IoT Based Environmental Monitoring System

Mr. Prajwal Bake[1], Mr. Shaunak Dandavate[2], Dr. Sharada Desai[3]
[1,2]*Electronics and Telecommunication Engineering, Vishwakarma Institute of Technology, Pune, India*
[3]*Professor, Electronics & Telecommunciation Engineering Vishwakarma Institute of Technology*

***Abstract*—This study presents an Internet of Things (IoT) based environmental monitoring and control system capable of capturing real-time data for multiple parameters temperature, relative humidity, air quality, soil moisture, atmospheric pressure, light intensity, and water levels. The system is built around an ESP32 microcontroller interfaced with a diverse set of sensors (DHT22, MQ135, BMP280, LDR, soil moisture sensor, HC-SR04), enabling continuous environmental assessment. A local 16×2 I²C LCD provides immediate on-site visualization, while Wi-Fi connectivity allows data upload to cloud platforms and remote monitoring via mobile applications and Telegram alerts. By integrating threshold-based automation, the system triggers automated responses (e.g., irrigation, ventilation) when environmental conditions deviate from predefined limits. In lab-scale testing, the system demonstrated stable performance, low latency, and minimal power consumption characteristics that make it suitable for scalable deployment. The proposed architecture draws on design principles validated in recent low-cost IoT environmental monitoring research, demonstrating that such platforms can be both affordable and reliable [1, 2]. The modular and extensible nature of the system renders it applicable to diverse domains, including precision agriculture, smart buildings, and urban-scale environmental monitoring.**

I. INTRODUCTION

Environmental monitoring is essential for sustainable development, smart agriculture, and intelligent urban management. Traditional monitoring methods rely on manual sampling or sporadic readings, which are time-consuming, labor-intensive, and prone to inconsistencies. By contrast, IoT-based systems offer continuous, automated, real-time data collection across multiple parameters. Over the past few years, several low-cost IoT monitoring solutions have emerged, highlighting the feasibility of cost-effective, scalable environmental sensing [11].

For instance, low-cost IoT air-quality stations using inexpensive sensors (e.g., MQ-135, DHT11, MQ-7) have been proposed, demonstrating real-time accessibility, cloud logging, and even blockchain integration for data transparency and integrity [11]. Similarly, soil-moisture management systems leveraging sensor nodes and automated irrigation have shown improved water use efficiency compared to traditional manual watering an essential consideration for sustainable agriculture [12]. These developments validate the potential of IoT frameworks to deliver continuous monitoring and automated control at low cost, strongly motivating the design of the present system However, existing solutions often remain limited in scope (e.g., only monitoring air quality or only soil moisture), lack comprehensive multi-parameter coverage, or focus on a single application such as agriculture or air quality. This paper addresses these gaps by integrating a broader sensor array into a unified platform, enabling versatile deployment across agriculture, indoor comfort management, and environmental surveillance.

II. LITERATURE REVIEW

Several studies have explored various aspects of IoT-based environmental monitoring and control. A low-cost IoT air-quality monitoring station was developed using sensors such as DHT11, MQ-135, and MQ-7 for assessing temperature, humidity, CO/CO_2 concentrations, and air quality, with data uploaded to a cloud platform and optionally stored using blockchain for enhanced data integrity [11]. This work underscores the viability of inexpensive sensor-based IoT stations for real-time monitoring and scalable deployment.

In the agricultural domain, a soil moisture management system was proposed for precision agriculture, utilizing sensor nodes, wireless communication, and cloud-based analytics for real-time monitoring and automated irrigation control. Testing revealed that the system significantly improved water use efficiency compared to manual watering, demonstrating the practicality of IoT driven irrigation management [12].

Other studies have extended soil health monitoring beyond moisture to include parameters such as electrical conductivity, pH, ultraviolet radiation, and nutrient content (N, P, K), combined with solar-powered sensor units highlighting the potential for comprehensive soil analysis using IoT frameworks [13].

Meanwhile, recent advances in low-cost environmental sensing frameworks validated against industry-grade instrumentshave demonstrated that miniaturized sensors, when properly calibrated, can achieve high accuracy (e.g., 97–98% agreement in $PM_{2.5}$ / NO_2 / PM_{10} measurements against reference-grade monitors) [14]. Inspite of this progress, most systems remain application- specific, offering either soil moisture sensing or air- quality monitoring, rarely both. Additionally, comprehensive automation (sensor-to-actuator pipeline), multi-parameter monitoring, and unified architectures applicable across domains remain underexplored. The present system aims to fill these gaps by offering a modular, extensible environmental monitoring platform integrating several sensing modalities, local and remote visualization, automated control logic, and low-power operation.

III. PROPOSED METHODOLOGY

The core of the system is the ESP32 microcontroller, selected for its integrated Wi-Fi and Bluetooth connectivity, dual-core architecture, and low-power operation features critical for continuous sensing systems. The ESP32 interfaces with a suite of heterogeneous sensors to capture a wide range of environmental parameters:

- DHT22: for ambient temperature and relative humidity
- MQ-135: for air-quality monitoring (gas concentration, pollution detection)
- BMP280: for atmospheric pressure sensing, supporting microclimate analysis
- LDR (Light Dependent Resistor): for ambient light intensity measurement
- Soil moisture sensor (capacitive or resistive type): for root-zone soil water content
- HC-SR04 ultrasonic sensor: for water-level or distance/level monitoring.

This sensor configuration provides comprehensive environmental insight, enabling the system to support applications ranging from agricultural soil management to indoor air and light regulation, and environmental surveillance.

Software & Communication Framework

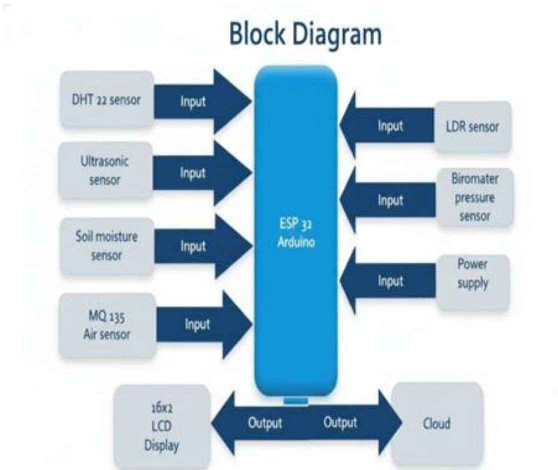
The software stack is implemented using Arduino IDE with C/C++ libraries for sensor interfacing, data acquisition, preprocessing (filtering and calibration), and network communication. The ESP32 continuously samples sensor data at predefined intervals, applies calibration and data validation, and displays results on a local 16×2 I²C LCD module, refreshing every five seconds to cycle through all monitored parameters.

Upon establishing Wi-Fi connectivity, the processed data are transmitted to cloud platforms for remote monitoring and data logging. The system is compatible with platforms such as Blynk for real-time dashboards and historical data graphs. Additionally, a Telegram bot is configured to deliver automated alerts every 30 seconds (or upon threshold-triggered events), enabling prompt remote notification and response.

The architecture also supports over-the-air (OTA) firmware updates, facilitating seamless software maintenance and feature upgrades without requiring physical hardware access a design consideration validated in similar IoT monitoring platforms [15]

Calibration and Data Integrity Considerations

Drawing on insights from recent calibration-focused studies, the system's calibration procedure follows best practices to ensure data reliability. For instance, low-cost environmental sensors deployed in urban settings such as the "Enviro-IoT" platform have demonstrated that with rigorous calibration and validation, low-cost sensors can achieve measurement accuracy comparable to reference-grade instruments, with reported accuracy levels of 97–98% for particulate matter and gaseous pollutants [14]. We adopt analogous calibration protocols for the MQ-135 (air- quality) and soil-moisture sensors to minimize drift and ensure consistency in real-world operation.



Here's how it works. First, the system grabs data from every sensor on a set schedule. Then the ESP32 steps in to filter, calibrate, and double-check that data. If something goes past a threshold like temperature spiking or humidity dropping the system reacts automatically. That could mean sending out an alert, turning on irrigation, or cranking up ventilation. You can watch all of this happen in real time right on the LCD screen. At the same time, the ESP32 sends the cleaned-up data to IoT cloud services, so you can check it from anywhere and keep historical records. And if anything unusual pops up, you get an instant Telegram alert to keep you in the loop.

A. Hardware Implementation

The core processing unit of the proposed system is the ESP32 microcontroller, selected for its integrated Wi-Fi and Bluetooth capabilities, dual-core architecture, and low-power operation. The ESP32 manages all essential computational tasks, including sensor interfacing, data acquisition, local processing, and wireless communication.

A set of heterogeneous sensors is interfaced with the microcontroller to capture key environmental variables. The DHT22 sensor provides temperature and relative humidity measurements with high stability, while the MQ-135 module enables detection of gaseous pollutants and assessment of ambient air quality. The BMP280 sensor is employed for atmospheric pressure monitoring, contributing to weather characterization and environmental analysis. Soil moisture levels are monitored using a capacitive probe, which is particularly relevant for agricultural and irrigation applications. Ambient light intensity is measured via an LDR, and the HC-SR04 ultrasonic sensor is used to determine distance or water-level variations.

For local visualization, a 16×2 I²C LCD module is integrated into the system. It cyclically displays sensor readings at five-second intervals, providing continuous access to real-time information. All components are powered through a regulated DC supply based on an LM7805 voltage regulator, ensuring a stable 5 V output for the ESP32 and connected sensors, thereby enhancing system reliability and operational safety.

B. Software Implementation

The software framework for the proposed system was developed using the Arduino IDE, utilizing C/C++ libraries for sensor integration, data handling, and network communication. The ESP32 continuously samples all connected sensors, acquiring real- time environmental data at regular intervals. The collected measurements undergo preprocessing, including filtering and formatting, to ensure consistency prior to display or transmission. Processed data are presented locally on a 16×2 I²C LCD module, which sequentially updates the readings in an organized and user-readable format. When network connectivity is established, the ESP32 transmits the data to cloud-based platforms. Blynk is employed for real-time visualization and remote monitoring, while Telegram is configured to deliver automated notifications at 30-second intervals, enabling immediate user awareness of abnormal conditions.

The system supports remote accessibility through mobile and web dashboards, ensuring continuous availability of environmental information. In addition to monitoring, the software incorporates threshold-based event detection; when a parameter exceeds predefined limits, the microcontroller automatically issues an alert through the configured communication channels. Furthermore, the implementation includes support for over-the-air (OTA) firmware upgrades, allowing seamless software updates without requiring physical access to the hardware

C. Results and Discussion

The IoT-based environmental monitoring system was assembled and evaluated under controlled laboratory conditions to verify its functional performance. The

ESP32 microcontroller was interfaced with sensors for temperature, relative humidity, air quality, soil moisture, light intensity, and atmospheric pressure, all of which provided continuous real-time measurements throughout the testing period.

A 16×2 I²C LCD module was employed for on-site monitoring, sequentially displaying each sensor parameter at five-second intervals. This configuration allowed clear visualization of individual readings without overcrowding the display interface. Remote monitoring capabilities were assessed using two communication platforms. The Blynk application facilitated real-time data visualization, graphical representation of sensor trends, and historical data logging. In parallel, a Telegram bot was configured to deliver automated alerts at 30-second intervals, using UTF-8 encoded symbols to enhance readability and ensure rapid interpretation.

The system demonstrated robust performance during evaluation. The ESP32 executed sensor acquisition and data processing with minimal latency, and Wi-Fi communication remained stable throughout the test duration. Alerts delivered through Telegram were consistently reliable, enabling remote users to remain informed even when away from the monitoring site. Additionally, the low power consumption of the overall architecture supports extended operational longevity, making the system well suited for continuous environmental monitoring applications.

D. Advantages, Limitations and Applications

Advantages

- Comprehensive Real-Time Monitoring:

The system simultaneously captures temperature, relative humidity, air quality, soil moisture, light intensity, and water- level measurements, enabling multi-parameter environmental assessment.

- Automated Notification Mechanism:

Automated alerting through Telegram and Blynk eliminates the need for manual inspection, ensuring timely awareness of abnormal conditions with minimal user intervention.

- Integrated Data Logging:

All sensor measurements are archived for subsequent analysis, supporting informed decision-making and long- term environmental management.

- Remote Accessibility:

Users can access live and historical environmental data from any location via cloud-integrated platforms such as Blynk, improving monitoring flexibility and responsiveness.

- Early Warning Capability:

Threshold-based detection mechanisms provide rapid notification of critical events—such as elevated pollutant levels or soil moisture deficits—facilitating prompt corrective action.

- Energy-Efficient Operation:

Low-power sensors and optimized automation workflows contribute to reduced energy consumption, enhancing system sustainability and suitability for long-duration deployment.

Limitations

- Dependence on Network Availability:

The remote monitoring functionality requires a stable internet connection; any disruption in connectivity temporarily restricts access to real-time data and system controls.

- Sensor Sensitivity to Environmental Conditions: Certain sensing modules, such as the MQ-135 and LDR, may exhibit performance deviations under extreme or highly variable environmental conditions, potentially affecting measurement accuracy.
- Calibration and Configuration Requirements:

The system is not fully plug-and-play; several sensors require initial calibration and parameter configuration to ensure reliable operation, which may increase setup complexity.

- Limited Spatial Coverage:

Monitoring is confined to the specific locations where sensors are deployed. Achieving broader coverage necessitates the installation of additional sensing units across the target area. or air purification systems would allow automatic system response based on live sensor feedback.

- Predictive Maintenance Capabilities: Utilizing sensor-derived operational metrics to forecast potential system faults could reduce downtime and improve reliability through pre-emptive maintenance scheduling.

Applications

- Agricultural Applications:

The system supports precision agriculture by monitoring soil moisture, ambient temperature, and relative humidity, enabling optimized irrigation scheduling and improved crop management.

- Smart Home and Building Automation: Continuous assessment of air quality, illumination levels, and thermal conditions contributes to enhanced indoor comfort, energy efficiency, and occupant safety in residential and commercial environments.
- Environmental Surveillance: The platform can be deployed to observe local environmental conditions such as atmospheric pollution, microclimatic variations, and water-level changes, facilitating data-driven environmental management.
- Industrial Monitoring:

Real-time measurement of temperature, humidity, and air quality supports compliance with occupational safety standards and promotes safer industrial working conditions.

- Educational and Research Use: The system provides a practical tool for teaching IoT concepts, sensor integration, and real-time data analysis, making it suitable for laboratory instruction and prototype development in academic settings

E. Future Scope

- Integration of Artificial Intelligence and Machine Learning:
  Incorporating AI/ML algorithms can enable predictive modeling of environmental variations and support autonomous decision-making for irrigation control, air purification, and thermal regulation.
- Cloud-Based Analytical Frameworks: Storing long-term historical datasets on cloud platforms would facilitate advanced analytics, trend identification, and automated reporting for comprehensive environmentalassessment.
- Mobile Application Development: A dedicated mobile application could enhance usability by offering real-time monitoring, instant notifications, and remote actuation capabilities within a unified interface.
- Expansion of the Sensor Network: The system may be extended through additional sensing modules such as CO_2 concentration, acoustic noise, ultraviolet index, and rainfall sensors to achieve more detailed environmental characterization.
- Energy Optimization Strategies: Incorporating low-power algorithms, adaptive duty cycling, and solar-powered sensor nodes would improve system sustainability and support long-term deployment in remote locations.
- Smart City Deployment:Scaling the architecture to cover distributed urban environments would enable integration with traffic management, waste handling, and water-distribution systems for comprehensive smart-city governance.
- Actuator Integration for Automated Control: Adding actuatorssuch as irrigation pumps, ventilation units,

F. Conclusion

Our Project IoT-based Environmental Monitoring System provides continuous, multi-parameter assessment of temperature, humidity, air quality, soil moisture, and ambient light intensity, delivering real-time insights for informed decision-making. Its cloud-enabled architecture enables users to remotely access data, receive immediate alerts, and respond proactively to environmental deviations rather than relying on periodic manual observations. Although the system's remote functionality depends on stable internet connectivity, the advantages automated monitoring, rapid anomaly detection, and improved environmental management significantly enhance its practical value. With its scalable design and modular sensor integration, the system demonstrates strong potential for deployment across diverse domains, including precision agriculture, intelligent home automation, and large-scale smart- city infrastructure.

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