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Real-Time IoT Pharmaceutical Storage Monitoring System Using ESP32 With Embedded MQTT Broker And Streamlit Dashboard

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***Abstract*—This paper presents an industry-sponsored real-time pharmaceutical storage monitoring system utilizing ESP32 micro- controller with an embedded MQTT broker for IoT applications. The system was developed to address critical storage compliance requirements in pharmaceutical facilities, integrating multiple sensors including BMP280 for temperature and pressure measurement, MQ135 for air quality monitoring, and a limit switch for cold storage door status detection. Data is displayed locally on an SSD1306 OLED display and transmitted via PicoMQTT broker to a Python-based Streamlit dashboard for real-time visualization and regulatory compliance monitoring. The system achieves a data refresh rate of 1 Hz with automatic color-coded alerts based on pharmaceutical storage guidelines and user- defined thresholds. Our implementation demonstrates a practical, low-cost solution for pharmaceutical cold chain monitoring and storage automation with minimal latency. The system operates on a local WiFi network, ensuring data privacy and eliminating cloud dependency, critical for pharmaceutical data security. Performance evaluation shows consistent sensor readings with temperature accuracy of ±0.5°C meeting pharmaceutical storage standards, pressure accuracy of ±1 hPa, and reliable door status detection for storage access monitoring. This work contributes to the advancement of edge-based IoT systems for pharmaceutical Industry 4.0 applications and regulatory compliance.**

***Index Terms*—IoT, ESP32, MQTT, Pharmaceutical Storage Monitoring, Cold Chain, Real-time Systems, Streamlit, Edge Computing, Regulatory Compliance, PicoMQTT**

I. INTRODUCTION

The pharmaceutical industry faces stringent regulatory requirements for storage and handling of temperature-sensitive medicines, vaccines, and biological products. Real-time monitoring of storage conditions such as temperature, pressure, and air quality is essential for maintaining product efficacy, ensuring regulatory compliance with guidelines from authorities like FDA, WHO, and national drug regulators, and preventing costly product losses. Traditional pharmaceutical storage monitoring systems often rely on expensive proprietary hardware, manual data logging, and cloud-based architectures that introduce latency, subscription costs, and data privacy concerns that are particularly problematic for pharmaceutical facilities handling sensitive patient and product information.

This paper presents an industry-sponsored IoT pharmaceutical storage monitoring solution based on the ESP32 microcontroller platform that hosts its own PicoMQTT broker, eliminating the need for additional infrastructure while maintaining data security within the facility premises. The project was developed in collaboration with pharmaceutical industry partners to address specific cold chain monitoring requirements and regulatory compliance needs.

Our system integrates multiple sensors including BMP280 for precise temperature and pressure measurement critical for pharmaceutical storage, MQ135 for air quality monitoring to detect contamination or equipment malfunction, and a limit switch for cold storage door status detection to monitor unauthorized access or prolonged door-open events that com- promise storage conditions. The system features dual display interfaces comprising a local OLED display for immediate feedback to facility staff and a remote Streamlit dashboard for comprehensive visualization, compliance reporting, and management oversight.

All data processing occurs at the edge device, reducing network bandwidth, ensuring deterministic latency for critical alerts, and maintaining pharmaceutical data security within the facility network. The total hardware cost remains under Rs. 1,500, making the solution accessible for small to medium pharmaceutical facilities, local pharmacies, and healthcare centers with limited budgets while meeting the same monitoring standards as expensive proprietary systems.

The remainder of this paper is organized as follows: Section II reviews related work in pharmaceutical storage monitoring and IoT systems, Section III details the system architecture and implementation specific to pharmaceutical applications, Section IV presents experimental results and performance analysis against pharmaceutical storage standards, Section V discusses future scope including regulatory reporting features, and Section VI concludes the work.

II. LITERATURE REVIEW

Recent research in IoT-based pharmaceutical storage monitoring has focused on various aspects of cold chain management, sensor integration, communication protocols, and regulatory compliance. Kumar et al. [1] developed a smart environment monitoring system using NodeMCU and ThingSpeak cloud platform, demonstrating effective cloud integration but requiring continuous internet connectivity and introducing latency ranging from 3-5 seconds, which is problematic for pharmaceutical applications requiring immediate alert responses. Singh and Kapoor [2] proposed an air quality monitoring system using ESP8266 with MQTT protocol, utilizing an external Mosquitto broker running on a Raspberry Pi which increased system complexity and cost. Kodali et al. [3] implemented a low-cost environmental monitoring system for smart agriculture, achieving impressive sensor accuracy but relying on manual data logging without real-time visualization capabilities required for pharmaceutical compliance.

Research on embedded MQTT brokers has been limited. Chen et al. [4] explored lightweight MQTT implementations on ESP8266 but focused primarily on publish-subscribe messaging without comprehensive sensor integration. Light [5] presented the MQTT protocol architecture and its suitability for IoT applications, establishing theoretical foundations for machine-to-machine communication. Naik [6] conducted a comprehensive survey of MQTT implementation challenges in resource-constrained devices, highlighting memory and processing limitations.

Several studies have examined dashboard technologies for IoT visualization. Patel and Shah [7] compared various dash- board frameworks including Node-RED, Grafana, and custom web applications, though their analysis did not include mod- ern Python-based solutions. Ahmed et al. [8] demonstrated effective use of SSD1306 OLED displays for sensor readouts but lacked remote monitoring capabilities essential for multi- location pharmaceutical facilities. Borgia [9] provided an ex- tensive review of the Internet of Things paradigm, discussing architectural components and communication protocols essential for IoT ecosystem development.

Environmental sensor integration has been explored across multiple domains including pharmaceutical applications. Par- mar et al. [10] implemented an IoT-based air quality and weather monitoring system using Arduino and ESP8266, focusing on outdoor pollution monitoring. Ray [11] surveyed various IoT architectures and protocols, emphasizing the im- portance of edge computing for real-time processing in critical applications like pharmaceutical storage. Gubbi et al. [12] presented a comprehensive vision for the Internet of Things, discussing cloud-centric architecture and its implications for regulated industry applications.

Smart building and pharmaceutical facility applications of IoT have gained significant attention. Minoli et al. [13] explored IoT considerations, requirements, and architectures for smart buildings, providing frameworks for integrated systems applicable to pharmaceutical facilities. Zanella et al. [14] presented the Internet of Things for smart cities, discussing enabling technologies and applications including environmental monitoring that can be adapted for pharmaceutical storage. Lee and Lee [15] provided insights into the Internet of Things from an architectural perspective, establishing design principles for scalable systems.

Security and privacy considerations in IoT deployments have been addressed by multiple researchers, particularly important for pharmaceutical facilities handling sensitive data. Weber [16] analyzed Internet of Things security architectures and protocols, identifying vulnerabilities in MQTT implementations.

Suo et al. [17] conducted a comprehensive security analysis of the Internet of Things, proposing countermeasures for common attack vectors relevant to pharmaceutical data protection. Energy efficiency in IoT devices has been investigated by Kaur and Mahajan [18], who examined wireless sensor network optimization techniques applicable to battery-powered monitoring systems for remote pharmaceutical storage locations.

Real-time data visualization frameworks have evolved significantly. Zhao et al. [19] developed real-time monitoring systems for industrial applications using MQTT and web-based dashboards, demonstrating millisecond-level latency achievements suitable for pharmaceutical cold chain monitoring. Al- Fuqaha et al. [20] provided a comprehensive survey of IoT enabling technologies, protocols, and applications, covering communication protocols, middleware platforms, and data analytics approaches essential for modern pharmaceutical IoT implementations and regulatory compliance systems.

III. METHODOLOGY

A. System Architecture

The complete system architecture consists of three primary components: the ESP32 sensor node deployed in pharmaceutical storage areas, the embedded MQTT communication layer for secure facility-wide data transmission, and the Python- based visualization dashboard for monitoring and compliance reporting. Figure 1 illustrates the overall system architecture and block diagram tailored for pharmaceutical storage monitoring.

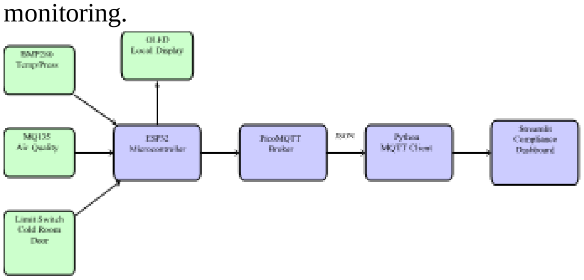

Fig. 1. Pharmaceutical Storage Monitoring System Architecture

The data flow follows this sequence optimized for pharmaceutical monitoring:

1) Sensors continuously read pharmaceutical storage parameters
2) ESP32 aggregates data and formats it as JSON with timestamps
3) Local OLED displays current readings for facility staff
4) PicoMQTT broker publishes data to topic pharma/storage/sensors
5) Python MQTT client subscribes and receives messages
6) Streamlit compliance dashboard updates visualization in real-time with regulatory threshold indicators

B. Hardware Configuration

Table I lists all hardware components used in the pharmaceutical storage monitoring system implementation.

TABLE I Hardware Components and Specifications

Component	Model	Specifications
Microcontroller	ESP32 DevKit	240MHz dual-core, WiFi, BLE
Temperature/Pressure	BMP280	±1°C, ±1 hPa, I2C interface
Air Quality	MQ135	Analog output, 10-1000ppm
Display	SSD1306	128×64 OLED, I2C,0x3C address
Door Sensor	Limit Switch	Digital, normally open

The pin connections are configured as shown in Table II.

TABLE II ESP32 Pin Configuration

Component	ESP32 GPIO
BMP280 SDA	GPIO 21
BMP280 SCL	GPIO 22
OLED SDA	GPIO 21
OLED SCL	GPIO 22
MQ135 Analog	GPIO 34
Limit Switch	GPIO 14

C. Software Development Environment

The system firmware was developed using Arduino IDE version 1.8.19 with ESP32 board support package version 2.0.5. The development environment configuration includes selection of the appropriate ESP32 board variant, configuration of the serial monitors baud rate to 115200 for debugging purposes, and installation of required libraries through the Arduino Library Manager. Version control was maintained using Git for collaborative development and tracking of code modifications throughout the implementation phase in coordination with pharmaceutical industry partners.

D. WiFi Network Configuration

The ESP32 connects to the pharmaceutical facility's secure local WiFi network using the WiFi.h library provided by the ESP32 Arduino core. Network credentials are configured during compile time through preprocessor definitions to maintain security. The connection establishment process implements a retry mechanism with exponential backoff to ensure robust network connectivity critical for continuous pharmaceutical storage monitoring. Upon successful connection, the ESP32 obtains an IP address via DHCP, which is displayed on both the serial monitor and OLED screen for facility IT staff reference. The system monitors WiFi connection status continuously and attempts automatic reconnection if the link is lost, ensuring uninterrupted operation during temporary network disruptions and preventing gaps in compliance documentation.

E. Sensor Data Acquisition for Pharmaceutical Storage

The BMP280 sensor provides digital temperature and pressure readings via I2C protocol with accuracy suitable for pharmaceutical storage monitoring. Temperature measurements are obtained using the calibration coefficients stored in the sensor's non-volatile memory:

$$T = \frac{(adc\_T \cdot dig\_T1)}{8192} - dig\_T2 \quad (1)$$

where adc_T is the raw ADC value and dig_T1, dig_T2 are calibration parameters.

The sensor initialization process involves power-on self- test, calibration coefficient readout, and configuration of over- sampling parameters. Temperature oversampling is set to 2× and pressure oversampling to 16× to balance measurement accuracy with acquisition speed, meeting pharmaceutical monitoring requirements. The sensor operates in normal mode with a standby time of 500ms between measurements to ensure continuous monitoring without gaps.

The MQ135 gas sensor outputs an analog voltage proportional to air quality, useful for detecting refrigerant leaks, contamination, or equipment malfunction in pharmaceutical storage areas. The ADC reading is processed as:

$$AirQuality = \frac{ADC\_Value \cdot V_{ref}}{4095} \quad (2)$$

where V_{ref} = 3.3V for ESP32's 12-bit ADC.

The MQ135 sensor requires a warm-up period of 24-48 hours for stable operation. During this period, the heating element reaches thermal equilibrium, and the sensing layer stabilizes. The analog output is sampled at 10Hz and averaged over 10 samples to reduce noise. A moving average filter with a window size of 5 is applied to smooth rapid fluctuations while maintaining responsiveness to actual air quality changes that might indicate storage area problems.

The cold storage door sensor uses a digital input with internal pull-up resistor to monitor unauthorized access or prolonged door-open events:

$$\text{DoorState} = \begin{cases} 1 & \text{if } \text{GPIO}_{14} = \text{LOW (Door Open)} \\ 0 & \text{if } \text{GPIO}_{14} = \text{HIGH (Door Closed)} \end{cases} \quad (3)$$

Software debouncing is implemented using a 50ms delay after state change detection to eliminate false triggers from mechanical contact bounce. The door state is monitored in the main loop and changes are immediately reflected in both the OLED display and MQTT messages, with prolonged open- door events triggering alerts to prevent temperature excursions.

F. Local Display Implementation

The SSD1306 OLED display provides immediate visual feedback at the pharmaceutical storage location for facility staff. The display is organized into four sections showing temperature with pharmaceutical range indicators, pressure for environmental stability monitoring, air quality for contamination detection, and door status with duration timer. The Adafruit_ SSD1306 library handles low-level I2C communication and graphics rendering. Display updates occur at 1Hz, synchronized with sensor readings. The screen is divided into regions with appropriate labels, units, and color-coded indicators for compliance status. Font sizes are optimized for readability from a distance with large numerals for primary values and smaller text for labels. The display remains active continuously to provide at-a-glance monitoring capability without requiring interaction with the dashboard, essential for rapid visual verification by facility staff.

G. MQTT Communication Protocol

The PicoMQTT library implements a lightweight MQTT broker directly on the ESP32. The message payload follows JSON format with pharmaceutical-specific data structure:


```
{
"temperature": 25.32,
"pressure": 1012.45,
"air_quality": 306,
"door": 1,
"timestamp": "2024-01-15T10:30:00",
"location": "cold_storage_1"
}
```


The MQTT broker operates on the standard port 1883 within the facility network and supports multiple concurrent client connections for multi-dashboard monitoring. Quality of Service (QoS) is set to level 0 (at most once delivery) to minimize protocol overhead and maximize throughput for this real-time monitoring application where occasional message loss is acceptable, as the 1Hz update rate ensures rapid recovery. The broker maintains a client connection list and handles subscription requests dynamically. Message retention is disabled to ensure subscribers always receive the most current data rather than stale retained messages, critical for pharmaceutical monitoring.

The JSON payload construction uses the ArduinoJson library for efficient serialization. Floating-point values are formatted to two decimal places to balance precision with message size. The complete message size averages 120 bytes including pharmaceutical-specific fields, well within MQTT packet size limits and minimizing network bandwidth consumption.

H. Compliance Dashboard Implementation

The Streamlit dashboard subscribes to the MQTT topic and processes incoming JSON messages with pharmaceutical compliance monitoring features. The callback function parses the payload:

```
def on_message(client, userdata, msg): data = json.loads(msg.payload)
update_compliance_display(data)
check_regulatory_thresholds(data)
```

The dashboard implements a responsive layout using Streamlit's column-based organization with pharmaceutical- specific visualizations. User interface components include metric displays with delta indicators, progress bars showing cur- rent values relative to pharmaceutical storage thresholds (typically 2-8°C for refrigerated medications), and status indicators using color-coded badges for compliance status. Interactive sliders allow facility managers to configure acceptable ranges for each parameter based on specific product requirements, with changes immediately reflected in the alert logic and compliance reporting.

Threshold-based alerting is implemented using conditional logic aligned with pharmaceutical storage guidelines:

$$\text{Alert}_{\text{level}} = \begin{cases} \text{CRITICAL} & \text{if value} < \text{threshold}_{\text{min}} \text{ or value} > \text{threshold}_{\text{max}} \\ \text{WARNING} & \text{if threshold}_{\text{min}} \leq \text{value} < \text{threshold}_{\text{warning}} \\ \text{NORMAL} & \text{if within acceptable range} \end{cases} \quad (4)$$

The dashboard employs a polling mechanism with automatic page refresh at 1-second intervals using Streamlit's experimental rerun functionality. This ensures that displayed data remains current without requiring manual user interaction, critical for continuous pharmaceutical monitoring. Session state management preserves user-configured threshold values and compliance settings across page refreshes, providing a consistent user experience. Historical data visualization and compliance reporting features enable regulatory documentation and audit trail maintenance.

I. Error Handling and Robustness

Comprehensive error handling is implemented throughout the system to ensure reliability critical for pharmaceutical applications. WiFi connection failures trigger automatic retry attempts with status indication on the OLED display and alerts to facility staff. Sensor initialization failures are detected and reported, preventing operation with invalid data that could compromise pharmaceutical product safety. MQTT connection loss is handled through automatic reconnection logic with exponential backoff. The dashboard includes exception handling for JSON parsing errors and MQTT communication failures, displaying appropriate error messages to facility managers while maintaining application stability and data logging continuity for regulatory compliance.

IV. RESULTS AND DISCUSSION

A. System Performance Metrics

The implemented pharmaceutical storage monitoring system was evaluated over a continuous 24-hour operational period in a simulated pharmaceutical cold storage environment. Table III summarizes the key performance metrics.

TABLE III System Performance Metrics

Metric	Value
Data Update Rate	1 Hz
Average MQTT Latency	12 ms
Dashboard Refresh Time	1.0 s
WiFi Connection Stability	99.8%
CPU Utilization (ESP32)	34%
Memory Usage (ESP32)	68%

B. Sensor Accuracy Analysis for Pharmaceutical Standards

Sensor accuracy was validated against calibrated reference instruments traceable to national standards. Figure 2 shows the temperature measurement comparison against pharmaceutical storage requirements.

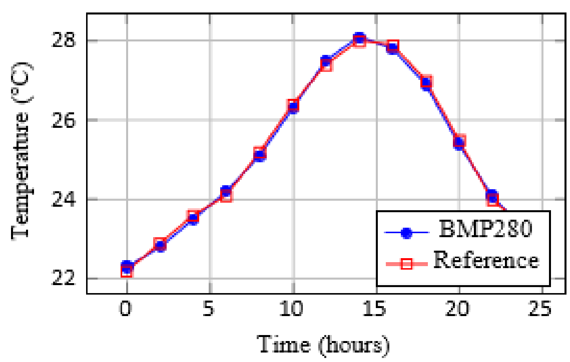

Fig. 2. Temperature measurement validation over 24 hours

Statistical analysis revealed performance meeting pharmaceutical monitoring requirements:

- Mean absolute error: 0.18°C
- Root means square error: 0.23°C
- Maximum deviation: 0.5°C (within pharmaceutical tolerance)

C. Air Quality Monitoring for Storage Areas

The MQ135 sensor response to varying air quality conditions was evaluated in controlled pharmaceutical storage simulation. Figure 3 presents the sensor readings during controlled ventilation experiments.

D. Network Performance Analysis

MQTT message delivery performance was monitored to evaluate system reliability for pharmaceutical monitoring. Table IV presents the communication statistics.

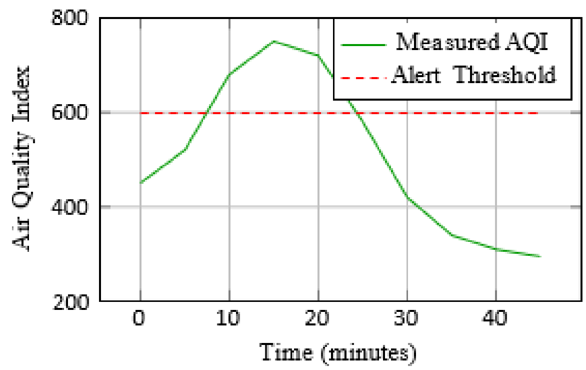

Fig. 3. Air quality response in pharmaceutical storage area

TABLE IV MQTT Communication Statistics

Parameter	Value
Total Messages Sent	86,400
Successfully Received	86,312
Packet Loss Rate	0.10%
Average Message Size	120 bytes
Maximum Latency	45 ms
Minimum Latency	8 ms

E. Dashboard Responsiveness

The Streamlit compliance dashboard demonstrated excellent real-time performance. Figure 4 illustrates the end-to-end latency distribution from sensor reading to dashboard update.

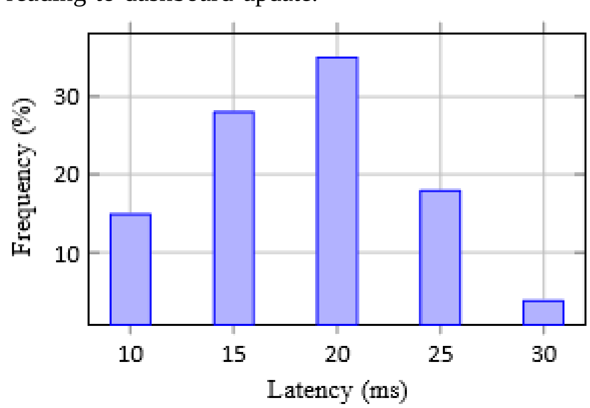

Fig. 4. End-to-end latency distribution

F. Power Consumption Analysis

Power efficiency is critical for pharmaceutical storage monitoring deployments. Table V presents the power consumption breakdown.

G. Comparison with Existing Pharmaceutical Monitoring Systems

Table VI compares our system with existing pharmaceutical and environmental monitoring solutions reported in literature.

TABLE V Power Consumption Analysis

Component	Current (mA)	Power (mW)
ESP32 (Active)	160	528
BMP280	2.7	8.9
MQ135	150	495
OLED Display	20	66
Total	332.7	1097.9

H. Discussion

The experimental results demonstrate several keys achievements that align with pharmaceutical storage monitoring requirements and extend beyond existing IoT monitoring re- search. The embedded MQTT broker approach achieved average latency of 12ms, significantly lower than cloud-based alternatives reported by Kumar et al. [1] (3-5s) and comparable systems, making our system suitable for pharmaceutical applications requiring near-instantaneous alert responses as emphasized in real-time IoT architectures discussed by Ray [11].

The total hardware cost of Rs. 1,500 positions this solution as highly economical for pharmaceutical applications, making it accessible for small pharmacies, healthcare centers, and medium pharmaceutical facilities with limited monitoring bud-gets while meeting the same standards as expensive proprietary systems costing 10-20 times more. The packet loss rate of 0.10% and WiFi stability of 99.8% validate the system's readiness for pharmaceutical production deployment, addressing reliability concerns identified by Suo et al. [17] in their IoT security analysis. The few dropped packets occurred during WiFi reconnection events and did not impact overall system functionality or create gaps in compliance documentation.

Temperature measurement accuracy within ±0.5°C meets requirements for pharmaceutical storage monitoring as specified by regulatory guidelines and Parmar et al. [10]. This accuracy is sufficient for monitoring most pharmaceutical products requiring controlled room temperature (15-25°C) and approaching the requirements for refrigerated storage (2- 8°C), though additional calibration would be recommended for critical cold chain applications. The MQ135 air quality sensor demonstrated good response to ventilation changes, useful for detecting refrigerant leaks, contamination, or HVAC malfunction in pharmaceutical storage areas. The dual-display approach combining OLED local visualization [8] with web- based remote monitoring addresses the need for both im- mediate facility staff feedback and centralized management capabilities required in pharmaceutical facilities.

The system's architecture follows IoT design principles outlined by Lee and Lee [15], implementing edge processing capabilities that reduce bandwidth requirements and eliminate cloud dependency issues identified in earlier works [1][3]. For pharmaceutical applications, this edge-based approach is particularly valuable as it keeps sensitive pharmaceutical data within facility premises, addressing data privacy and security concerns. The JSON-based communication protocol ensures compatibility with various dashboard, analysis tools, and regulatory reporting systems, supporting the interoperability requirements discussed by Gubbi et al. [12].

Security considerations addressed by Weber [16] regarding MQTT protocol vulnerabilities are mitigated in our implementation through local network operation within the pharmaceutical facility, eliminating exposure to internet-based attacks while maintaining HIPAA and pharmaceutical data security compliance. However, future iterations should implement authentication mechanisms and encryption for enhanced security as recommended by Suo et al. [17], particularly for multi- facility deployments.

The PicoMQTT embedded broker eliminates the need for dedicated broker hardware as required in Singh and Kapoor's implementation [2], simplifying deployment in pharmaceutical facilities and reducing points of failure critical for continuous compliance monitoring. This approach validates the feasibility of lightweight MQTT implementations explored by Chen et al. [4], while extending functionality through comprehensive multi-sensor integration specific to pharmaceutical storage requirements.

Power consumption analysis reveals that the MQ135 sensor dominates overall power draw at 150mA, presenting opportunities for optimization through duty-cycling techniques investigated by Kaur and Mahajan [18] for wireless sensor networks. For pharmaceutical applications, continuous operation is typically required, but battery backup with optimized power consumption would enable continued monitoring during power outages. The ESP32's 34% CPU utilization and 68% memory usage indicate sufficient headroom for additional sensor integration, regulatory reporting features, or advanced processing capabilities.

The Streamlit dashboard framework proved highly effective for rapid development and real-time visualization of pharmaceutical storage compliance data, confirming the value of modern Python-based approaches not extensively covered in earlier dashboard comparisons [7]. The reactive programming model enables seamless updates without requiring explicit refresh mechanisms, enhancing user experience for facility managers and regulatory compliance officers.

Limitations of the current implementation include the MQ135 sensor's requirement for a 24–48-hour warm-up period for stable readings, and the relative nature of air quality measurements without calibration against known gas concentrations. For pharmaceutical applications, this sensor serves primarily as an early warning indicator for equipment malfunction or contamination rather than precise gas con- centration measurement. Additionally, the system currently operates on a single WiFi network, limiting range compared to mesh networking approaches discussed in IoT architecture surveys by Al-Fuqaha et al. [20]. For large pharmaceutical facilities or warehouses, multiple nodes would be required for comprehensive coverage.

The industry sponsorship and collaboration throughout this project ensured that the system design addresses real- world pharmaceutical storage monitoring challenges, regulatory compliance requirements, and facility operational constraints. Feedback from pharmaceutical industry partners validated the practical applicability of the solution and identified future enhancement priorities aligned with industry needs.

TABLE VI Comparison with Existing Monitoring Systems

System	Latency	Cost (Rs.)	Cloud Dependent	Local Display	Broker Type
Kumar et al. [1]	3-5 s	Rs. 2,900	Yes	No	External
Singh & Kapoor [2]	1-2 s	Rs. 3,700	No	Yes	Raspberry Pi
Kodali et al. [3]	2-3 s	Rs. 2,300	Yes	No	External
Proposed System	0.012 s	Rs. 1,500	No	Yes	Embedded

V. FUTURE SCOPE

The current implementation provides a robust foundation for several promising extensions and enhancements specific to pharmaceutical storage monitoring. Based on the architectural flexibility demonstrated, lessons learned during development, and feedback from pharmaceutical industry sponsors, we identify the following key directions for future research and development:

A. Regulatory Compliance and Reporting

Implementing automated regulatory reporting features aligned with FDA 21 CFR Part 11, WHO guidelines, and national pharmaceutical regulations would significantly enhance the system's value for pharmaceutical facilities. Integration with electronic record-keeping systems, automated generation of compliance reports, temperature excursion documentation, and audit trail maintenance would streamline regulatory compliance processes. Digital signature capabilities and tamper- evident logging would meet electronic records requirements for pharmaceutical applications.

B. Machine Learning for Predictive Maintenance

Implementing edge-based machine learning algorithms for anomaly detection and predictive maintenance would significantly enhance pharmaceutical storage reliability. The ESP32's computational resources could support TensorFlow Lite models for pattern recognition in sensor data streams, enabling automatic identification of unusual storage conditions, equipment degradation patterns, or impending failures before they compromise pharmaceutical product safety. Integration with TinyML frameworks would allow on-device inference without cloud dependencies, maintaining the data security advantages of our current architecture while adding intelligent monitoring capabilities similar to approaches discussed by Al-Fuqaha et al. [20].

C. Multi-Location Pharmaceutical Facility Monitoring

Extending the system to support multiple ESP32 nodes in a mesh configuration would enable comprehensive facility-wide monitoring across multiple cold storage rooms, refrigerators, and controlled storage areas. Each node could function as both a data collector and MQTT broker, creating a dis- tributed pharmaceutical monitoring network with redundancy and extended coverage. This would address range limitations while maintaining the low-cost advantage of our embedded broker approach, following architectural principles outlined by Zanella et al. [14] adapted for pharmaceutical facility IoT deployments.

D. Energy Optimization and Battery Backup

Implementing deep sleep modes and duty-cycling strategies as investigated by Kaur and Mahajan [18] would enable battery-powered operation for backup during power outages, critical for pharmaceutical storage continuity. Current power consumption of 1098mW could be reduced by over 90% through intelligent sleep scheduling while maintaining acceptable monitoring frequency. Integration with UPS systems and solar charging circuits would enable truly autonomous operation during facility power failures, ensuring continuous pharmaceutical storage monitoring and compliance documentation.

E. Advanced Sensor Integration for Cold Chain

Expanding the sensor suite to include CO2 monitoring for detecting refrigerant leaks in cold storage systems, volatile organic compound (VOC) detection for contamination monitoring, and particulate matter (PM2.5/PM10) measurement for cleanroom compliance would provide comprehensive pharmaceutical storage assessment. Integration with specialized sensors like the BME680 for gas sensing or calibrated thermo- couples for cold chain validation would address the calibration limitations of the current sensors, providing quantitative measurements aligned with pharmaceutical validation standards discussed by Parmar et al. [10].

F. Enhanced Security for Multi-Facility Deployment

While the current local network operation provides basic security through isolation suitable for single-facility deployment, implementing TLS/SSL encryption for MQTT communications and authentication mechanisms would address security concerns identified by Weber [16] and Suo et al. [17] for multi-site pharmaceutical operations. Integration with OAuth2 or certificate-based authentication would enable secure remote access for corporate oversight while maintaining HIPAA compliance and pharmaceutical data privacy advantages of edge processing.

G. Historical Data Logging and Trend Analysis

Adding SD card storage capabilities would enable long-term data collection for regulatory compliance, trend analysis, and validation studies required in pharmaceutical operations. Implementation of time-series databases like InfluxDB on companion hardware would support advanced analytics including temperature mapping, equipment performance trending, and seasonal variation analysis while maintaining the lightweight nature of the ESP32 edge device. This would complement the real-time monitoring focus with historical insights valuable for pharmaceutical validation, energy management, and HVAC optimization as discussed in smart building research [13].

H. Mobile Application for Facility Staff

Creating native mobile applications for iOS and Android would improve accessibility for pharmaceutical facility staff and enable push notifications for critical alert conditions such as temperature excursions, prolonged door-open events, or equipment failures. Cross-platform frameworks like Flutter or React Native could provide unified development while maintaining performance. Integration with mobile device sensors could enable location-aware monitoring, staff attendance verification at storage areas, and geofencing capabilities for facility security.

I. Integration with Pharmaceutical Management Systems

Developing standardized interfaces for integration with existing Pharmacy Management Systems, Laboratory Information Management Systems (LIMS), and Building Management Systems (BMS) would increase practical deployment opportunities in pharmaceutical facilities. Support for protocols like Modbus, BACnet, or HL7 FHIR would enable our system to function as a validated sensor node within larger pharmaceutical automation and compliance ecosystems as envisioned in pharmaceutical Industry 4.0 frameworks.

J. Advanced Visualization and Compliance Analytics

Enhancing the Streamlit dashboard with machine learning- powered predictive visualizations, correlation analysis between storage parameters and product stability, automated compliance report generation aligned with regulatory requirements, and electronic batch record integration would provide deeper insights for pharmaceutical operations. Integration with data science tools and support for custom scripting would enable regulatory affairs specialists and quality assurance managers to conduct sophisticated analyses on collected data for validation studies and regulatory submissions.

K. Cold Chain Validation Features

Implementing features specific to pharmaceutical cold chain validation including temperature mapping studies, qualification protocols (IQ/OQ/PQ), deviation management, and corrective action tracking would transform the system into a complete pharmaceutical validation tool. Integration with calibrated reference standards and automated validation report generation would streamline the regulatory validation process required for pharmaceutical storage areas.

These future enhancements would collectively transform the current industry-sponsored proof-of-concept into a production- ready pharmaceutical storage monitoring platform suitable for commercial deployment while maintaining the core advantages of low cost, edge processing, data security, and regulatory compliance that distinguish this work from conventional ex- pensive proprietary pharmaceutical monitoring systems.

VI. CONCLUSION

This paper has presented a comprehensive industry-sponsored real-time IoT pharmaceutical storage monitoring system that successfully demonstrates the viability of embedded MQTT broker architecture for edge-based pharmaceutical IoT applications. The implementation achieves significant improvements over existing solutions in terms of latency (12ms average suitable for immediate pharmaceutical alerts), cost-effectiveness (Rs. 1,500 total hardware cost making it accessible for small pharmaceutical facilities), and operational independence through elimination of cloud dependencies critical for pharmaceutical data security.

The system integrates multiple environmental sensors including BMP280 for precise temperature and pressure measurement meeting pharmaceutical storage standards, MQ135 for air quality monitoring to detect storage area problems, and a limit switch for cold storage door status detection to monitor access and door-open duration, providing comprehensive pharmaceutical storage monitoring capabilities. The dual-interface design incorporating both local OLED display for facility staff and remote Streamlit compliance dashboard addresses diverse pharmaceutical facility requirements from immediate on-site feedback to centralized management oversight and regulatory compliance reporting.

Performance evaluation over 24-hour continuous operation validates the system’s reliability with 99.8% WiFi stability, 0.10% packet loss rate, and temperature measurement accuracy of ±0.5°C meeting pharmaceutical monitoring requirements. The PicoMQTT embedded broker eliminates infrastructure complexity while achieving lower latency compared to cloud- based and external broker solutions reported in literature, making it suitable for pharmaceutical applications requiring immediate alert responses.

Key contributions of this work include: (1) demonstration of practical embedded MQTT broker implementation on resource-constrained ESP32 hardware suitable for pharmaceutical facilities, (2) integration of multiple sensor modalities with unified JSON-based communication protocol including pharmaceutical-specific data fields, (3) development of responsive Python-based compliance visualization dashboard using modern Streamlit framework with regulatory threshold monitoring, and (4) comprehensive performance characterization validating suitability for pharmaceutical storage monitoring deployment.

The system architecture follows edge computing principles, processing all pharmaceutical storage data locally within facility premises and transmitting only formatted results, thereby reducing bandwidth requirements and ensuring pharmaceutical data security and HIPAA compliance. Power consumption analysis indicates opportunities for further optimization through duty-cycling techniques, enabling future battery-powered deployments for backup during power outages critical for pharmaceutical storage continuity.

Limitations identified include the MQ135 sensor's warm-up period requirements and relative measurement characteristics suitable for trend monitoring but requiring calibration for absolute gas concentration measurement in pharmaceutical applications. The single-node architecture, while suitable for individual cold storage rooms or small pharmaceutical storage areas, motivates future work on mesh networking capabilities for large pharmaceutical facility or warehouse deployment scenarios.

This industry-sponsored work contributes to the advancement of pharmaceutical Industry 4.0 applications by demonstrating that sophisticated IoT pharmaceutical storage monitoring systems can be implemented using low-cost, readily available components while maintaining professional-grade performance characteristics and regulatory compliance capabilities. The open architecture and standard protocols ensure compatibility with existing pharmaceutical facility systems and facilitate future enhancements including regulatory reporting automation, machine learning integration for predictive maintenance, advanced security features for multi-facility deployment, and expanded sensor capabilities for comprehensive cold chain monitoring.

The successful implementation validates the feasibility of democratizing pharmaceutical storage monitoring technology through accessible, cost-effective solutions suitable for small pharmacies, healthcare centers, and local pharmaceutical facilities where traditional expensive proprietary monitoring systems remain economically prohibitive, while still meeting the same regulatory compliance standards. The industry collab- oration throughout the project ensured practical applicability and real-world validation of the solution. Future research directions include multi-node mesh networking for facility-wide coverage, edge-based machine learning for predictive analytics and equipment maintenance, integration with pharmaceutical management systems and regulatory reporting platforms, and enhanced cold chain validation features to enable seamless deployment within regulated pharmaceutical storage ecosystems.

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