devices such as extractors to be activated to reduce gases or particulate matter in the system, which is identified by a red light. For the last stage, the display shows a range of 70 to 100 along with a message on the monitoring platform saying “Evacuate Area,” indicating a high level of atmospheric pollution coming from the area. The system activates a red light along with a siren that is built into the module, allowing for alerts in cases of excessive gas release or excessive suspended material that could cause damage not only to the lungs but also to the eyes and skin. For calibration in the industrial environment to be implemented, values

captured by the sensors during an average, high-productivity workday were used, obtaining the following results.

Table 3. Ranges of environmental variables in sensors

Sensor	Moderate	High
SCD41	1500ppm	3200ppm
SPS30	140ug/m3	350ug/m3
SGP41	200ug/m3	400ug/m3
MQ-136	20ppm	85ppm
MQ-7	15ppm	75ppm
SHT31	28°C	35°C
SHT31	45%HR	80%HR

After implementation, modifications were made to the activation circuit of the extractor on the control panel, as well as the respective operational tests of a specific area that presented a higher detection rate and the mandatory use of a face respirator, for post-implementation comparison. The objective is to implement the system throughout the industrial plant, located in Cerro Colorado, Arequipa, for metalworking purposes. Monitoring was carried out for 15 days prior to implementation, revealing a high level of contamination throughout the plant, with the metallizing and chrome areas showing a considerable increase in the index. However, the operators did not show any discomfort because they are constantly moving. For this reason, the SSOMA area, which is responsible for supervising compliance with safety regulations, oversees issuing warnings for prevention purposes, as well as providing training on the correct use of PPE. Since supervision is not always constant, operators violate certain rules that, over time, can cause respiratory problems affecting occupational health in the industrial plant. This post-implementation study is detailed after implementation at the industrial plant, with 30 days of monitoring.

5. Tests and Results

The proposed IoT system was evaluated in an industrial environment with the presence of gases and particulate matter produced by the machining of components in the industrial plant. It was installed in the metallization area, where particulate matter residues present high levels of atmospheric pollution after manual monitoring, as well as in the hard chrome plating area, where the electroplating process emits harmful and highly polluting gases for operators. The tests were carried out over a period of 30 days, covering two stages: pre-implementation and post-implementation, allowing for a direct comparison by means of manual monitoring, operator consultation, and a table of values through the system, thanks to sensors that took periodic measurements every 10 seconds and sent data through the main electronic card. These variables are sent to cloud storage via the UART connection on the respective supervision PC for statistical analysis and historical traceability.

Likewise, the RSSI in db achieved between the communication of both cards from the area and the supervision point is viable since they are located at nearby points shown in the following table.

Table 4. RSSI range between the implemented LoRa modules

Distance	RSSI	State
50m	-35dBm	Sucess
100m	-42dBm	Sucess
150m	-45dBm	Sucess
200m	-48dBm	Sucess

Prior to implementation, high concentrations of pollutants were recorded in the atmosphere of the critical areas mentioned above, due to the absence of continuous monitoring and the activation of mitigation systems. The values captured 15 days before the system was launched in both areas are shown below.

Table 5. Manual values obtained in the area

Parameter	Average value	Condition
CO ₂	2400ppm	High Risk
H ₂	65ppm	High Risk
PM _{2.5}	114ug/m ³	High Risk
PM ₁₀	250ug/m ³	High Risk
VOC	242ug/m ³	Elevated
%H	80%	Elevated
Toxic gases	80ppm	High Risk

Following the implementation of the IoT system, an automatic response to air pollution events was obtained, as it allows for the automatic activation of extractors, visual and audible alarms, as well as immediate recommendations for the use of PPE or evacuation. The average levels obtained in both affected areas after 30 days of implementation are shown below.

Table 6. Risk reduction after implementation

Parameter	Average value	Condition
CO ₂	950ppm	60.41%
H ₂	24ppm	63.07%
PM _{2.5}	36ug/m ³	68.42%
PM ₁₀	94ug/m ³	62.40%
VOC	96ug/m ³	60.33%
Toxic gases	42ppm	60.65%

The level of exposure reduction for the operator was calculated using:

$$Exp (\%) = \frac{c_{before} - c_{after}}{c_{before}} \times 100$$

This equation is applied to the different pollutants, obtaining a 60 to 68% reduction in risk in both areas. These

values are based on continuous monitoring, automatic activation of the extractor, and reduced exposure time due to light alerts. To compare monitoring values, the operator's assessment of possible contamination in their environment is considered, as they sneeze due to allergies to harmful gases. Manual monitoring of gas or particle levels in the environment is also considered, along with manual activation of extractors (see Figure 8), and the system is implemented automatically for the activation and monitoring of these critical variables (see Figure 9).

Table 7. Improvement obtained after implementation

Parameter	Post implementation	Improvement
CO ₂	60.41%	39.59
H ₂	63.07%	36.93
PM _{2.5}	68.42%	31.58
PM ₁₀	62.40%	37.60
VOC	60.33%	39.67
Toxic gases	60.65%	39.35

Table 8. Manual monitoring values

Min	H ₂	CO ₂	PM _{2.5}	PM ₁₀	%H
1	38	950	85	160	72
10	55	1280	115	205	67
15	60	1420	128	218	65
20	64	1500	138	228	63

The average data collection time was 4 hours, during which the IoT system sent data to the cloud, allowing graphs to be generated and traceability to be established according to events that occurred during an average working day. Samples from a 20-minute period are used so as not to be too extensive. The results obtained show the versatility and efficiency of the proposed system, reducing operators' exposure to critical contaminants and promoting a culture of protection. According to this first monitoring in a real environment, the system was left to work for 15 days for subsequent calibration until reaching the 30-day testing phase, during which the process of adapting personnel to this system to determine the use of personal protective equipment, activation of extractors, or evacuation progressively improved.

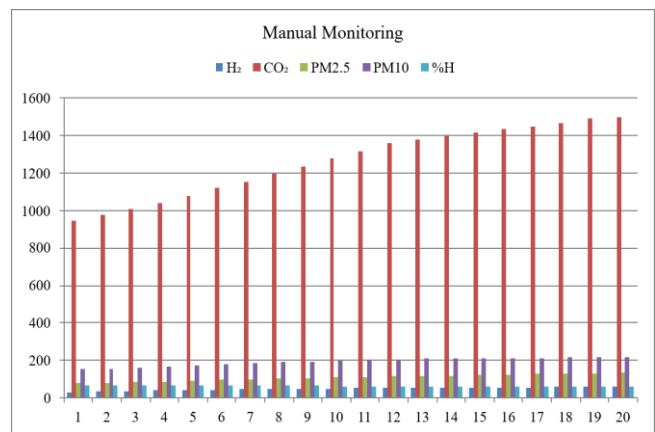


Fig. 8 Manual monitoring

Table 9. Automatic monitoring values

Min	H ₂	CO ₂	PM _{2.5}	PM ₁₀	%H
1	40	800	100	190	70
10	18	780	40	90	61
15	9	680	30	65	56
20	6	710	22	50	51

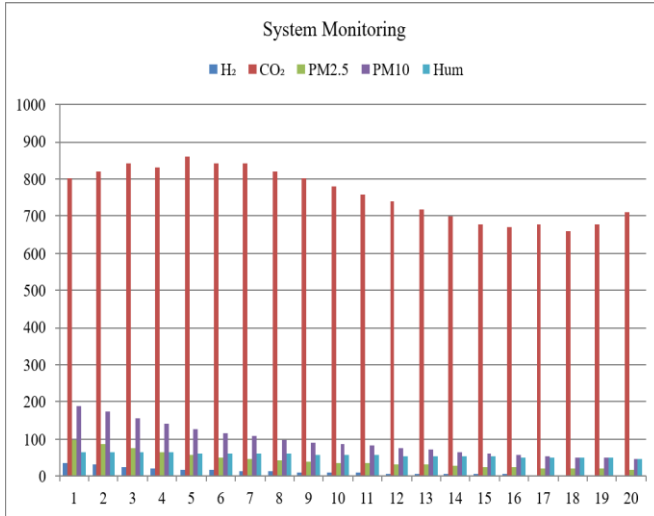


Fig. 9 Monitoring of the implemented system

6. Conclusion

The IoT system for monitoring industrial air quality implemented in the metalworking and electrochemical industries offers an effective solution for real-time detection of critical pollutants such as H₂, CO₂, PM_{2.5}, and PM₁₀, as well as humidity in the environment for applications in metallization and hard chrome plating, with the possibility of further extending the reading variables obtained by the sensors for different processes. The results obtained showed a reduction in concentrations of harmful gases and particulate matter of up to 68.42%, significantly improving environmental conditions within the work area. This reduction not only contributes to the protection of personnel health but also optimizes compliance with industrial and environmental safety regulations, such as ISO 45001, by reducing the risk of exposure to toxic substances, contributing to sustainable production and improvements in working conditions.

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