

Integrating Indigenous Knowledge and IoT for Smart Resource Management in Household Grain Flour Storage practices in South India

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Abstract:

Efficient management of household food and natural resources is essential for reducing post-harvest losses, improving food security, and promoting sustainable storage practices. Indigenous grain and flour preservation methods have traditionally utilized locally available materials such as neem, turmeric, tulsi, garlic, and wood ash; however, their effectiveness is strongly influenced by temperature, humidity, moisture, storage duration, and climatic variability. This study proposes an IoT-enabled smart resource management framework that integrates indigenous preservation practices with real-time monitoring for sustainable household grain flour storage. A six-bin modular storage system is designed with ESP32-based sensing nodes to monitor temperature, relative humidity, flour moisture, CO₂, volatile organic compounds, storage quantity, and storage duration. The collected data are intended to support continuous assessment of storage conditions, early identification of deterioration, and efficient utilization of preservation, storage, and energy resources. A secondary experimental dataset derived from published grain-storage studies will be used to evaluate the proposed framework through correlation analysis and Principal Component Analysis (PCA). The dominant storage parameters identified through PCA will support the development of a Storage Health Index (SHI) for classifying storage conditions and generating appropriate preservation and management recommendations. The proposed framework aims to reduce food wastage, optimize indigenous preservation resources, minimize unnecessary manual intervention and energy consumption, and improve household storage decision-making under variable climatic conditions. The study provides a sustainable pathway for integrating indigenous knowledge, IoT sensing, and data-driven resource management in household grain flour storage.

Keywords: Indigenous Grain Storage, *Household Grain flour Storage*, Indigenous Knowledge Systems, Internet of Things (IoT), Smart Grain Storage, Post-Harvest Management, Food Security, Sustainable Agriculture

INTRODUCTION:

Food grains constitute the foundation of food security and nutritional well-being for billions of people worldwide, particularly in developing countries where cereals, pulses, and millets form the staple diet. India is one of the world's largest producers of rice, wheat, maize, millets, and pulses, contributing significantly to global food production. However, ensuring food availability extends beyond crop production and depends equally on effective post-harvest management. According to national and international estimates, a considerable proportion of food grains is lost annually during storage due to insect infestation, fungal contamination, rodent attacks, moisture migration, and inadequate storage facilities. These post-harvest losses not only reduce food availability but also affect farmers' income, increase economic losses, and threaten national food security. Consequently, improving grain storage has become a critical component of sustainable agricultural development. Indian households have relied on indigenous grain storage systems that evolved through local experience, environmental adaptation, and traditional knowledge. Before the introduction of commercial storage technologies, rural communities developed storage structures using locally available materials such as bamboo, mud, clay, wood, straw, stone, and earthen pots. These structures, commonly known as *Kothi*, *Kanaja*, *Sanduka*, bamboo granaries, mud bins, wooden storage chests, and earthen containers, were designed to protect grains from moisture, insects, rodents, and adverse climatic conditions while maintaining grain quality over extended periods. Such storage systems continue to be used in many parts of India because they are affordable, environmentally sustainable, easy to maintain, and compatible with local cultural practices.

In addition to traditional storage structures, Indian households have developed numerous indigenous preservation practices for protecting stored grains. Natural materials including neem (*Azadirachta indica*) leaves, turmeric powder (*Curcuma longa*), wood ash, garlic (*Allium sativum*), camphor, tulsi (*Ocimum sanctum*), mustard oil, dried chilli pods, and other botanical products have been traditionally incorporated into stored grains to repel insects, suppress fungal growth, and improve storage life. These preservation techniques are based on generations of empirical knowledge and represent an important component of Indigenous Knowledge Systems (IKS). Unlike synthetic chemical pesticides, these traditional methods are generally biodegradable, inexpensive, locally available, and environmentally friendly. Their continued use demonstrates the practical value of indigenous knowledge in supporting sustainable post-harvest management and household food security. The proposed research is expected to bridge the gap between indigenous knowledge and modern digital technologies by developing a sustainable, affordable, and scalable smart storage solution suitable for rural households. The outcomes will contribute to reducing post-harvest losses, enhancing household food security, promoting environmentally friendly storage practices, and preserving India's rich indigenous knowledge systems. Furthermore, the study provides a pathway for integrating traditional agricultural practices with

digital agriculture and precision post-harvest management, supporting national and global goals related to sustainable food systems, climate resilience, and rural development. This paper is conceptual in scope: it synthesises evidence from published South Indian case studies to justify and specify a proposed IoT-enabled indigenous storage framework; prototype fabrication, field deployment, and empirical validation of the framework are outlined as the immediate next phase of this research programme rather than reported here.

Recent developments in digital agriculture have created new opportunities for enhancing traditional storage systems. The Internet of Things (IoT) has emerged as an enabling technology capable of continuously monitoring environmental conditions using interconnected sensors and communication networks. IoT-based monitoring systems can provide real-time information on storage temperature, relative humidity, grain moisture, carbon dioxide concentration, and other indicators associated with grain deterioration. Early detection of unfavorable storage conditions enables timely intervention, reducing post-harvest losses and improving grain quality. Compared with conventional inspection methods, IoT technologies offer continuous monitoring, automated alerts, remote accessibility, and data-driven decision support, making them increasingly attractive for agricultural applications. The present research proposes the development of an IoT-enabled indigenous grain and flour storage framework for Indian households. The study aims to document traditional storage structures and preservation practices, identify critical environmental factors affecting storage quality, integrate low-cost IoT monitoring technologies with indigenous storage systems, and evaluate their effectiveness in reducing post-harvest losses. By bridging indigenous knowledge with modern technological innovation, the proposed framework seeks to contribute to sustainable agriculture, household food security, digital transformation of post-harvest management, and the long-term preservation of India's rich traditional knowledge systems. The outcomes of this research are expected to provide a scalable and affordable smart storage model that can benefit rural communities while supporting national initiatives in digital agriculture, climate-resilient food systems, and sustainable rural development.

LITERATURE REVIEW

Indigenous grain storage practices have long played an important role in household food security, particularly in rural communities where storage systems are constructed from locally available and low-cost materials. Traditional structures such as Kothi, Kanaja, Sanduka, bamboo granaries, mud bins, earthen pots, and wooden containers have been widely documented in India. Bisheko et al. [1] highlighted the affordability, environmental suitability, and sustainability of these systems, while Vaidheki et al. [2] documented traditional storage infrastructures specifically in India and Tamil Nadu. These systems utilize materials such as bamboo, clay, mud, straw, and wood, thereby reducing construction costs and dependence on energy-intensive storage technologies. However, problems such as moisture ingress, insect infestation, fungal contamination, rodent attack, and inadequate aeration can reduce storage effectiveness [1], [2]. Consequently, scientific enhancement of indigenous systems is required without losing their resource-efficient characteristics.

Natural and botanical materials constitute another important component of indigenous grain preservation. Prakash et al. [3] documented several eco-friendly practices involving neem, turmeric, wood ash, chilli, garlic, and other locally available materials. Similar practices involving neem, ash, garlic, turmeric, and botanical products have been reported in other indigenous storage systems [4], [5]. Scientific studies have indicated that several botanicals possess insecticidal, repellent, or antifungal properties, providing a basis for their continued application in sustainable post-harvest management [6]. These materials are particularly attractive for household storage because of their local availability and relatively low cost. Nevertheless, the literature indicates that dosage, application methods, long-term effectiveness, and quality impacts are not yet adequately standardized [3], [6].

An important limitation of existing research is that most studies concentrate on whole-grain storage, whereas household storage of processed products such as wheat flour, rice flour, millet flour, and pulse flours has received comparatively limited attention. Sakthidevi and Manimozhi [7] specifically examined botanical materials used for grain flour storage among rural households in Tamil Nadu and reported the use of natural materials such as neem leaves and dried chillies for protecting flour from infestation and spoilage. Their study also emphasized the need for further scientific investigation of the effects of traditional preservation methods on flour quality, nutritional characteristics, and shelf life. This indicates an important opportunity to scientifically evaluate indigenous flour-preservation practices under controlled household storage conditions.

Indigenous knowledge extends beyond physical storage structures and includes grain selection, drying, moisture control, pest management, and periodic monitoring. Duguma [4] and Kumar and Kalita [8] emphasized that such knowledge contributes to household food security and reduces dependence on costly external storage and chemical preservation technologies. Traditional practices also have sustainability advantages because they generally require low energy inputs and utilize renewable or locally available resources. Thus, indigenous storage can be considered a form of household resource management involving food, natural materials, labour, energy, and economic resources. However, modernization and changing lifestyles may contribute to the gradual loss of such knowledge, emphasizing the need to document and scientifically strengthen these practices. Parallel to indigenous storage research, recent developments in IoT-based grain monitoring have introduced continuous measurement of storage conditions. Priyadarsani et al. [9] reviewed IoT applications in food-grain storage and identified temperature, relative humidity, moisture, and gas composition as important parameters for detecting potentially unfavourable storage conditions. Integration of sensor networks, cloud computing, and data analytics can support early identification of deterioration, insect activity, and quality loss. Bogala [10] further reviewed technological developments in Indian grain processing and storage, including sensor-based monitoring, hermetic storage, renewable-energy-assisted systems, IoT, artificial intelligence, and other smart technologies. However, high implementation cost, infrastructure requirements, technical complexity, and limited rural connectivity remain barriers to adoption of advanced systems by household and small-scale users.

Recent experimental research demonstrates the feasibility of real-time monitoring in grain storage. IoT-based systems have been applied for monitoring temperature, humidity, moisture, and gas-related parameters under controlled and bulk-storage conditions. Such studies demonstrate the value of continuous sensing compared with periodic manual inspection. However, most existing smart storage systems are designed for commercial warehouses, silos, or large-scale agricultural applications rather than household flour storage. Therefore, there remains a need for low-cost, decentralized monitoring systems that can operate with indigenous preservation methods and provide simple decision support for household users.

The literature therefore reveals a clear separation between two research streams: indigenous storage and preservation practices, which emphasize local resources, affordability, and sustainability, and IoT-enabled smart storage, which emphasizes real-time monitoring, automation, and data-driven decision-making. Very limited research has attempted to integrate these approaches into a single household-oriented framework. In particular, there is limited quantitative assessment of how traditional preservation materials influence storage conditions and flour quality when monitored continuously using IoT technologies. There is also insufficient investigation of resource utilization, energy consumption, storage capacity, preservation material requirements, and economic feasibility within such integrated systems.

Based on the reviewed literature, the major research gaps are identified as follows:

1. Limited research on flour storage: Most existing studies focus on whole grains, while household storage of wheat, rice, millet, and pulse flours remains comparatively under-investigated.
2. Insufficient scientific validation: Indigenous materials such as neem, turmeric, ash, garlic, and other botanicals have been widely documented, but their standardized effectiveness for processed flour storage requires further evaluation.
3. Limited South Indian documentation: Region-specific studies of indigenous household storage practices, particularly in South India, remain fragmented.
4. Absence of an integrated framework: Indigenous preservation practices, household storage management, IoT monitoring, and data-driven decision support have rarely been investigated as a unified system.
5. Limited resource and economic assessment: Few studies simultaneously examine storage losses, preservation-material utilization, energy requirements, monitoring costs, shelf life, and economic benefits.
6. Limited quantitative decision support: Existing traditional practices generally depend on experiential observation, while IoT studies often focus on monitoring rather than translating sensor information into simple household management decisions.

Accordingly, there is a need for an affordable and resource-efficient IoT-enabled household storage framework that combines indigenous preservation practices with continuous monitoring and intelligent decision support. The proposed study addresses this gap through a six-bin modular storage system incorporating indigenous preservation treatments, real-time sensing, multivariate analysis, and a Storage Health Index (SHI). The framework is intended not merely to monitor

storage conditions but to support efficient management of food, indigenous preservation materials, energy, storage capacity, labour, and information resources. To the best of the authors' knowledge, the integrated application of indigenous household grain/flour preservation, continuous IoT monitoring, PCA-based analysis, SHI-based decision support, and resource-management assessment represents a relatively unexplored research direction for South Indian household storage systems.

RESEARCH METHODOLOGY

The proposed research adopts a mixed-method research design comprising field documentation, prototype development, experimental validation, and performance evaluation. The research is designed to integrate indigenous household grain and flour storage practices with Internet of Things (IoT)-based monitoring technologies to develop a smart storage framework capable of reducing household wastages during storage while preserving traditional knowledge systems.

Documentation of Indigenous Storage Practices

A field survey conducted among rural households across selected agro-climatic regions of South India to document indigenous storage practices. Information regarding storage structures, preservation materials, storage duration, commonly stored grains and flours, and traditional pest management methods collected using structured questionnaires, interviews, and field observations. Data will be collected on traditional storage structures, grain and flour types stored, indigenous preservation materials, storage duration, pest management practices, household storage capacity, frequency of inspection, and environmental conditions. The collected information used to identify the most commonly practiced indigenous storage systems for prototype development.

Selection of Indigenous Storage System

Based on the survey findings, one or more representative traditional storage structures (e.g., earthen pot, bamboo bin, wooden container, or metal storage vessel) the better material out of the easily available stainless-steel containers were used in this experimental evaluation. Selection is based on frequency of household use, ease of modification, storage capacity, regional adaptability, and cost-effectiveness.

Design and Development of IoT-Based Smart Storage System

An IoT-enabled monitoring system will be designed and integrated with the selected indigenous storage structure.

Hardware Components

- ESP32 Microcontroller
- Temperature Sensor (DS18B20)
- Relative Humidity Sensor (SHT31 or DHT22)
- Grain Moisture Sensor
- CO₂ Sensor (MH-Z19B)
- Load Cell for Weight Monitoring
- Optional Camera Module for Pest Detection
- Rechargeable Battery / Solar Power Supply

Software Components

- Embedded firmware
- Cloud database
- Mobile application
- Web dashboard
- Alert notification module

The developed system will continuously monitor storage conditions and transmit real-time data through Wi-Fi or LoRa communication.

Experimental Evaluation

Two storage systems will be compared under identical environmental conditions. Experimental Setup for the System A shows traditional Indigenous Storage System B shows traditional Storage integrated with IoT Monitoring. Both systems will store identical quantities of grains and flour for a predetermined storage period of 3months. The materials used are Rice flour, Wheat flour, Bengal gram flour, and Maida flour.

System Architecture: Sensor-to-User Data Flow

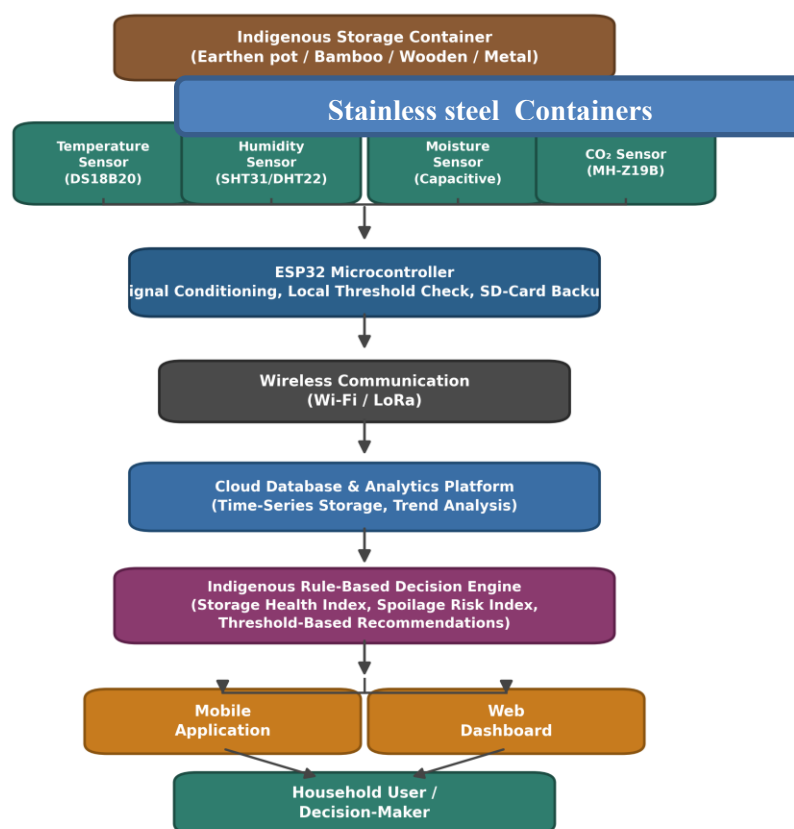


Figure 4. System architecture diagram showing the sensor-to-user data flow: environmental sensors mounted on the storage container feed the ESP32 microcontroller, which transmits data

over Wi-Fi/LoRa to the cloud platform; the rule-based decision engine then pushes threshold-based recommendations to the household user through the mobile application and web dashboard.

Performance Parameters

The following parameters will be monitored periodically.

- Physical Parameters are Temperature (°C) Relative Humidity (%), Flour Moisture (%), Biological Parameters are Insect Population, Rodent Damage, Fungal Growth, Microbial Load
- Quality Parameters are Weight Loss, Colour, Odour, Nutritional Quality, Shelf Life
- IoT Performance parameters are Sensor Accuracy, Data Transmission Reliability, Alert Response Time, Battery Performance.
- Data Analysis done using the collected data will be analysed using appropriate statistical techniques.
- Statistical Methods used for solution methods were used here are Descriptive Statistics, Analysis of Variance (ANOVA), Student's t-test, Correlation Analysis, Regression Analysis

Each statistical technique is selected for a specific purpose within this framework. Descriptive statistics (mean, standard deviation, range) will summarise baseline temperature, humidity, moisture, and pest-infestation trends for each storage system. ANOVA is appropriate because the design compares more than two storage conditions (e.g., multiple grain/flour types or multiple time points) simultaneously, making it more suitable than repeated pairwise tests. The Student's t-test is appropriate for the core two-group comparison in this study — Traditional Storage (System A) versus IoT-Integrated Storage (System B) — under identical storage duration and conditions. Correlation analysis is used to examine the strength and direction of association between environmental variables (e.g., relative humidity and moisture content, or temperature and insect activity) prior to modelling. Regression analysis is then applied to quantify how one or more environmental predictors (temperature, humidity, moisture) explain variation in storage-quality outcomes (weight loss, insect infestation, shelf life), which supports the threshold values used by the decision-support system. Data visualization shows the Temperature trends, Humidity profiles, Moisture variation, Pest infestation curves, Quality deterioration graphs

Development of Decision Support System

Based on sensor data and indigenous knowledge, a decision-support framework will be developed to recommendations on Dry grains before storage, replace neem leaves, increase ventilation, reduce moisture level, inspect storage container, perform periodic cleaning Recommendations will be generated automatically through predefined threshold values. The proposed IoT-enabled indigenous storage framework will be validated by comparing its performance with conventional storage practices using the following indicators: Reduction in post-harvest losses, Improvement in grain quality, Shelf-life extension, Reduction in insect infestation, Cost-effectiveness, User acceptance, Energy consumption

The study is expected to develop a low-cost IoT-enabled indigenous grain and flour storage framework capable of continuously monitoring storage conditions, providing real-time decision

support, reducing post-harvest losses, extending shelf life, and preserving traditional household storage knowledge. The proposed framework will contribute to sustainable food security by integrating indigenous management practices with modern digital technologies suitable for rural households in India.

Synthesis of Case Study Findings and the Need for an IoT-Based Monitoring System

The comparative analysis of published case studies from South India indicates that indigenous household grain and flour storage systems remain effective because of their low cost, environmental sustainability, and cultural acceptance. Earthen pots, bamboo baskets, mud granaries, wooden containers, and metal vessels continue to be widely used for storing rice, paddy, millets, pulses, and wheat in rural households. Natural preservation materials such as neem leaves, turmeric powder, wood ash, garlic, dried chilli, and camphor are frequently incorporated to reduce insect infestation and prolong storage life. Although these practices provide reasonable protection under normal storage conditions, their effectiveness is strongly influenced by seasonal climatic variations and household storage environments.

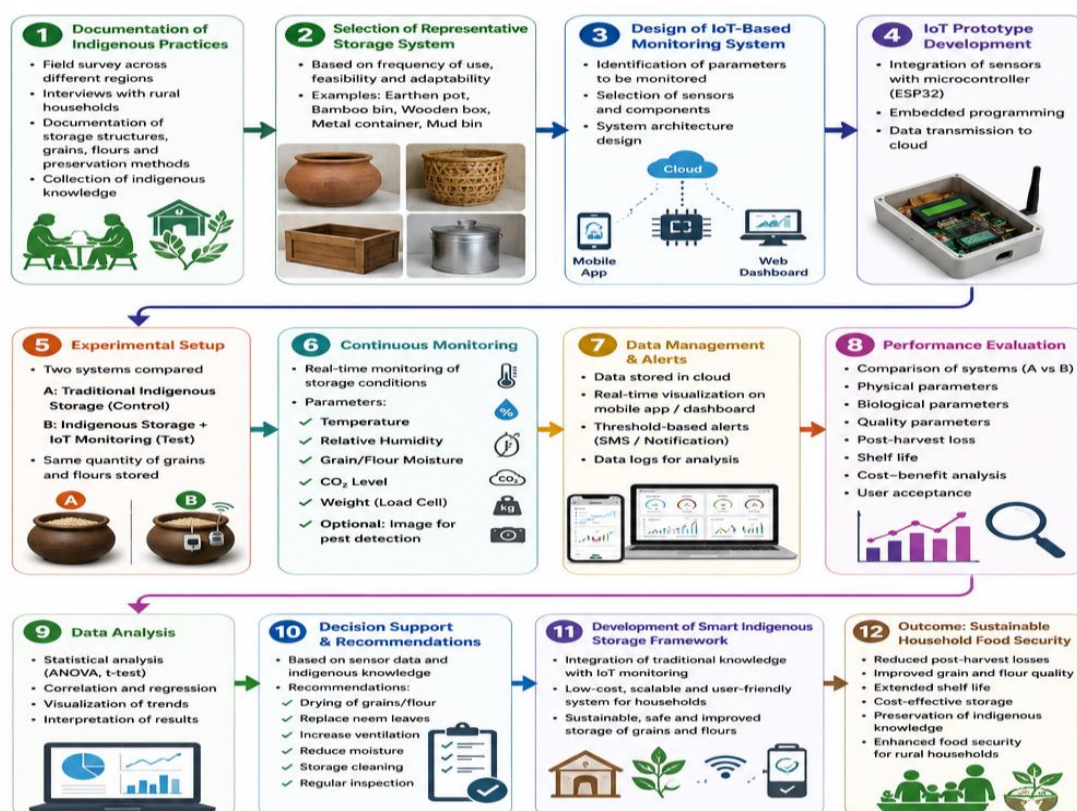


Figure 1. Overall research workflow of the proposed study, showing the four methodological phases from documentation of indigenous storage practices through IoT-based prototype development and experimental evaluation.

The reviewed studies consistently indicate that climatic variability has become one of the major factors affecting household grain storage. During the southwest and northeast monsoon seasons, increased atmospheric humidity leads to moisture absorption by storage containers and stored grains. Higher grain moisture promotes fungal growth, insect multiplication, unpleasant odour, discoloration, and quality deterioration. Similarly, elevated ambient temperatures during summer accelerate insect development, increase grain respiration, and reduce storage life. Traditional storage systems rely primarily on periodic visual inspection, and therefore deterioration is often detected only after significant quality loss has occurred. The case studies also reveal that household storage conditions differ considerably depending on building design, ventilation, roofing materials, floor construction, and storage location. Grain stored near kitchens, external walls, or poorly ventilated rooms is exposed to higher temperature and humidity fluctuations compared with grain stored in elevated, shaded, or well-ventilated locations. These environmental variations directly influence insect infestation, mould development, and grain moisture content. However, very few households continuously monitor these parameters, resulting in delayed corrective actions.

Another important observation from the literature is that indigenous botanical preservatives gradually lose their effectiveness with time. Neem leaves dry out, camphor sublimates, turmeric loses its volatile compounds, and ash becomes less effective after prolonged exposure to moisture. Since there is no mechanism for continuously assessing storage conditions, households generally replace these materials only after visible signs of infestation appear. Consequently, preventive storage management is replaced by corrective action after deterioration has already begun.

The literature further indicates that processed grain products such as rice flour, wheat flour, ragi flour, and pulse flours are more vulnerable to environmental changes than whole grains because of their larger surface area and increased susceptibility to moisture absorption, lipid oxidation, insect attack, and microbial spoilage. Nevertheless, scientific monitoring of flour storage conditions is rarely reported, creating an important gap in household post-harvest management. These findings collectively demonstrate that the major limitations of indigenous household storage systems are not the storage structures themselves but the absence of continuous environmental monitoring and timely decision support. Integrating Internet of Things (IoT)-based monitoring technologies with traditional storage systems can address these limitations by providing real-time measurement of storage conditions and early warning before quality deterioration becomes visible.

Table 2. Synthesis Matrix Mapping Climatic/Storage Issues Reported in the Reviewed South Indian Case Studies to the Proposed IoT Parameters, Sensors, and Decision-Support Actions

Climatic /Storage Issue	Common Observation in South Indian Studies	Impact on Grain/Flour	IoT Parameter	Suggested Sensor	Decision Support
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High relative humidity (monsoon)	Moisture uptake in storage containers	Fungal growth, caking, spoilage	Relative humidity	SHT31/DH T22	Dry grains, improve ventilation
High summer temperature	Faster insect development	Increased grain damage	Temperature	DS18B20	Move storage to a cooler location
Moisture ingress	Increased grain/flour moisture	Reduced shelf life	Grain moisture	Capacitive moisture sensor	Re-dry and reseal
Poor ventilation	Condensation and stale air	Mould growth	Temperature + RH	Combined sensor	Increase air circulation
Botanical protectants losing efficacy	Neem/camphor effectiveness declines	Increased pest risk	Time + environmental conditions	Sensor + reminder logic	Replace botanical materials
Early biological activity	No visible symptoms initially	Hidden spoilage	CO ₂ /VOC	MH-Z19B or BME688	Inspect storage immediately
Long storage duration	Quality gradually declines	Nutritional and sensory loss	Multi-parameter trend	Sensor suite	Recommend stock rotation

INTEGRATION OF NATURAL PRESERVATION PRACTICES WITHIN THE PROPOSED IOT-BASED INDIGENOUS STORAGE FRAMEWORK

The literature indicates that South Indian households have traditionally relied on a variety of natural ingredients to preserve grains and grain flours during storage. Botanical materials such as neem leaves (*Azadirachta indica*), turmeric (*Curcuma longa*), garlic (*Allium sativum*), dried red chilli, camphor, tulsi (*Ocimum sanctum*), curry leaves, wood ash, and mustard oil have been widely used because of their insect-repellent, antimicrobial, antifungal, and moisture-regulating properties. These indigenous preservation methods are inexpensive, environmentally friendly, readily available, and have been transferred across generations through traditional knowledge systems. However, their effectiveness is influenced by storage duration, climatic conditions, ambient temperature, relative humidity, and the gradual degradation of the active compounds present in these natural materials. One of the major limitations of current household storage practices is the absence of continuous monitoring of storage conditions. Traditional preservation methods are generally applied only at the time of storage, while replacement of botanical materials is performed based on visual observation or prior experience rather than scientific assessment.

Consequently, deterioration in storage conditions often remains undetected until insect infestation, fungal growth, unpleasant odour, or quality loss becomes visible. This reactive approach reduces the effectiveness of indigenous preservation methods, particularly under increasingly variable climatic conditions characterized by high temperature, elevated humidity, and irregular rainfall.

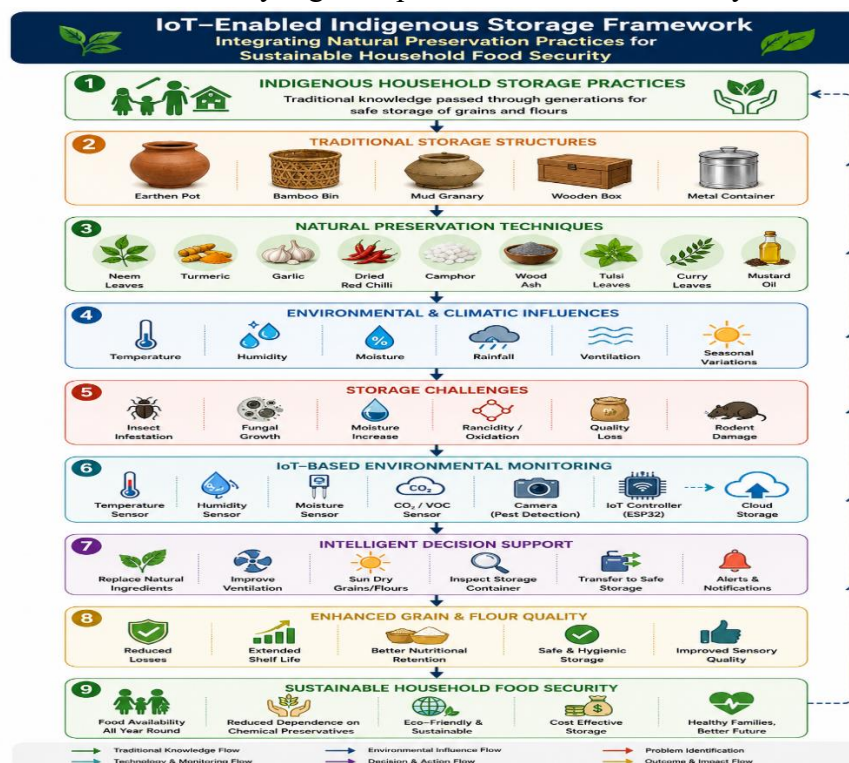


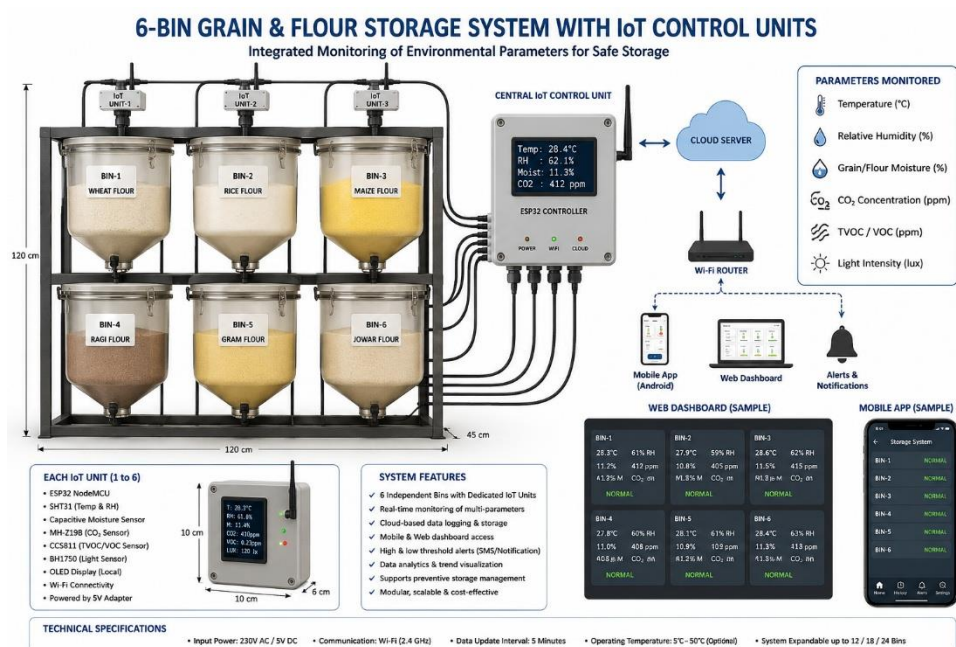
Figure 2. Conceptual integration of IoT-based environmental monitoring with the indigenous storage unit, illustrating how sensor data and rule-based decision support complement traditional botanical preservation practices.

The proposed IoT-based indigenous storage framework addresses this limitation by integrating environmental monitoring with traditional preservation practices. Instead of replacing indigenous knowledge, the IoT monitoring system functions as a decision-support tool that continuously observes critical storage parameters including temperature, relative humidity, grain or flour moisture, and indicators of biological deterioration. Based on predefined threshold values, the system can generate timely recommendations such as improving ventilation, sun-drying stored products, replacing neem leaves or camphor, inspecting storage containers, or reducing storage duration. Such recommendations complement the indigenous management practices already followed by households while improving their effectiveness through real-time environmental monitoring. The proposed framework therefore establishes a synergistic relationship between traditional preservation techniques and modern digital technologies. Indigenous botanical materials continue to serve as the primary preservation mechanism, whereas the IoT monitoring system provides early warning and evidence-based decision support to optimize their performance under changing environmental conditions. This integrated approach preserves traditional

knowledge while enhancing storage efficiency, extending the shelf life of grains and grain flours, reducing post-harvest losses, and improving household food security. The framework further supports sustainable agriculture by minimizing dependence on synthetic chemical preservatives and promoting environmentally responsible household storage practices.

Experimental Setup of the IoT-Based Indigenous Grain and Flour Storage Monitoring System

The proposed experimental setup is designed to monitor the environmental conditions of traditional household grain and flour storage systems while preserving indigenous storage practices. Unlike conventional smart storage systems developed for industrial silos, the proposed platform is intended for household-scale storage structures commonly used in South India, including earthen pots, bamboo baskets, wooden storage boxes, mud granaries, and stainless-steel containers.



The experimental facility consists of two major subsystems: (i) the Indigenous Storage Unit and (ii) the IoT-Based Monitoring Unit. The Indigenous Storage Unit contains food grains and grain flours preserved using traditional botanical materials such as neem leaves, turmeric powder, garlic cloves, wood ash, camphor, dried chillies, and tulsi leaves. These natural ingredients act as eco-friendly preservatives against insect infestation and microbial deterioration. The IoT-Based Monitoring Unit continuously measures critical environmental parameters influencing storage quality. Temperature and relative humidity are monitored using digital environmental sensors to evaluate climatic variations inside the storage container. A capacitive moisture sensor estimates moisture changes within the stored grains or flour, while CO₂ and volatile organic compound (VOC) sensors detect early biological activity associated with insect respiration and fungal spoilage. All sensor data are acquired by an ESP32 microcontroller, which performs local data

processing and transmits the measurements to a cloud database through a Wi-Fi communication module. The cloud platform stores time-series sensor data and performs threshold-based analysis to identify abnormal storage conditions. Based on predefined decision rules derived from indigenous household storage practices, the system generates recommendations such as replacing botanical preservatives, improving ventilation, sun-drying grains or flour, inspecting storage containers, or reducing storage duration. The processed information is presented to users through a mobile application and a web-based dashboard, allowing continuous monitoring of household storage conditions. The following are the step by step procedure for the experiment.

Data Acquisition

The environmental sensors installed inside or near the indigenous storage container continuously monitor storage conditions, including temperature, relative humidity, moisture content, CO₂ concentration, and volatile organic compounds (VOCs). These parameters are selected because they directly influence grain and flour quality during storage.

Signal Conditioning and Processing

The sensor outputs are conditioned, filtered, and digitized before being processed by the ESP32 microcontroller. The controller removes noise, validates sensor readings, and prepares the data for analysis.

Local Decision Making

The ESP32 compares the measured values against predefined threshold limits based on grain storage standards and indigenous storage practices. If any parameter exceeds the permissible range, the controller immediately flags the storage condition as requiring attention.

Wireless Communication

The processed sensor data are transmitted through the ESP32's Wi-Fi module to a secure cloud database. Simultaneously, a local copy is stored on an SD card to ensure data availability even during network interruptions.

Cloud-Based Analytics

The cloud platform stores historical sensor data, analyzes long-term trends, evaluates climatic influences, and calculates storage quality indicators such as a Storage Health Index and a Spoilage Risk Index.

Indigenous Decision Support

Instead of recommending chemical treatments, the decision-support engine applies a rule base derived from indigenous household storage practices. Recommendations may include replacing neem leaves, replenishing camphor, improving ventilation, sun-drying grains or flour, cleaning the storage container, or consuming older stored products first.

User Notification

The recommendations and storage status are communicated to users through a mobile application and web dashboard, enabling timely interventions to maintain grain and flour quality.

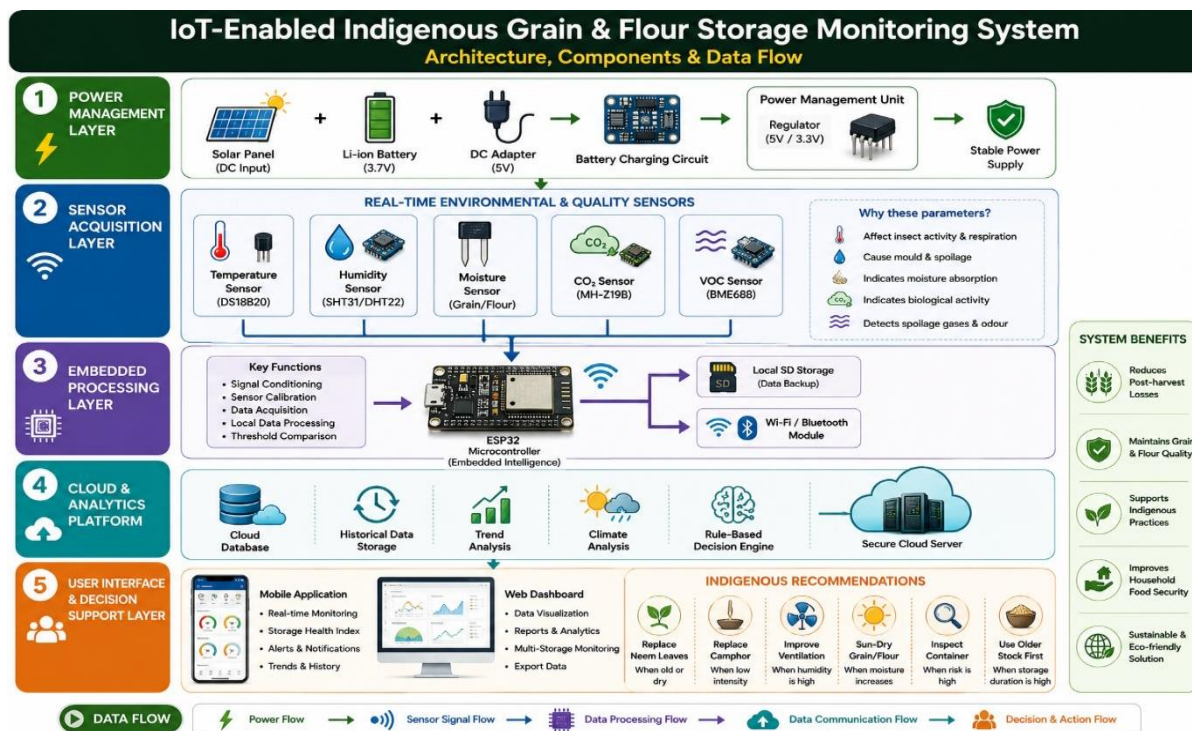


Figure 3. Seven-step scientific working principle of the proposed IoT-enabled indigenous storage monitoring system, from sensor data acquisition through cloud-based analytics to user notification.

The proposed facility therefore combines indigenous preservation knowledge with real-time environmental sensing to create an intelligent decision-support system capable of reducing post-harvest losses while maintaining the sustainability and cultural relevance of traditional storage practices.

Case Study

This case study investigates the performance of an IoT-enabled indigenous grain flour storage system consisting of six independent storage bins under varying climatic conditions and storage durations. Each bin stores a different grain flour and incorporates a distinct indigenous preservation treatment, enabling a comparative evaluation of traditional storage practices. IoT sensors continuously monitor key environmental and storage-quality parameters, including temperature, relative humidity, flour moisture, CO₂ concentration, VOC levels, light intensity, insect infestation, fungal growth, colour change, and odour. The study is conducted over a 90-day storage period under representative South Indian climatic conditions to understand the influence of environmental variations on flour quality and shelf life. Owing to the large number of correlated sensor variables, Principal Component Analysis (PCA) is employed to identify the dominant factors governing storage performance, reduce data dimensionality, and classify the effectiveness of different preservation treatments. The findings are expected to support the development of a scientifically validated IoT-assisted indigenous storage framework and provide practical

recommendations for sustainable household grain flour storage.

Parameter Study for Different Storage systems

Parameter	Overall Observation	Need for IoT
Temperature	Strong seasonal variation affects grain quality	Continuous temperature sensing
Relative Humidity	Primary factor influencing moisture uptake	RH sensor with alerts
Moisture Content	Critical determinant of spoilage	Grain/flour moisture monitoring
Insect Infestation	Increases under warm, humid conditions	Early warning and trend analysis
Fungal Growth	Linked to prolonged high humidity	VOC and CO ₂ sensing
Natural Preservatives	Effective but efficacy decreases over time	Replacement reminders based on storage conditions
Flour Storage	More vulnerable than whole grains	Enhanced monitoring and shelf-life prediction
Climate Change	Increased variability challenges traditional practices	Real-time environmental monitoring and decision support

Parameter Study at Different Storage Periods

Storage Days	Temp (°C)	RH (%)	Moisture (%)	CO ₂ (ppm)	VOC (ppb)	Insect Count	Fungal Score	Colour Change	Odour Score
Day 0	27	55	10.8	420	5	0	0	None	Fresh
Day 15	29	62	11.0	450	8	0	0	None	Fresh
Day 30	31	68	11.5	520	15	1	0	Slight	Normal
Day 45	33	75	12.2	650	28	2	1	Moderate	Mild
Day 60	34	80	13.1	790	42	4	2	Moderate	Slight Rancidity
Day 75	35	85	14.0	920	60	6	3	High	Rancid
Day 90	36	90	15.2	1100	95	10	5	Severe	Spoiled

Principal Component Analysis (PCA) for Parameter Study

Principal Component Analysis (PCA) was selected because the proposed IoT-enabled grain flour storage system generates a large number of correlated environmental and quality parameters, including temperature, relative humidity, flour moisture, CO₂ concentration, VOC levels, insect infestation, fungal growth, colour change, and odour. These variables are interdependent and often influence storage quality simultaneously, making it difficult to identify the dominant factors using conventional statistical methods.

PCA is a multivariate statistical technique that transforms correlated variables into a smaller set of uncorrelated principal components while retaining most of the information contained in the

original dataset. This dimensionality reduction enables the identification of the most influential factors governing grain flour deterioration under different storage durations, climatic conditions, and indigenous preservation treatments.

The use of PCA in this study offers several advantages:

- Reduces data complexity by summarizing numerous IoT sensor variables into a few principal components.
- Identifies the dominant environmental factors affecting grain flour quality and shelf life.
- Reveals relationships among storage parameters, helping to understand interactions between temperature, humidity, moisture, gas emissions, and biological spoilage.
- Classifies storage conditions and treatments by grouping bins with similar storage characteristics and preservation performance.
- Supports the development of a Storage Health Index (SHI) by selecting the most significant variables contributing to storage quality.
- Facilitates visualization of multidimensional IoT data through score plots and loading plots, enabling easier interpretation of storage behaviour.
- Improves decision-making for optimizing indigenous preservation methods and storage conditions based on objective statistical evidence.

Key Results Derived from the Case Studies

The evidence synthesis suggests that:

1. Traditional storage structures remain effective when properly maintained and are well adapted to local climatic conditions.
2. Botanical preservatives such as neem, turmeric, garlic, ash, and camphor provide environmentally friendly protection against storage pests and spoilage.
3. Temperature, relative humidity, and moisture are the dominant environmental factors affecting the quality of stored grains and flours.
4. Grain flours are consistently reported as more susceptible to moisture absorption, rancidity, fungal growth, and quality degradation than whole grains.
5. Current household practices rely on visual inspection, resulting in delayed detection of adverse storage conditions.
6. No reviewed study reported an integrated system combining indigenous preservation practices with continuous IoT-based environmental monitoring specifically for household grain and flour storage in South India.
7. These findings provide a strong rationale for the proposed IoT-enabled Indigenous Grain and Flour Storage Monitoring Framework, which enhances traditional practices through real-time sensing, early warning, and culturally appropriate decision support

DISCUSSION ON THE RESULTS

The following subsections interpret the key results summarised above in relation to the wider literature, rather than restating them; each subsection therefore focuses on a distinct implication (scientific relevance, climatic drivers, botanical efficacy, the flour-storage gap, the case for IoT

monitoring, knowledge integration, comparison with existing technologies, and practical implications) instead of repeating the same finding from multiple angles.

Indigenous Household Storage Systems Continue to be Scientifically Relevant

The comparative analysis of published case studies indicates that indigenous household storage systems remain an integral component of food security across South India. Case studies from Tamil Nadu, Karnataka, Kerala, Andhra Pradesh, Telangana, and Puducherry consistently demonstrate that earthen pots, mud granaries, bamboo baskets, wooden bins, and metal containers continue to be used because of their affordability, environmental sustainability, and compatibility with local climatic conditions. Sundaramari et al. (2011) documented several traditional grain storage structures unique to South Tamil Nadu, including *Kuthir*, *Kulumai*, *Kaambara*, and *Modappanai*, illustrating how local communities adapted storage designs to regional climatic conditions. Similarly, Naveena et al. (2016, 2017) reported that tribal communities in Karnataka continue to preserve cereals and millets using bamboo baskets, mud pots, and traditional granaries supported by botanical preservation practices. These observations agree with the comprehensive review by Bisheko et al., who concluded that indigenous grain storage systems remain sustainable, economically viable, and environmentally friendly despite rapid modernization (Bisheko et al., 2023). Taken together, these consistent findings across states indicate that the proposed framework should preserve these structures unmodified rather than replace them, positioning IoT monitoring purely as an add-on layer.

Climatic Variability is the Primary Driver of Storage Deterioration

A recurring observation across the reviewed case studies is the strong influence of climatic conditions on household grain and flour storage. South India's monsoon climate is characterized by high relative humidity, elevated temperatures, and seasonal fluctuations that accelerate moisture absorption, insect multiplication, fungal contamination, and grain respiration. The Tamil Nadu and Kerala case studies consistently reported higher storage losses during humid monsoon periods, while studies from Karnataka and Telangana highlighted increased insect infestation during summer months. These findings indicate that storage deterioration is primarily governed by environmental conditions rather than deficiencies in indigenous storage structures themselves. Recent reviews on post-harvest technologies similarly emphasize that temperature and relative humidity are the dominant environmental variables controlling grain quality and storage stability, highlighting the importance of continuous monitoring under changing climatic conditions (Bogala, 2025). This distinction matters for the proposed framework: because deterioration tracks climate rather than structural design, the sensor suite should prioritise humidity and temperature thresholds over structural modifications to the storage containers themselves.

Scientific Basis of Indigenous Botanical Preservation

The reviewed case studies consistently identified neem leaves, turmeric powder, wood ash, garlic, camphor, dried chilli, and tulsi leaves as the most commonly used natural preservatives for protecting grains and grain flours. These botanical materials are valued because they are inexpensive, biodegradable, locally available, and possess insect-repellent, antimicrobial, and

antifungal properties. Nevertheless, the effectiveness of these materials depends on environmental conditions and decreases gradually with prolonged storage. Case studies from Tamil Nadu and Karnataka reported that households usually replace botanical preservatives only after visible deterioration occurs, resulting in delayed intervention. This finding suggests that indigenous preservation methods themselves remain effective but require timely management to maximize their protective effect. Bisheko et al. similarly argued that indigenous preservation practices should be scientifically enhanced rather than replaced, thereby preserving traditional knowledge while improving storage performance (Bisheko et al., 2023).

This delayed-replacement pattern is precisely the gap the proposed decision-support engine targets: rather than asking households to judge efficacy by eye, threshold-based alerts can prompt replacement while the botanical protectant is still effective.

Household Grain Flour Storage Represents an Important Research Gap

The literature synthesis demonstrates a clear imbalance between research on whole grain storage and household grain flour storage. While numerous studies have investigated the storage of paddy, rice, maize, millets, and pulses, comparatively few have examined the preservation of rice flour, wheat flour, ragi flour, or pulse flours under household conditions. The available case studies indicate that grain flours exhibit greater susceptibility to moisture absorption, lipid oxidation, fungal growth, insect infestation, and sensory deterioration because of their increased surface area and disrupted grain structure. Despite this higher vulnerability, continuous monitoring of flour storage conditions has received limited scientific attention. Consequently, grain flour storage represents an important research opportunity within indigenous post-harvest management systems. This imbalance is a direct justification for the flour-specific sensors and moisture thresholds built into the proposed framework, rather than simply reusing whole-grain monitoring parameters.

Justification for IoT-Based Environmental Monitoring

One of the most significant findings emerging from the comparative analysis is that the principal limitation of indigenous storage systems is the absence of continuous environmental monitoring rather than deficiencies in the storage structures themselves. Existing household practices depend almost entirely on periodic visual inspection, preventing early detection of adverse storage conditions. Consequently, corrective actions are often implemented only after insect infestation, fungal growth, moisture accumulation, or quality deterioration has become visible. Recent technological reviews emphasize that IoT-enabled monitoring systems provide continuous measurement of temperature, relative humidity, moisture, carbon dioxide concentration, and volatile compounds, enabling predictive storage management instead of reactive intervention. However, existing smart storage technologies are predominantly designed for commercial warehouses and large-scale grain silos, with limited applicability to rural household storage systems (Bogala, 2025).

Integration of Indigenous Knowledge with IoT Technologies

The proposed IoT-enabled indigenous storage framework directly addresses the gaps identified through the case study analysis. Rather than replacing traditional storage structures, the framework

integrates environmental sensing with indigenous preservation practices. The proposed monitoring system continuously evaluates temperature, relative humidity, grain or flour moisture, carbon dioxide concentration, and volatile organic compounds while interpreting these measurements using a rule-based knowledge system derived from traditional household practices. For example, elevated humidity may generate recommendations to sun-dry grains, improve ventilation, or replace neem leaves, whereas prolonged high temperatures may trigger alerts to inspect stored flour or relocate storage containers. This approach transforms indigenous knowledge into an intelligent decision-support system while preserving its cultural relevance and practical applicability.

Comparison with Existing Smart Storage Technologies

On comparison most reported IoT-based storage systems were on focus with industrial silos and commercial warehouses, the proposed framework is specifically designed for household-scale indigenous storage systems. Recent reviews have highlighted that current digital grain storage technologies often require substantial investment, continuous electrical power, and technical expertise, thereby limiting their adoption among rural households. In contrast, the proposed framework is intended to complement existing earthen pots, bamboo baskets, mud granaries, and metal containers without requiring major modifications. Consequently, the proposed system provides a low-cost, scalable, and culturally compatible solution for improving household grain and flour storage while preserving traditional knowledge systems (Bogala, 2025).

Practical Implications

The findings have important implications for household food security, climate adaptation, and sustainable agriculture. Integrating indigenous storage practices with IoT-based monitoring can reduce post-harvest losses through early detection of unfavorable environmental conditions while minimizing dependence on synthetic chemical preservatives. The proposed framework further supports climate-resilient storage management by enabling households to respond proactively to seasonal variations in temperature and humidity. From a policy perspective, the framework offers opportunities for integration into agricultural extension programmes, Farmer Producer Organizations (FPOs), Self-Help Groups (SHGs), and rural digital agriculture initiatives, thereby facilitating widespread adoption of affordable smart storage technologies.

Research Contribution

This study contributes to the literature in five significant ways. First, it synthesizes published evidence on indigenous household grain and grain flour storage practices across South India. Second, it identifies climatic variability as the primary factor influencing household storage performance. Third, it highlights the limited scientific investigation of indigenous flour storage compared with whole grain storage. Fourth, it demonstrates that the principal limitation of traditional storage systems is the lack of continuous environmental monitoring rather than inadequacies in the storage structures themselves. Finally, it proposes an IoT-enabled Indigenous Grain and Flour Storage Framework that integrates traditional botanical preservation methods with real-time environmental sensing and knowledge-based decision support. This integration provides

a scientifically grounded pathway for preserving indigenous knowledge while advancing sustainable post-harvest management under changing climatic conditions.

Limitations

This study is conceptual in nature and is based on the synthesis of published evidence from South Indian case studies rather than on original field data. No prototype has yet been built, and no empirical or field validation of the proposed IoT-enabled framework has been carried out. The environmental thresholds, decision rules, and performance expectations described in this paper are therefore drawn from the literature and from engineering design principles, not from measured outcomes. Prototype implementation, laboratory testing, and household-level field validation across diverse agro-climatic regions constitute the necessary next phase of this research programme.

CONCLUSION AND FUTURE WORK

This study proposes an IoT-enabled smart resource management framework for sustainable household grain flour storage by integrating indigenous preservation practices with digital monitoring technologies. The proposed six-bin system enables continuous monitoring of temperature, relative humidity, flour moisture, CO₂, VOCs, storage quantity, and storage duration, providing a scientific basis for efficient storage management. The integration of indigenous preservatives with IoT-based monitoring supports better utilization of locally available resources while reducing food losses and unnecessary manual intervention. PCA-based analysis provides a means of identifying the dominant parameters influencing storage deterioration, while the proposed Storage Health Index (SHI) enables simple assessment and timely management decisions. The framework also supports low-power operation, efficient use of storage capacity, and data-driven household resource management under variable climatic conditions. Overall, the proposed approach demonstrates the potential of combining indigenous knowledge, IoT, and data analytics to develop a sustainable, climate-resilient, and resource-efficient household grain flour storage system. Future research should focus on integration of artificial intelligence and machine learning can further enhance the framework by enabling spoilage prediction, shelf-life estimation, and intelligent decision support. Future developments may also include a Storage Health Index (SHI), multilingual mobile applications, cloud-based monitoring, and economic feasibility analysis to improve user adoption. Additionally, extending the framework to the storage of spices, pulses, oilseeds, and other household food products will broaden its applicability and contribute to sustainable, climate-resilient, and technology-enabled post-harvest management.

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