

APPLICATION OF ARDUINO SENSORS IN AIR QUALITY MONITORING

Benjamin Radetić ^{1*}, Nikola Sakač ¹

¹ University of Zagreb, Faculty of Geotechnical Engineering, Hallerova aleja 7, 42000 Varaždin, Croatia

*Email of corresponding author: bradetic@gfv.hr

Abstract: Air quality monitoring has become essential for understanding the impact of pollutants on health and the environment. This paper explores the implementation of Arduino-based sensors in air quality monitoring, providing an affordable and effective solution for tracking pollutants such as PM_{2.5}, NO₂, and CO₂. The system comprises interconnected components, including sensors for particulate matter, temperature, humidity, and volatile organic compounds, supported by real-time data visualization platforms like ThingSpeak. These sensors enable real-time data collection, analysis, and visualization, allowing users to identify pollution sources and make informed decisions for pollution reduction. The integration of IoT platforms enhances spatial resolution and accessibility of air quality data, offering valuable insights for personal, scientific, and regulatory applications. The study highlights the advantages of using cost-effective, portable sensors for improving environmental monitoring and supporting sustainable urban development.

Keywords: Air Quality Monitoring, Arduino sensors, IoT platforms, Environmental Protection.

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1. INTRODUCTION

Air, water, soil, Earth's crust, energy, and material and cultural heritage compose the environment - a natural and comprehensive system that enables the existence and development of organisms and humans. Any alteration in the state of the environment or failure to take necessary actions to prevent environmental quality changes is considered as "pollution." This term refers to emissions of pollutants, heat, vibrations, or noise into the air, water, or soil, potentially impacting environmental quality, human health, and material assets. Pollution sources can be natural, such as volcanic eruptions and seismic activities, or anthropogenic, stemming from direct or indirect human activities like vehicular traffic, agriculture, and industry (Narodne Novine 2013).

Given that we spend most of our time indoors, assessing the air quality in these environments (microenvironments) is critical for determining overall exposure to polluted air. Air quality sensors are essential tools for monitoring and safeguarding our environment. By detecting pollutants like particulate matter (PM), nitrogen dioxide (NO₂), and ozone (O₃), these sensors provide real-time data on air quality. Such information is vital for identifying pollution sources, evaluating regulatory measures, and guiding policy decisions aimed at reducing harmful emissions. Continuous air quality monitoring reduces pollution's impact on human health and ecosystems, promoting sustainable and cleaner living environments (Ho et al. 2005).

Traditional air quality monitoring methods, while accurate, are often expensive, time-consuming, and require extensive infrastructure, making them inaccessible for smaller-scale or real-time applications. In recent years, advancements in affordable technologies, such as Arduino-based sensors, have revolutionized air quality monitoring. Arduino, an open-source electronic platform, allows for the integration of various sensors and components to create custom, portable systems offering a practical and scalable solution for individuals, researchers, and local authorities. To extract valuable insights from field measurements, efficient visualization and analysis are essential given the growing number of sensors and the expanding amount of air quality data available. To enhance environmental protection decision-making, this process includes gathering, processing, visualizing, and interpreting data utilizing a variety of software tools and platforms. For example, such data can be visualized through graphs, pollution maps, and interactive platforms such as ThingSpeak, OpenAQ or Geographic Information System (GIS) (Sanders 2008; Hilary Kelechi et al. 2022; S et al. 2024).

2. ENVIRONMENTAL POLLUTION

Environmental pollution is a global issue, with air, water, and soil acting as carriers for various contaminants. For instance, ocean currents and migrating fish transport pollutants across regions, wind disperse radioactive materials globally and leachate from waste sites contaminates soil and reduces its quality. Thus, environmental pollution can be categorized as (National Geographic 2022):

- a) Water pollution
- b) Soil pollution
- c) Air pollution.

2.1. Water pollution

Water is a very important biological and ecological factor of the living world on Earth due to its special physical and chemical properties. Water pollution is an alteration in the appearance or physical and chemical composition of water as a result of a change in the concentration of certain substances (pesticides, metals, hormones, antibiotics) or energy (heat or radioactivity) that can cause negative consequences for its consumers (humans, animals and plants). Water pollution is not limited to surface water, but also applies to groundwater, seas and oceans (Owa 2013; Britannica 2025). Some of the sources of water pollution are wastewater - sewage (discharges from households and public institutions), industrial wastewater (industries discharge several inorganic and organic harmful substances), agriculture (excess fertilizers, pesticides, herbicides, insecticides), various power plants (water as a coolant where hot water is discharged into the environment - a sudden increase in temperature) (Peirce, Weiner and Aarne 1998).

2.2. Soil pollution

Industrialization, war, mining, agriculture and rapid urbanization have a major impact on soil. Soil pollution refers to the presence of a foreign substance in the soil and thus has a harmful effect on any organism. Soil is an important component of the environment because it has the function of food production and enables the process of photosynthesis, so soil pollution itself reduces the availability of food for living beings. Any agricultural product grown on polluted soils can cause serious consequences for human and animal health. As the population grows, the need for food production also grows, so it is of great importance to keep the soil healthy. If the soil is heavily polluted, remediation of such soil is carried out using various methods such as phytoextraction, photodegradation, phytovolatilization or evapotranspiration, which aim to return the soil to its original state, that is, the state before the pollution occurred. Sources of soil pollution can be natural (fires and volcanic eruptions) and anthropogenic (acid rain, waste, agriculture, sewage) (Hakeem et al. 2014).

2.3. Air pollution

Air pollution is one type of environmental pollution that, by altering the natural properties of the atmosphere, can cause harm to human health, quality of life, and the environment. It can occur as indoor or outdoor pollution. Clean air is essential for life on our planet. Considering that air pollution causes approximately 7 million premature deaths worldwide each year, its reduction is crucial on local, regional, and continental scales. In Europe, concentrations of air pollutants like particulate matter (PM), nitrogen oxides (NO_x), sulfur oxides (SO_x), and volatile organic compounds (VOCs) have decreased over the past several decades (Tan 2014; World Health Organization 2022; European Environment Agency 2024a). As of 2021, around 75% of Europe's population lives in urban areas (European Environment Agency 2024c). According to the European Environment Agency (EEA), PM, NO₂, and O₃ are considered the most harmful pollutants to human health, primarily caused by human activities. For some of these pollutants, concentration levels exceeded the World Health Organization (WHO) air quality guidelines, as reported by the EEA in 2020 (European Environment Agency 2024b). Despite reductions in total emissions across the European Union (EU), urban populations remain at risk (European Environment Agency 2022; World Health Organization 2022).

Air pollution involves the emission of primary and secondary pollutants into the atmosphere from natural sources (e.g., volcanic eruptions, seismic activities) and anthropogenic sources (e.g., motor vehicles, agriculture, and industry) (Tan 2014). Primary pollutants (e.g., PM, SO₂, NO_x, NH₃, CO, CH₄, NMVOC, BaP) are emitted directly into the atmosphere, while secondary pollutants (e.g., O₃, PM, NO₂) form in the atmosphere through chemical reactions involving primary pollutants (European Environment Agency 2022).

To raise awareness, reduce exposure to pollution, and highlight the associated health risks, the WHO has been publishing air quality improvement guidelines since 1987. In September 2021, WHO released the latest guidelines titled "WHO global air quality guidelines: particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide, and carbon monoxide" (World Health Organization 2021). These guidelines are not legally binding and are based solely on health considerations. Their goal is to provide recommendations for reducing air pollutants to lower the global health burden caused by ambient and indoor air pollution.

The European Air Quality Index provides real-time insights into air quality across Europe, using data from over 3,500 monitoring stations. It measures five key pollutants (PM₁₀, PM_{2.5}, O₃, NO₂, and SO₂) and reflects their potential health impacts. Users can view data from the past 48 hours, forecast the next 24 hours, and filter stations by type (traffic, industrial, or background). The index helps users monitor air quality in their area or while traveling, enhancing awareness of environmental and health conditions (European Environment Agency 2025).

Since most of our time is spent indoors, determining air quality in such environments is crucial for assessing overall exposure to polluted air. A microenvironment represents the area where we spend most of our time and has specific pollutant concentrations during that period. **Table 1** provides an overview of typical urban microenvironments, their pollution sources, and associated pollutants ([World Health Organization 2021](#)).

Table 1. Presentation of microenvironments with associated sources and pollutants typical for urban environments ([World Health Organization 2021](#))

MICROENVIRONMENT	SOURCES	POLLUTANTS
Home	Cooking, space heating, parked vehicles, hobbies, smoking, household products, pets, rodents, insects	PM, CO, NO _x , VOCs, allergens
Transportation environments	Vehicle and industrial emissions, road dust, background pollution, smoking	PM, including ultrafine PM, CO, NO _x , VOCs, O ₃ , carcinogens, aeroallergens
Streets	Vehicle emissions, road dust, background pollution	PM, including ultrafine PM, CO, NO _x , VOCs, O ₃ , carcinogens, lead
Work environments	Industrial processes, smoking, background pollution	PM, CO, NO _x , VOCs, carcinogens
Entertainment environments	Cooking and space heating, background pollution, smoking	PM, VOCs, carcinogens

Unlike outdoor air, indoor air circulates continuously, leading to the accumulation of pollutants and their potential increase. Indoor air quality (IAQ) refers to the characteristics of the environment within enclosed spaces that can impact human health and quality of life. These characteristics include pollutant concentrations as well as temperature and humidity levels. Polluted indoor air significantly contributes to both short-term and long-term health effects. Common symptoms associated with poor indoor air quality include eye, nose, and throat irritation, headaches, nausea, dizziness, and fatigue. In some cases, prolonged exposure may lead to acute and chronic respiratory diseases such as asthma, lung cancer, or pneumonia.

Health issues related to indoor air pollution are associated with two concepts: Sick Building Syndrome (SBS) and Building Related Illness (BRI). SBS describes disorders and symptoms experienced by individuals due to poor air quality in enclosed spaces, while BRI refers to diagnosable illnesses directly attributed to specific airborne pollutants within a building ([Tan 2014](#)).

Additionally, poor indoor air quality reduces workplace productivity. Common sources that contribute to diminished IAQ include wood and coal stoves, tobacco smoke, vehicle exhaust, and heating and air conditioning systems. Effective monitoring of IAQ ensures clean air free of potentially harmful substances and compounds ([World Health Organization 2021](#)).

3. SENSORS

To protect the environment and prevent the introduction of harmful pollutants into its components, it is essential to conduct environmental monitoring. Current methods are expensive and require significant time for sample collection and analysis. Moreover, the reliability of laboratory analyses can be compromised during sample collection, transport, storage, and processing. Therefore, there is an increasing need for precise, cost-effective, and long-term methods for monitoring environmental pollution ([Ho et al. 2005](#)).

3.1. Environmental sensors

Environmental protection sensors are devices that collect data and information about the environment in which they operate. These sensors include those designed to measure soil conditions, temperature and humidity, gases, precipitation, wind speed, light, or air quality. The collected data is transmitted to control units within the system, where it is processed and analyzed to improve environmental and life quality. The development of such sensors is driven by the demand for small, affordable, and reliable devices that are relatively simple, compact, cost-efficient, and perform well. By enhancing the capability of individual sensors, their performance improves, allowing for more accurate readings of phenomena that traditionally required extensive signal or data processing, such as mass flow sensors or gas sensors. Sensor systems and their components are sometimes exposed to harsh environmental conditions (e.g., very high humidity, pressure, and temperature), which necessitates a focus on their durability. Environmental sensors can be described as small computer systems with basic interfaces, limited computing power, memory, and communication equipment, and an independent power source (e.g., batteries). These devices are made of electronic and other physical or chemical materials designed to detect or measure physical properties (e.g., heat, light, sound, pressure, humidity, substances, or movement) and convert them into signals that can be used by individuals, devices, instruments, or machines. The energy source significantly determines the lifespan of environmental sensors, while data transmission is one of the most energy-intensive operations for such devices.

Size and cost limitations lead to corresponding restrictions on resources like energy, memory, processing speed, and data throughput. These limitations encourage research into environmental sensors to develop more energy-efficient designs and enable wider distribution. The demand for smaller, more energy-efficient sensors capable of autonomous operation under harsh conditions stimulates advancements in robust, fault-tolerant sensors and systems (Sanders 2008).

Using low-cost sensors suitable for *in situ* applications enables the measurement of specific pollutants within a given area. However, the capabilities of such sensors are limited by technological development (Ho et al. 2005), and their precision often falls short of the standards required by regulatory authorities or government agencies. Despite these limitations, they provide valuable insights into air quality and support data processing for scientific purposes. Additionally, they enhance the spatial resolution of official monitoring stations and can be used by citizens for personal air quality monitoring and protection (World Health Organization 2021).

3.2. Application of Arduino sensors in air quality

Arduino is an open-source electronic platform based on the simple use of hardware and software through a physical programmable board and software, also known as the Integrated Development Environment (IDE), located on a personal computer. This platform is used to write and transfer computer code to the physical board. Arduino can communicate with buttons, LED lights, motors, speakers, GPS units, cameras, the internet, and even smartphones or TVs. This flexibility, combined with the fact that Arduino software is free, and the hardware boards are relatively inexpensive, has led to the creation of a large community of users who contribute to the development of Arduino-based projects. A more detailed description of how Arduino works and an example of its application is presented in the study (Topić 2022).

3.2.1. Experimental setup

This paper provides an example of a sensor system for air quality measurement based on several interconnected sensors and components which are shown in **Table 2**.

All sensors were mounted on an acrylic board (**Figure 1**) and powered through a USB connection to ensure stable operation.

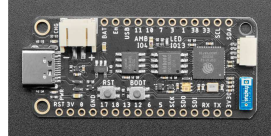

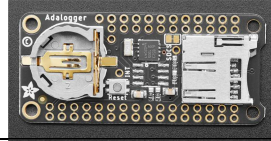



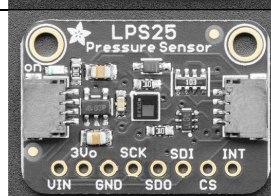


Figure 1. Arduino-based sensor system for air quality monitoring used in the research

The central control unit of the system is the FeatherS2 microcontroller by Adafruit which manages the monitoring of numerous environmental parameters, such as PM, CO₂, VOCs, temperature, humidity, and pressure. Every part of the system is interfaced with FeatherS2, which additionally features wireless connectivity and sends real-time air quality data to a remote server for continuous monitoring. The fundamental components include the FeatherS2-ESP32 microcontroller, Adafruit FeatherWing OLED display which shows air quality indicators in real time, Adalogger FeatherWing - RTC + SD board that adds both a battery-backed datalogging and micro SD card storage. Those three boards were connected on top of each other using stacking headers. The rest of the sensors, Adafruit HTS221 sensor for temperature and humidity, Adafruit LPS25 sensor for absolute pressure, Adafruit CCS811 air quality sensor for measuring CO₂ equivalent and total VOCs, and Adafruit PMSA003I air quality sensor for the detection of PM_{1.0}, PM_{2.5} & PM₁₀ particles were also connected using stacking headers, as well as compatible cables or so called STEMMA connectors for easy wiring without the need for soldering. The key

component of air pollution monitoring systems is the microcontroller. Using Wi-Fi, Bluetooth, or cellular networks, this component receives, analyzes or transmits sensor data to a cloud server or writes it locally. While Adalogger makes it simple to write data and store it locally on a micro-SD card, the display enables user interaction with the system and provides a straightforward method of instantaneous information retrieval. Moreover, sensors that measure air pollution also require power to function. While mobile sensors use batteries, permanent installations use an external power source (Hilary Kelechi et al. 2022; S et al. 2024).

Table 2. Sensors and components of a system used for air quality measurement (Adafruit Industries 2025)

	FeatherS2 - ESP32-S2 Feather (plug-and-play board for communication with other sensors) 32-bit 240 MHz single-core processor Optimised power path for low-power battery usage (3.3V) USB-C type connector with 21x GPIO pins
	Adafruit FeatherWing OLED (128x64 1.3" monochrome OLED screen for desired data print)
	Adalogger FeatherWing - RTC + SD (board that allows data to be written to a micro-SD card in real time without the use of an external power source)
	Adafruit PMSA003I Air Quality Breakout (sensor for the detection of PM _{1.0} , PM _{2.5} & PM ₁₀ particles) I2C communication protocol, 3 - 5V DC power Particle Range of measurement: 0.3~1.0, 1.0~2.5, 2.5~10 Micrometer Particle Resolution: 1 µg/m ³ Working Temperature Range: - 10 ~ 60 °C Working Humidity Range: 0~99%
	Adafruit CCS811 Air Quality Sensor Breakout (sensor for measuring CO ₂ equivalent and total VOCs, VOC & eCO ₂) I2C communication protocol, 3 - 5V DC power eCO ₂ : 400 to 8192 ppm VOC: 0 to 1187 ppb
	Adafruit HTS221 (sensor for temperature and humidity) I2C communication protocol Temperature: - 40 - 120 °C; ±0.5 °C Humidity: 0-100%; ±3,5% 3 - 5V DC power
	Adafruit LPS25 (sensor for absolute pressure) I2C communication protocol, 3 - 5V DC power Pressure: 260-1260 hPa; ±0,2hPa

Data acquisition was managed through the Arduino IDE, using publicly available Adafruit libraries, where each library was installed using the Library Manager to ensure proper functionality of the sensors. Libraries needed for the system were as follows: Adafruit SH110x library, Adafruit GFX Graphics Core library, RTCLib library, Adafruit PM25AQI, Adafruit CCS811 library, Adafruit HTS221 library, Adafruit LPS2X library, and ThingSpeak Communication library.

The Arduino-based system was programmed to continuously collect and process data from multiple sensors, including PM (PMSA003I), CO₂ and VOC (CCS811), temperature and humidity (HTS221), and pressure (LPS25). Each reading was time-stamped using the RTC (Real Time Clock) module and simultaneously stored locally on an SD card, displayed in real time on an OLED screen, and transmitted via WiFi to the ThingSpeak IoT platform. This ensured redundancy in data storage and enabled both local and remote monitoring of environmental conditions.

The code was structured to initialize sensors, start OLED screen, RTC and SD card and prepare Wi-Fi and ThingSpeak connection, while main loop collects readings every 60 seconds, logs data locally to the micro-SD card, prints them on the OLED screen, and sends values to the ThingSpeak cloud platform. It was programmed to continuously collect and process data from multiple sensors, including PM (PMSA003I), CO₂ and VOC (CCS811), temperature and humidity (HTS221), and pressure (LPS25). Each reading was time-stamped using the RTC module and simultaneously stored locally on an SD card, displayed in real time on an OLED screen, and transmitted via WiFi to the ThingSpeak IoT platform. This ensured redundancy in data storage and enabled both local and remote monitoring of environmental conditions. The pseudocode of the acquisition loop is summarized as follows: sensor initialization - data acquisition - local storage - cloud transmission - repeat cycle. This structure ensured a consistent data stream for visualization and later statistical analysis.

Such sensor system enables the collection of data and information about the distribution and frequency of exposure to the harmful effects of pollutants in indoor environments. It provides valuable information for health risk assessment and insights into the behavior of the sensor system in different settings. For instance, poor indoor air quality reduces productivity and contributes to an increased number of workplace absences. By using sensors, air quality monitoring (specific pollutants) is made possible, allowing users to gain insight into the air quality of their surroundings and take timely measures to prevent or reduce pollution.

In indoor spaces, the placement of sensors can significantly affect the accuracy of the collected data. Sampling near emission sources results in higher pollutant concentrations compared to those measured at other locations in the same space. Therefore, sensors should be positioned away from ventilation systems, heating devices, and direct light exposure. They should ideally be installed at least 1 meter (preferably 2 meters) from walls and 1.5 meters above the floor, while minimizing interference with regular activities (PortASAP and cost 2021). The system used in the research was located in Varaždin city (Northern part of the Republic of the Croatia) and placed in a controlled indoor environment (living room, East-West orientation, approximately 24-30 °C depending on the winter or summer periods, relative humidity 45–55%, decent amount of sunlight without direct exposure to sunlight) to evaluate its performance (Figure 2).

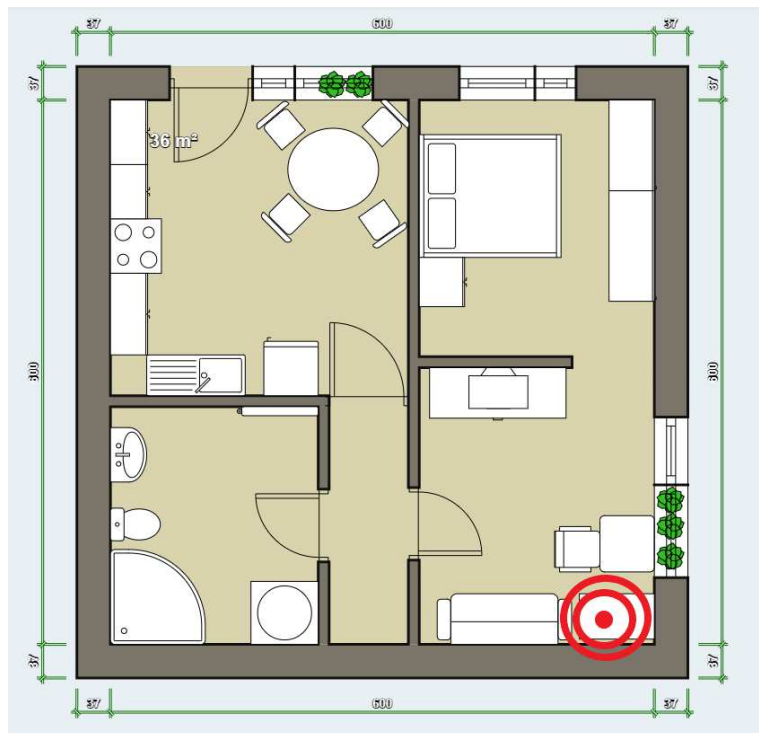


Figure 2. Sketch of the building apartment in which the Arduino-based sensor was placed

After successful sensor installation, it is possible to monitor the current state of concentrations of certain pollutants and parameters in real time.

3.3. Analysis and monitoring

Monitoring air quality data has become essential for understanding and mitigating the impact of pollutants on health and the environment. With the increasing number of sensors and the growing availability of air quality data, effective visualization and analysis are crucial for deriving meaningful insights from field measurements. This process involves the collection, processing, visualization, and interpretation of data using various software tools and platforms to improve decision-making related to environmental protection (Ho et al. 2005).

Long-term monitoring of indoor CO₂, PM and VOCs is important since they change with the seasons, and are significantly affected by ventilation rates, which may also vary from season to season because of occupants changing ventilation habits throughout the year (Huang et al. 2018).

The collected data was analyzed with the aim of comparing seasonal variations and identifying effect of certain activities (training, staying home, ventilation, going to work) on pollutant concentrations during the week. For this purpose, two one-week datasets were extracted, representing the winter (Jan 01, 2024 – Jan 07, 2024) and summer periods (Jun 1, 2024 – Jun 7, 2024), respectively. Boxplot analysis was applied to visualize the distribution of pollutants such as PM_{2.5}, PM₁₀, CO₂, TVOC (Figure 3), with addition of temperature and relative humidity (Figure 4), providing a clear overview of median values, variability, and extreme concentrations. This approach enabled a direct comparison between the two seasons and highlighted differences in pollutant levels.

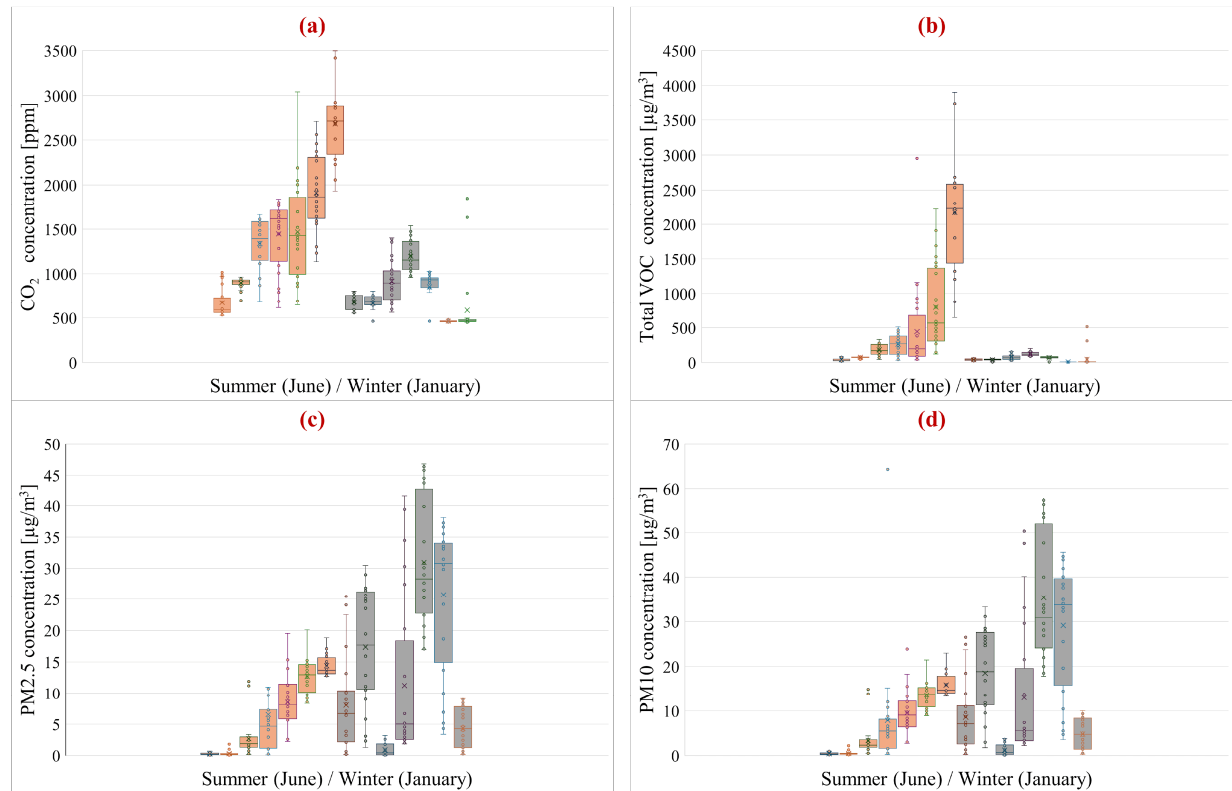


Figure 3. Boxplot comparison of summer and winter concentrations: (a) CO₂ (b) Total VOCs (c) PM_{2.5} and (d) PM₁₀ (Source: Author)

Figure 3(a) shows CO₂ concentrations during one summer and one winter week measured in *parts per million* ranging from around 500 to approximately 3500 ppm. The summer period (June) shows higher CO₂ concentrations, with median values around 1000–2000 ppm and occasional peaks above 3000 ppm. This suggests reduced ventilation efficiency or more frequent occupancy of closed indoor spaces during summer (e.g., use of air conditioning with closed windows). It can be concluded that with 1st and 2nd of June 2024 (first two boxes) being Saturday and Sunday (weekend), the concentration of all pollutants is significantly lower compared to the rest of the week, suggesting that less time was spent in the apartment due to more outdoor activities. On the other hand, winter period (January) shows lower concentrations, with most values below 1000 ppm and significantly fewer outliers. Such results may be due to more frequent ventilation during the heating season (e.g., opening windows briefly to reduce condensation or as part of daily habits) or no one being in the apartment. According to (Air Standard | RESET® 2025), concentrations under 1000 ppm are generally considered as the threshold for adequate ventilation in indoor spaces, with lower levels indicating better air quality.

Furthermore, total VOCs concentrations (Figure 3(b)) during summer show gradual increase of concentrations over the week. The increase is related to indoor space conditions (temperature, humidity and ventilation) as well as the activities such as cooking and use of cleaning products, disinfectants and scented candles. The winter period has much lower and constant concentrations due to lower temperatures, ventilation of the room and the fact that during this period, there were less activities due to holidays.

When it comes to TVOC concentrations, levels under 500 µg/m³ (Air Standard | RESET® 2025) are generally considered acceptable for indoor air quality. According to the data, only two days showed higher concentrations while the rest of the days were within recommended health limits.

The boxplots for PM_{2.5} and PM₁₀ concentrations reveal very similar seasonal patterns, which is expected given the strong correlation between these two particle fractions (Figure 3(c-d)). During the summer period (June),

particle concentrations were generally lower, although a gradual increase was observed over the course of the week. In contrast, the winter period (January) displayed higher overall concentrations with more pronounced variability from day to day. This indicates that indoor particle levels are influenced both by seasonal conditions and by daily activities or ventilation practices. The similarity between $PM_{2.5}$ and PM_{10} results suggests that the main sources of indoor particles affect both fine and coarse fractions simultaneously, without significant difference in seasonal trends. WHO recommends 24-hour average concentrations of $15 \mu\text{g}/\text{m}^3$ and $5 \mu\text{g}/\text{m}^3$ for annual averages (World Health Organization 2021). As shown in **Figure 3(c-d)**, the observed concentrations during both summer and winter weeks remained within these guideline values, suggesting that indoor particle levels in the monitored environment comply with WHO recommendations.

Additionally, temperature and relative humidity were also monitored and analyzed as shown in **Figure 4**. In the case of the temperature (**Figure 4(a)**), winter period shows stable values around 24°C due to constant heating with occasional drops indicating the ventilation of living space. Relative humidity (**Figure 4(b)**) follows similar patterns as temperature. Increased ventilation causes higher variations of the values as a result of the fresh air exchange. Summer period, in both temperature and relative humidity, shows higher variations of the values influenced by outdoor conditions, ventilation and air conditioning. Higher summer temperatures also contributed to increased VOC concentrations, while lower winter humidity may have favored longer suspension of PM particles.

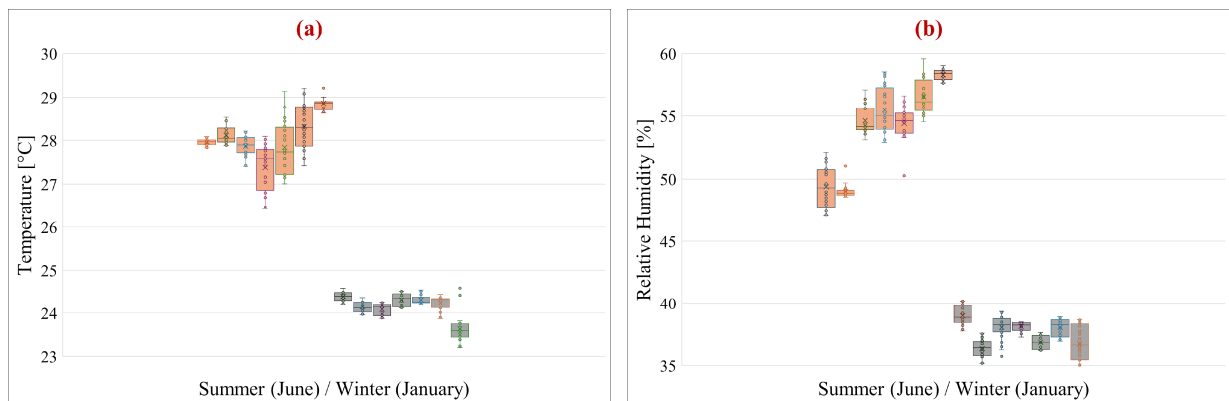


Figure 4. Seasonal variation of: (a) indoor temperature and (b) relative humidity for the selected seasonal periods

In addition, to better understand daily variations, time-series plot was generated for selected parameters (e.g., CO_2 , VOCs and PM), covering a 24-hour cycle average across the seven-day period (**Figure 5**). These plots were supplemented with annotations of personal routines (e.g., cooking, training, sleeping), which allowed the identification of activity-related peaks in pollutant concentrations. For instance, PM levels showed rapid increases during periods of indoor occupancy before going to work at the time of breakfast preparation (between 06:00 and 08:00), while VOC spike was observed during cooking activities (between 16:00 and 19:00) due to frying. The increase in CO_2 concentrations was also recorded in the morning and during cooking activities later in the afternoon. Regarding training period (between 19:00 and 22:00), when no one is home, there was decrease in the CO_2 and VOC concentrations while during the sleeping period, all pollutants concentrations were stabilizing. In general, spikes were recorded during certain activities while the rest of the time concentrations were in decline.

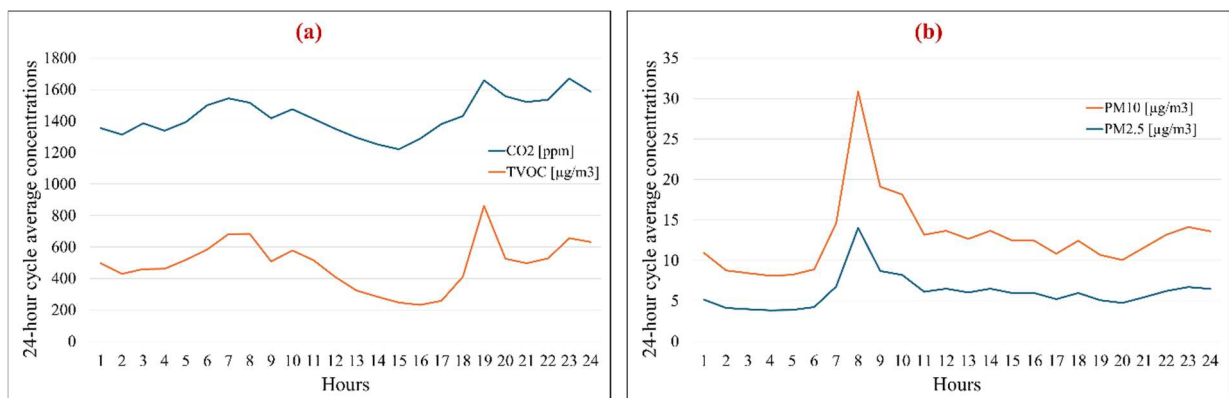


Figure 5. Average 24-hour concentration profile over the seven-day period: (a) CO_2 and TVOC and (b) PM_{10} and $PM_{2.5}$

The combination of seasonal comparison and daily pattern analysis provided a comprehensive understanding of indoor air quality dynamics. While no formal error quantification was conducted, the study primarily focused on identifying temporal trends and the influence of human activities and ventilation on pollutant levels, rather than on achieving high-precision quantitative measurements. This methodological approach highlights the practical applicability of low-cost sensors for contextual and exploratory environmental monitoring.

Effective data visualization makes complex air quality datasets more comprehensible, providing researchers and the public with insights into the current state of the environment. For example, such data can be visualized through graphs, pollution maps, and interactive platforms. Graphs display concentrations of various pollutants (PM_{2.5}, NO₂, O₃) over specific time periods, highlighting peak values and seasonal changes (Figure 3). Pollution maps are useful for spatial analysis as they depict pollutant concentrations across geographic areas, identifying hotspots and potential pollution sources. Using platforms like GIS and Google Earth, spatial data can be displayed on maps to show the distribution and density of pollution. GIS tools can model air quality for spatial analysis and develop exposure models accessible to the general public for self-assessment and visualization of pollutant spatial distribution (Figure 6) (Aniceto et al. 2021; Mohd Shafie et al. 2022; Saleh and Khader 2022). Additionally, interactive platforms offer real-time visualization of air quality data, integrating various graphs and maps to provide an overview of current environmental conditions (Hassan et al. 2024).

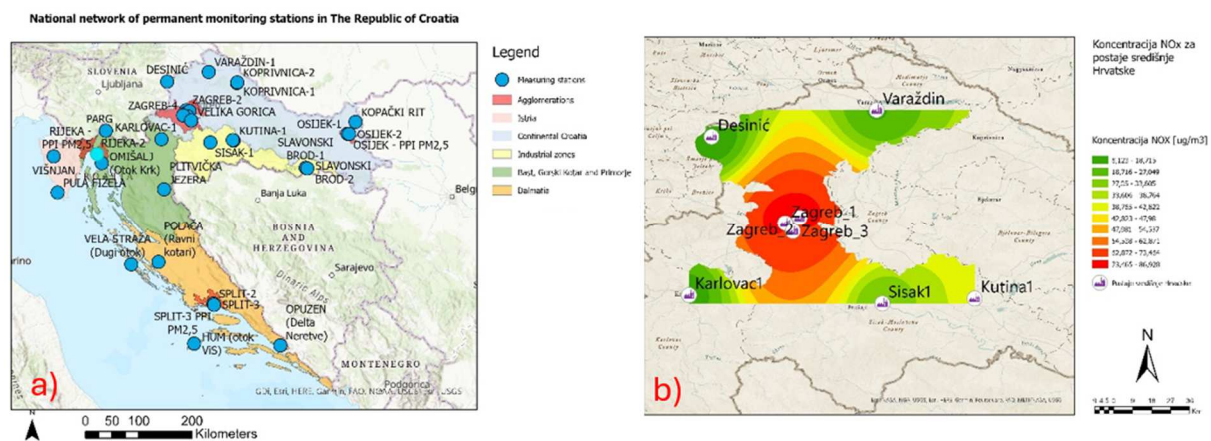


Figure 6. Data representation in ArcGIS software: a) measuring stations for air quality monitoring in the Croatia; b) mean NOx concentration in central Croatia

ThingSpeak is an IoT platform (Internet of Things) that enables the storage, visualization, and analysis of real-time data via the internet as shown on the Figure 7. It allows communication by sending data from the user's sensors and devices to ThingSpeak servers, providing simultaneous visualization of live data along with the ability to send notifications and alerts. ThingSpeak has a wide range of applications, such as remote sensor monitoring on farms to develop models for increasing crop yields and reducing costs, tracking energy usage, monitoring air quality, and supporting various research projects (Hilary Kelechi et al. 2022; ThingSpeak 2023). In air quality monitoring, ThingSpeak enables the integration of air quality sensors to track various air pollutants providing real-time insights. Its ability to generate alerts and notifications makes it a valuable tool for both personal and environmental applications, enhancing decision-making and promoting air quality awareness.

Figure 7 illustrates the live data visualization interface of the ThingSpeak platform. The screenshot was included to demonstrate how sensor readings are transmitted, stored, and displayed in real time through the cloud-based dashboard and therefore serves as a representation of the system's functionality.

On the other hand, OpenAQ is the largest open-source, open-access repository of air quality data in the world. It is an open-access data platform that provides unrestricted access to the data by combining information from public, academic, and private sources. It offers standardized and easily readable data on airborne pollutants. The platform provides tools for data visualization, exploration, and integration to promote research, policymaking, and public awareness (Figure 8). As a community-based open-source platform, OpenAQ strives to be open, transparent, user-oriented, sustainable, and technologically advanced (OpenAQ 2025).

The analysis of air quality data also involves various statistical methods and computational models to interpret trends, predict future pollution levels, and evaluate the effectiveness of mitigation measures. Commonly used tools and methods include simple statistical techniques (median, mean values, standard deviations) to summarize data, machine learning methods (neural networks and regression models) to predict air quality based on historical data and meteorological variables, and Air Quality Models (AQMs) that simulate the dispersion of pollutants in the atmosphere (El-Harbawi 2013; Iskandaryan, Ramos and Trilles 2020).

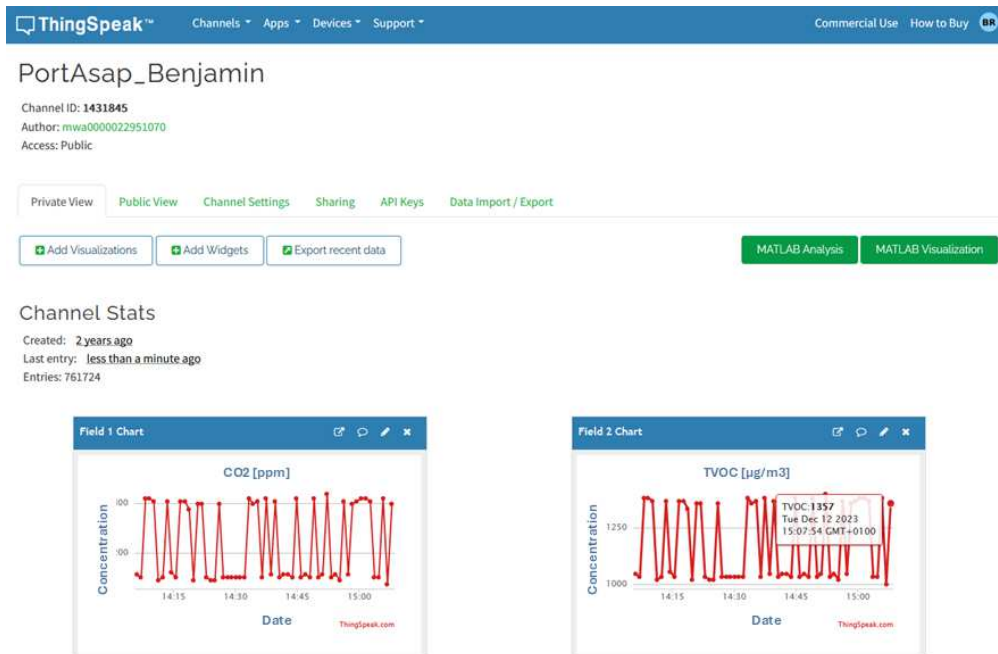


Figure 7. Data collection and visualization through the ThingSpeak platform

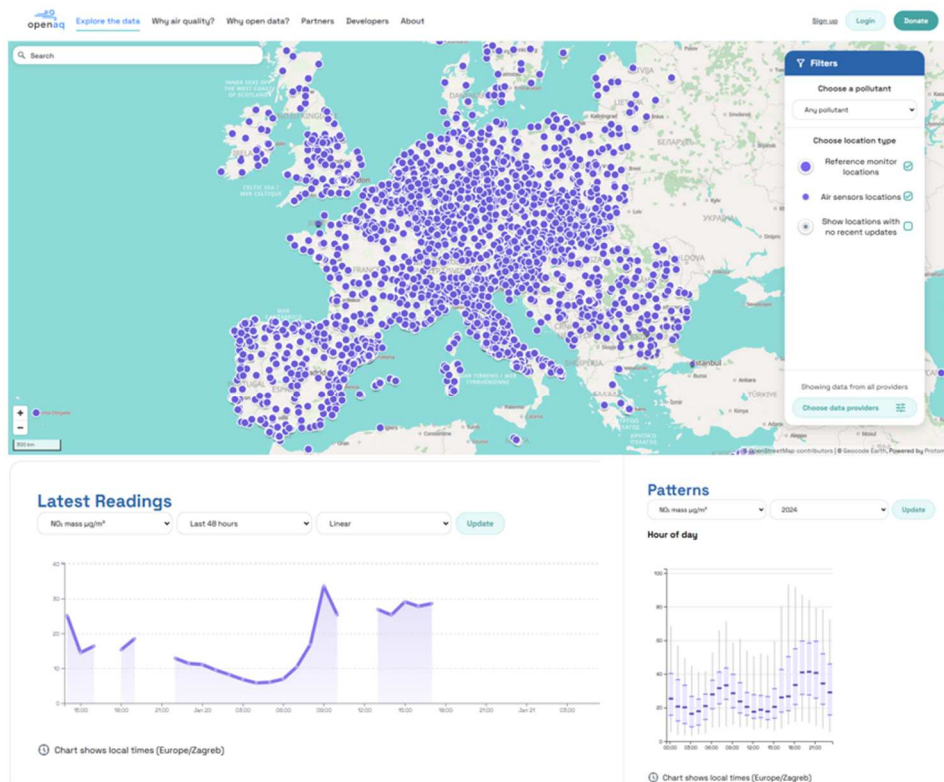


Figure 8. OpenAQ platform (OpenAQ 2025)

4. CONCLUSION

This study demonstrated the potential of an Arduino-based sensor system for indoor air quality monitoring, integrating multiple low-cost sensors for simultaneous measurement of particulate matter, CO₂, VOCs, temperature, and humidity. The system provided reliable, real-time data through local storage and cloud-based visualization, confirming the suitability of low-cost platforms for continuous environmental monitoring.

The analysis of two representative seasonal periods (winter and summer) revealed clear variations in pollutant concentrations influenced by ventilation, human activity, and indoor environmental conditions. CO₂ and VOC

concentrations were higher during summer due to limited ventilation and increased temperatures, while PM concentrations exhibited slight fluctuations but remained within WHO recommended limits. Temperature and humidity trends further supported the interpretation of pollutant dynamics across seasons.

Although no formal error estimation was performed, the primary focus of this research was to explore temporal and behavioral patterns rather than high-precision calibration. The approach highlighted the practical applicability of low-cost sensors for contextual air quality assessment, illustrating how environmental data can reflect everyday routines and ventilation habits.

Overall, the combination of affordable sensing technologies, IoT data management, and contextual analysis provides a foundation for personal and community-level air quality awareness, supporting future research and the development of smart environmental monitoring systems.

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