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Design and Implementation of a Scalable LoRaWAN-Based Air Quality Monitoring Infrastructure for the Kurdistan Region of Iraq

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Abstract

Air pollution threatens human and environmental health worldwide. A Harvard study in partnership with UK institutions found that fossil fuel pollution killed over 8 million people in 2018, accounting for 1 in 5 fatalities worldwide. Iraq, including the Kurdistan Region of Iraq, has a major environmental issue in that it ranks second worst in 2022 due to the high level of particulate matter, specifically $PM_{2.5}$. In this paper, a LoRa-based infrastructure for environmental monitoring in the Kurdistan Region has been designed and developed. The infrastructure encompasses end-node devices, an open-source network server, and an IoT platform. Two AirQNodes were prototyped and deployed to measure particulate matter values, temperature, humidity, and atmospheric pressure using manufacturer-calibrated PM sensors and combined temperature, humidity, and atmospheric sensors. An open-source network server is adopted to manage the AirQNodes and the entire network. In addition, an IoT platform has also been designed and implemented to visualize and analyze the collected data. The platform processes and stores the data, making it accessible for the public and decision-making parties. The infrastructure was tested and results validated by deploying two AirQNodes at separate locations adjacent to existing air quality monitoring stations as reference points. The findings demonstrated that the AirQNodes reliably mirrored the trends and patterns observed in the reference monitors. This research establishes a comprehensive infrastructure for monitoring air quality in the Kurdistan Region of Iraq. Furthermore, complete ownership of the system can be attained by possessing and overseeing the critical components of the infrastructure, which encompass the end devices, network server, and IoT platform. This integrated strategy is especially crucial for the Kurdistan Region of Iraq, where cost-efficiency and enduring sustainability are vital, yet such a structure is absent.

Keywords: LoRa; particulate matter; IoT platform; LPWAN; KRI

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1. Introduction

Air quality is a fundamental environmental issue impacting human health and well-being. The World Health Organization (WHO) has recognized air pollution as a significant worldwide health threat, accounting for over 7 million premature deaths each year [1]. The accumulation of fine particulate matter (PM), particularly with a diameter of 2.5 μm or less that may penetrate deep into the lungs and into the circulation, causing respiratory and cardiovascular illness, is especially hazardous [2,3]. In particular, PM2.5 exposure

accounted for 62% of the overall air pollution-related fatalities globally in 2019, contributing to 4.14 million deaths [4,5].

In Iraq, including the Kurdistan Region of Iraq (KRI), air quality faces serious challenges. Iraq ranked second worst globally in air quality as of 2022, with PM2.5 levels about double the WHO-recommended guideline of 5 $\mu g/m^3$ [6]. Numerous factors contribute to this situation: industrial operations, vehicular emissions, dust storms, and the combustion of fossil fuels [7].

Although there are dedicated governmental departments in Iraq and the KRI, such as Iraqi Environmental Protection and Improvement (IEPI) [7] and the Board of Environmental Protection and Improvement (BEPA) [8], which have established air quality regulations and standards, there is presently no active or systematic protocol established for ongoing air pollution monitoring, especially in the Kurdistan Region [9]. Although the KRI adopts stricter limits, for instance for the PM2.5 level, than the rest of Iraq, and while Federal Iraq enforces tighter 24 h exposure limits than the U.S. EPA, the region is still ranked among the most polluted in the world [9].

Despite these challenges, the region is deficient in adequate air quality monitoring, which results in a significant void in environmental data collection and analysis for both decision-makers and the public. Traditional air quality monitoring systems typically rely on expensive, stationary monitoring units that offer limited geographic coverage and require substantial maintenance. These limitations rendered them inappropriate for widespread application in emerging areas like the KRI.

Recent years have seen the extensive adoption of Internet of Things (IoT) technology, enabling the creation of cost-effective, distributed monitoring networks that provide real-time data on air quality parameters across vast geographic areas [10]. LoRa, a low-power and long-range technology, facilitates extensive communication distances with minimal energy consumption, rendering it ideal for battery-operated sensors in remote or dispersed locations [11]. LoRa-based systems provide real-time monitoring of air quality parameters, including particulate matter, temperature, humidity, and atmospheric pressure, when combined with appropriate sensor technologies and data handling platforms.

This paper's work started from an MSc research project aimed at designing and implementing air quality monitoring infrastructure in the KRI, as the region lacks any existing system for monitoring air pollution. The paper aims to develop a comprehensive infrastructure that considers designing air monitoring devices and network infrastructure to a centralized platform for monitoring with geospatial visualization. In addition, the proposed system needs to utilize economical sensors and energy-efficient communication protocols to establish a sustainable monitoring network that delivers consistent and reliable data on air quality indicators. The platform features a web-based visualization and analysis component that renders data accessible to the public and decision-makers, facilitating informed policy decisions and enhancing public awareness of air quality issues.

This study involves the design, implementation, and deployment of LoRaWAN end-node devices to monitor air quality parameters, specifically PM2.5, as well as temperature, humidity, and pressure. A low-power microcontroller (MCU) development board was utilized along with a Sensirion SPS30 PM sensor, which employs laser scattering, to quantify particulate matter with high precision. For monitoring humidity, temperature, and pressure parameters, a combined BME280 was employed. Both sensors can operate in a very low power consumption mode that makes them ideal for integration with LoRaWAN infrastructure.

A principal advantage of LoRaWAN technology compared to other Low Power Wide Area Network (LPWAN) technologies such as Sigfox and NB-IoT is its ability to establish and sustain a private IoT infrastructure, allowing organizations to own and control all

elements, including end-node devices, gateways, network servers, and the IoT platform. Moreover, it has the advantage of its adaptability, open standard, and appropriateness for low-power, long-range communication with sensors [12–14]. This type of ownership enables complete control, customization tailoring, and enhanced data security, as all communications remain within the organization's infrastructure, eliminating reliance on external internet access or third-party services. The establishment of such a system is especially crucial for the KRI and other developing nations, whose IoT infrastructure remains less established than in more industrialized regions.

2. Background and Related Works

2.1. Air Pollution and Pollutants

Air pollution refers to the environmental contamination caused by biological, physical, or chemical agents that alter atmospheric parameters. Air pollution is defined as the concentration of hazardous gases in the environment [15]. Environmental toxic gases include ground-level ozone (O_3), carbon monoxide (CO), carbon dioxide (CO_2), ammonia (NH_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), benzene (C_6H_6), and airborne PMs [16].

Climate change is a critical issue that profoundly affects numerous aspects of humanity, with direct consequences for public health. Furthermore, climate change negatively impacts air quality, which in turn harms people's respiratory health. Indoor and outdoor air pollution persist as significant threats to human health. Air pollution is considered one of the most significant environmental health concerns, according to WHO standard data [6]. The combined effects of rapid urbanization and expanding economies significantly elevate air pollution, posing a substantial risk to human health. This has led to an increased global disease burden that poses considerable risks to the population [17].

Air pollution arises from both natural and manmade sources, with human activities being the predominant contributors since the onset of industrialization. Combustion operations are essential, particularly the incineration of petroleum, coal, and biomass for energy production. Outdoor air pollution stems from various sources, including terrestrial, aerial, and aquatic transportation; industrial activities and energy generation; and biomass combustion, such as wildfires, agricultural waste incineration, and urban refuse burning. Moreover, construction activities and surface dust resuspension add to outdoor pollution, while the long-range atmospheric distribution of pollutants exacerbates urban air quality issues [1].

Furthermore, air pollution is a significant concern, primarily attributed to the use of detrimental fuels for heating and cooking, as well as the combustion of materials like candles, incense, and tobacco. Non-combustion sources, such as volatile organic compounds (VOCs) emitted during home renovations, consumer products like cleaning agents, and electrical devices such as printers, also contribute considerably [18].

Airborne contaminants from these sources include PM2.5, PM10, and ultrafine particles; gaseous pollutants such as ammonia, carbon monoxide, nitrogen dioxide, sulfur dioxide, ozone, and organic pollutants. Certain pollutants, such as nitrates and sulfates, are generated by air interactions, but others, such as radon and its decay products, moisture, and biological agents, contribute to indoor air pollution [6].

PM2.5, in particular, can infiltrate the respiratory and circulatory systems and cause health and environmental problems. PM2.5 comes from residential and environmental air pollution. Fossil fuel burning by automobiles, power plants, industrial operations, agricultural activities, wildfires, and construction dust all contribute to ambient PM2.5. Household PM2.5 is mostly caused by indoor use of solid fuels like wood and coal for cooking and heating, which is common in low- and middle-income countries with limited access to cleaner energy [6].

In 2019, PM2.5 exposure was responsible for 4.14 million fatalities globally, or 62% of all deaths attributable to air pollution [1]. Asian and African nations have the greatest illness burden from PM2.5 exposure, especially China and India, which together represent 58% of the worldwide death burden attributed to PM2.5 [19].

PM2.5 exposure has been related to a wide range of negative health effects throughout many physiological systems. Among the most direct are respiratory impacts as these tiny particles may get deep into the lungs and aggravate disorders like bronchitis, asthma, and other long-term respiratory illnesses [20]. Long-term exposure raises the risk of heart attacks, an abnormal rhythm of the heart, and disruption of blood supply to the brain, including strokes; therefore, cardiovascular effects are also well documented [21]. Furthermore, mounting data point to PM2.5 exposures possibly aggravating neurological conditions like Parkinson's disease and Alzheimer's disease [22]. PM2.5 has been linked to type 2 diabetes; 13.4% of its worldwide burden is related to ambient air pollution and 6.5% to residential sources [23]. Children, elderly people, and those with pre-existing medical issues are among the demographic categories more vulnerable to these effects [1].

2.2. Air Quality Standards

Air quality standards are the foundation of air quality management. Regulatory agencies develop and enforce such guidelines to define the permissible amount of air pollution for a country or area. They provide the concentration of pollutants in ambient air during a designated average period [1].

Air quality regulations vary across countries, each using its own Air Quality Index (AQI) system to evaluate and convey pollution levels based on various contaminants and their health implications. The United States uses a 0–500 AQI scale established by the Environmental Protection Agency (EPA), while Canada uses the Air Quality Health Index (AQHI), which spans from 1 to 10+ and is predicated on health hazards associated with comparable contaminants [24]. In Europe, the European Air Quality Index (EAQI) classifies air quality into categories ranging from "Good" to "Extremely Poor" [25]. The UK uses the Daily AQI (DAQI), which spans from 1 to 10 across four categories [26]. The South Korea's Comprehensive AQI (CAI) uses a 0–500 scale [27]. Singapore employs the Pollutant Standards Index (PSI), using the highest pollutant sub-index as the aggregate value [28]. Hong Kong has transitioned to the AQHI model, which likewise uses a 1–10+ scale [29]. In contrast, China and India possess national AQI systems that evaluate six principal pollutants; India, for instance, categorizes air quality from "Good" to "Severe." [30]. Moreover, Atmotube has created its own Air Quality Score (AQS) for real-time personal assessment, spanning from 0 (very polluted) to 100 (exceptionally clean), using PM and VOC data. Each system seeks to elucidate intricate pollution data to safeguard and enhance public health [31].

In this paper, the US AQI for PM2.5 was adopted due to its thoroughness and international acknowledgement. The EPA scale is divided into six categories, each designated by a color and a number that reflects the level of pollution in the air and its possible effects on the health of the public [32] as presented in Table 1:

Table 1. AQI levels according to EPA Standard [22].

AQI Category	AQI Range	Color	Description
Good	0–50	Green	The air quality is classified as excellent, and air pollution is little or no risk
Moderate	51–100	Yellow	The air quality is acceptable, but some pollutants may provide moderate risks for health to just a small portion of the population

Table 1. *Cont.*

AQI Category	AQI Range	Color	Description
Unhealthy for Sensitive Groups	101–150	Orange	The general public is unlikely to be affected; however, people with lung illnesses, elderly people, and kids are at heightened risk.
Unhealthy	151–200	Red	All people may start to encounter health problems; vulnerable populations can encounter more severe outcomes
Very Unhealthy	201–300	Purple	A health warning has been issued; all individuals may encounter increasingly severe health consequences.
Hazardous	301–500	Maroon	Health alerts about emergency situations; the whole population is at an increased risk of impact.

In 2024, EPA amended its National Ambient Air Quality Standards (NAAQS), lowering the yearly PM2.5 from 12 $\mu g/m^3$ to 9 $\mu g/m^3$, but maintaining the 24 h level at 35 $\mu g/m^3$. These modifications concern long-term health effects [33].

The World Health Organization (WHO) issued its revised air quality recommendations in 2021, establishing more rigorous standards: 5 $\mu g/m^3$ yearly and 15 $\mu g/m^3$ during a 24 h period. These values are based on the most recent scientific knowledge intended to mitigate health hazards on a global basis [1].

The KRI has set a yearly average PM2.5 limit of 10 $\mu g/m^3$ and 24 h averages of 20 $\mu g/m^3$. These values are higher than WHO guidelines and the U.S. EPA standards, indicating that improvements in air quality are necessary to safeguard human health in the region [9]. Table 2 shows a comparison of the PM2.5 limits between the US EPA, WHO, and KRI.

Table 2. PM2.5 limits based on different standard guidelines.

Parameter	U.S. EPA NAAQS (Revised 2024)	WHO Guidelines (2021)	Kurdistan Region of Iraq (Observed)
Annual PM2.5 Limit	9 $\mu g/m^3$	5 $\mu g/m^3$	10 $\mu g/m^3$
24 h PM2.5 Limit	35 $\mu g/m^3$	15 $\mu g/m^3$	20 $\mu g/m^3$

2.3. IoT Technologies for Air Quality Monitoring

The IoT has transformed environmental monitoring through facilitating the deployment of networked sensors that can collect and transmit data in real-time [34]. To ensure effective air quality monitoring, sensors must transmit data to a control center, creating a network that is easily scalable, reliable, and with minimal complexity [35].

2.3.1. Low Power Wide Area Network Technologies

LPWAN is a type of wireless communication technology that is ideal for devices requiring extended operational durations without frequent recharging, since it offers extensive coverage, low data transfer rates with minimal packet sizes, and prolonged battery longevity [36].

The LPWAN has been developed to satisfy the increasing needs of IoT applications, especially in settings where data and power requirements are constrained. There are several LPWAN technologies that exist, including LoRa, Sigfox, and NB-IoT. LoRa is especially advantageous for environmental monitoring due to its low power consumption, extensive range, and cost-effectiveness [37].

2.3.2. LoRa and LoRaWAN Technologies

LoRa is working in unlicensed sub-GHz industrial, scientific, and medical (ISM) ranges. LoRa is owned by Semtech to standardize LPWANs. LoRa offers long-range communications with up to five kilometers in urban areas and up to 15 km or more in rural regions with line of sight [38].

LoRaWAN, a standard created and managed by the LoRa Alliance, is an open networking protocol and powered by the MAC layer networking tool. Using a LoRa physical layer, it specifies the higher tiers of long-range wide-area networks. Three distinct device classes (A, B, and C) defined by the LoRaWAN standard each have distinctive transfer and power consumption characteristics, therefore enabling adaptability in deployment depending on application need [39]. Figure 1 shows a typical LoRaWAN architecture. The architecture comprises end devices to collect data from the environment, gateways to pick up the signals sent by end devices, a network server as the central component to carry all the required intelligence to manage the network, and an application server to process application-specific data messages received from end devices.

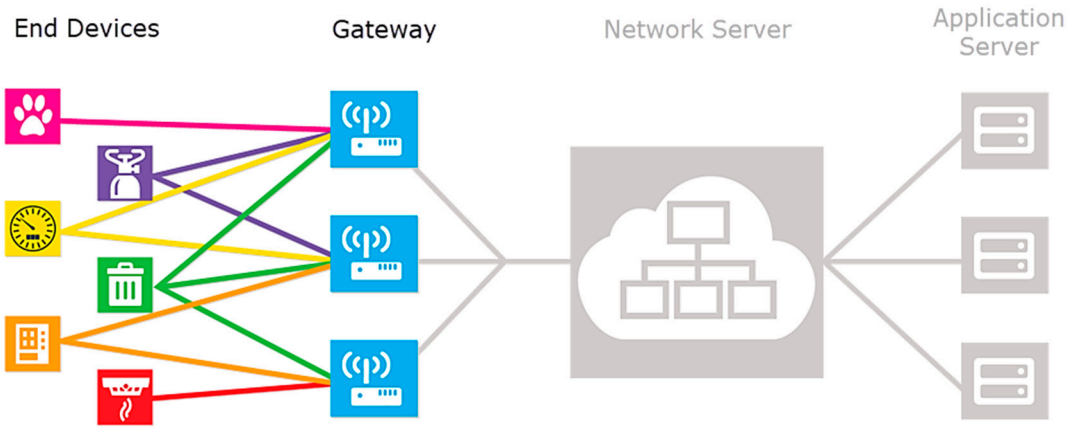


Figure 1. Typical LoRaWAN architecture [40].

LoRaWAN's robust security features, such as message encryption and secure join procedures for mutual authentication, allow LoRaWAN to guarantee that only authorized devices may access the network and that data remains encrypted throughout the communication process [41].

2.4. Review of Existing LoRa-Enabled Air Quality Monitoring Systems

Several studies have explored the use of LoRa technology for air quality monitoring. A review of recent implementations provides valuable insights into system designs, components, and performance characteristics.

Purnomo et al. [42] developed a cost-effective, sustainable IoT system for monitoring particulate matter using LoRa technology. The system employed the SEN0117 PM sensor and Arduino Mega microcontroller, powered by a 50-watt solar panel. While effective, the system was limited to a serial monitor interface and tested in only 20 locations.

In [43], a system for monitoring indoor air quality has been implemented using the ESP32 microcontroller and G5 PMS5003 dust sensor, with Wi-Fi for data communication. Although the system achieved acceptable accuracy, the battery life was limited to only 4 h of continuous operation.

A LoRa IoT repeater system to extend communication range for air quality monitoring stations has been developed by Khonrang et al. [44]. The system utilized Arduino Nano/Mega microcontrollers and various gas and PM sensors, including PMS3003 for

PM2.5 and PM10 measurements. The implementation of repeaters successfully extended the network range but faced challenges with packet drops and inter-channel interference.

Another work presented in [45] presented a Wireless Sensor Network (WSN) designed using LoRa technology for particulate matter monitoring. The system incorporated a Honeywell HPMA115c0-004 air quality sensor, an ATmega2560 microcontroller, and a Raspberry Pi for data storage. The Python Dash library was used for data visualization. While the system achieved satisfactory performance, the GPS component consumed significant energy, limiting battery life.

Similarly, a recent study [46] detailed the design and implementation of a self-sustaining IoT sensor network throughout the Dallas–Fort Worth region to monitor particulate matter levels. The system utilized economical PM sensors with machine learning calibration, LoRaWAN communication, GPS for geographical mapping, and solar-powered energy independence. The project utilized adaptive power management and open-source principles to showcase a sustainable, cost-effective, and scalable method for real-time urban air quality monitoring, with considerable consequences for public health [46].

A further study suggested a comprehensive unmanned aerial system (UAS) outfitted with specialized air quality sensors to quantify pollutants including CO, O_3, and NO_2. The technology utilized LoRa connectivity and a real-time web application for data visualization, overcoming the constraints of conventional monitoring networks by improving portability, accessibility, and coverage in remote locations. Initial assessments indicated the viability of this economical method for adaptable air quality surveillance in regulated airspace [47].

On the other hand, a hybrid dual-band IoT-based environmental monitoring subsystem was incorporated into intelligent transportation systems (ITS) to assess air quality and meteorological parameters in conjunction with traffic data. The system employed LoRa and LoRaWAN connections to facilitate real-time environmental monitoring at traffic stations, with proof-of-concept findings validating its effectiveness in urban road settings. This method emphasizes the potential of integrating traffic management with environmental monitoring to tackle pollution issues in highly populated regions [48].

Finally, Pang et al. [49] designed a real-time indoor air quality monitoring system using IoT and LoRa technology, monitoring seven environmental parameters, including PM2.5 and PM10. The system utilized the STM32F103C8T6 microcontroller and the OneNET IoT platform for remote data access. A key finding was that protective shells reduced particulate measurement accuracy, highlighting the importance of sensor placement and design.

Table 3 shows a summary of the key components and limitations of these abovementioned systems.

Table 3. Summary of the key components and limitations of these existing systems.

Study	MCU	Sensors	Battery	Platform	Technology	Limitations
Purnomo et al. [42]	Arduino Mega (Arduino S.r.l., Monza, Italy)	SEN0117 PM Sensor	20 Ah, 50 W PV Panel	Serial Monitor	LoRa	Limited coverage; focus on PM2.5 only
Irbah et al. [43]	ESP32 Devkit 1 (Espressif Systems, Taipei City, Taiwan)	G5 PMS5003	Two 2200 mAh Lithium	Blynk Dashboard	Wi-Fi	The battery lasts only 4 h
Khonrang et al. [44]	Arduino Nano, Mega (Arduino S.r.l., Monza, Italy)	MQ-9, PMS3003	Solar-Charged Battery	SPI Communication	LoRa IoT Repeater	Packet drops; interference issues
Zafra-Pérez et al. [45]	ATmega2560 (Microchip Technology Inc., Chandler, AZ, USA)	Honeywell HPMA115c0-004	3.7 V/3 Ah Lithium	Python Dash	LoRa WSN	GPS consumes high energy
Wijeratne et al. [46]	ATSAMD21G18 (Microchip Technology Inc., Chandler, AZ, USA)	IPS7100 for PM, BME280 for climate	3.7 V, 6600 mAh Lithium-Ion.	Grafana Toolbox	LoRa	Limited communication range in urban environments

Table 3. *Cont.*

Study	MCU	Sensors	Battery	Platform	Technology	Limitations
Parra-Medina et al. [47]	Arduino Uno, ATmega 328P (Arduino S.r.l., Monza, Italy)	MQ7, MQ131, MICS6814 A1035 GPS	Battery Pack (no detail)	Pollution Tracking and Evaluation for Climate Analysis (PTECA) custom	LoRa	The limitation is the battery life, and the accuracy of low-cost sensors
Lishev et al. [48]	ARM® Cortex® M0+ Core (Arm Limited, Cambridge, UK)	PMS7003, ENS160, SCD40, AHT21, J305 tube:	6600 mAh lithium-polymer. 2 6 V, 1 W Photovoltaic cells	ThingSpeak	LoRa	Inexpensive sensors that have not been calibrated
Pang et al. [49]	STM32F103C8T6 (STMicroelectronics, Plan-les-Ouates, Switzerland)	PMS5003	Not specified	OneNET IoT	LoRa	Shell reduces PM measurement accuracy

Upon reviewing the systems, some notable deficiencies and opportunities for improvement were identified. Energy efficiency continues to be a critical issue, as numerous current solutions exhibit high energy consumption, rendering them inappropriate for off-grid applications. The reliance on generic platforms, such as ThingSpeak [50], Blynk [51] or Datacake [52], which are not tailored to the specific needs of diverse places, diminishes effectiveness due to the lack of platform customization. The high material costs render the implementation of these systems in resource-constrained environments impossible, presenting a significant barrier to cost-effectiveness.

Moreover, the primary deficiency noted in the literature is the lack of a comprehensive design methodology that integrates the complete infrastructure, from sensor nodes to the IoT platform. Most current research emphasizes individual components, such as sensor nodes or the IoT platform, rather than comprehensive end-to-end solutions, hence constraining scalability, especially in developing regions where such systems are essential.

To address the limitations of the systems, a comprehensive infrastructure has been proposed, comprising one or more LoRaWAN end devices, henceforth referred to as AirQNode, to measure and transmit particulate matter, temperature, humidity, and pressure to an IoT platform for monitoring and visualization. The AirQNode is based around the Arduino MKR WAN 1310 development board, along with low-power Sensirion SPS30 and BME-280 sensors for measuring particulate matter, temperature, humidity, and pressure, providing ultra-low power consumption, extensive communication range, and excellent measurement precision. The solution utilizes ChirpStack, an open-source LoRaWAN network server, on the cloud side to manage the network and transmit data to the IoT platform. The platform is a centralized framework that coordinates the network and consolidates data from the AirQNodes to facilitate real-time monitoring and analysis of air quality. The subsequent section outlines the detailed design of all components.

3. System Design and Implementation

This section provides a detailed description of the various components of the proposed system for monitoring air quality, starting with the proposed architecture, the AirQNode, the gateway, the network server, and the IoT platform.

3.1. Proposed System Architecture

The proposed LoRaWAN-based system for monitoring air quality is shown in Figure 2. The architecture provides a comprehensive solution, from end devices to the IoT platform that offers complete full control over the system's components and data. The system is comprised of one or more AirQNodes deployed at separate locations in the region to measure PMs, temperature, humidity, and pressure. The collected data is processed and sent via LoRa signals to gateways. The gateways are standard LoRaWAN gateways to relay data to ChirpStack, which acts as a network and application server to manage

AirQNodes and gateways. ChirpStack is integrated, through APIs, with the IoT platform, which comprises a back-end system and a front-end user interface to provide real-time data monitoring and visualization. The next sections provide details of each part.

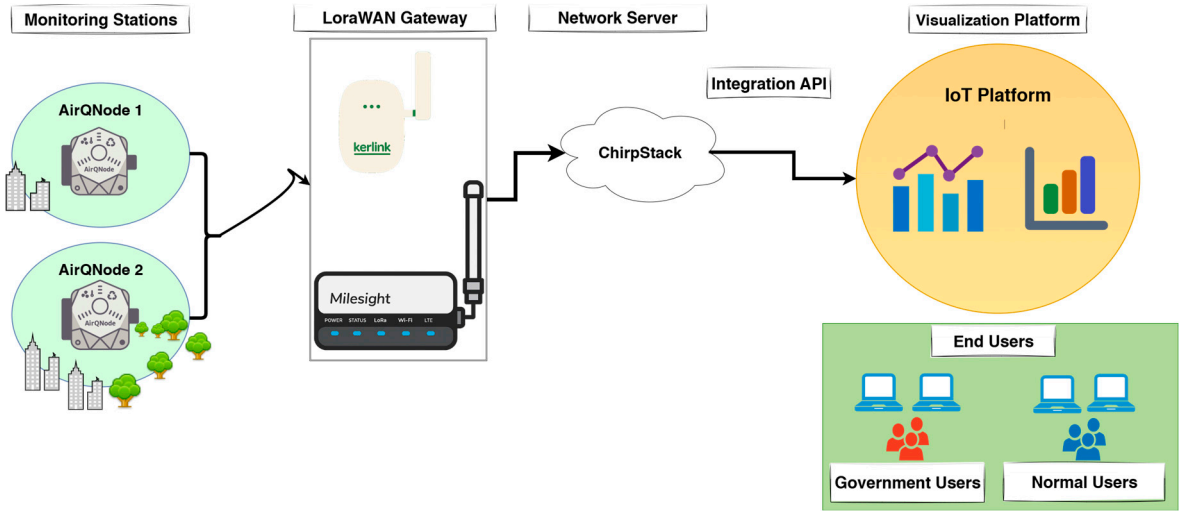


Figure 2. Proposed LoRaWAN-based air quality monitoring infrastructure.

3.2. AirQNode

The AirQNode is a LoRaWAN end device, which is the fundamental part of the system that collects data from the environment, processes it, and sends it to the IoT platform. It is designed for optimal performance while maintaining low power consumption and cost. The AirQNode is based around the Arduino MKR WAN 1310 microcontroller (MCU) connected with low-power Sensirion SPS30 PM and BME-280 combined sensors for collecting PMs, temperature, humidity, and pressure. Figure 3 shows the various parts of the AirQNode. The sensors are connected to the MCU through the Inter-Integrated Circuit (I2C) two-wire serial communication protocol commonly used to connect sensors and other peripheral devices to an MCU. Figure 3 shows detailed wiring connections for the AirQNode parts. The components were prototyped using an MKR Proto Large Shield for easy wiring and testing, and the final assembly was housed in a plastic enclosure for protection. For this work, two nodes were assembled; the actual AirQNode prototype is presented in Figure 4. For prototyping of a single AirQNode, the bill of essential components used is listed in Table 4. The prototype node is significantly more affordable than current outdoor monitoring stations that employ LoRaWAN or Wi-Fi technologies [53,54].

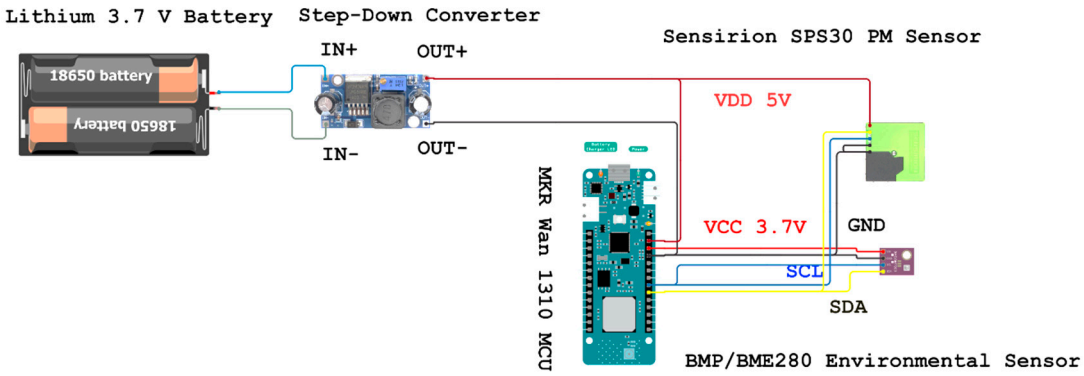


Figure 3. The AirQNode wiring diagram.

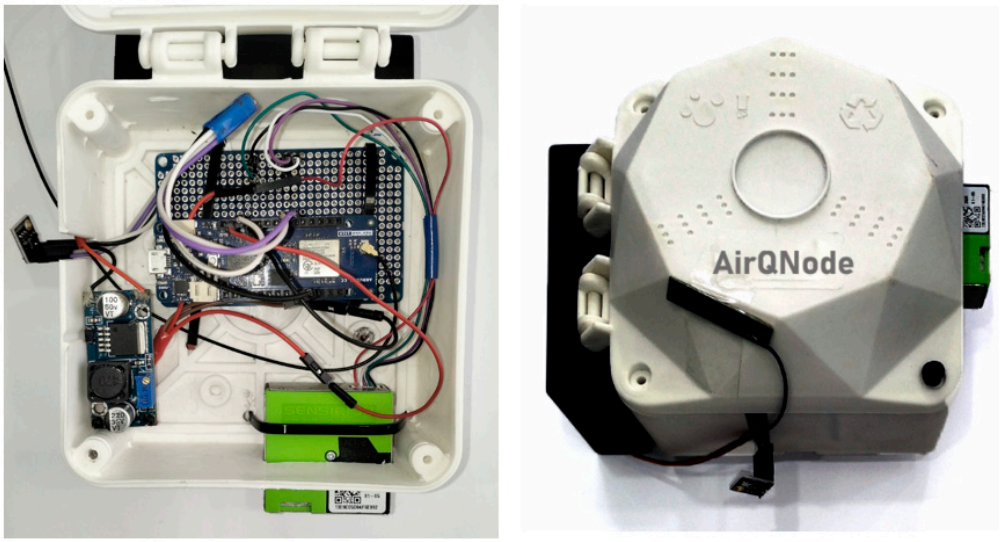


Figure 4. The AirQNode prototype. (**a**) Internal view of the AirQNode prototype, showing the assembled components, including the microcontroller, sensors, voltage regulator, and wiring layout. (**b**) External view of the AirQNode enclosure, designed for compact deployment in outdoor environments.

Table 4. Bill of essential materials utilized for prototyping a single AirQNode.

Component	Number	Cost (USD)	Source
Arduino MKR WAN 1310 Board (Arduino S.r.l., Monza, Italy)	1	35.33	Arduino ABX00029 Arduino MKR WAN 1310 Board
Sensirion SPS30 sensor (Sensirion AG, Stäfa, Switzerland)	1	36.63	SPS30 Sensirion AG | Sensors, Transducers | DigiKey
BME280—Pressure, Humidity, and Temperature Sensor (Bosch Sensortec GmbH, Reutlingen, Germany)	1	4.99	BME280—Pressure, Humidity, and Temperature Sensor | ElectroMake
Arduino MKR Proto Large Shield (Arduino S.r.l., Monza, Italy)	1	5.69	Arduino TSX00002 Arduino MKR Proto Large Shield
18650 Battery Holder (ongguan Bangteng Hardware Electronics Co., Ltd., Dongguan, China)	1	1.49	18650 Battery Holder
Lithium-Ion Rechargeable Battery 18650, 3.7 V, 2600 mAh (EEMB Co., Ltd., Shenzhen, China)	2	7	Lithium-Ion Rechargeable Battery, 3.7 V, 2600 mAh

The subsequent sections provide a thorough explanation of the specifications and features of each component.

3.2.1. MCU

The Arduino MKR WAN 1310 was chosen for AirQNode due to its integrated LoRa capabilities and low power consumption. The MKR WAN 1310 offers significant advantages over alternatives such as Arduino UNO or ESP32, particularly in terms of power efficiency and native LoRa support [55]. By utilizing the deep sleep mode functionality, we were able to dramatically reduce power consumption during inactive periods, extending battery life from days to months. Additionally, the microcontroller's rich set of communication interfaces, such as SPI, I^2C, and UART, makes it well suited for interfacing with various sensors. Its compact form factor further enhances its suitability for prototyping any LoRaWAN-based end devices.

3.2.2. Sensors

Sensirion SPS30

For particulate matter measurements, the Sensirion SPS30 sensor, shown in Figure 5, was selected. It uses laser scattering technology to detect and count particles of different size categories. The sensor draws air through a measurement chamber where a laser beam illuminates the particles. The scattered light is detected by a photodiode, and the signal is processed to determine particle concentrations in different size ranges [56,57]. Figure 6 depicts how the sensor works.

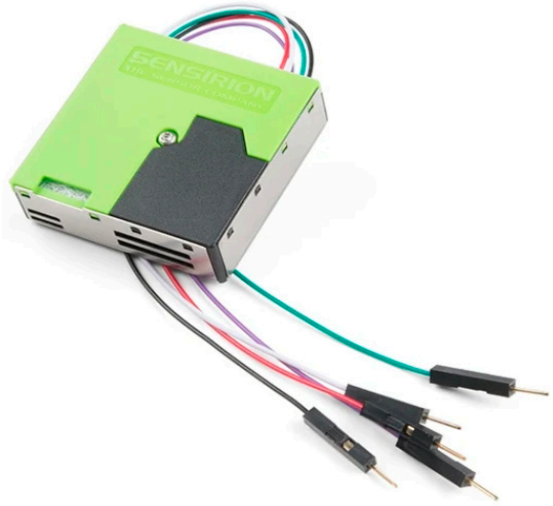


Figure 5. Sensirion PM sensor SPS30.

SPS30 offers several advantages over alternatives, as it has already been calibrated using high-end, routinely supported standard devices such as the TSI DustTrak DRX 8533 Ambient and the TSI OPS 3330 to guarantee low batch-to-batch fluctuation [56]. Additionally, it measures PM1.0, PM2.5, PM4.0, and PM10 simultaneously with a high precision ($\pm$[5 µg/m^3 + 5% m.v.]). The automatic cleaning function ensures long-term stability [57]. The sensor has a low power usage option in idle and sleep modes [58]. This sensor supports I^{2}C and UART interface options and has a small volume of (41 mm × 41 mm × 12 mm) [59].

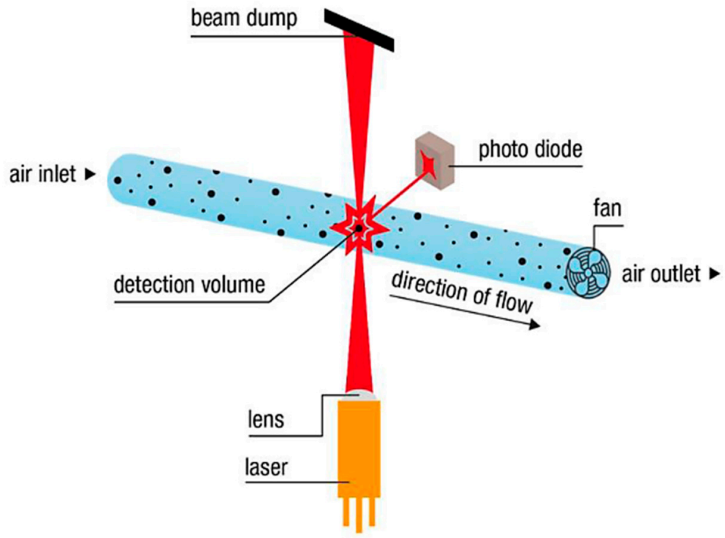


Figure 6. Measurement principle of Sensirion PM sensors [56].

The SPS30 sensor module operates in three distinct modes: measurement, idle, and sleep. Upon power-up, the sensor defaults to idle mode. From idle mode, the sensor can transition either to measurement mode or sleep mode. In continuous measurement mode, with a sampling interval of 1 s, the current consumption ranges between 45 and 65 mA. In contrast, sleep mode significantly reduces power consumption by approximately a factor of 1000 compared to measurement mode. These modes are depicted in Figure 7.

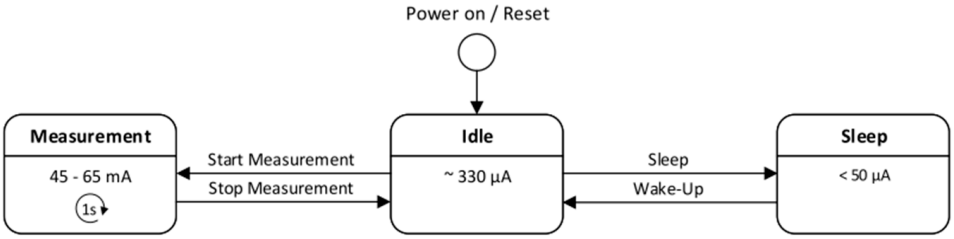


Figure 7. The different operating modes of the SPS30 PM sensor [58].

BME280

The BME280 combined sensor is an integrated environmental sensor to measure temperature, humidity, and atmospheric pressure. Its small dimensions and little power use make it ideal for IoT implementations. The sensor provides exceptional linearity, precision, durable stability, little current consumption, and robust electromagnetic compatibility. Its rapid response time facilitates real-time contextual awareness and uniform performance at diverse temperatures. The BME280 delivers measurements of temperature from 40 °C to 85 °C with an accuracy of ±1.0 °C, humidity from 0% to 100% RH with an accuracy of ±3%, and pressure in the atmosphere from 300 to 1100 hPa. These environmental parameters enhance the PM2.5 data by providing contextual insights, facilitating a deeper comprehension of the correlations between temperature, humidity, and pressure and air quality levels [60].

3.2.3. Power Supply Unit

To power AirQNode, two options were considered, including 5V DC via the built-in microUSB port or the 5VIN pin, and through 3.7 V Li-Ion/Li-Po batteries. As the SPS30 sensor requires a 5 V supply, the first option was chosen. When mains electricity is available, the AirQNode is powered using a standard USB adapter connected to the microUSB port. When mains power is inaccessible in the deployment location, the AirQNode is powered through the 5VIN pin, which is supplied by a DC-to-DC converter circuit converting the voltage from two connected 3.7 V, 2600 mAh lithium batteries in series to the required 5 V.

According to the firmware operation illustrated in Figure A1, in Appendix A, the MCU and sensor function in a continuous duty cycle. For example, if the AirQNode takes measurements at 5 min intervals, it initially remains operational for 40 s for initialization and taking measurements. The node subsequently enters a data transmission phase via the LoRa transmitter. The system finally enters a deep sleep mode for 4.5 min (270 s). This cycle subsequently continues indefinitely. The current consumption was measured for initialization and measurements, LoRa packet transmission, and deep sleep mode, returning values of 75 mA, 50 mA, and 1 mA, respectively.

Table 5 lists the current for each mode and power consumption during one hour of operation.

Table 5. AirQNode power consumption at 5 min intervals.

Mode	Duration (seconds)	Current Consumption (mA)	Instantaneous Current Consumption per Hour (mAh)	Cycles per Hour	Power Consumption (mWh)
Initialization and measurements	40	75	(40 × 75)/3600 = 0.833	3600/320 = 11.25	0.833 × 11.25 × 5 V [1] = 46.85
LoRa transmission	10	50	(10 × 50)/3600 = 0.138		0.138 × 11.25 × 5 V = 7.76
Deep sleep	270	1	(270 × 1)/3600 = 0.075		0.075 × 11.25 × 5 V = 4.22
Total	320	126	1.046		58.83

[1] The operating voltage of the AirQNode is 5 V.

The calculation suggests that the AirQNode consumes around 59 mWh. When the AirQNode is powered by two lithium batteries (3.7 V, 2600 mAh), it will produce approximately 19 Wh, allowing the batteries to last for 322 h or 13.4 days (19 Wh/59 mWh = 322 h/24 h = 13.4 days). A lithium polymer battery charger board, paired with a standard 5 W solar panel, can be integrated into the power supply unit to recharge the batteries during daylight hours. This allows the AirQNode to function as a self-powered device.

3.2.4. Gateway

The LoRaWAN gateway serves as the bridge between the sensor nodes and the network server. For this implementation, we used two different gateways, Milesight UG65 and Wirnet iFemtoCell-Evolution. With a quad-core CPU and an SX1302 LoRa chip, the Milesight gateway device is built to withstand harsh conditions and is compatible with several frequency bands. It uses the LoRaWAN 1.0.2 protocol and is an 8-channel device with 512 MB of DDR4 RAM. The gateway supports several backhaul options, including Ethernet, 4G/3G cellular networks, and Wi-Fi. It is perfect for extensive outdoor IoT deployments because it is compatible with the ChirpStack Network Server and has a communication range of up to 15 km in line-of-sight. A small and smart indoor LoRaWAN gateway, the Kerlink iFemtocell is made to function dependably in difficult settings like garages, basements, and underground spaces. It has automatic fallback to 3G or 2G and supports both Ethernet and 4G [61,62]. Figure 8 shows the photos of these gateways.



Figure 8. The two used LoRa Gateways: (**a**) Kerlink iFemtoCell-Evolution (**b**) Milesight UG65.

3.2.5. AirQNode Firmware

The AirQNode firmware was created using the Arduino IDE and is intended to perform many critical functions. This includes initialization and configuration of the sensors, LoRa communication settings, and system variables. It manages data collection by

gathering measurements from the SPS30 and BME280 sensors. Upon data collection, it is processed and packaged into structured packets appropriate for transmission. The firmware integrates power management measures, including entering deep sleep mode between measurement cycles, to improve energy efficiency. Communication with the LoRaWAN network is facilitated by the administration of network joining protocols and data transfer mechanisms. Figure A1, in Appendix A, presents the pseudocode implementation of the firmware, and the flowchart outlining the main functions for AirQNode firmware can be seen in Figure A2 in Appendix A.

3.2.6. Network Server

The LoRaWAN Network Server (LNS) is crucial to the LoRaWAN architecture, managing the network's operations, including routing, security, and device configurations. LNS processes packet data from gateways and directs this information to the corresponding application server, and vice versa.

To enable flexible and secure IoT deployments, an open-source LNS such as ChirpStack is essential. In contrast to proprietary and free community LNS [63,64], it offers complete customization and vendor independence, rendering it suitable for research and industrial applications.

ChirpStack is an open-source LNS that can be used to set up and manage LoRaWAN networks. It supports the latest LoRaWAN specifications and includes multi-tenant capabilities, allowing for the management of different deployment zones within a single system. Its API-driven design facilitates seamless integration with custom applications, while its scalable architecture can support thousands of connected devices.

In this work, the ChirpStack server was used as the network server, and it was deployed on a cloud on a dedicated server infrastructure to provide reliable and continuous access. It performs several essential tasks, including authenticating and activating LoRaWAN end devices, deduplicating data when the same message is received by multiple gateways, handling MAC commands, managing Adaptive Data Rate (ADR), and scheduling downlink transmissions. The server was configured to operate within the EU868 frequency band (EU863–870 MHz), which is well suited for use in the KRI. To ensure the confidentiality and integrity of transmitted data, security was implemented using LoRaWAN's AES-128 encryption at both the network and application layers [65]. For this work, two different gateways were registered on the ChirpStack server: Milesight UG65 and Kerlink iFemtoCell-Evolution.

The AirQNodes were registered and activated on ChirpStack, using the Over-the-Air (OTAA) activation method, as it is the most secure and reliable method, connecting them to the LoRaWAN infrastructure for data transmission. In addition, the Integration API uses an HTTPS connection, which was established to send the collected data to the IoT platform.

3.2.7. IoT Platform

The IoT platform serves as both a dashboard and the primary user interface for the system, providing capabilities for data visualization, analysis, and administration. Establishing a proprietary IoT ecosystem for LoRaWAN applications, versus relying on third-party solutions such as Blynk [51] or Datacake [52], offers substantial advantages in terms of data privacy, scalability, and long-term adaptability. Preconfigured platforms, even though convenient, may limit personalization and data ownership, hence hindering flexibility in research or industrial applications. By creating an autonomous platform, organizations retain full authority over data security, network infrastructure, and protocol enhancements. Furthermore, self-hosted systems ensure sustainable scalability and reduce dependency on external vendors.

In this work, a platform was custom developed utilizing the Laravel PHP framework and a MySQL database backend to address the special requirements of the KRI. This customized system, in contrast to standard off-the-shelf systems, accommodates English, Kurdish, and Arabic languages, interfaces with local governmental infrastructures, and has unique visualization capabilities for different groups.

A primary feature is a real-time monitoring interface that presents the current air quality condition for all AirQNodes. The platform facilitates historical data analysis, enabling users to examine patterns over several timeframes, such as hourly, daily, monthly, seasonal, and yearly. Geospatial visualization is facilitated by interactive maps that depict the distribution of air quality throughout the area. An integrated alarm system informs users when air quality levels pass a predefined threshold. Additionally, the platform provides data export capabilities in many formats to facilitate study and reporting, along with user management features for public users, researchers, and administrators.

The platform was designed using the MVC (Model-View-Controller) architecture and interacts with the ChirpStack network server via a RESTful API. The system utilizes Breeze, Spatie, Tailwind CSS, jQuery, and JavaScript frameworks to provide front-end responsiveness and accessibility across various platforms, including smartphones and tablets.

Furthermore, on the IoT platform side, to optimize power efficiency and simplify AirQNode design, raw sensor data were transmitted in real-time without considering the actual time when the measurements are taken. The IoT platform then processes and averages the data at the end of each measurement period. This approach eliminates the need for complex real-time clock circuits on the AirQNodes. By offloading the computational task of data averaging to the IoT platform, the AirQNodes can maintain a simpler and more power-efficient architecture. The IoT platform, accessible via https://www.kaqi.krd/home, KAQI, which represents the Kurdistan Air Quality Initiative, provides a centralized hub for real-time monitoring and historical data analysis. The following figures present the main user interface and features of the IoT platform.

Figure 9, an OpenStreetMap with scale, coordinates, and compass indicator, provides a geographical overview of the AirQNodes deployed across the monitored region. Each node's PM2.5 Air Quality Index is visualized using a color-coded schema.

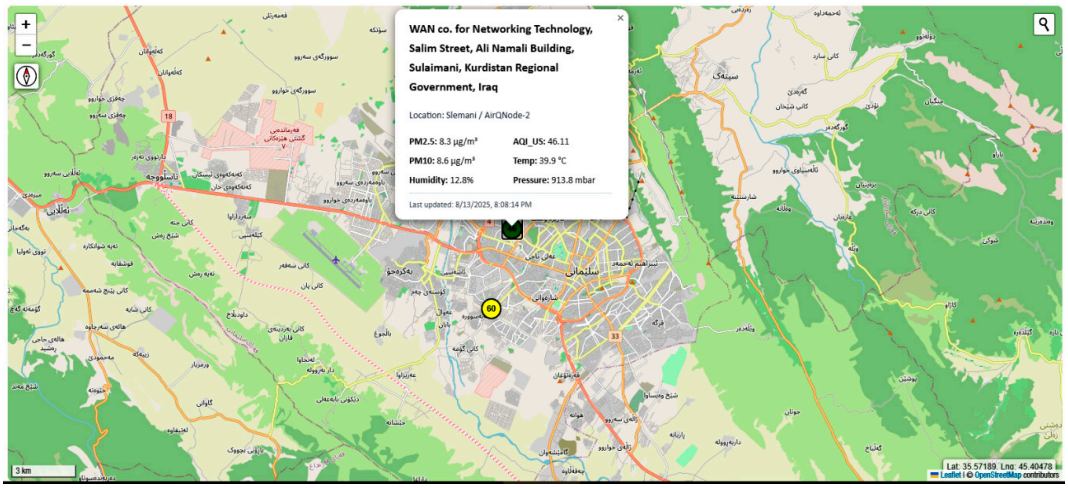


Figure 9. Geographic distribution of the AirQNodes.

In Figure 10, parameters of particulate matter concentrations (PM1, PM2.5, PM4, and PM10), temperature, humidity, and atmospheric pressure are listed.

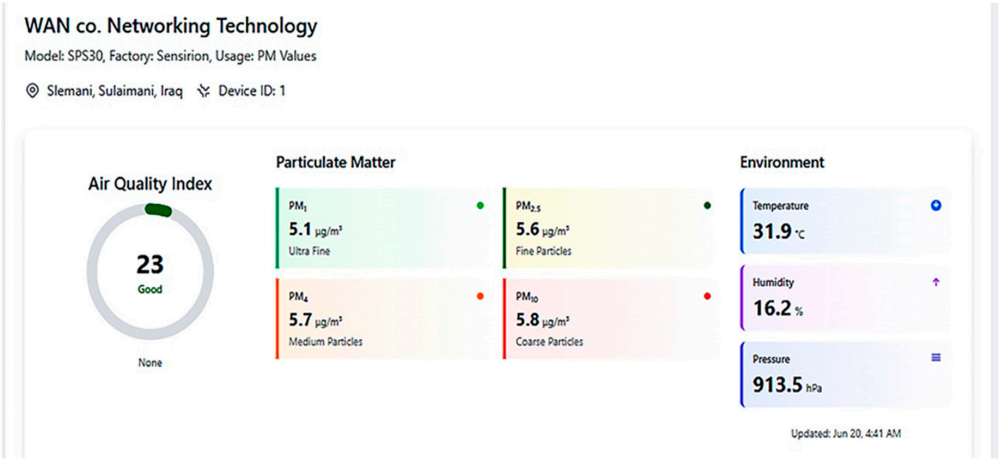


Figure 10. Detailed real-time AirQNode interface.

Figure 11 presents an illustration chart of PM2.5 concentration rise and fall patterns across a specific period.

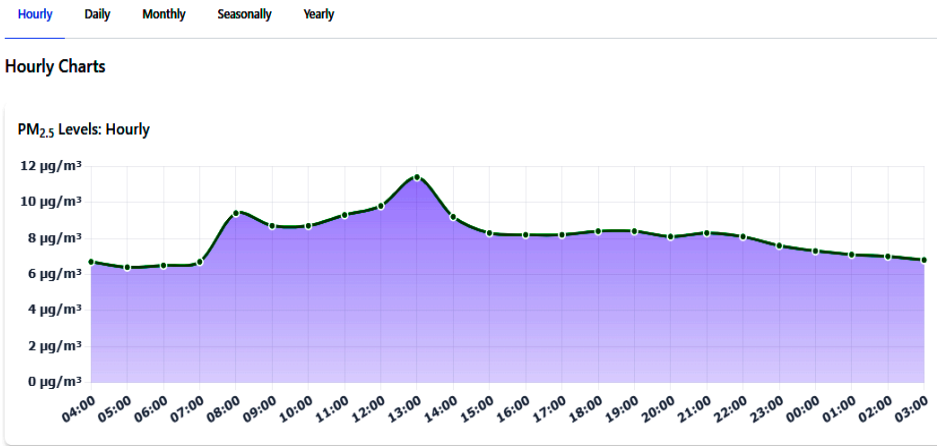


Figure 11. Variation in PM2.5 concentration chart, based on a specified period.

Figure 12 provides statistical summaries of key parameters, including average, minimum, and maximum values for particulate matter, temperature, humidity, and pressure.

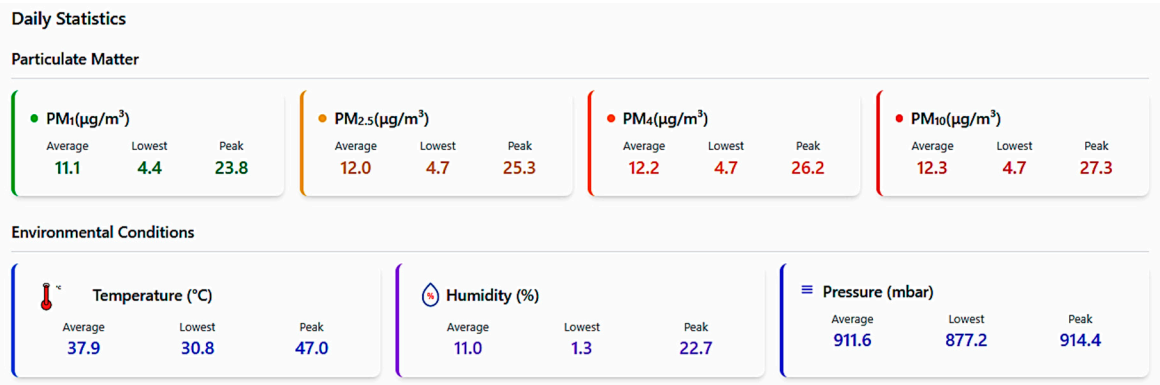


Figure 12. Daily statistical summary of air quality and environmental conditions.

Figure 13 visualizes periodical PM values, including PM1.0, PM2.5, PM4.0, and PM10.0, as recorded by the AirQNode node.

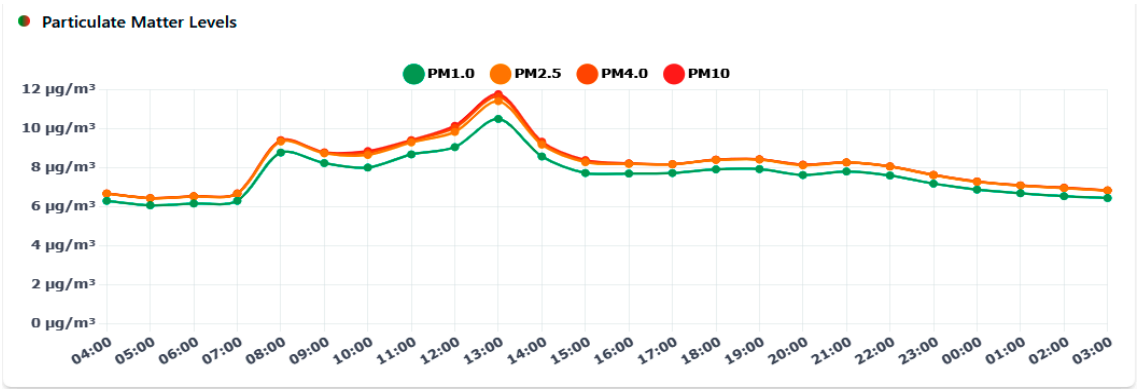


Figure 13. Variation in PM concentration values, chart based on a specified period.

Figure 14 visualizes periodical environmental variations, including temperature, humidity, and atmospheric pressure, as recorded by the sensor node.

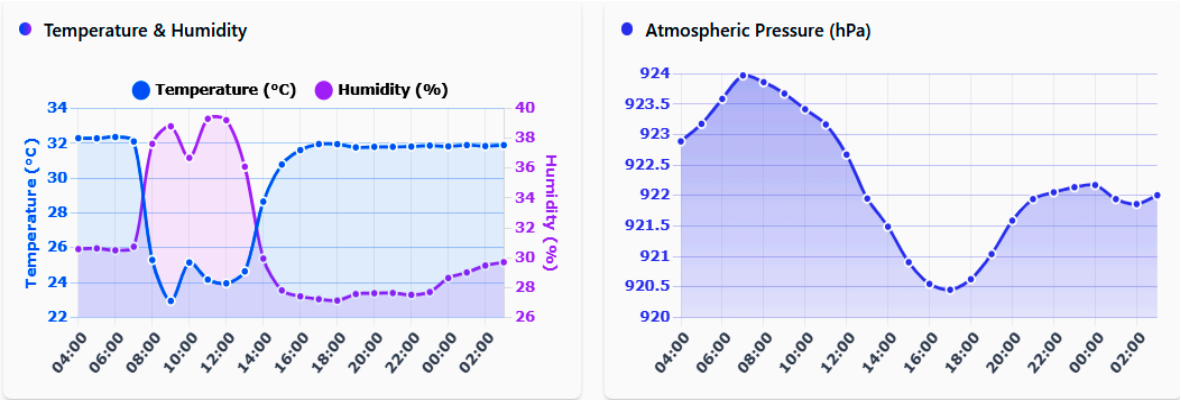


Figure 14. Variation of environmental concentration chart, based on a specified period.

Figures A3 and A4, in Appendix A, present the main dashboard interface of the air quality monitoring system. It displays real-time measurements of particulate matter and environmental parameters. Figure A5, in Appendix A, shows the permission management interface, enabling system administrators to assign, change, or revoke user roles and access levels in accordance with established security protocols.

4. Results and Discussion

This section describes the results of the tests, deployment, and validation of the proposed infrastructure. Additionally, the discussion on the results is presented here. The testing was conducted several times indoors and outdoors to collect data.

Although the Sensiron SPS30 PM has already been calibrated by the manufacturer against a TSI OPS 3330 or a TSI DustTrak DRX 8533 [66], we aimed to validate the AirQNode measurements by comparing the measurements with reference data collected by official reference monitoring devices in the region. Acquiring such references was challenging, as the governmental bodies and departments in the region who are responsible for monitoring air quality lack the requisite equipment.

IQAir, a Swiss air quality technology firm, operates the AirVisual platform, which offers real-time air quality data, including PM values globally, and has established several air quality monitoring stations in the region known as AirVisual outdoor monitors [67]. The IQAir AirVisual outdoor monitors are professional-grade monitors that measure various environmental parameters, including PM1, PM2.5, PM10, temperature, humidity, and

atmospheric pressure, and calculate AQI and provide real-time data to the public via its accessible worldwide AirVisual platform [68].

We decided to position the AirQNodes adjacent to IQAir's current AirVisual outdoor monitors, with one station in the Technical College of Informatics, Sulaimani Polytechnic University, Chwar Chra campus [69] and another one situated on the premises of a local tech firm [70].

In collaboration with the local tech firm, we installed one of the gateways on their premises and deployed one of the AirQNodes outdoor adjacent to their existing air quality monitor. Figure 15 shows the deployment of the AirQNode on the local tech firm's premises.

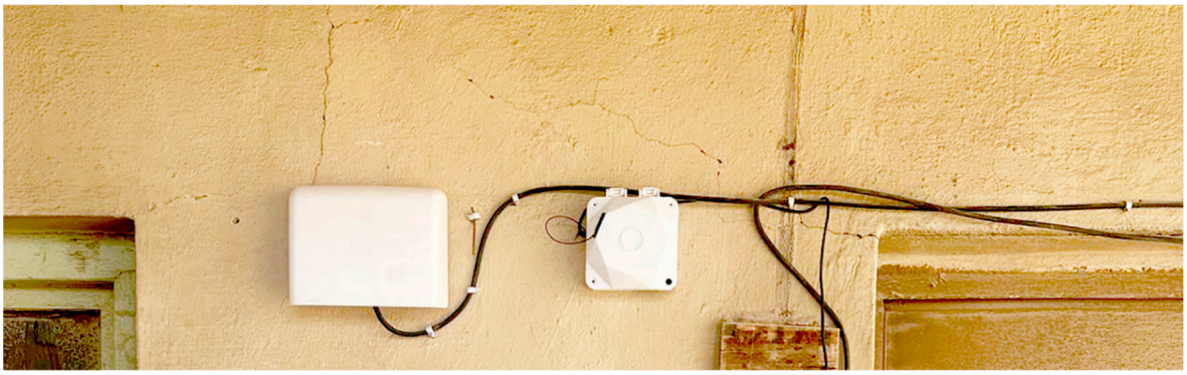


Figure 15. Deployment of the AirQNode outdoor near the IQAir AirVisual outdoor monitor on the local tech firm's premises.

The AirQNode was programmed to take measurements in approximately 5 min intervals, from the 23rd July (00:00) to the 2nd August 2025 (00:00), for a total of approximately 11 days. For the purpose of comparison with the IQAir data, which was available on an hourly average, an hourly average was calculated for the AirQNode measurements as well. As the main focus here is on measuring PM2.5 levels and calculating US AQI, only these measurements are presented here; other PM values and environmental parameters such as temperature, humidity, and atmospheric pressure are presented in Figure A6, Figure A7, and Figure A8, respectively, in Appendix A.

Figures 16 and 17 show the hourly average of PM2.5 measurements and the US AQI of the AirQNode, respectively.

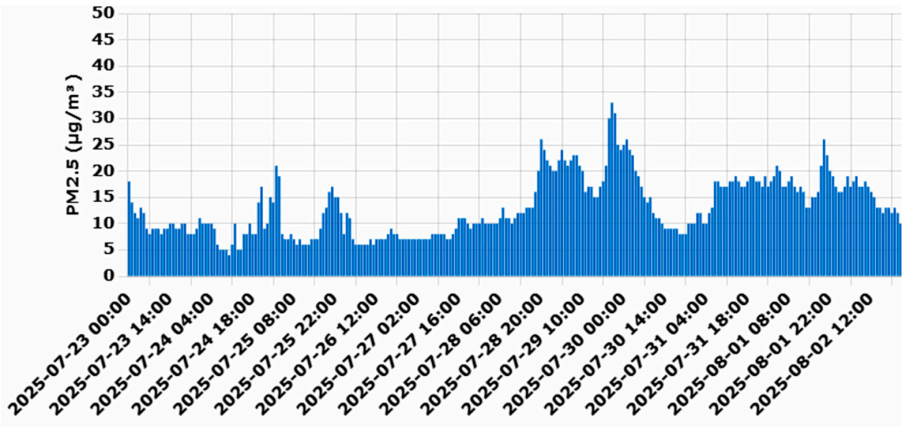


Figure 16. The AirQNode outdoor hourly average of PM2.5 level at the local tech firm location.

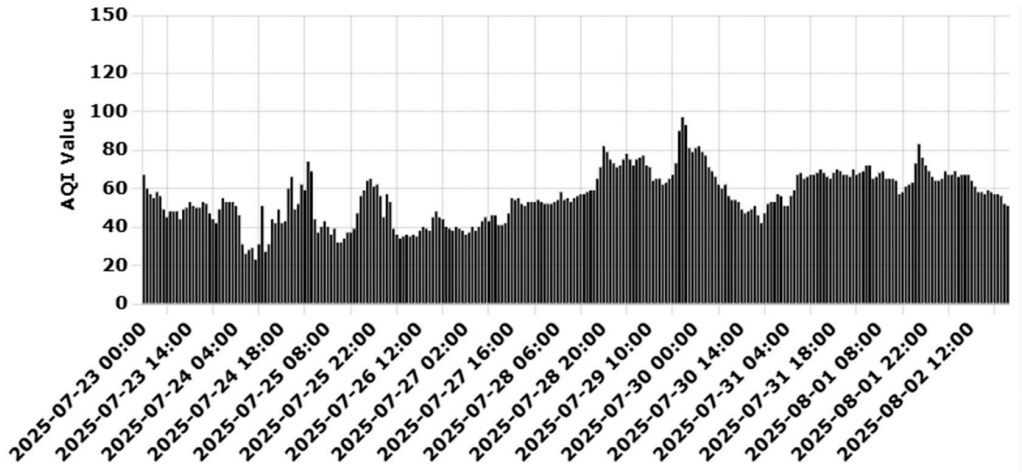


Figure 17. The AirQNode outdoor hourly average of the US AQI at the local tech firm location.

We obtained data from the IQAir AirVisual outdoor monitor of the local tech firm location for the same timeframe for both the PM2.5 level and the US AQI and plotted and presented them in Figures 18 and 19, respectively.

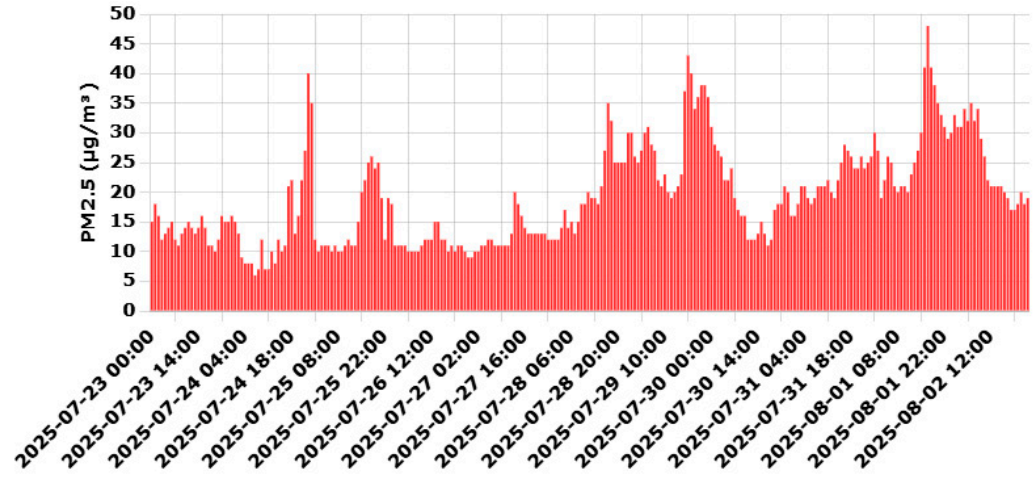


Figure 18. The IQAir AirVisual outdoor monitor PM2.5 levels at the local tech firm location.

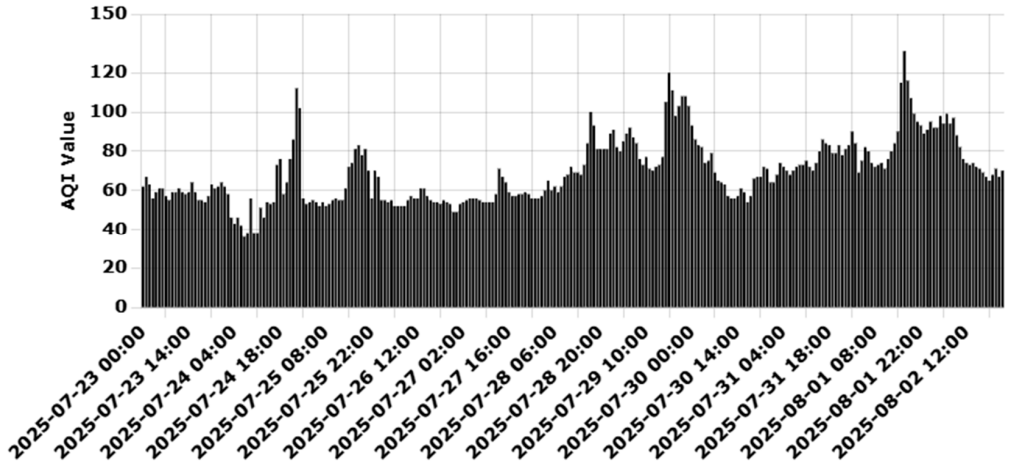


Figure 19. The IQAir AirVisual outdoor monitor US AQI at the local tech firm location.

For comparative purposes, the PM2.5 levels and US AQI of both the AirQNode and the AirVisual outdoor monitor are drawn on a graph and presented in Figures 20 and 21, respectively.

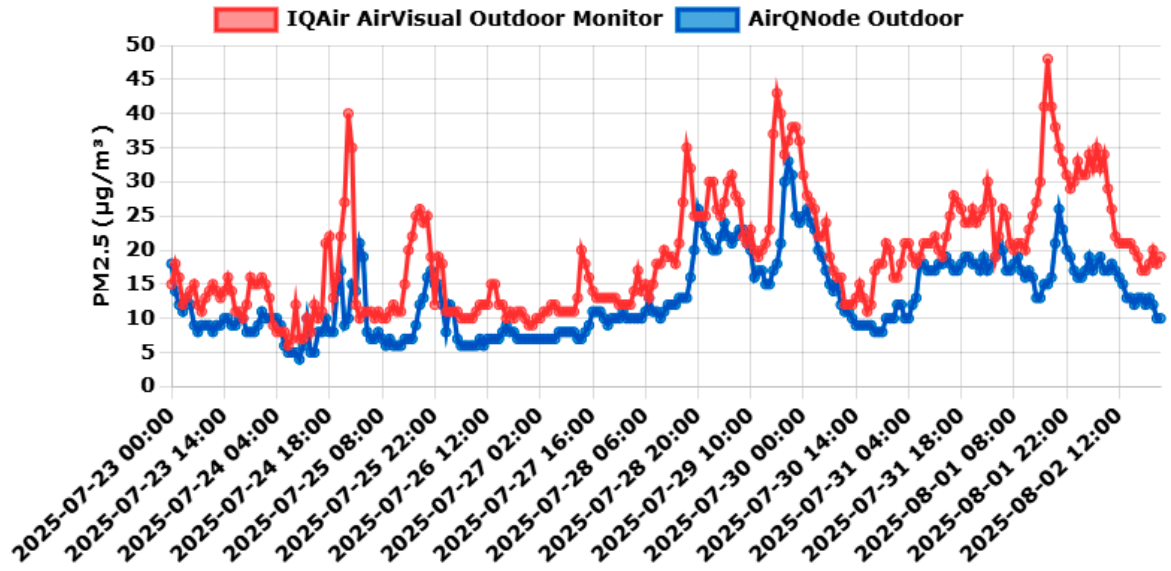


Figure 20. The PM2.5 levels of both the AirQNode outdoor and the IQAir AirVisual outdoor monitor at the local tech firm location.

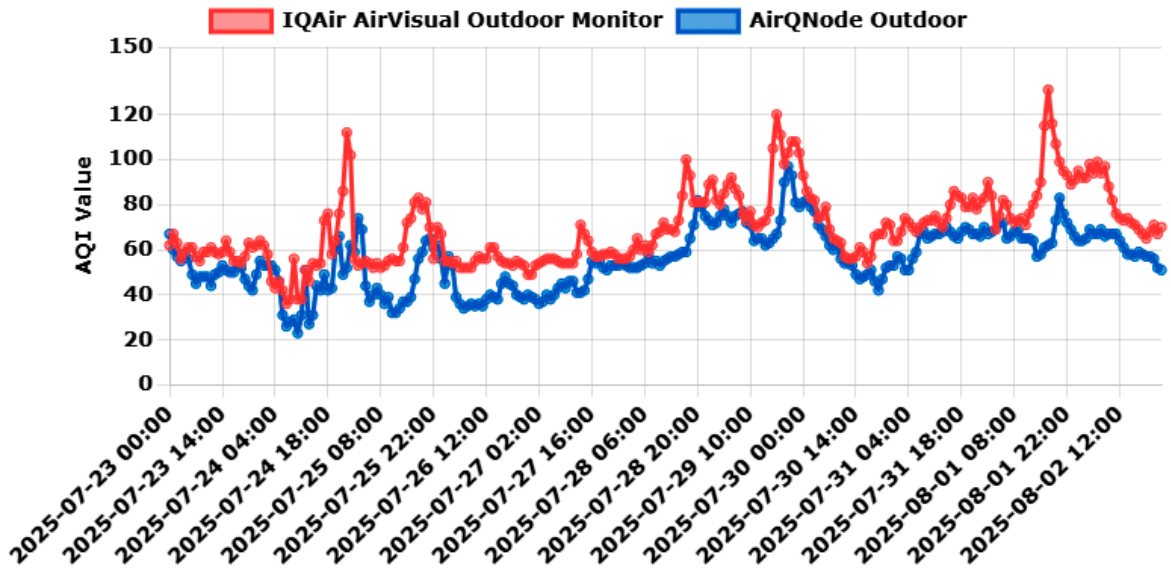


Figure 21. The US AQI Index of both the AirQNode outdoor and the IQAir AirVisual outdoor monitor at the local tech firm location.

As shown in Figures 20 and 21, it is evident that the trends of both measurements are identical. However, the AirQNode results appear to be lower than those of the IQAir AirVisual outdoor monitor in most readings.

To validate, the correlation coefficient, denoted by 'r', between the AirQNode and the IQAir AirVisual outdoor monitor measurements, were calculated and the scatter plot and regression line were presented for both PM2.5 levels and US AQI and are shown in Figures 22 and 23.

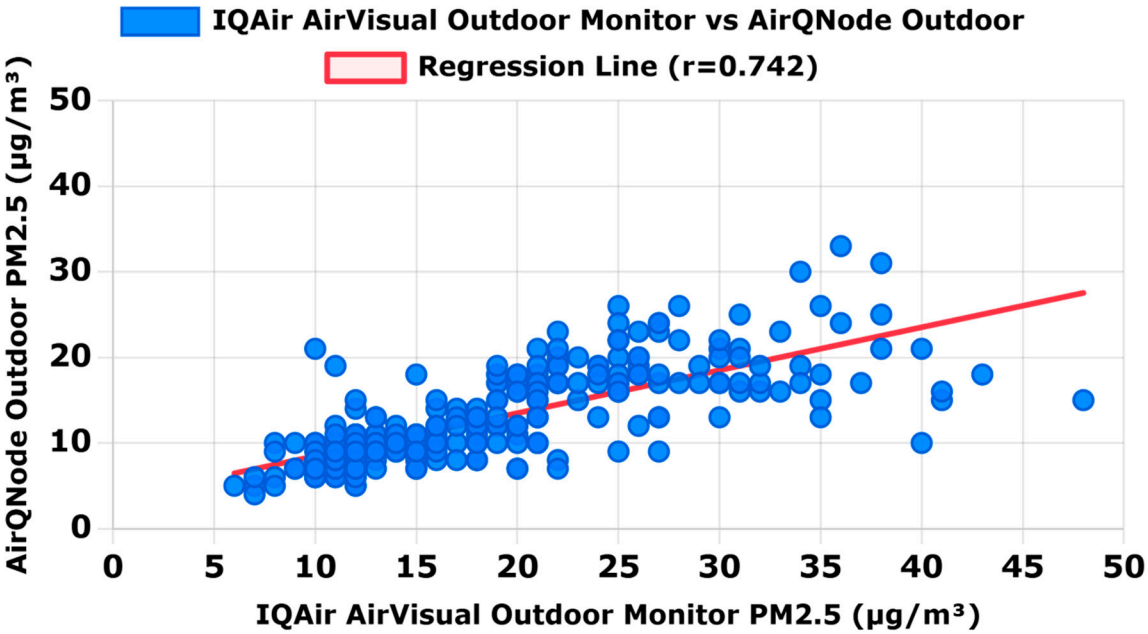


Figure 22. Correlation and regression line between AirQNode outdoor and IQAir AirVisual outdoor monitor for hourly average of PM2.5 level at the local tech firm location.

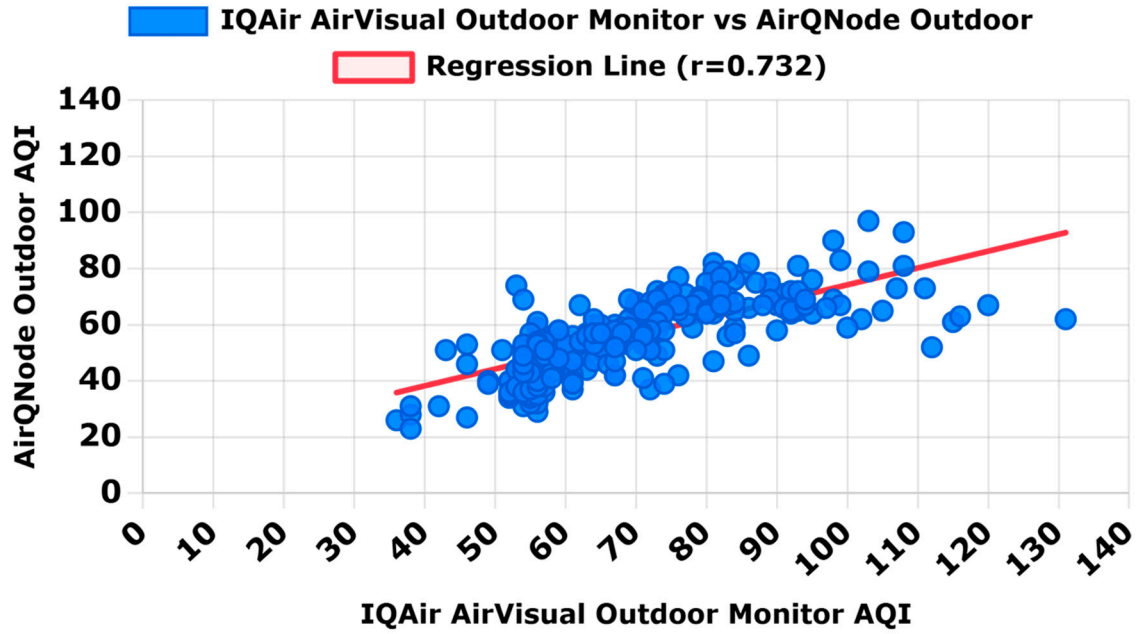


Figure 23. Correlation and regression line between AirQNode outdoor and IQAir AirVisual outdoor monitor for hourly average of US AQI at the local tech firm location.

The results of the correlation coefficient analysis of both figures reveal a strong relationship, as both exceed 0.7, between the measurements of the AirQNode and the IQAir AirVisual outdoor monitor for the local tech firm location. To quantify the comparison and analyze the disparities in readings between the two stations, the Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) were computed. The MAE and RMSE values for PM2.5 were 6.318 µg/m^3 and 8.224 µg/m^3, respectively, while for US AQI, the MAE and RMSE values were 14.056 AQI and 17.574 AQI, respectively.

The discrepancies in measurements and estimates may be attributed to the advanced calibration approach employed by IQAir. Their calibration methodology encompasses a multi-faceted process that includes anomaly detection and environmental adjustments

based on temperature, humidity, pollutant composition, and geographical history. Additionally, they utilize satellite imagery to detect pollution sources and implement localized adjustments using their AI-driven methodology. This was obtained as clarifications from the IQAir. The raw data for the AirQNode was presented unmodified and without modifications.

For the Technical College of Informatics deployment, two tests were carried out: one in an outdoor environment and another in an indoor setting. A gateway was installed in one of the labs to provide LoRaWAN network coverage for the campus.

For the outdoor test, one AirQNode was installed adjacent to the college's current IQAir air quality monitor mounted at a height of three meters above the floor. Figure 24 shows the deployment of the AirQNode in both outdoor and indoor settings.



(**a**) (**b**)

Figure 24. (**a**) The outdoor deployment of the AirQNode near the IQAir AirVisual outdoor monitor on the premises of the Technical College of Informatics, Sulaimani Polytechnic University, Chwar Chra campus. (**b**) The indoor deployment of the AirQNode in one of the offices of the Technical College of Informatics, Sulaimani Polytechnic University, Chwar Chra campus.

The AirQNode was programmed to take measurements in approximately 5 min intervals, from 29th July (00:00) to the 8th August 2025 (00:00), for a period of 11 days. An hourly average of PM2.5 levels and US AQI were calculated for the AirQNode and are presented in Figures 25 and 26.

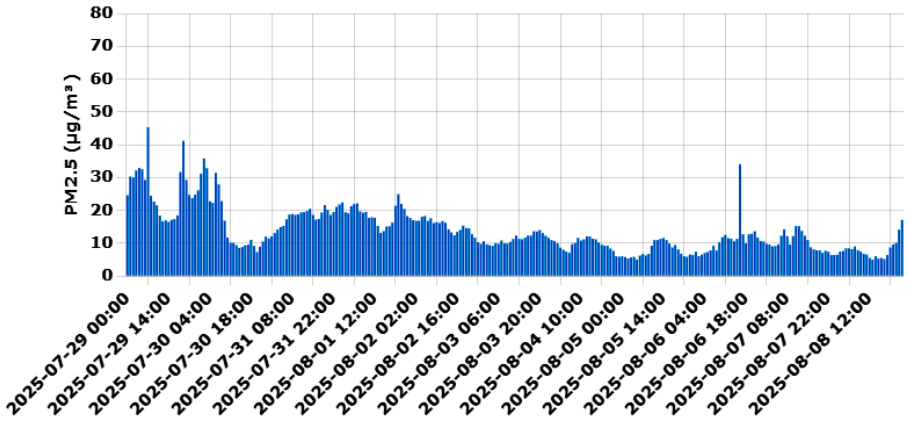


Figure 25. The AirQNode outdoor hourly average of PM2.5 level on the premises of the Technical College of Informatics, Sulaimani Polytechnic University, Chwar Chra campus.

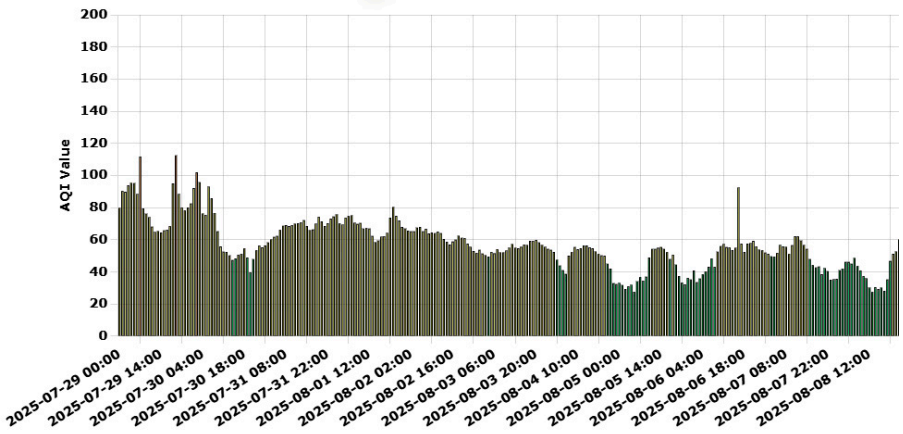


Figure 26. AirQNode outdoor hourly average of US AQI index on the premises of the Technical College of Informatics, Sulaimani Polytechnic University, Chwar Chra campus.

For this location, we obtained the data from the IQAir AirVisual monitor for the same timeframe for both PM2.5 level and US AQI and plotted and presented them in Figures 27 and 28, respectively.

For comparative purposes, the PM2.5 levels and US AQI of both the AirQNode and the IQAir AirVisual outdoor monitor are drawn on a graph and presented in Figures 29 and 30, respectively.

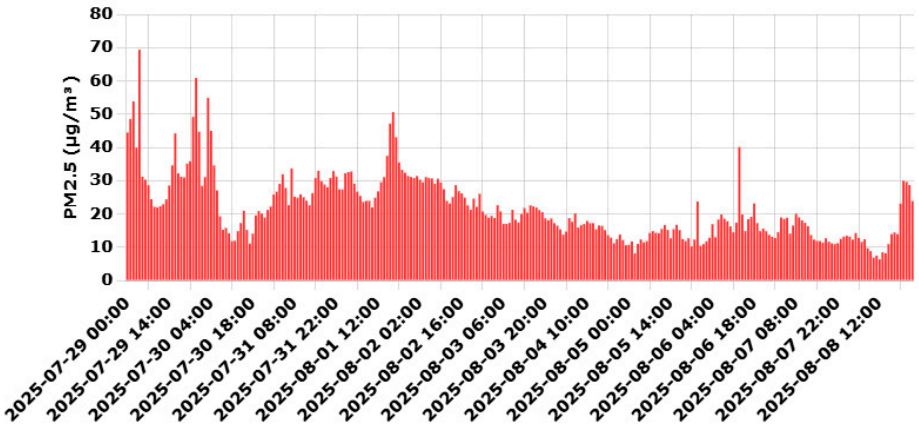


Figure 27. The IQAir AirVisual outdoor monitor PM2.5 level on the premises of the Technical College of Informatics, Sulaimani Polytechnic University, Chwar Chra campus.

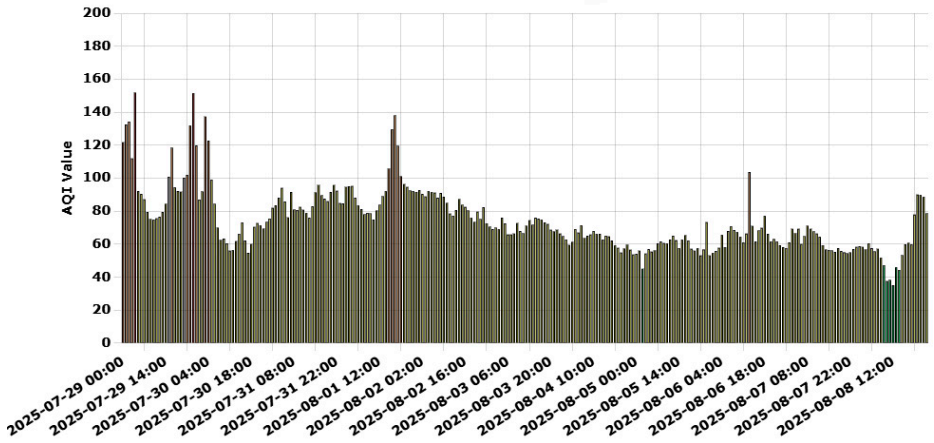


Figure 28. The IQAir AirVisual US AQI on the premises of the Technical College of Informatics, Sulaimani Polytechnic University, Chwar Chra campus.

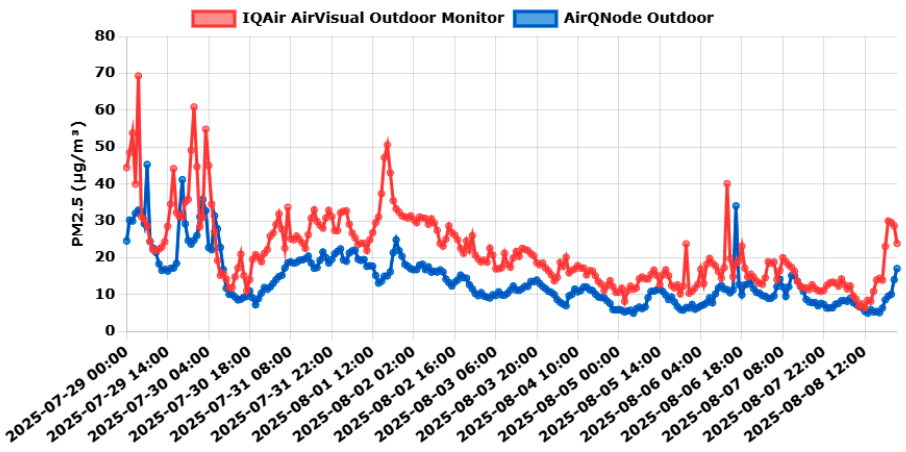


Figure 29. PM2.5 levels of both the AirQNode outdoor and the IQAir AirVisual outdoor monitor on the premises of the Technical College of Informatics, Sulaimani Polytechnic University, Chwar Chra campus.

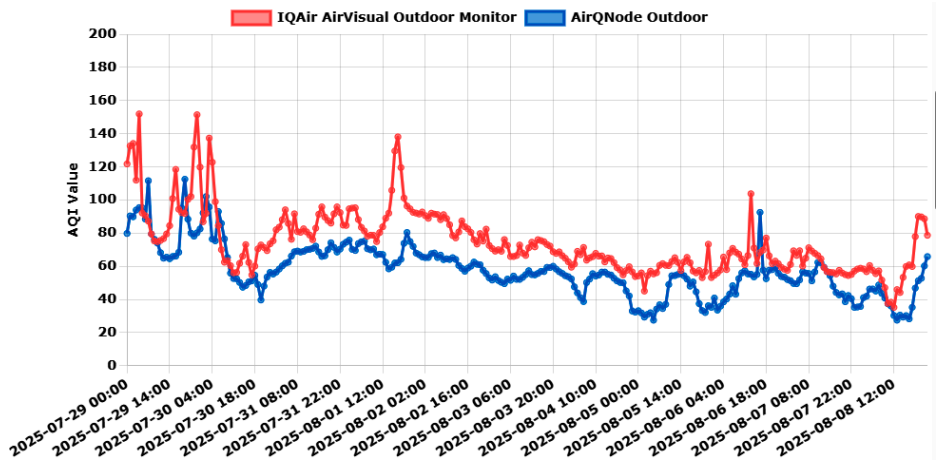


Figure 30. The US AQI of both the AirQNode outdoor and the IQAir AirVisual outdoor monitor on the premises of the Technical College of Informatics, Sulaimani Polytechnic University, Chwar Chra campus.

Figures 29 and 30 clearly demonstrate that the trends of both measurements are identical as well. Nonetheless, the IQAir AirVisual outdoor monitor registered higher PM2.5 levels and computed a higher US AQI compared to the AirQNode. To provide

insight, the correlation coefficient 'r' between the AirQNode and the IQAir AirVisual outdoor monitor measurements was calculated, and the scatter plot and regression line were presented for both PM2.5 levels and US AQI and are shown in Figures 31 and 32.

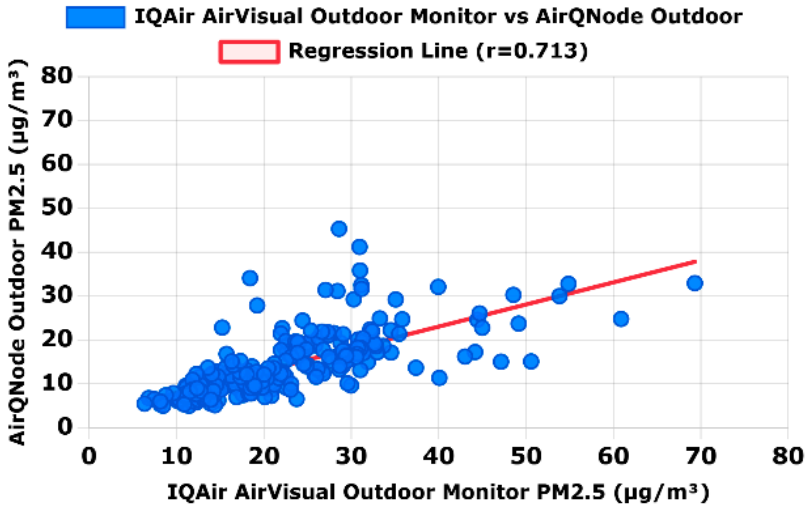


Figure 31. Correlation and regression line between the AirQNode outdoor and the IQair AirVisual outdoor monitor for hourly average of PM2.5 level at the Technical College of Informatics, Sulaimani Polytechnic University, Chwar Chra campus.

Similarly, the correlation coefficient of both figures indicates a robust relationship, as they are both higher than 0.7 between the measurements of the AirQNode and the IQAir AirVisual outdoor monitor.

Figures 29 and 30 reveal a discrepancy between the measurements of the AirQNode and the IQAir AirVisual outdoor monitor, with the latter exhibiting greater values in both measurements and computations compared to the AirQNode.

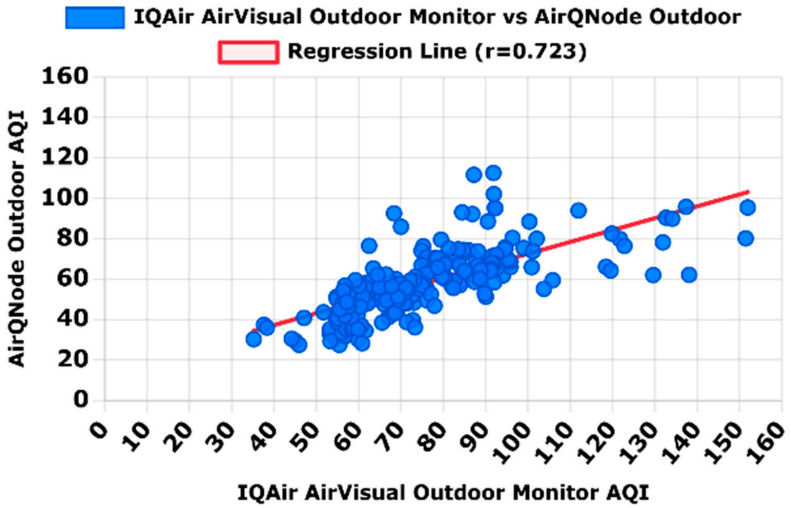


Figure 32. Correlation and regression line between the AirQNode outdoor and the IQAir AirVisual outdoor monitor for hourly average of US AQI at the Technical College of Informatics, Sulaimani Polytechnic University, Chwar Chra campus.

To quantify the comparison and analyze the disparities in readings between the two stations, MAE and RMSE were computed. The MAE and RMSE values for PM2.5 were 8.522 µg/m^3 and 10.553 µg/m^3, respectively. These values are slightly higher than the values computed for the local tech firm; the rationale for this was that the timeframe for this deployment was more polluted than the preceding period.

For US AQI, the MAE and RMSE values were 18.015 AQI and 21.618 AQI, respectively. As previously stated, the same explanation presented for the previous deployment results might be applied as well to explain the differences in measurements and estimates.

The AirQNode indoor was also programmed and deployed, see Figure 24b, to take measurements in approximately 5 min intervals from the 10th of July (14:00) to the 15th of July 2025 (02:00). Figures 33–37 show the results of this deployment.

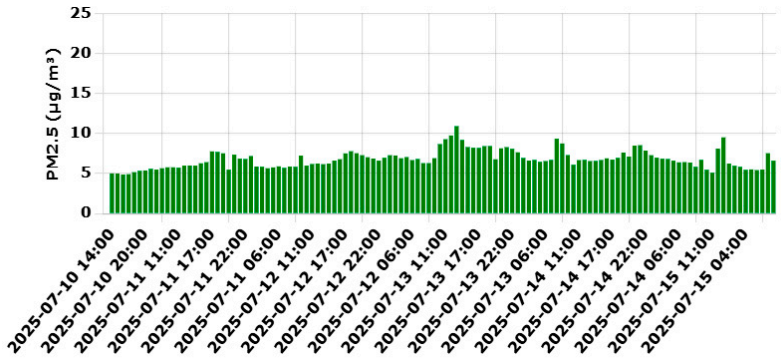


Figure 33. The AirQNode indoor hourly average of PM2.5 level in one of the offices of the Technical College of Informatics, Sulaimani Polytechnic University, Chwar Chra campus.

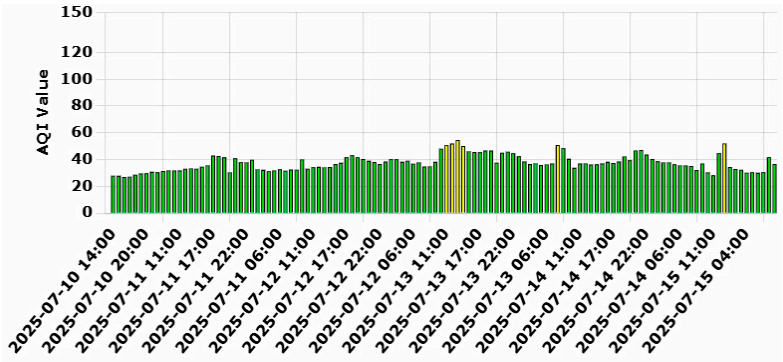


Figure 34. AirQNode indoor hourly average of US AQI in one of the offices of the Technical College of Informatics, Sulaimani Polytechnic University, Chwar Chra campus.

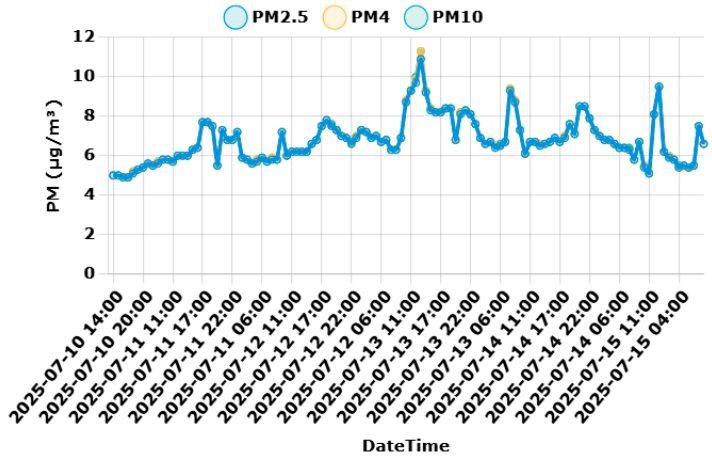


Figure 35. The AirQNode indoor hourly average of PM2.5, PM4, and PM10 levels in one of the offices of the Technical College of Informatics, Sulaimani Polytechnic University, Chwar Chra campus.

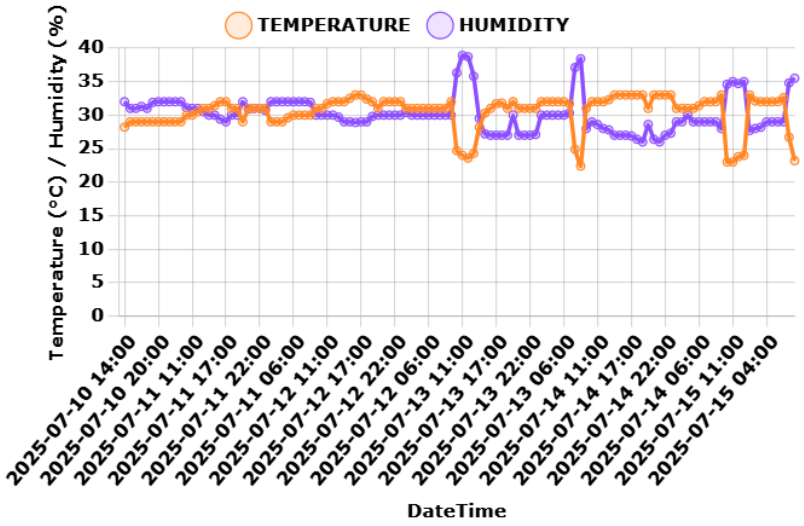


Figure 36. The AirQNode indoor hourly average of temperature and humidity levels in one of the offices of the Technical College of Informatics, Sulaimani Polytechnic University, Chwar Chra campus.

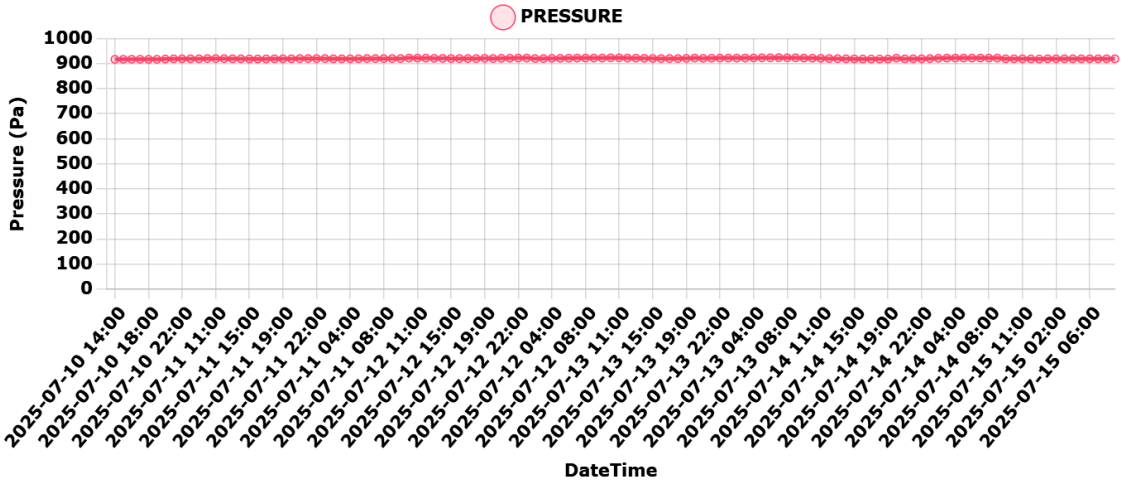


Figure 37. The AirQNode indoor hourly average of atmospheric pressure levels in one of the offices of the Technical College of Informatics, Sulaimani Polytechnic University, Chwar Chra campus.

The results provide a consistent measurement of the AirQNode for PM values, temperature, humidity, and air pressure over the entire duration.

After completing these initial tests, the AirQNodes are now left deployed outdoors, at the locations shown in Figures 15 and 24a, on the premises of the Technical College of Informatics and the tech firm to collect data for longer periods of time for further analysis and studies.

5. Conclusions

This study proposed, designed, implemented, and deployed a LoRaWAN infrastructure in real-world locations. The research involved prototyping two AirQNodes for the collection of PM values, temperature, humidity, and atmospheric pressure data. Additionally, an open-source network server was utilized to manage the AirQNodes and the overall network. Furthermore, an IoT platform has been designed and implemented for the visualization and analysis of the collected data. The platform processes and stores data, rendering it accessible to the public and decision-makers.

The results were validated by deploying the AirQNodes at various locations near existing air quality monitors, which served as reference points. The results demonstrated

that the AirQNode consistently reflected the trends and patterns identified in the reference monitors. Nonetheless, the AirQNodes recorded lower PM values, hence lower US AQI values, compared to those captured by the reference devices. These may be attributed to the utilization of an improved calibration technique and algorithm for the reference monitors, while the raw data from the AirQNodes were presented.

The acquisition of air quality data in the KRI presented significant challenges. The infrastructure serves as a centralized platform for the collection of air quality data in the region, allowing for the deployment of additional AirQNodes as required.

This research work will be relevant to the Board of Environmental Protection and Improvement in the KRI. The result establishes a comprehensive infrastructure for monitoring air quality. Total ownership of the system can be attained through the acquisition and management of essential infrastructure components, including end devices, network servers, and the IoT platform. This integrated approach is crucial for the KRI, where cost-effectiveness and long-term sustainability are vital, yet such a system is currently absent.

The study did not assess sensor calibration as the main focus, as the sensors employed are pre-calibrated by the manufacturer and the primary objective was to establish a comprehensive infrastructure. Future research may incorporate machine learning techniques to forecast air quality trends and integrate additional environmental pollutants, including ozone, carbon monoxide, sulfur dioxide, and nitrogen dioxide.

Author Contributions: Conceptualization, N.A.M.; Methodology, N.A.M.; Software, N.A.M.; Validation, N.A.M.; Formal analysis, N.A.M.; Investigation, N.A.M.; Resources, N.A.M.; Writing—original draft, N.A.M.; Writing—review & editing, B.I.S.; Visualization, N.A.M.; Supervision, B.I.S.; Project administration, N.A.M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

```
Setup
Initialize serial, LoRaWAN module
Try join LoRaWAN network (6 attempts)
Initialize SPS30 sensor (5 probe attempts)
Initialize BME280 sensor
Set auto-cleaning interval

Main Loop
REPEAT forever:
    Check/retry LoRaWAN connection
    Wake SPS30 sensor
    Wait 16s for stabilization

    measurements = Take30Measurements()
    Stop and sleep SPS30

    IF valid measurements THEN
        Display readings
        IF LoRaWAN connected THEN
            Send data to server
        ELSE
            Log locally
        END IF
    ELSE
        Send error to server
    END IF

    MCU Deep sleep 4 minutes
END REPEAT

Take30Measurements
FOR i = 0 to 29:
    Wait for SPS30 data ready
    Read SPS30 PM values
    Read BME280 temp/humidity/pressure

    IF PM values valid (0-1000 µg/m³) THEN
        Add to running totals
        Increment valid counter
    END IF

    Wait 1 second
END FOR

Calculate averages from valid readings
Return measurement data

LoRaWAN Functions
AttemptJoin():
    FOR attempt = 1 to 6:
        Try join network
        IF success RETURN true
        Wait with progressive backoff
    END FOR
    RETURN false

CheckAndRetry():
    IF not connected AND retry interval
passed THEN
        Try rejoin (3 attempts)
    END IF

SendData():
    Verify connection (rejoin if needed)
    Pack measurements into 20-byte payload
    Send via LoRaWAN
    Return success/failure
```

Figure A1. The AirQNode firmware pseudocode implementation.

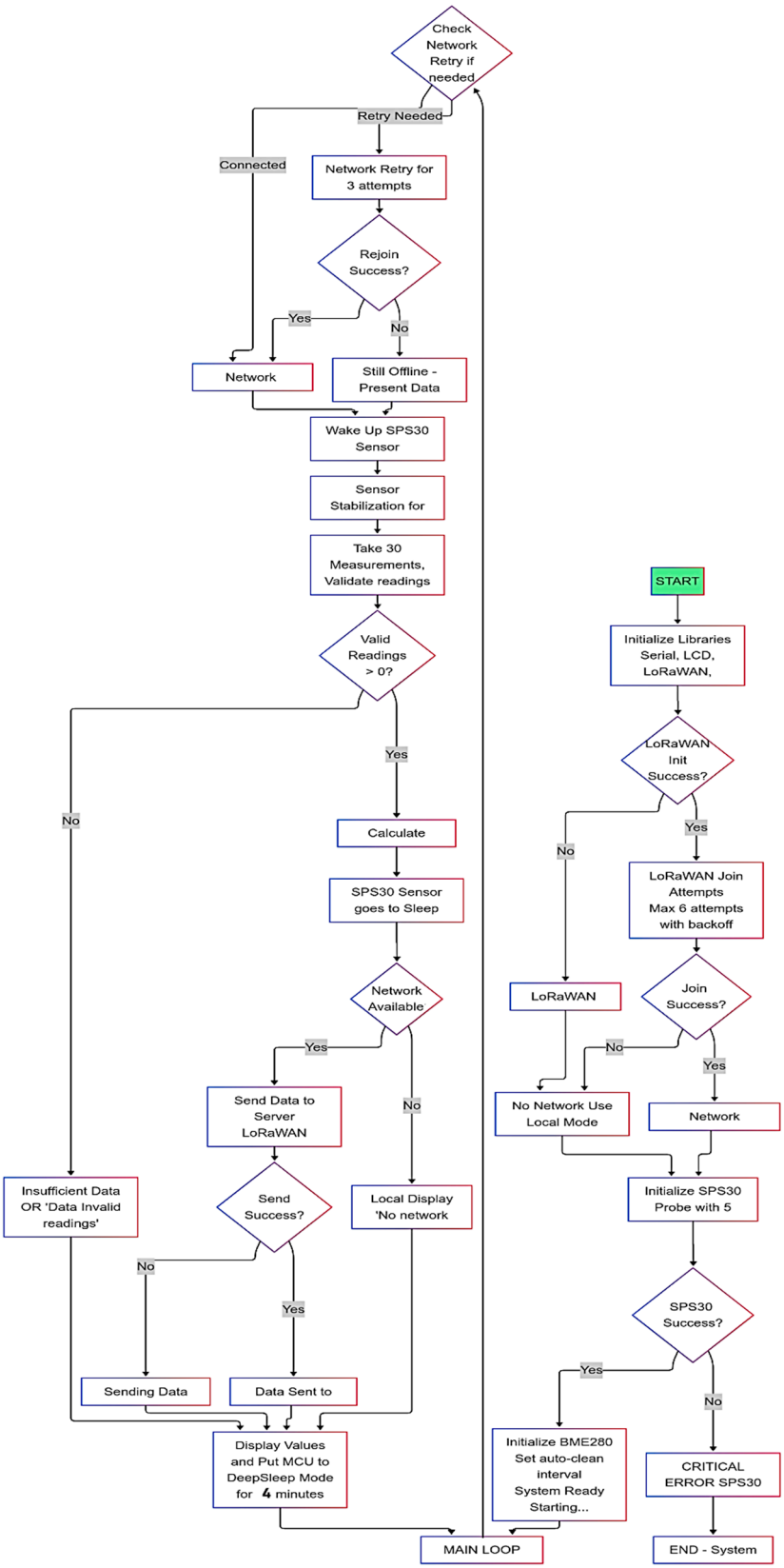


Figure A2. Flowchart of AirQNode firmware.

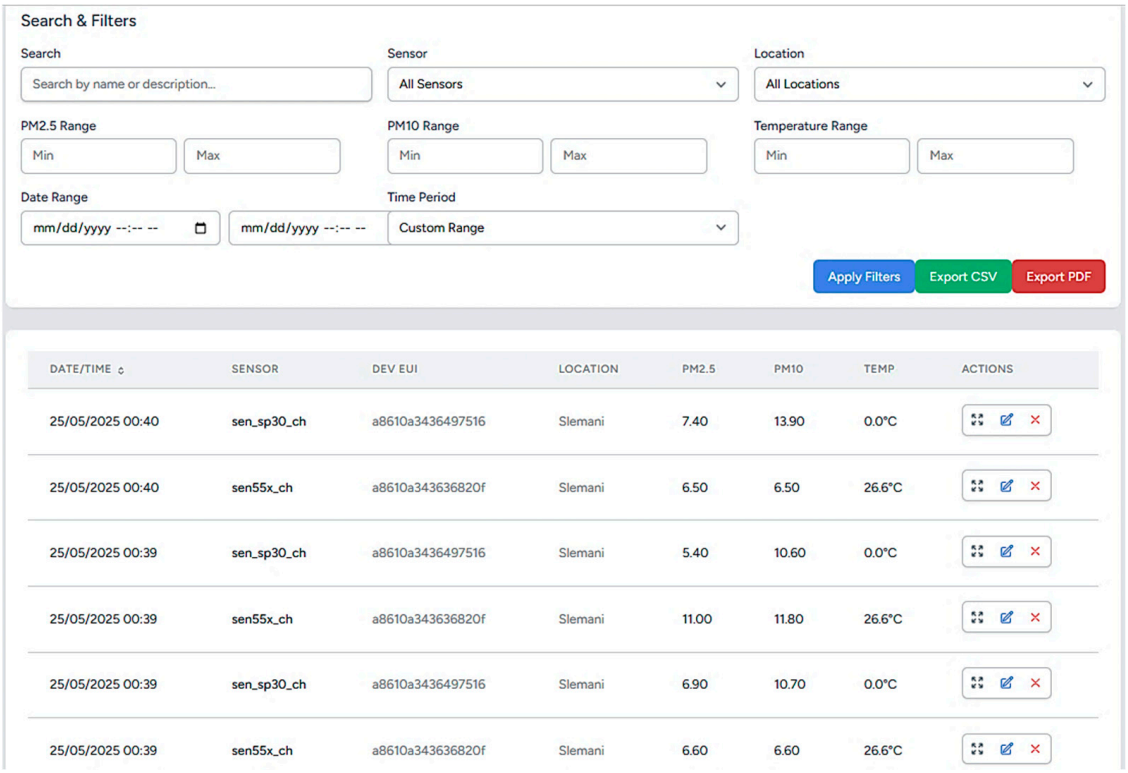


Figure A3. Real-time sensor dashboard interface.

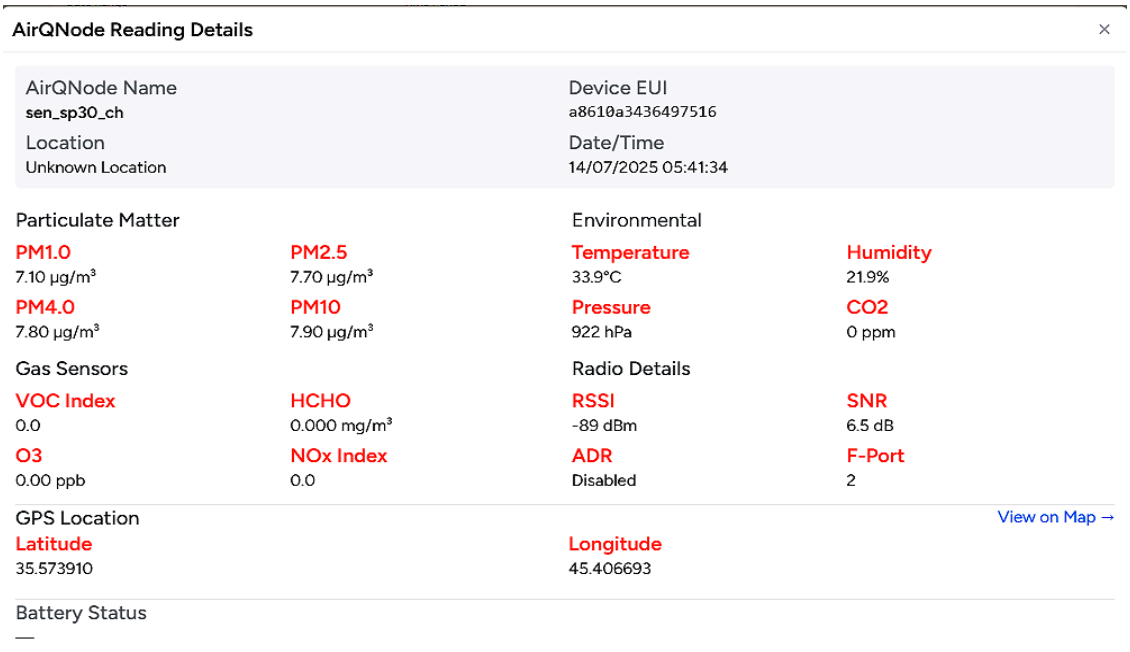


Figure A4. Detailed sensor readings from the dashboard interface.

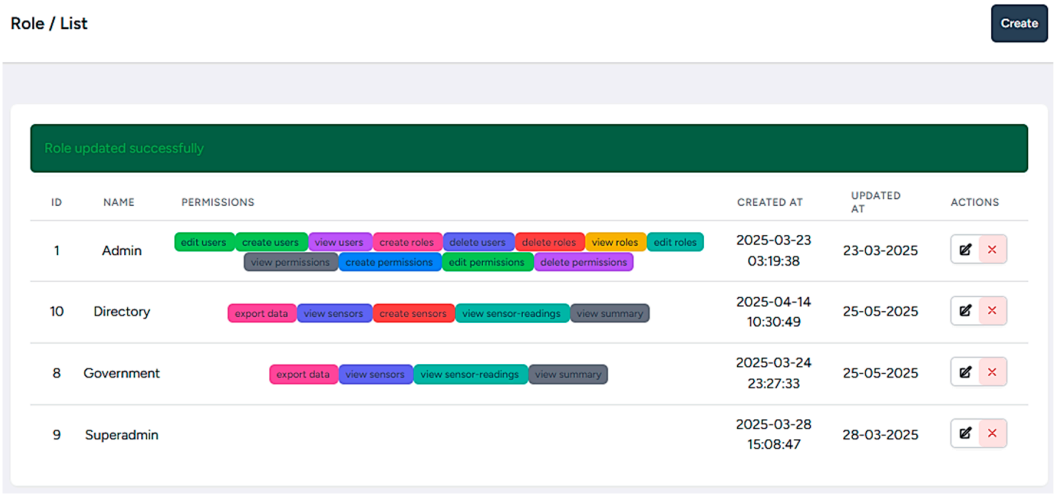


Figure A5. User role privileges and permissions dashboard.

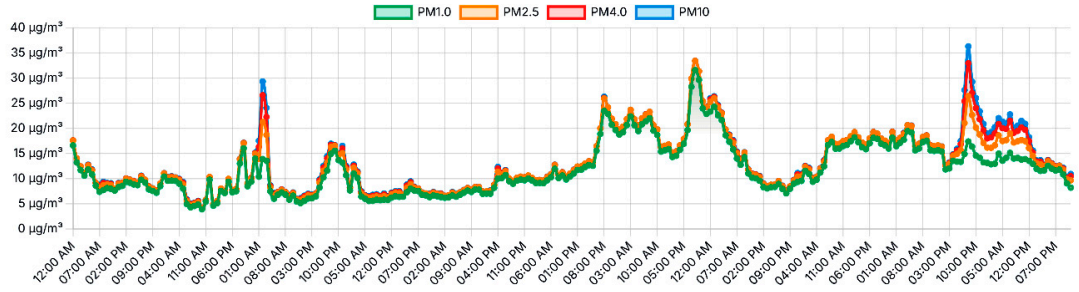


Figure A6. AirQNode outdoor hourly average of PMs value levels on the premises of the local tech firm location.

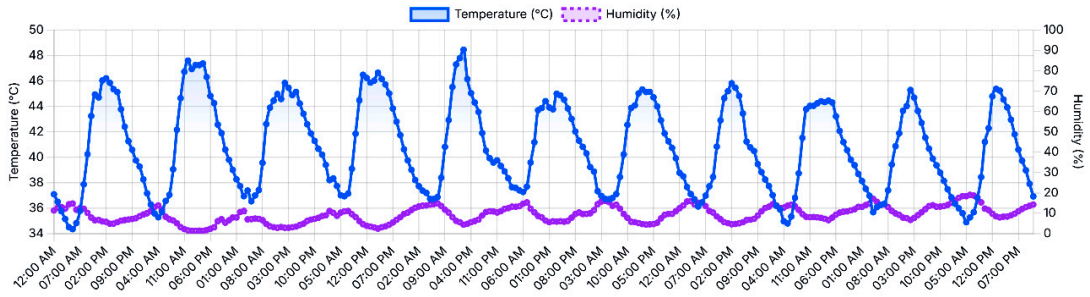


Figure A7. The AirQNode outdoor hourly average of temperature and humidity levels on the premises of the local tech firm location.

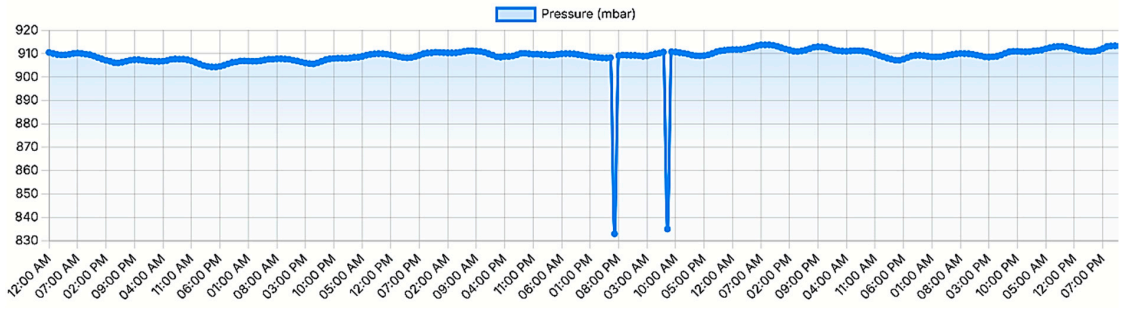


Figure A8. The AirQNode outdoor hourly average of atmospheric pressure levels on the premises of the local tech firm location.

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