A Smart IoT-Based Environmental Monitoring System for Clinical Labs: Focus on Temperature, Humidity and Air Quality

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***Abstract*—Clinical laboratories require accurate and continuous environmental monitoring to ensure the integrity of biological samples, reagents, and laboratory instruments. Environmental deviations, especially in temperature and air quality, can compromise test accuracy and violate regulatory standards such as ISO 15189. This paper presents the design and development of a smart IoT-based environmental monitoring system tailored for clinical lab environments. The system focuses on real-time monitoring of laboratory freezer temperature, ambient room temperature, humidity, and air quality. It utilizes ESP32 microcontrollers integrated with DS18B20 temperature sensors, DHT11 temperature and humidity sensors, and MQ-135 gas sensors to provide comprehensive environmental surveillance. Data is transmitted via Wi-Fi to a cloud-based dashboard, offering remote access, historical data logging, and customizable alert mechanisms for threshold breaches. To optimize energy consumption, the system incorporates power-efficient features such as deep sleep modes and adaptive sampling intervals. The prototype demonstrates consistent and accurate performance in a working laboratory setting. By offering real-time insights and automated alerts, the system minimizes the risks associated with manual monitoring and enhances compliance readiness. The proposed solution is low-cost, modular, and scalable, making it suitable for deployment in both large and resource-limited clinical laboratories.**

***Index Terms*—IoT, Clinical Laboratory, ESP32, Temperature, Humidity, Air, Analysis**

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I. Introduction

Environmental control is a fundamental requirement in clinical laboratories, as it directly affects the accuracy and reliability of diagnostic testing. Parameters such as temperature, humidity, and air quality must be continuously monitored and maintained within defined ranges to ensure the stability of reagents, the preservation of biological samples, and the optimal performance of laboratory equipment [1], [2]. For instance, fluctuations in freezer temperature can compromise the integrity of stored specimens, leading to erroneous test results and potential harm to patients. The ISO 15189:2022 standard mandates laboratories to document and maintain environmental conditions as part of their quality management system [3].

However, many clinical laboratories, especially in resource-limited settings, continue to rely on manual monitoring methods such as handwritten logs and periodic spot checks. These approaches are time-consuming, susceptible to human error, and lack the ability to issue real-time alerts in case of environmental threshold violations. Moreover, such methods do not provide continuous data logging or remote access capabilities, which are essential for modern quality assurance and audit compliance.

To overcome these limitations, this paper proposes a smart IoT-based environmental monitoring system. By integrating low-power microcontrollers with digital sensors and cloud technologies, the system offers automated, real-time, and remote monitoring of key environmental variables. The proposed solution is scalable, energy-efficient, and suitable for both small and large clinical laboratory environments, improving compliance and operational resilience.

II. Background and Related Work

Environmental monitoring is a vital component of quality assurance in clinical laboratories. The ISO 15189:2022 standard emphasizes the importance of maintaining appropriate environmental conditions—specifically temperature, humidity, and air cleanliness—to ensure the validity of test results and protect sample integrity [3]. It requires laboratories to implement documented procedures to monitor, record, and respond to environmental fluctuations that may adversely affect analytical performance or equipment functionality.

Several prior studies have explored the use of environmental monitoring systems in healthcare and laboratory settings. Traditional methods involve the use of standalone digital thermometers, data loggers, and manual charting [1]. Although effective in some contexts, these approaches often suffer from limitations such as infrequent data collection, lack of automation, and the inability to provide real-time notifications during parameter breaches. Recent advances have proposed semi-automated systems that use programmable logic controllers (PLCs) or SCADA systems; however, these are typically expensive and complex, limiting their accessibility for small or resource-limited laboratories [4], [5].

Gaps remain in the adoption of fully automated, real-time, and cloud-connected environmental monitoring solutions that are both cost-effective and scalable. Existing commercial systems tend to be proprietary and costly, often lacking flexibility for customization and integration with laboratory information systems (LIS). This gap highlights the need for affordable, IoT-based alternatives that offer continuous monitoring, real-time alerts, remote access, and long-term data logging. The proposed system addresses these challenges by leveraging open-source hardware and cloud platforms to develop a modular and standards-compliant monitoring solution suitable for clinical laboratory environments.

III. System Architecture

The proposed IoT-based environmental monitoring system (Figure-1) is designed to ensure real-time acquisition, transmission and visualization of critical environmental parameters—temperature, humidity and air quality—within clinical laboratory settings. The architecture consists of three major components: hardware (sensing and control unit), connectivity (data transmission protocols), and software (data visualization and alerting).

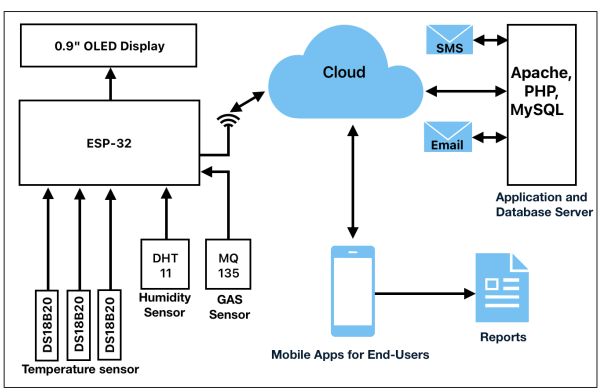

Fig. 1: System Architecture of IoT-Based Environmental Monitoring

A. Hardware Components

The core processing unit is the ESP32 microcontroller for its built-in Wi-Fi capabilities, low power consumption, and support for multiple input/output (I/O) interfaces. The IoT-based environmental sensing system (Fig-2) is using the following microcontroller and sensors:

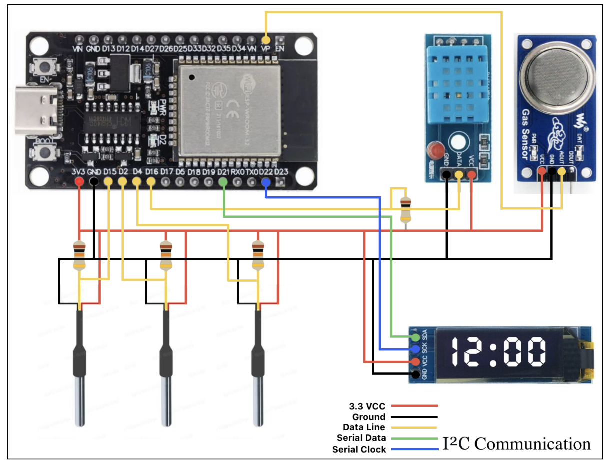

Fig. 2: Connection Diagram of IoT Based System

- **ESP-32** -The ESP32 is a powerful, low-cost microcontroller with integrated Wi-Fi and Bluetooth, ideal for IoT applications. It supports multiple sensors and offers deep sleep functionality for energy efficiency. In this system, ESP32 handles data collection, processing, and wireless transmission to cloud platforms[7], enabling real-time environmental monitoring in clinical laboratories.
- **DHT22** – The DHT11 is a low-cost digital sensor used to measure temperature and relative humidity. It offers decent accuracy for general-purpose monitoring and is widely used in embedded and IoT projects.
- **MQ-135** – The MQ-135 is a widely used gas sensor designed to detect air quality by measuring levels of harmful gases such as ammonia, benzene, and carbon dioxide. It provides an analog output proportional to gas concentration, making it suitable for indoor environmental monitoring in clinical laboratories to ensure safe air conditions.
- **DS18B20** – The DS18B20 is a digital temperature sensor known for its accuracy and waterproof design, making it ideal for monitoring temperatures in harsh or wet environments. It communicates via a 1-Wire protocol, allowing multiple sensors on a single bus, and is used here to monitor freezer temperatures in clinical labs.
- **OLED/LCD Display** – A local visual interface for displaying real-time values on-site.

B. Connectivity

Data collected from the sensors is transmitted using the built-in Wi-Fi module of the ESP32. The MQTT (Message Queuing Telemetry Transport) protocol is employed due to its lightweight nature and suitability for low-bandwidth IoT applications. MQTT **??** ensures reliable message delivery between IoT nodes and the cloud server. Following the

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Algorithm-1 for data Transmission using MQTT protocol [**?**].

Algorithm 1 Multi-Sensor IoT Data Logger with MQTT Transmission

Initialize three DS18B20 temperature sensors
Initialize DHT11 temperature & humidity sensor
Initialize MQ-135 gas sensor
Initialize OLED display
Initialize WiFi module
Initialize MQTT client
Connect to WiFi network
Connect to MQTT broker
while True **do**
    Read temperature from DS18B20-1 and store in $temp\_1$
    Read temperature from DS18B20-2 and store in $temp\_2$
    Read temperature from DS18B20-3 and store in $temp\_3$
    Read temperature from DHT11 and store in dht_temp
    Read humidity from DHT11 and store in dht_hum
    Read analog value from MQ-135 and store in $mq135\_val$
    Display $temp\_1$, $temp\_2$, $temp\_3$, dht_temp, dht_hum, $mq135\_val$ on OLED
    Format all sensor readings as JSON string $message$
    Publish $message$ to MQTT topic
    Wait for 10 seconds
end while

C. Cloud Integration and Dashboard

The proposed system utilizes an MQTT-based communication framework to enable efficient, lightweight data transmission from ESP32 IoT nodes. Environmental parameters—such as temperature, humidity, and air quality—are published by the devices to an MQTT broker in real time. A backend service, developed using PHP with the CodeIgniter MVC framework [8], [9], subscribes to these MQTT topics via a PHP MQTT client (phpMQTT). Upon receiving the data, the controller module parses and stores it into a structured MySQL database, while performing threshold checks to trigger alerts when critical values are exceeded. The web-based dashboard, built on the CodeIgniter view layer, presents a mobile-responsive interface with real-time charts, sensor logs, and historical trend analysis. Role-Based Access Control (RBAC) ensures user authentication and secure access. This modular and scalable architecture avoids third-party cloud dependencies, reduces latency, and provides complete control over infrastructure while allowing easy future integration with machine learning and analytics tools.

- Real-time visualization of temperature, humidity, and air quality data.
- Historical trend analysis and downloadable logs.
- Configurable alert system for threshold violations.
- Automated SMS and email notifications to authorized personnel upon threshold breaches.

D. Software Stack

The firmware for the ESP32 is written in Arduino C/C++ using the Arduino IDE. It manages sensor readings, sleep cycles, and MQTT communication with the broker. The backend of the dashboard is implemented using either PHP (CodeIgniter MVC framework), depending on deployment preference and scalability requirements. The backend handles MQTT subscription, data parsing, database storage, and alert generation.

Frontend visualization is achieved using HTML5, Bootstrap 5, and JavaScript-based charting libraries such as Chart.js. These tools allow for dynamic rendering of real-time data and historical trends. The user interface includes data tables, trend graphs, threshold configuration options, and alert logs. The dashboard also supports responsive design to ensure accessibility on mobile and tablet devices.

This modular software stack ensures high interoperability, scalability, and ease of customization—making it suitable for clinical lab environments with evolving monitoring requirements.

IV. Results and Discussion

The proposed IoT-based environmental monitoring system was deployed in a clinical laboratory and evaluated over a continuous period of 30 days. During this time, the system successfully captured real-time variations in key environmental parameters, including storage temperatures (freezers/refrigerators), ambient room temperature and humidity, and indoor air quality levels.

Alerts were accurately generated whenever any parameter exceeded its predefined threshold, demonstrating the reliability of the threshold-based notification mechanism. These alerts were communicated via SMS and email to designated personnel, enabling prompt corrective actions. The system's real-time dashboard proved effective for both immediate observation and retrospective analysis through visual trend graphs.

Power consumption was also analyzed during the observation period. By utilizing deep sleep modes and dynamic sampling intervals, the system maintained energy-efficient performance. Estimations based on current draw suggest that the ESP32 nodes, when battery-powered, can operate continuously for up to one month without recharging, confirming the system's suitability[10] for long-term deployment in clinical environments.

V. Conclusion

This research demonstrates the feasibility and effectiveness of a smart, IoT-based environmental monitoring system tailored for clinical laboratory settings. By integrating multiple low-cost sensors—including temperature, humidity, and air quality modules—with an ESP32 microcontroller and a custom cloud-based dashboard, the system provides real-time data acquisition, visualization, and alerting capabilities. The proposed architecture not only helps maintain the integrity of biological samples and reagents but also supports regulatory compliance such as ISO 15189:2022 standards. Furthermore, the implementation of power-efficient firmware and cost-effective components makes the system highly scalable and suitable for long-term deployment.

The cloud integration using PHP (CodeIgniter) and MySQL ensures secure data storage, accessibility, and analysis, while SMS and email alerts enhance timely response to environmental deviations. Future enhancements may involve incorporating machine learning algorithms for predictive alerting and integrating the system with Laboratory Information Management Systems (LIMS) to achieve complete automation in quality monitoring and documentation.

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