Scientific Research Publishing

Engineering, 2026, 18(2), 30-44
https://www.scirp.org/journal/eng
ISSN Online: 1947-394X
ISSN Print: 1947-3931

Design, Assembly and Simulation of an Environmental Prototype Station IoT Based on Arduino Mega 2560 and Multiparameter Sensors

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How to cite this paper: Sonny, M.N., Emmanuel, N.D. and Crispin, N.B. (2026) Design, Assembly and Simulation of an Environmental Prototype Station IoT Based on Arduino Mega 2560 and Multiparameter Sensors. *Engineering*, **18**, 30-44.
https://doi.org/10.4236/eng.2026.182003

Received: December 13, 2025
Accepted: February 1, 2026
Published: February 4, 2026

Abstract

Environmental monitoring is today a key challenge for public health, urban planning, and scientific research. Official monitoring stations, although highly accurate, remain expensive and difficult to deploy in developing countries. This study presents the design, assembly, and laboratory simulation of an environmental prototype station based on the Arduino Mega 2560 board and has a set of multiparameter sensors (temperature, humidity, carbon dioxide, fine particles, air pollutants, light intensity, and rainfall). The system integrates wireless communication technologies (LoRa and Wi-Fi via ESP-01), local data storage on a SD card, and real-time display through an OLED screen. The adopted methodology combines a detailed technical description of the components, optimized wiring, and has step-by-step laboratory simulation procedure. The results demonstrate the reliability of the sensors, the stability of communications, and the relevance of the proposed modular architecture. This prototype offer has a low cost and open-source solution suitable for academic contexts and urban resource-limited areas. Future improvements include the integration of solar energy sources, advanced sensor calibration, and connection to IoT platforms such as The Things Network.

Keywords

Arduino Mega 2560, Internet of Things (IoT), Environmental Sensors, LoRa, ESP-01, Low-Cost Monitoring Station

1. Introduction

The question of environmental monitoring becomes more and more central in Contemporary scientific and political debates [1] [2]. The challenges linked to climate change, air pollution, and rapid urbanization call for the establishment of reliable monitoring systems capable of providing real-time and large-scale data. According to the World Health Organization [3], close of 99% of the population world breathing air that does not meet recommended quality standards has significant impacts on public health, particularly in terms of respiratory and cardiovascular diseases. Similarly, the Intergovernmental Panel on Climate Change [4] emphasizes the importance of having robust environmental databases to support adaptation and mitigation policies.

Traditionally, the environmental monitoring systems [5]-[8] relies on fixed and certified stations often expensive and limited in number, above all in the developing countries [9]. This constraint creates an imbalance in infrastructure measurement between rich regions and those lacking it, particularly in sub-Saharan Africa, especially in the Democratic Republic of Congo. In this context, emerging digital technologies—especially the Internet of Things (IoT) and open-source microcontrollers—appear as a promising alternative [10] [11]. Indeed, these solutions offer the possibility of designing low-cost, modular, interoperable, and easily deployable systems [12].

The rise of accessible electronic platforms like Arduino or ESP8266/ESP32 [13] [14] has significantly democratized the construction of scientific prototypes. These microcontrollers allow the integration of various environmental sensors (temperature, humidity, gas, particulate matter, light, rain), while also providing processing, storage, and communication capabilities [15] [16]. The Arduino Mega 2560 [17] [18], in particular, is known for its multiple inputs/outputs digital and analog its memory more important than that of the Arduino Uno, and the ability to manage multiple serial interfaces simultaneously [19]. These features make it a platform of choice for projects requiring the integration of numerous modules.

A second determining factor is data communication. LoRa (Long Range) and Wi-Fi (ESP-01/ESP8266) technologies respectively enable low-power long-distance transmission and direct internet connectivity. Several recent studies demonstrate the effectiveness of LoRa for deploying environmental sensor networks [20] [21] covering vast geographical areas [22] [23]. As for the Wi-Fi, it remains a flexible solution for real-time data transfer to servers or cloud platforms, thus facilitating visualization and analysis.

The use of these technologies also responds to a growing demand for open science. By making accessible hardware and software solutions available, researchers and local stakeholders can design tools adapted to their socio-economic context. This dynamic is already visible with projects like AirSensEUR [24], an open-source station European source, or again the citizen sensors deployed by the local communities within the framework of participatory science initiatives [25].

The project presented in this article registers in this logic. It aims as a design, to go up and to simulate in the laboratory an environmental prototype station integrating an Arduino board The Mega 2560 [26] [27], several multiparameter sensors (temperature, humidity, CO_2, particulate matter, various gases, light intensity, rain), an OLED display, local memory via SD card, a real-time clock (RTC), and two wireless communication modes (LoRa and ESP-01 Wi-Fi). The objective is twofold: to demonstrate the technical feasibility of such a station with readily available components, and to validate its operation in the laboratory before future field deployment.

2. Materials and Methods

The design of this environmental prototype station required careful consideration of component selection, their hardware and software organization, and the experimental procedure followed in the laboratory. The methodological approach adopted rests on a modular architecture and evolving, inspired of the current practices in embedded engineering systems and the Internet of Things (IoT). *The instruments that are commonly used are thermometer ThermoPro TP*55 *Digital Thermometer, HTC* 1 *hygrometer, portable* CO_2 *detector CM* 1106-*NH and lux meter led DT* 3809. *Matlab enabled us to simulate the prototype* (**Figure 1**).

Figure 1. Instruments commonly used in the laboratory.

2.1. Design of General Architecture

From the earliest stages of the project, it was essential to define a clear and coherent architecture in order to ensure the compatibility among the different modules. The heart of East system constituted by an Arduino board The Mega 2560 was chosen for its numerous digital and analog inputs/outputs, as well as its four hardware UART ports, essential for managing multiple operating sensors in serial communication simultaneously. This board acts as the conductor of device, coordinating the collection of the data, their treatment, their display and their transmission.

Around this central unit gravitate several subsystems:

- A set of different environmental measuring sensor parameters (temperature, humidity, gases, particles, brightness, rain),
- of the modules communication allowing their local transmission or distant data,
- of the peripherals storage and of temporal synchronization,

- Thus, that a local intended display has a view in real time of the information collected.

To ensure interconnection, we opted for standardized communication buses that limit the risk of conflicts among the modules. Thus, I^{2}C was reserved for coupling the OLED screen and of the real clock time, the SPI has served for the map SD and the module LoRa SX1278, and the different ports UART of their map Arduino have allowed to separate the communication series between the CO$_2$ sensor (MH-Z19B), the fine particle sensor (SDS011) and the Wi-Fi module (ESP-01). This methodical cutting has allowed obtaining a robust system, flexible and easily debuggable (Figure 2).

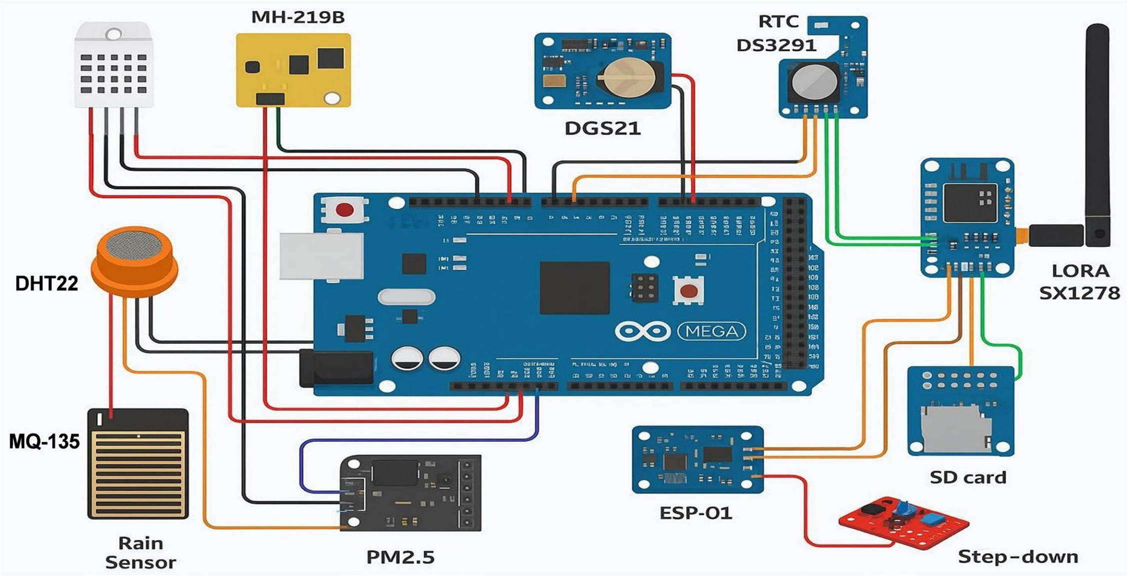


Figure 2. Conceptual diagram of prototype material architecture in Proteus 9 (Arduino at the center, connected to sensors, communication modules and peripherals).

2.2. Central Microcontroller: Arduino Mega 2560

The choice of a microcontroller was obvious. Unlike the Arduino Uno, limited to a single hardware serial port and relatively small memory, the Arduino Mega 2560 features:

54 digital pins, of which 15 usable in PWM;

16 analog ideal entrances for the analog sensors as the MQ-135 and the rain sensor;

4 material ports UART (Serial, Serial 1, Serial 2, Serial 3), allowing each serial module have an independent connection;

256 kB of flash memory and 8 KB of RAM (SRAM) are more than sufficient for the support of the gourmand libraries as those of LoRa, from the OLED SSD1306 screen or the SD card.

This technical configuration makes it a preferred platform in the construction of complex scientific prototypes, as already shown by similar work in environmental IoT [28] (Table 1).

Table 1. Main feature techniques of the Arduino Mega 2560.

Characteristic	Description/Value
Microcontroller	ATmega2560
Architecture	8 bits
Functioning Tension	5 V
Food Tension recommended	7 V has 12 V
Food Tension maximum	6 V has 20 V
Flash Memory	256 Ko (of which 8 KB used speak bootloader)
SRAM	8 KB
EEPROM	4 KB
Clock Frequency	16 MHz
Number of pins digital I/O	54 pins (of which 15 can be used as exits PWM)
Analog entries number	16 entrances
Fluent by pin I/O	20 my
Fluent maximum on the 3.3 V pin	50 my
Communication Interfaces	UART (4), SPI, I^{2}C, USB
USB Connector	Kind B
Analog-Digital Converter (ADC)	10 bits
Dimensions	101.52 mm × 53.3 mm
Weight	37 g

2.3. Environmental Sensors: Description and Justification of the Choice

The objective of prototype being to provide a multiparameter version of several additional sensors have been integrated into the environment.

- DHT22 (Temperature and humidity): selected for its good precision (±0.5˚C and ±2% HR) and its ease of integration. It offers reliable measurement for climatology or indoor comfort monitoring applications.
- MH-Z19B (Carbon Dioxide, CO_2): NDIR infrared sensor, with a range of 0 to 5000 ppm and a precision of ±50 ppm + 5%. It has been retained for its reliability and its possibility of calibration, essential criterion for a scientist station [29].
- MQ-135 (Various Gases): This semiconductor sensor responds to a wide range of polluting gases. (ammonia, benzene, fumes). Though its measures require a calibration, it constitutes an interesting indicator of global air quality [30].
- SDS011 (Particles) thin, PM2.5 and PM10): based on a technology laser of broadcast, this sensor is known for its sensitivity and accuracy (±10 μg/m^3). Recent studies [31] demonstrate its relevance for monitoring urban pollution.
- LDR (Photoresistor): used as a sensor of brightness. Tough basic, it provides useful information on local lighting conditions.
- Rain sensor (analog): detects the presence of humidity on its surface allows us

to estimate the relative intensity of precipitation.

Each of these sensors meets a specific need and their joint integration gives the prototype a multidisciplinary character, ranging from meteorology to monitoring air pollution (Table 2).

Table 2. Specification techniques of the sensors integrated at prototype (range of measurement, precision, communication protocol).

Sensor	Setting measures	Range of measures	Precision/ Resolution	Communication protocol	Additional remarks
DHT22	Temperature, Humidity	-40 has 80˚C; 0% - 100% HR	±0.5˚C; ±2% RH	Digital (1-wire)	Response time ~2 s, requires 10 kΩ pull-up
MH-Z19B	CO_2 (ppm)	0 - 5000 ppm	±50 ppm or ±5%	UART/PWM	Infrared calibratable sensor
MQ-135	Gases (NH_3, NOx, benzene, fumes)	10 - 1000 ppm (approx.)	Variable depending on gas	Analog (0 - 5 V)	Preheating time ~24 h; requires calibration
SDS011	Particles PM2.5/PM10	0 - 1000 µg/m^3	±10 µg/m^3 or ±10%	UART	Integrated fan, controlled speed air
GP2Y1010AU0F	PM2.5 particles	0 - 800 µg/m^3	±10%	Analog (0 - 5 V)	Optical sensor, sensitive to fine dust
LDR (photoresistivity)	Brightness (lux)	1 - 10,000 lux	Variable depending on resistance	Analog (0 - 5 V)	Simple and economical, non–linear answer
Rain sensor (analog)	Rainfall/Relative humidity	0% - 100% wet surface	Qualitative/variable	Analog (0 - 5 V)	Proportional output has water conductivity

2.4. Modules of Communication

The ability of the system has to transmit the data in real time constitutes a fundamental criterion. Two complementary technologies have been integrated:

- ❖ LoRa SX1278: reknown for its long range and its weak consumption energy, it allows to transmit the data on several kilometers in free field. Based on chirp modulation spread spectrum, it is particularly suited to urban environments where obstacles disrupt transmissions (Augustin *et al.*, 2016).
- ❖ ESP-01 (ESP8266): This little module Wi-Fi assures the direct connection has Internet via a local network. It can transmit data in MQTT or HTTP format, facilitating integration with the platforms of visualization such as ThingsBoard, Node -RED or Grafana.

These two complementary modules assure the station a double ability of communication, both local and global, thus guaranteeing its flexibility of use.

2.5. Storage Peripherals and Temporal Synchronization

In order to give back the station autonomous, two components have been integrated:

1) A drive of map SD, allowing the local recording of the measures at CSV format. This solution guarantees data backup even in the event of a network outage;

2) A real clock time DS3231, extremely precised, which timestamps each meas-

ure and ensures the temporal continuity of the tracking (even in the event of a microcontroller restart).

2.6. Local Display

The 0.96-inch SSD1306 OLED screen, connected via I^2C, was chosen for its compact size and low power consumption. It allows to display in the main direct measures (temperature, humidity, CO_2, fine particles), thus offering a fast diagnostic interface.

2.7. Food System

The East prototype powered by an external source of 12 V DC, regulated has 5 V via a step-down. The sensitive modules as the LoRa SX1278 and the ESP-01 require a food stabilized at 3.3 V, supplied by a specific regulator (AMS1117). This configuration avoids the risk of overheating or malfunction due to voltage variations.

2.8. Experimental Procedure of Laboratory Simulation

The laboratory simulation has followed up a progressive and rigorous approach in order to restrict the risks of errors and ensuring the validity of the results (Table 3):

Table 3. Plan of laboratory simulation (steps, tested modules, expected results).

Stage	Tested modules	Objective/Aim	Procedure/Activity	Expected results
1	Food and wiring	The modules are properly powered and that there is continuity of wiring	Connect the Arduino, sensors, and OLED screen according to the diagram; measure the voltage on each module	All modules receive the appropriate voltage (5 V/3.3 V), not of short circuit
2	Sensor DHT22 (Temperature & Humidity)	Test the accuracy of environmental measurements	Read the data all take 10 seconds and compare with a reference hygrometer/thermometer	The values are consistent with the instrument references (±2˚C, ±5% HR)
3	Sensor MH-Z19B (CO_2)	Check the gas detection and calibration	Simulate of the known CO_2 concentrations and observe the answer sensor	The sensor correctly detects concentrations and displays the value on OLED screen
4	MQ-135 (Quality of the air/gas miscellaneous)	Test the sensitivity to pollutants	Expose the sensor has ambient air and sources of simulated pollution	Variation of analog signal depending on the presence of pollutants
5	Sensor PM2.5	Check the measurement of thin particles	Generate of the simulated smoke (e.g., candle, steam) and read the values on Arduino	PM2.5 concentrations are increasing proportionally to the presence of particles
6	LDR And rain sensor	Test the light measurements and precipitation	Simulate day/night for the coolant and add a few water drops for rain sensor	LDR noted light variation; sensor rain drop detectors and sends signal
7	LoRa communication/ ESP-01	Testing the data transmission to remote server	Send the data collected to a receiving module or cloud server	Data correctly received remotely without loss
8	OLED screen	Check display data	Display all the measurements collected by the sensors	Clear display and has a day of all the data
9	Full simulation	Check the total integration of the prototype	Execute the complete program with all sensors and module assets	Data from all sensors are measured, displayed and transmitted correctly; no bus conflict I^2C/SPI

1) Progressive assembly: each sensor was individually integrated into the system, starting with the simplest (DHT22, LDR) before moving to the more complex modules (MH-Z19B, SDS011, LoRa, ESP-01).

2) Unit test: for each sensor, a minimal sketch (Arduino program) was used to verify the proper functioning of the hardware and the associated library.

3) Progressive integration: After unitary validation, the different modules have been added to the main sketch, taking care to avoid library and communication conflicts.

4) Final validation: once the complete system was assembled, cycle measurements were executed, including data acquisition, display, recording to SD card and transmission via LoRa and Wi-Fi.

3. Results

This section presents successively the results relating to the measurement of environmental parameters, the local data recording, their real-time display, and finally their transmission via the LoRa and Wi-Fi communication modules.

3.1. Environmental Measures

The set of sensors has answered in accordance to specification techniques announced by the manufacturers. The initial tests consisted of comparing the data raw materials of the prototype with reference on instruments available in the laboratory such as digital ThermoPro TP55 Digital Thermometer, HTC 1 hygrometer, portable CO_2 detector CM 1106-NH and lux meter led DT 3809.

The results show good agreement between measurements, with small average deviations consistent with the expected accuracy of low-cost sensors (**Table 4**).

Table 4. Comparative measures data (prototype vs reference instruments).

Setting	Prototype (average)	Reference (average)	Gap relative
Temperature (˚C)	26.4	26.1	+1.1%
Humidity (%)	58.2	57.0	+2.1%
CO_2 (ppm)	432	420	+2.8%
PM2.5 (µg/m^3)	15.6	14.8	+5.4%
Brightness (lux)	310	305	+1.6%
Rain detection (binary)	Detected presence	Confirmed presence	Concordant

These discrepancies, although present, remain within the tolerance range of the sensors used. They confirm the relevance of system for an environmental indicator and participatory follow up, even though regular calibration would be necessary for professional use.

3.2. Local Data Registration

The system successfully saved the measurements to the SD card in CSV format.

Each line included an accurate timestamp provided by the real-time clock (RTC DS3231) follow up of the measured values. This format facilitates direct import into statistical software analysis (Excel, R, Python).

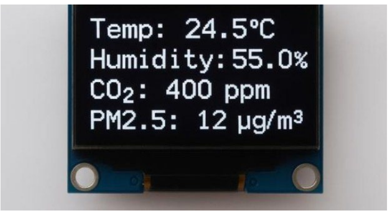
CSV Extract file generated by the prototype:

Date	Time	Temperature (˚C)	Humidity (%)	CO_2 (ppm)	PM2.5 (μg/m^3)	PM10 (μg/m^3)	Brightness (lux)	Rainfall
2025-09-09	10:15:32	26.4	58.2	432	15.6	22.3	310	1
2025-09-09	10:20:32	26.6	57.9	428	14.9	21.7	295	0
2025-09-09	10:25:32	26.5	58.1	435	16.2	23.0	320	0

This reliable registration constitutes a guarantee of traceability and assures a continuity of the data in case of loss of network connection.

3.3. Display in Real Time

The SSD1306 OLED screen accurately displayed the measurements in cyclic scrolling mode. This useful feature proved during debugging and rapid inspection phases in the laboratory. The interface was legible, even in weak brightness, confirming the relevance of this component selection (**Figure 3**).



```
Temp: 24.5°C
Humidity:55.0%
CO2: 400 ppm
PM2.5: 12 µg/m³
```

Figure 3. OLED Display during the simulation (temperature, humidity, CO_2, PM2.5).

3.4. The Data Transmission via LoRa and Wi-Fi

The tests of communication have confirmed the robustness of adopted architecture:

1) The LoRa SX1278 module enabled to transmit data on a distance of over 800 meters in semi-open field, with a rate of loss lower than 5%. This performance is consistent with previous studies (Augustin *et al.*, 2016) and validates the adaptability of the system for outdoor use. For optimal LoRa range testing, the key technical parameters to configure are the SF12 Spreading Factor, a BW Bandwidth of 125 kHz, and a Maximum Transmit Power of 14 dBm.

2) The ESP-01 (Wi-Fi) module ensured real-time data transmission to a local cloud platform (via MQTT protocol). The values were then displayed in a table of edge (dashboard) simple, confirming interoperability of system with the modern IoT tools (Node-RED, Grafana).

3.5. Visualization Chart of the Data

The data issues of the simulation have been represented below the shape of graphs in order to assess temporal trends (**Figure 4**, **Figure 5**).

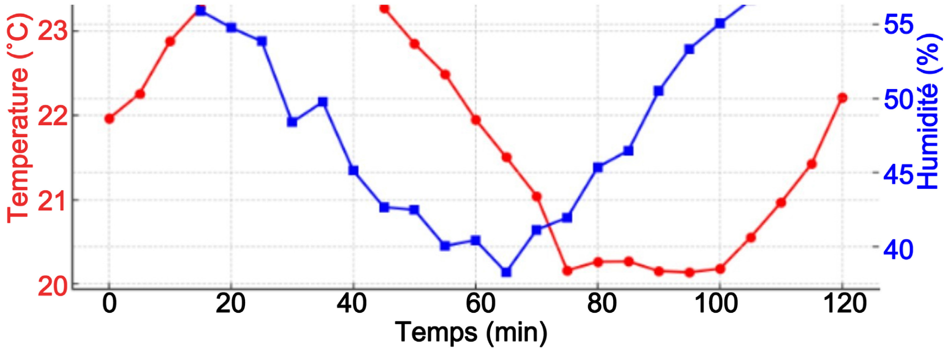


Figure 4. Temporal evolution of the temperature and humidity during 2 hours of simulation.

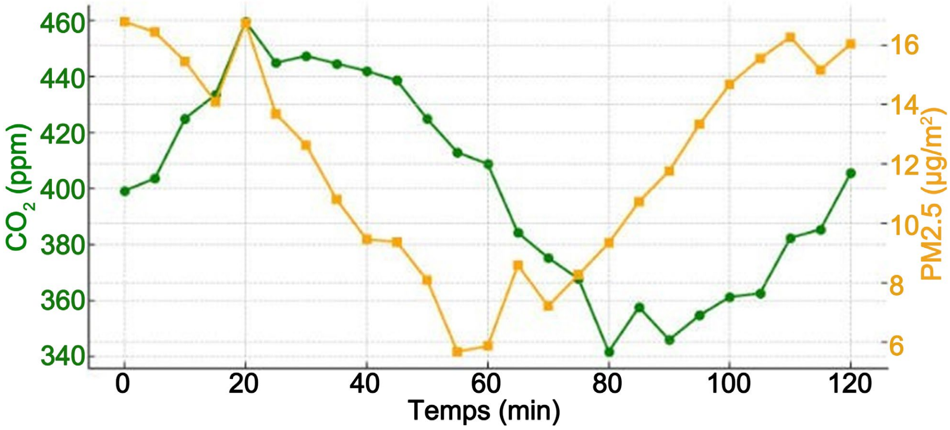


Figure 5. Measured concentrations in CO_2 and PM2.5 on the same period.

These graphs put in evidence the stability of system and the ability of prototype has followed continuous variations in environmental parameters.

The main results obtained can be summarized as follows:

1) The sensors have provided the measures consistent with the instruments of reference, with small differences (≤5%).

2) The recording local on map SD has revealed reliable and usable for further analyses.

3) The OLED display offers a direct practical and clear reading.

4) The modules LoRa and Wi-Fi guarantee a double redundancy of communication, local (long range) and global (Internet connection).

5) The visualization graphs confirm the stability of system and the relevance for indicative monitoring sensors.

These results constitute a key stage towards the validation of prototype, opening the way as a discussion in-depth on its performance, its boundaries and its perspective improvement.

4. Discussion

The design and laboratory simulation of the Arduino-based environmental prototype station The Mega 2560 sensors demonstrate that it is possible to develop low-cost, modular, and interoperable systems for environmental monitoring [15] [16]. However, as with any experimental setup, the results should be interpreted with caution, taking into account the technical limitations of the sensors and the challenges associated with their integration.

The comparative results (**Table 1**) have shown the weak gaps between the prototype sensors and reference instruments confirmed that the solution can provide reliable indicative measurements. However, the absolute accuracy remains lower than that of officially accredited stations (Kumar and al., 2015). For example, the sensors of thin particles low cost as the SDS011 are sensitive to relative humidity and require regular calibration to remain consistent with reference stations. To calibrate the MQ-135 sensors, principal calibration methods are such as fresh air calibration, calculation of Ro (Reference Resistance), potentiometer adjustment, humidity/temperature correction and the use of libraries. For SDS011 calibration, methods commonly used include real-world colocation, linear regression correction, relative humidity modeling, and clean-air calibration [31].

Likewise, the sensor MQ-135, though versatile, does not allow to discriminate the different gases present and reacts strongly to variations in ambient temperature. This limits its use to an indicative pollution detector role, rather than a quantitative instrument [25].

Thus, the prototype responds to a logic of observatory citizen or academic platform for training and applied research, but cannot replace a certified station for environmental regulations.

The adopted architecture is based on Arduino use of the Mega 2560 and separate communication buses (UART, I^2C, SPI) enabled the integration of more than ten modules and sensors without major conflicts. The success of the simulation confirms the relevance of the modular approach.

The choice of a double communication (LoRa and Wi-Fi) reinforces the resilience of the system:

- The LoRa assures a blanket long distance, useful in rural areas or in distributed networks [23].
- The Wi-Fi via ESP-01 allows a direct connection as Internet and the sending towards cloud platforms (MQTT, HTTP).

This essential redundancy for the contexts or access has irregular Internet, but continued data collection remains necessary.

From the recent confirmed studies, the interest to develop the low cost systems of environmental monitoring is for example:

- [9] have observed that the networks of citizen sensors can complete official stations by providing finer spatial coverage.
- [12] have evaluated several sensors of thin particles low cost and concluded that, despite uncertainties, they are useful for detecting relative variations.
- [18] [32] used LoRaWAN-based IoT architectures for monitoring in real time of the quality of the air, with the relative results of those obtained in this study.

These comparisons locate our work in an international tendency aiming as an environmental democratized monitoring using open-source technologies and the Internet of Things.

5. Conclusions

The design, assembly, and laboratory simulation of an environmental prototype station resting on the Arduino Mega 2560 platform and a panoply of low-cost sensors demonstrate the feasibility of a modular system, flexible and accessible for the environment monitoring. The results obtained show that:

- The sensors deployed (temperature, humidity, CO_2, fine particles, various gases, brightness, rain) provide consistent measures with the instruments of reference, within the limits of their nominal accuracy.
- Architecture material, combining bus UART I^2C and SPI, has permitted to integrate more of ten modules without major interference, confirming the robustness of the modular approach.
- The double communication without thread (LoRa long scope and Wi-Fi via ESP-01) reinforces the resilience of the system, opening the way to usage scenarios in both urban and isolated areas.
- Local recording (SD card) and real-time display (OLED) ensure the data continuity and an immediate consultation, two crucial advantages for academic and applied research contexts.

However, the limitations observed, including the sensitivity of the ESP-01 module to power supply, the need to calibrate certain sensors (SDS011, MQ-135), and the management of the volume of generated data, confirm that this prototype should be considered as a proof of concept rather than as a solution that can be immediately deployed on a large scale.

The main contribution of this work resides in the demonstration that an embedded low cost system and open source can be designed for answer to environmental monitoring needs in contexts with limited resources. Unlike official stations which are often expensive and few in number, this type of solution democratizes environmental data collection, paving the way:

- of the participatory science projects involving citizens;
- of the educational applications for the students in electronics, computer sciences and environmental sciences;
- of the distributed sensor networks, capable of completing the stations of reference with a best spatial blanket.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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