

Low-Cost IoT-Based Smart Grain Monitoring System for Sustainable Storage Management [†]

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Abstract

Efficient grain storage is critical for ensuring food security, particularly in regions with hot and humid climates where environmental fluctuations can accelerate spoilage. This study presents the development of a low-cost, Arduino-based Smart Grain Monitoring System designed to continuously monitor key storage parameters. The system integrates sensors to measure temperature, relative humidity, air quality, and the weight of stored grains—factors essential for the early detection of microbial activity, fermentation, or structural degradation. Data is transmitted wirelessly in real time to a mobile application via the Blynk IoT platform, allowing for remote access, alerts, and trend analysis. The system is designed to be affordable, scalable, and easy to deploy in agricultural settings with limited infrastructure. To enhance mechanical performance and usability, the sensor system is housed in a reflective glass silo enclosure that provides both thermal insulation and visual grain access. A 3D CAD model was developed to optimize the placement of electronics and ensure structural integrity. Key features include custom mounts for sensors and electronics, a top lid for grain refill and hygiene, and a stable base for load cell installation. This integrated framework offers a reliable, real-time monitoring solution that supports proactive grain management and reduces post-harvest losses in rural storage environments.

Keywords: smart grain storage; IoT; environmental monitoring; ESP32; sensors; Arduino UNO

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1. Introduction

Food grain storage is a fundamental component of global food supply chains, with storage losses significantly affecting food security and economic stability, particularly in developing countries. According to the FAO, post-harvest losses of cereal grains in some developing countries can exceed 30%, mostly due to improper storage conditions and lack of monitoring systems [1]. In tropical and subtropical regions, high temperatures and humidity levels provide ideal conditions for the growth of molds, proliferation of insects, and increased microbial activity, all of which contribute to spoilage and deterioration of grain quality [2].

Traditional storage systems often rely on manual inspections and lack real-time data collection. This results in delayed responses to environmental fluctuations that could lead to irreversible damage to stored grains [1]. In recent years, the advent of the Internet of Things (IoT) has enabled the development of automated systems that can remotely monitor environmental parameters critical to grain preservation, such as temperature, relative humidity, CO₂ levels, and weight [3].

Numerous studies have highlighted the benefits of IoT-based monitoring in agricultural contexts. Ref. [4] demonstrated the positive impact of a mobile IoT solution on maize drying and storage in Rwanda, leading to improved grain safety. Similarly, Ref. [5] used an ESP32-based system to track grain moisture levels with high accuracy, proving the effectiveness of such platforms in data collection and cloud transmission. Ref. [6] emphasized the importance of modular design and real-time alert systems to improve user interaction and reduce dependence on manual observation.

Despite these advances, many existing solutions still suffer from drawbacks such as high-power consumption, complex wiring, and reliance on GSM networks with recurring costs [7]. There remains a need for low-cost, energy-efficient, and Wi-Fi-based systems that are easy to deploy in low-resource environments. This work aims to address these gaps by introducing a fully integrated smart grain monitoring system that utilizes a single ESP32 board to collect, process, transmit, and visualize data. The use of a reflective enclosure, 3D printed components, and a rechargeable battery ensures that the system is not only functional but also sustainable and adaptable to real-world agricultural scenarios.

2. Methods

2.1. System Architecture

The system comprises the following components:

- DHT11: for temperature and humidity
- MQ135: for CO₂ and air quality
- Load Cell (HX711 amplifier): for grain weight
- ESP32 microcontroller
- 16x2 LCD with I2C module
- Rechargeable lithium-ion battery with TP4056 charger module
- Data Transmission: via the Blynk platform over Wi-Fi
- 3D Housing: transparent, reflective acrylic silo with modular slots for electronics

The ESP32 is programmed to collect data every 30 s, transmit it to the Blynk dashboard, and trigger local alarms if critical thresholds are breached (e.g., >27 °C or >70% RH).

The overall structure of the proposed monitoring solution is illustrated in the system block diagram (Figure 1), which shows the integration of sensors, microcontroller, power supply, and cloud connectivity. The architecture of the Smart Grain Monitoring (SGM) System is illustrated in Figure 1, highlighting the integration of sensors, processing unit, power supply, and IoT-based data transmission components.

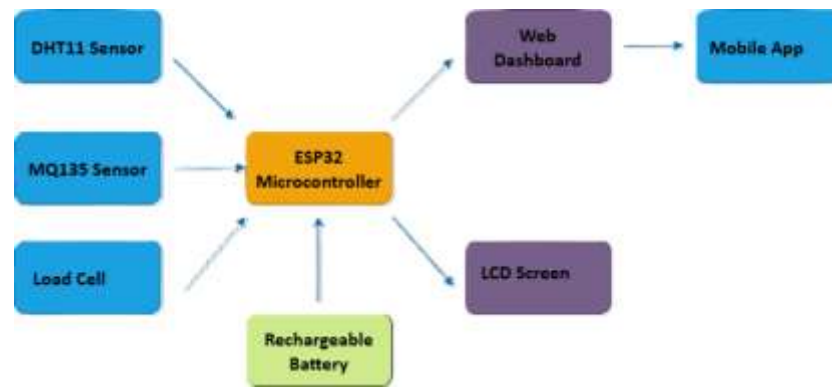


Figure 1. Block diagram of the proposed Smart Grain Monitoring System, integrating temperature, humidity, CO₂, and weight sensors with ESP32 microcontroller, power supply, and IoT communication via the Blynk platform.

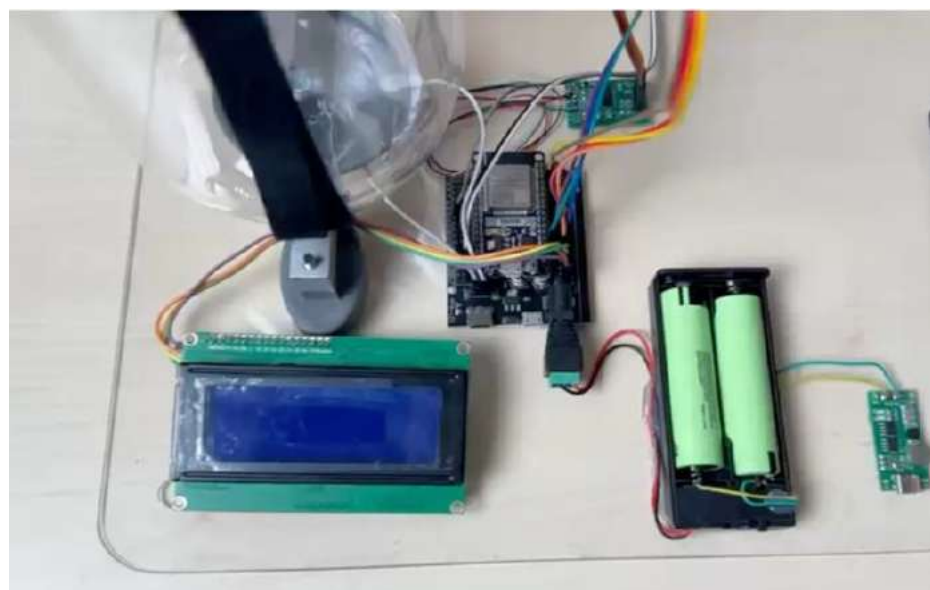


Figure 2. diagram of the Smart Grain Monitoring (SGM) System. The setup integrates a DHT11 sensor (temperature and humidity), MQ135 sensor (air quality), load cell (weight), ESP32 microcontroller, rechargeable battery with charging circuit, LCD display, and Blynk IoT platform for real-time data visualization.

2.2. 3D Design and Fabrication

Using SolidWorks, a cylindrical enclosure was modeled to house the sensors in optimal vertical alignment. The design includes a top lid for refilling grains, sensor mounts, and a bottom platform for the load cell. The enclosure comprises three key structural zones: (1) the sensor mounts, positioned around the middle cylindrical section, are designed as flanged protrusions to accommodate sensors for temperature, humidity, and gas detection; (2) the grain chamber, forming the main vertical body, stores the grain and enables consistent sensor exposure; and (3) the base platform, located at the bottom, supports the entire structure and provides a flat surface for integrating load cells to measure the grain weight. The material selection considered thermal insulation, structural rigidity, and visibility [6] as detailed in Table 1. The mechanical structure of the storage enclosure was modeled using SolidWorks to ensure optimal sensor alignment and component accessibility (Figure 3).

Table 1. Selected materials for key components of the Smart Grain Monitoring System enclosure, based on mechanical performance, thermal insulation, corrosion resistance, and visibility requirements.

Component	Material	Justification	Reference
Grain Chamber (Main Body)	Polycarbonate (PC)	Provides strength and transparency for visual monitoring of grains.	[8]
Inner Insulation Liner	Expanded Polyurethane Foam	Offers excellent thermal insulation to minimize heat transfer.	[9]
Sensor Mounts	Aluminum 6061-T6	High strength-to-weight ratio and corrosion resistance, ideal for precision sensor support.	[10]
Load Cell Platform	Aluminum 6061-T6	Provides a rigid and stable base necessary for accurate load cell readings.	[10]
Top Lid	Polycarbonate (PC)	Maintains material compatibility and transparency for grain refill access.	[8]
Structural Legs/Support Frame	Stainless Steel or Mild Steel	Ensures structural integrity, especially in humid or corrosive environments.	[11]

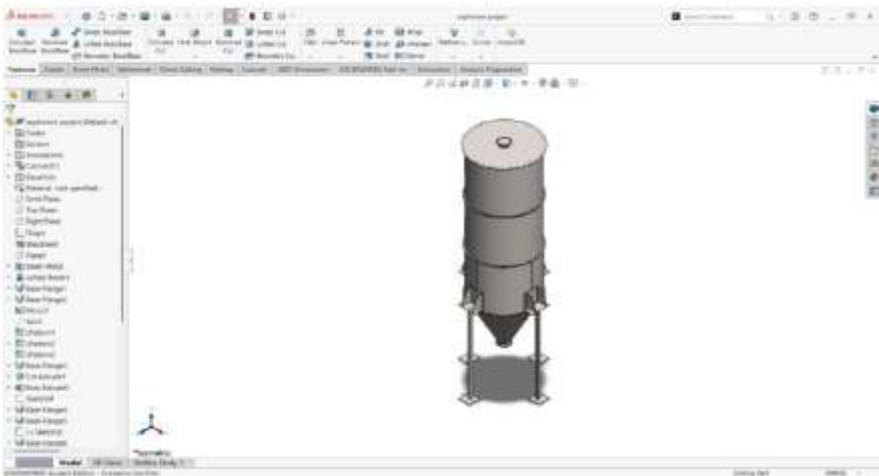


Figure 3. SolidWorks 3D CAD model of the Smart Grain Monitoring System enclosure showing sensor mounts, grain chamber, and base for load cell integration.

3. Results and Discussion

3.1. Environmental Monitoring

Field tests showed accurate sensor readings within $\pm 2\%$ of calibrated values. Over a 48-h trial, the system reliably detected humidity spikes during simulated wet conditions and CO₂ build-up during grain fermentation. The ideal and observed values for key grain storage parameters are summarized in Table 2. The ideal ranges were adapted from prior studies on post-harvest storage conditions [1,2]. Real-time monitoring of grain storage parameters was visualized through the Blynk mobile application, which displayed trends for temperature, humidity, CO₂ levels, and weight (Figure 4).

Table 2. Grain Preservation Main Factors Influencers.

Parameter	Ideal Range	Observed Range	Remarks
Temperature	10–25 °C [2]	24.1–28.3 °C	Exceeded threshold at noon
Relative Humidity	50–65% RH [2]	60–75% RH	Alert triggered at 70% RH
CO ₂ Level	<1000 ppm [2]	750–1300 ppm	Exceeded during closed lid
Weight Loss	≤1% per month [1]	Negligible	Within safe range

These results align with [4], who reported similar performance in real-world grain storage monitoring scenarios.

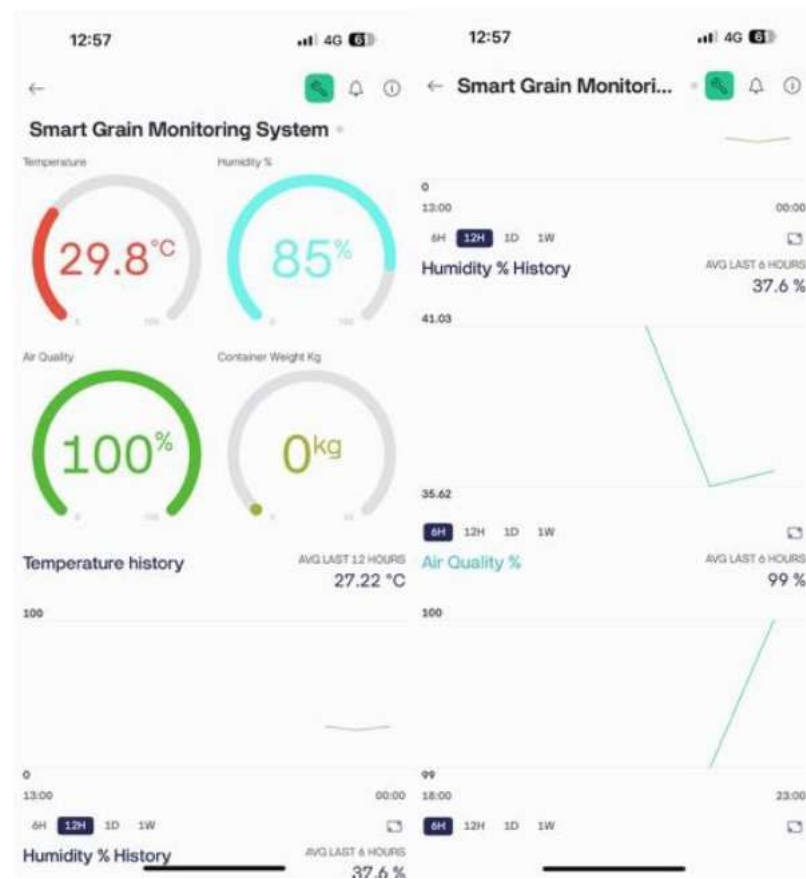


Figure 4. Screenshot of the Blynk IoT mobile application displaying real-time sensor data: temperature, humidity, CO₂ concentration, and grain weight.

3.2. Power and Connectivity

The rechargeable battery supported approximately three days of operation per charge. Blynk-based Wi-Fi transmission remained stable across 2.4 GHz networks in rural test areas. Users accessed alerts and trend data remotely via smartphone.

3.3. Comparison with Other Systems

Unlike systems that depend on GSM networks, spreadsheets, or multi-board setups [2,5], this design consolidates all functions into a single ESP32 board. The Blynk platform eliminates the need for cellular data plans or complex cloud backends.

4. Conclusions

This paper presents a compact and cost-effective IoT solution for real-time grain monitoring. The integration of temperature, humidity, air quality, and weight sensing on a single ESP32 board offers a simple, scalable system suitable for remote or under-resourced settings. 3D design enhancements ensure thermal efficiency and maintain hygiene. Future work includes solar integration, LoRaWAN communication, and AI-based spoilage detection.

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