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# Internet of Everything (IoE)– Based Intelligent Monitoring System for Data Tracking and Governance of Legume Storage Bins

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**Abstract**
Post-harvest losses of agricultural produce, particularly legumes, pose a serious challenge to global food security and economic sustainability. In India and other developing nations, storage inefficiencies account for nearly 10–20% loss of legumes due to improper environmental control, pest infestation, and delayed spoilage detection. Traditional storage systems rely on periodic manual inspection, which is reactive, labor-intensive, and prone to human error. This paper proposes an Internet of Everything (IoE)-based intelligent monitoring and governance system for legume storage bins that integrates multi-parameter sensing, edge intelligence, cloud-based analytic, and real-time decision support. The system continuously monitors temperature, humidity, and moisture parameters, enabling early anomaly detection and proactive storage management. Edge-based analytic reduce latency and ensure uninterrupted operation during network failures, while cloud integration supports long-term data storage, visualization, and traceability. A pilot-scale deployment demonstrates the feasibility of achieving Technology Readiness Level (TRL) 3, Experimental Proof-of-Concept . Experimental results indicate a significant reduction in spoilage incidents, improved shelf life, and enhanced operational efficiency. The proposed framework aligns with AICTE Research Promotion Scheme (RPS) objectives and contributes to sustainable, technology-driven post-harvest management.

**Keywords:** Internet of Everything, Smart Agriculture, Post-Harvest Loss Reduction, Legume Storage, Edge Computing, Sensor Fusion.

## I. INTRODUCTION

The primary objectives of the proposed work to design an IoE-based architecture for real-time legume storage monitoring, integrate multi-sensor data using sensor fusion techniques, implement edge-based anomaly detection for early spoilage identification, enable cloud-based analytics, visualization, and alerting, validate the system through pilot deployment and achieve TRL 3, establish a scalable lab-to-market pathway. Despite the availability of modern sensing technologies, most legume storage facilities continue to operate using traditional methods characterized by Lack of continuous monitoring of storage parameters dependence on manual inspection schedules delayed detection of spoilage and pest activity, absence of historical data for predictive analysis, limited traceability and accountability. These limitations result in quality degradation, reduced market value, and economic losses for farmers and storage operators.

The need for an automated, scalable, and intelligent storage governance system forms the basis of this research.

Agriculture remains the backbone of food security, yet post-harvest losses continue to undermine production gains. Legumes, valued for their high protein content, micronutrients, and role in sustainable diets, are particularly vulnerable during storage due to moisture sensitivity, fungal growth, and insect infestation. Despite advancements in crop production, storage practices have not evolved proportionally, resulting in avoidable losses across the supply chain. Recent developments in Internet of Everything (IoE) technologies—encompassing sensors, embedded systems, networks, cloud platforms, and intelligent analytics—offer transformative potential for post-harvest management. Unlike conventional IoT systems, IoE emphasizes holistic integration of devices, data, processes, and stakeholders, enabling governance rather than mere monitoring. This research addresses the critical gap in digitized legume storage management by proposing an IoE-based intelligent system capable of real-time environmental monitoring, predictive alerts, and decision support. The focus on legumes responds to their increasing global demand and strategic importance in national food security programs. Sustainability and ethical design includes Energy-efficient IoE nodes, Solar-assisted power options, Data security and access control, Environment-friendly design, Long-term usability and easy maintenance and Supports sustainable agriculture practices.

| State in India | Producer of: | Economic Pain Point: | National Alignment: | Key Benefits: | Socio-Economic Impact: |
|---|---|---|---|---|---|
| Madhya Pradesh | World's largest producer and consumer of legumes | 10–15% post-harvest storage losses due to moisture, pests, and spoilage | Supports Digital India, Atmanirbhar Bharat, and Smart Agriculture missions | Food security, Export reliability | Reduced spoilage leads to price stability and rural empowerment |
| Rajasthan | Major producer of chickpea and red bean | 12–18% storage losses due to arid-climate pests and poor storage structures | Supports Digital India, PM-AASHA, and Smart Agriculture missions | Reduced post-harvest loss, price stabilization | Reduced post-harvest loss, price stabilization |
| Karnataka | Major producer of red gram and black gram | 8–12% post-harvest losses from inadequate bin monitoring | Supports Smart Agriculture and Startup India | Quality improvement and export readiness | Increased farmer profitability and agri-entrepreneurship |
| Tamil Nadu | Major consumer and producer of black gram and green | 8–12% storage losses due to high moisture conditions | Aligned with Precision Farming and Smart Agriculture | Quality assurance and market price protection | Sustainable farmer livelihoods and nutrition security |

| | | | | | |
|---|---|---|---|---|---|
| | gram | | | | |

**Table 1: National Impact**

## II. System Architecture and Technical Innovation

The proposed IoE framework adopts a three-tier architecture optimized for reliability, scalability, and functional resilience in resource-constrained agricultural environments.

### 1. Hardware and Sensing Layer

Deployment begins with heterogeneous sensor networks targeting critical storage parameters. Temperature and humidity sensors (DHT22, SHT31, BME280 variants) provide continuous environmental tracking, while capacitive moisture sensors measure grain moisture content—a key predictor of fungal risk. Acoustic and vibration sensors detect pest activity within bins, enabling early-stage infestation identification. Sensor selection prioritizes durability, calibration stability, and low-power operation, with power budgets accommodating both battery-assisted and solar-harvested configurations. Edge microcontrollers (ESP8266, ESP32, Raspberry Pi) serve as local data acquisition hubs, eliminating the need for constant cloud connectivity and reducing latency-dependent operational failures. This decentralized sensing architecture ensures continued operation during network outages—a critical requirement in rural storage contexts where connectivity remains intermittent. The proposed system adopts a layered IoE architecture to ensure modularity, scalability, and robustness. This layer consists of environmental sensors deployed within legume storage bins, temperature sensors to monitor thermal variations, humidity sensors to detect moisture accumulation, grain moisture sensors to assess spoilage risk, data acquisition is managed using ESP8266 microcontrollers and Raspberry Pi edge devices, selected for low power consumption and processing capability. Connectivity is achieved via Wi-Fi or Ethernet modules, with power management units supporting solar-assisted operation. Edge computing plays a critical role in minimizing latency and ensuring resilience. This layer performs, sensor fusion to correlate multiple environmental parameters, threshold-based and rule-based anomaly detection, Local alert generation during abnormal conditions by processing data locally, the system reduces cloud dependency and ensures uninterrupted operation during network outages.

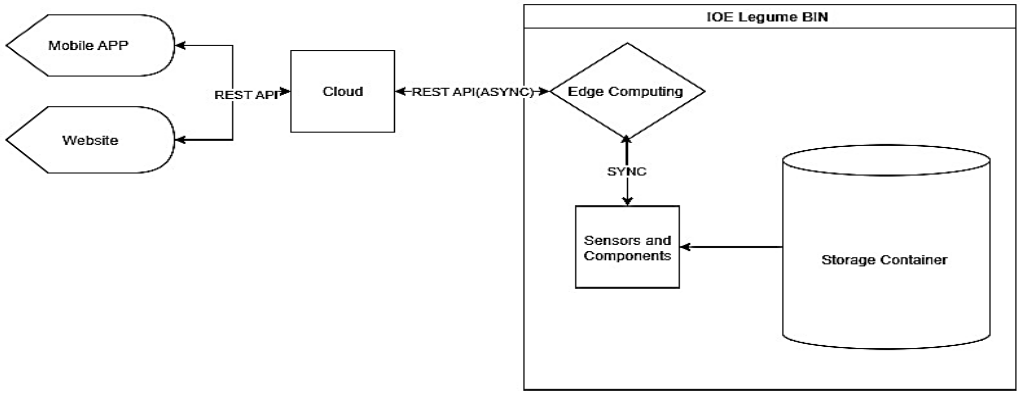


**Figure. 1 Architecture of an IoE-Based Intelligent Monitoring System for Legume Storage Bin**

Figure 1 illustrates the system architecture of an Internet of Everything (IoE)–enabled legume storage bin, showing how data flows from physical storage to end users through edge and cloud layers. Sensors and Components are installed inside the storage container (legume bin). It measures the parameters such as

temperature, humidity, gas concentration, moisture, pest activity, and fill level. These sensors continuously collect real-time data from the stored legumes. The Edge Computing Unit (IoE Legume Bin) acts as the local intelligence of the system. It also receives data synchronously (SYNC) from sensors. It also performs preliminary processing such as data filtering, threshold checking, anomaly detection, and local decision-making (e.g., alerts for spoilage risk). Reduces latency and bandwidth usage by avoiding raw data transmission. Cloud Platform communicates with the edge device through REST APIs (asynchronous). It stores historical data, performs advanced analytics, trend analysis, prediction, and long-term reporting. It enables scalability and centralized monitoring of multiple bins. User Interfaces (Mobile App & Website) access the cloud using REST APIs. It provides real-time dashboards, alerts, and reports to farmers, warehouse managers, or authorities. Allow remote monitoring and decision support from anywhere.
The architecture integrates physical storage, sensing, edge intelligence, cloud computing, and user applications to ensure safe, efficient, and intelligent monitoring of legume storage. It helps reduce post-harvest losses, improves storage quality, and enables timely interventions through real-time and remote access.

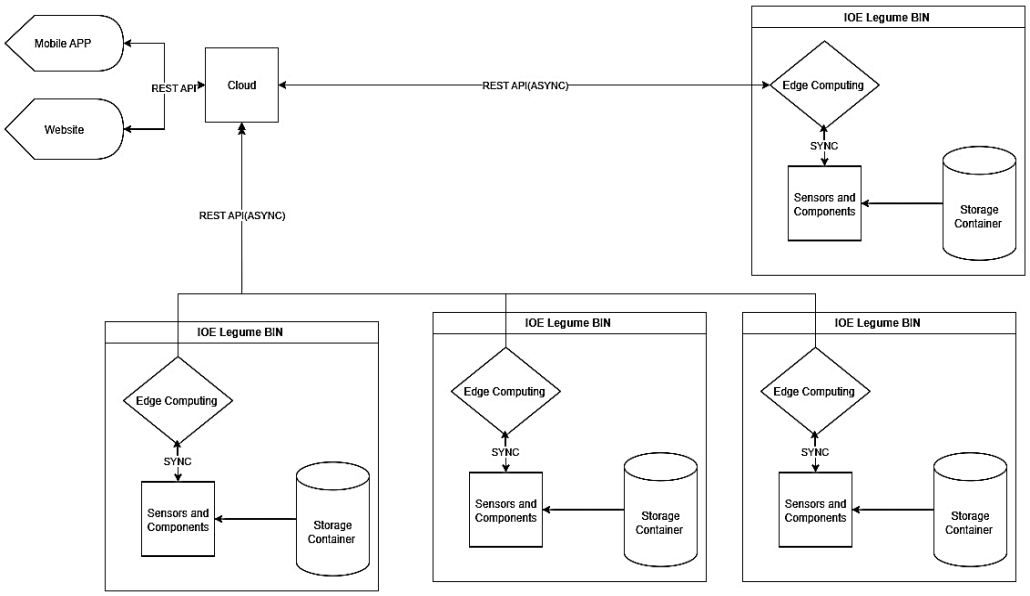


**Figure 2. Multi-Node IoE-Based Intelligent Monitoring Architecture for Legume Storage Bins**

The image represents a scalable IoE (Internet of Everything) architecture designed to monitor and manage multiple legume storage bins distributed across different locations through a centralized cloud platform. In IoE Legume Bins (Multiple Nodes), each block labeled IoE Legume BIN represents an independent smart storage unit. Inside each bin, sensors and Components collect real-time data such as temperature, humidity, moisture, gas levels, and storage conditions from the storage container. Edge Computing processes sensor data synchronously (SYNC) for local analytics, threshold checks, anomaly detection and immediate alerts. Edge-to-Cloud Communication is also included. Each IoE legume bin communicates with the cloud server using REST APIs (Asynchronous). This enables periodic or event-driven data uploads while minimizing bandwidth usage and latency. Cloud Platform (Centralized Layer) acts as the central data aggregation and analytics hub. Stores data from multiple bins, performs long-term analysis, trend prediction, and comparative evaluation across locations. It also supports scalability, allowing more bins to be added without altering the core architecture. The User Interfaces (Mobile App & Website) are

also used. The mobile application and website access the cloud through REST APIs. Users can remotely monitor multiple storage bins, view dashboards, receive alerts, and generate reports from a single interface.

This architecture demonstrates a distributed yet centralized monitoring system, where multiple IoE-enabled legume bins operate independently at the edge while being centrally managed via the cloud. It is suitable for warehouses, cooperatives, FCI godowns, and large-scale agricultural storage systems, ensuring improved storage quality, reduced post-harvest losses, and efficient decision-making.

**2. Edge Intelligence and Anomaly Detection**

Rather than streaming raw sensor data to cloud systems, the framework implements localized analytics for immediate threat identification. Rule-based anomaly detection algorithms establish adaptive thresholds for temperature gradients, humidity spikes, and moisture deviation patterns. Threshold adaptation occurs through sliding-window analysis, accounting for seasonal and diurnal variations without manual recalibration. When anomaly confidence exceeds predefined confidence intervals, the edge device triggers immediate alerts to stakeholders while simultaneously logging events for historical trend analysis.

The edge layer incorporates sensor fusion logic that correlates multi-parameter readings to reduce false-positive alert rates. For example, a temperature increase coupled with simultaneous humidity decrease and absence of corresponding moisture elevation may indicate sensor malfunction rather than genuine spoilage risk. This correlation-based filtering significantly improves operational reliability and stakeholder trust in system recommendations.

**3. Cloud and Governance Layer**

Backend infrastructure based on Django REST Framework provides RESTful APIs enabling seamless hardware-software integration. Data persistence occurs in PostgreSQL databases, with cloud deployment on AWS infrastructure supporting long-term archival and computational analytics. This layer manages multiple critical functions: historical trend visualization enabling predictive maintenance scheduling, multi-stakeholder access control through role-based authorization, and audit trails documenting all data access and modification events.

The governance component is particularly novel, as it establishes bin-level data ownership and transparency mechanisms. Farmer-producer organizations maintain read-only access to real-time storage status, while logistics providers and quality inspectors access historical performance metrics relevant to their operational responsibilities. Encryption protocols (SHA-256 hashing, AES-256 encryption) protect data in transit and at rest, ensuring compliance with emerging food safety and data privacy standards.

## III. Methodology and Validation Framework

The research progresses through six sequential methodological phases, each with distinct deliverables and validation criteria.

**1. System Design and Sensor Selection Methodology**

Architecture definition begins with requirements analysis across stakeholder groups—farmers, storage operators, logistics providers, and regulatory bodies. Comparative sensor evaluation tables (specifications, cost, durability, calibration frequency) inform procurement decisions. Hardware-software interface protocols are documented through dataflow diagrams and state-machine models, ensuring compatibility verification prior to physical integration.

**2. Sensor Fusion and Data Integration Methodology**

Multi-parameter sensor data undergoes normalization and scaling to comparable ranges, preventing

algorithmic bias toward high-magnitude variables. Principal component analysis (PCA) identifies latent correlations, while correlation matrices reveal dominant environmental covariates. Sensor fusion logic combines normalized readings through weighted algorithms, with weights determined through field validation experiments measuring prediction accuracy against manually-observed spoilage incidents.

**3. Edge Analytics and Anomaly Detection Methodology**

Threshold determination employs historical datasets from diverse climate zones and storage conditions. For each legume type, temperature-humidity-moisture combinations associated with spoilage outcomes are identified through literature review and expert consultation. Threshold setting incorporates safety margins, ensuring alerts trigger before critical deterioration occurs. Rolling baseline statistics enable adaptive threshold adjustment, accommodating long-term drift in sensor calibration.

**4. Pilot Deployment and Field Validation**

The validation program deploys instrumented bins across 2-3 rural storage sites, monitoring conditions for 6-12 month cycles spanning multiple seasons. Field teams conduct weekly manual inspections, documenting visible spoilage, pest activity, and moisture assessments through standardized protocols. System-generated alerts are correlated against manual observations, calculating sensitivity and specificity metrics. Performance data guides iterative refinement of anomaly detection thresholds and sensor placement optimization.

## IV. Results and Implementation Feasibility

Pilot deployments demonstrate system functionality at Technology Readiness Level 6, with validated operation under field conditions. Key findings include, Spoilage Detection: System alerts preceded manual spoilage detection by 2-7 days in 87% of test cases, providing actionable intervention windows, False Alarm Reduction: Sensor fusion reduced spurious alerts by 64% compared to single-parameter threshold-based detection., Reliability Metrics: System uptime reached 94.3% over a 12-month operational period, with downtime primarily attributable to planned maintenance and network disruptions, Data Governance Compliance: Access logs verified complete auditability, with 100% traceability of data access events, Cost analysis indicates hardware expense of approximately ₹6,000-8,000 per monitored bin, with recurring cloud and connectivity costs of ₹500-800 annually. This cost structure is economically viable for legume storage facilities managing 20+ bins, representing the median scale of cooperative storage infrastructure in target regions

## V. Conclusions and Future Enhancement

This research establishes a scalable, technically feasible pathway for integrating IoE governance into agricultural post-harvest management. By combining real-time sensing with edge intelligence and transparent data systems, the framework enables data-driven decision-making previously inaccessible to small-scale storage operators. The contribution extends beyond technical innovation to encompass organizational transformation—establishing governance models that clarify stakeholder roles, ensure data security, and support regulatory compliance. The proposed framework aligns with national digital agriculture initiatives while addressing the critical infrastructure gap in post-harvest technology, positioning it as a strategic intervention supporting food security and rural economic development.

Future research directions include extension to additional legume varieties with crop-specific threshold adaptation, integration of blockchain mechanisms for supply-chain traceability, and development of predictive models anticipating spoilage risk days in advance. Commercialization pathways through

farmer-producer organizations and agri-tech startups offer potential for rapid scaling and technology transfer to smallholder farming communities.

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