

A Techno-Economic Framework for Energy-Efficient and Intelligent Cold Storage Management in Agricultural Supply Chains

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ABSTRACT

Smallholder farmers face high post-harvest losses due to the costly, grid-dependent cold chains with limited monitoring and market access. The current study presents an integrated framework combining Photovoltaic (PV) refrigeration with Phase-Change Materials (PCM) for thermal buffering, Internet of Things (IoT) monitoring, a Controlled-Atmosphere (CA) loop, and a lightweight mobile marketplace. A 200 L prototype was deployed for 30 days in a peri-urban cluster near Dharwad, India. The present study evaluated the daily energy use, temperature/Relative Humidity (RH) stability, shelf life, price realization, and 3-year Return On Investment (ROI). With PCM, energy fell by ~28% (to 2.5–2.7 kWh/day from 3.4–3.6 kWh/day), while the chamber temperature held within ± 1.1 °C with <6% RH variation. The shelf life extended up to 4 \times , and app users realized ~22% higher prices, yielding an estimated 3-year ROI of ~2.05 \times . Compared with conventional storage, the results highlight the joint value of PCM-assisted cooling, closed-loop IoT/CA control, and market linkage for smallholders.

Keywords-Smart cold storage; solar-powered refrigeration; IoT monitoring; phase change materials; controlled atmosphere; post-harvest management; smallholder farmers; energy efficiency

I. INTRODUCTION

Cold storage is pivotal for preserving the quality and shelf life of perishable agricultural products, thereby reducing the post-harvest losses and stabilizing the farmer income. In developing economies—particularly agrarian nations, such as India—an estimated 25–30% of fruits and vegetables are lost due to the absence of timely cooling, inefficient logistics, and inadequate temperature-controlled storage [1]. These losses depress the profitability and contribute to national-level food insecurity and agri-supply-chain inefficiencies. Despite the growing adoption of cold storage in urban and industrial settings, small- and medium-scale farmers in rural areas remain marginalized by economic and logistical constraints [2]. Centralized units are often distant and energy-intensive, requiring high Capital Expenditure (CAPEX) and Operational Expenditure (OPEX), while they typically lack adaptability, monitoring, or control aligned with the diverse crop needs and dynamic market demands [2, 3].

Conventional cold chains rely on centralized, grid-powered refrigeration that is energy-intensive and poorly suited to smallholder needs. Such systems lack scalability and flexibility, limiting the accessibility in decentralized

agricultural contexts. Innovations, involving modular and mini-container designs, improve the energy efficiency and adaptability, yet the rural deployments remain limited [4]. Solar-powered cold storage, PV systems coupled with battery backup or thermal energy storage via PCM, have emerged as a viable alternative for off-grid regions. It has been reported that PV-based systems reduce the operating costs while maintaining stable cooling for perishables, making them promising for small- and medium-scale farmers. The integration of IoT and Wireless Sensor Networks (WSN) enhances the real-time monitoring and automation in cold storage. Battery-free, solar-powered sensors reduce the energy consumption and improve the reliability, allowing for the dynamic control of the environmental conditions and early detection of spoilage. Additionally, IoT-based temperature and RH tracking meets sustainability and technical requirements, thereby improving the decision-making accuracy. Direct-to-Consumer (D2C) supply models supported by Information and Communication Technology (ICT) platforms are emerging to shorten the supply chains and empower the farmers. Although underutilized in cold-chain contexts, ICT-based market linkages show strong potential to improve the income and transparency for smallholders.

Nevertheless, integrated and cost-effective solutions that jointly combine renewable energy, IoT-based monitoring and control, and market connectivity remain scarce for decentralized, smallholder-focused deployments [1-4]. These challenges underscore the need for a decentralized, energy-efficient, and intelligent cold-storage framework that conserves energy while integrating digital tools to strengthen the market connectivity [5]. Conventional systems face four persistent constraints: they are energy-intensive, relying on grid electricity or diesel, which in weak-grid settings leads to thermal instability [6], and entail high CAPEX/OPEX, limiting the deployment and scalability across farming clusters. They lack real-time monitoring and control, leading to overcooling and poor crop-specific tuning. Additionally, they are disconnected from the market signals, as most units do not provide a digital interface for price monitoring or demand forecasting [7]. These gaps motivate a techno-economic framework that treats intelligence, modularity, and digital integration as first-class design principles [8].

The present work develops a sustainable, intelligent cold-storage framework tailored to resource-constrained agricultural communities.

II. SYSTEM ARCHITECTURE AND METHODOLOGY

The proposed techno-economic cold-storage framework is mapped to three core objectives: energy-efficient cold storage, farmer-consumer digital engagement, and intelligent CA management. The architecture consists of four tightly integrated modules: renewable-powered cold storage, IoT-based monitoring, a digital marketplace interface, and an ML-driven CA unit.

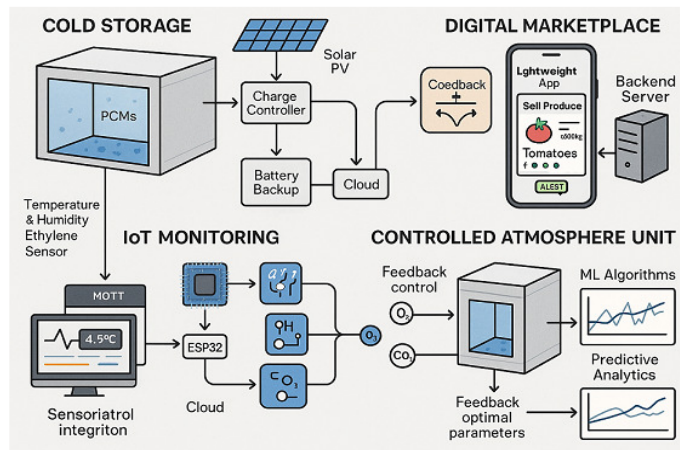


Fig. 1. Proposed smart cold storage framework.

Figure 1 illustrates the integrated architecture of the proposed smart cold-storage framework, which combines four core modules, energy-efficient cold storage, IoT-based environmental monitoring, digital marketplace access, and a CA unit—each contributing to scalable, sustainable, and intelligent post-harvest management [9].

The architecture comprises four tightly integrated modules:

- A cold-storage module powered by a solar PV system with a charge controller and battery backup to ensure continuous refrigeration in off-grid conditions, with the chamber thermally stabilized using PCM to reduce the energy fluctuations and preserve the temperature during power loss or peak load.
- An IoT monitoring layer in which sensors (temperature, RH, ethylene, CO₂) feed an ESP32-based controller that publishes data to the cloud via MQTT, with a real-time dashboard that displays readings and triggers anomaly alerts to maintain optimal environmental conditions.
- A digital marketplace interface (mobile/web) that allows farmers to list stored products, track freshness, and connect directly with consumers or vendors, while the backend manages the pricing updates, inventory data, and interactions to improve the transparency and margins.
- A CA unit that adjusts O₂ and CO₂ via feedback control, using IoT sensor data to actuate valves and maintain the target compositions, with ML-based analytics suggesting optimal storage parameters and forecasting price windows to align the storage duration with the demand peaks.

This architecture provides a modular, cost-effective, and intelligent cold-storage solution tailored to smallholder farmers, addressing the energy inefficiencies, post-harvest losses, and limited market access through integrated sensing, data-driven control, and digital engagement.

A. Cold Storage Design Using Renewable Energy Sources

To ensure the sustainability and reduce the operational costs, the cold-storage unit is powered by a PV system with an MPPT charge controller and battery backup, ensuring stable operation under variable solar irradiance and at night. To minimize the load and maintain thermal equilibrium, the chamber is lined with PCM that absorbs and releases latent heat, buffering the temperature fluctuations and reducing the compressor cycling. PV generation is routed through the MPPT to the battery and simultaneously supplies the storage control system. The energy-flow and usage metrics, including surplus generation, are logged to a cloud platform for transparency and operational efficiency tracking. The energy balance for the system can be described by:

$$P_{\{gen\}}(t) = \eta_{\{pv\}} \cdot A_{\{pv\}} \cdot G(t) \tag{1}$$

where $P_{\{gen\}}(t)$ is the power generated time $t(w)$, $\eta_{\{pv\}}$ is the PV efficiency, $A_{\{pv\}}$ is the Panel area (m²), and $G(t)$ is the Solar irradiance at time $t (W/m^2)$.

To ensure the continuity of cooling, the system includes a battery bank and an MPPT charge controller. During periods of low insolation, PCM act as thermal buffers, storing latent heat:

$$Q_{\{PCM\}} = m_{\{pcm\}} \cdot L_f \tag{2}$$

where $Q_{\{PCM\}}$ is the latent heat stored/released (J), $m_{\{pcm\}}$ is the Mass of PCM (kg), and L_f is the latent heat of fusion (J/kg). This PCM buffering maintains the chamber temperature at 4–10 °C, optimizing the compressor duty cycles and minimizing the energy spikes.

B. IoT-Enabled Environmental Monitoring

To monitor the storage conditions in real-time, the system is equipped with a suite of environmental sensors, including: Temperature and humidity sensors (e.g., DHT22) [10], ethylene sensors for fruit ripening, and CO₂ sensors to detect the gas buildup. Each sensor node follows:

$$S_i(t) = f(V_{\{out\}}, T_{\{ref\}}, R_s) \quad (3)$$

where $S_i(t)$ represents the reading of sensor i as a function of output voltage $V_{\{out\}}$, reference temperature $T_{\{ref\}}$, and sensor resistance R_s .

These sensors connect to an ESP32 controller or a Raspberry Pi single-board computer, which collects, filters, and publishes data over MQTT. The readings are visualized on a cloud dashboard (e.g., AWS IoT Core or Blynk) that provides live feedback and threshold-based alerts, notifying farmers or operators immediately regarding the anomalies that could affect the produce quality. By closing the loop, this module enables precise climate control, supports data-driven decision-making, and minimizes manual intervention, directly improving energy efficiency and production quality [11].

C. Digital Marketplace Integration

To enable a direct interaction between the farmers and end consumers or aggregators, a lightweight mobile/web application is developed [12]. Through the app, farmers can:

- List products stored in the cold chamber.
- Update the quantity, quality, and expected price.
- Track freshness metrics based on the environmental conditions.

The application uses a cloud-hosted backend (Firebase or Django) that exposes a RESTful Application Programming Interface (API) for authentication, database management, and request handling. A smart pricing component adjusts the pricing recommendations based on the shelf life, local demand patterns, and historical price data. The app includes freshness scoring, F_s , defined as:

$$F_s = 100 - \alpha \cdot (T_{\{avg\}} - T_{\{opt\}})^2 - \beta \cdot t_{\{storage\}} \quad (4)$$

where $T_{\{avg\}}$ is the average temperature in storage, $T_{\{opt\}}$ is the optimal temperature for produce, $t_{\{storage\}}$ is the Time stored (hours or days), α and β are the weighting constants based on spoilage sensitivity. A higher F_s indicates better freshness and is shown to buyers in real-time.

This digital integration eliminates the intermediaries, provides better price realization for farmers, and gives consumers access to fresh, locally stored products [12].

D. CA Unit Design

The CA unit provides automated regulation of O₂ and CO₂ inside the storage chamber to slow the respiration and aging in fruits and vegetables. A feedback control loop, driven by real-time gas sensors, maintains crop-specific atmospheric setpoints [13].

The CA unit ensures optimal gas composition through real-time gas regulation and ML-guided prediction. Gas control (O₂/CO₂) follows a feedback control loop:

$$u(t) = K_p \cdot e(t) + K_i \int e(t) dt + K_d \cdot \frac{d e(t)}{dt} \quad (5)$$

where $u(t)$ is the control signal to the actuator, $e(t)$ is the error between the setpoint and the measured gas concentration, and K_p , K_i , K_d are the PID controller constants.

ML models, such as linear regression or time series forecasting, predict the future gas composition and price peaks:

$$P_{\{future\}} = \theta_0 + \theta_1 t + \theta_2 T_{\{storage\}} + \theta_3 C_{\{gas\}} \quad (6)$$

where $P_{\{future\}}$ is the predicted optimal price window, $C_{\{gas\}}$ is the current gas composition, t is the forecast horizon, and θ_1 are the learned coefficients. This enables the system to adjust the atmosphere proactively and align the product release with the peak market demand, enhancing the revenue.

III. PROTOTYPE IMPLEMENTATION AND TESTBED SETUP

Figure 2 illustrates the integrated architecture of the smart cold storage prototype, showcasing its energy, sensing, control, and communication modules. A 400 W PV panel with battery backup powers a 200 L PCM-lined chamber, maintaining 4–10 °C internal temperatures. The environmental conditions are monitored using a DHT22 sensor for temperature and RH (accuracy: ± 0.5 °C, $\pm 2\%$ RH, with low cost) and an MQ135 sensor for CO₂ air quality, given its sensitivity to gases relevant to perishable-produce storage. An ethylene sensor is also included; all sensors interface with a Raspberry Pi 4. The Raspberry Pi 4 regulates cooling via relays and transmits real-time data to an IoT cloud dashboard over MQTT. Farmers can remotely monitor freshness indicators, temperature, and inventory (e.g., "Tomatoes: 250 kg") and list produce for sale through a mobile app. This setup enables energy-efficient storage, digital market access, and data-driven decision-making optimized for smallholder deployment [13].

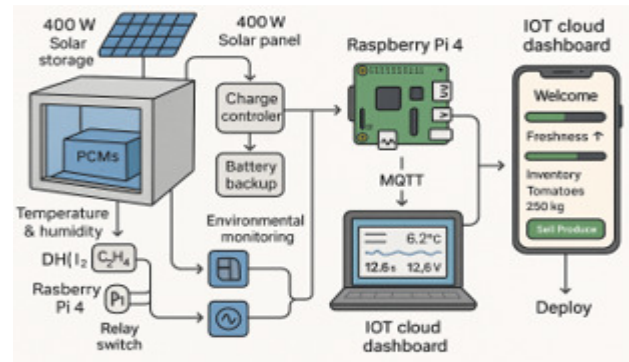


Fig. 2. Architecture and process flow.

A. Cloud and Interface Integration

To enable real-time monitoring and control, the system utilized MQTT for efficient communication between the Raspberry Pi 4 and the cloud server. The sensor data temperature, RH, CO₂, and ethylene were transmitted at regular intervals and visualized on an interactive cloud dashboard. This interface allowed users to track the environmental trends, view the compressor and battery status, set threshold limits, enable autoregulation, and receive threshold-based alerts on critical deviations [14].

Complementing the dashboard, a cross-platform mobile application was built using Flutter with a Firebase backend. The app enabled farmers to monitor production conditions, list items according to quantity and location, and access market-driven price suggestions. Designed for low-bandwidth environments, it bridged cold storage management with market engagement, making the system practical and accessible for rural users [15, 16].

B. Deployment and Use Case

The complete prototype was deployed in a peri-urban farming cluster near Dharwad, India, and tested with a cooperative of approximately 10–15 smallholder farmers producing tomatoes, spinach, and cucumbers. During the pilot, the chamber maintained an average internal temperature of $6.2\text{ }^{\circ}\text{C} \pm 1.1\text{ }^{\circ}\text{C}$, preserving perishables for 5–7 days without noticeable spoilage. The monitoring stack issued alerts when RH exceeded 85% or CO₂ surpassed 600 ppm, prompting corrective actions via automated relay control. Farmers reported visibly improved freshness, particularly for leafy vegetables, and used the added buffer to time deliveries more strategically. Several delayed sales by 2–3 days, capturing the dynamic price peaks and achieving an average 15–20% increase over immediate harvest-day sales.

IV. RESULTS AND DISCUSSION

A. Energy Efficiency Metrics

The system's energy efficiency was evaluated over the 30-day deployment by comparing the daily energy consumption with and without PCM (setpoint range 4–10 °C). Including PCM, reduced the daily consumption by approximately 25–30%, demonstrating effective thermal buffering. On average, the system consumed 2.5–2.7 kWh/day with PCM, versus 3.4–3.6 kWh/day without the latter. Figure 3 shows the day-wise energy consumption trends over the 30-day deployment.

B. Environmental Stability

The IoT-controlled system maintained the temperature fluctuation within $\pm 1.1\text{ }^{\circ}\text{C}$ and the humidity variation under $\pm 6\%$ RH, as demonstrated in the plotted trends. The active monitoring and relay-controlled actuation ensured a fast correction of the environmental deviations, maintaining ideal preservation conditions for sensitive product types.

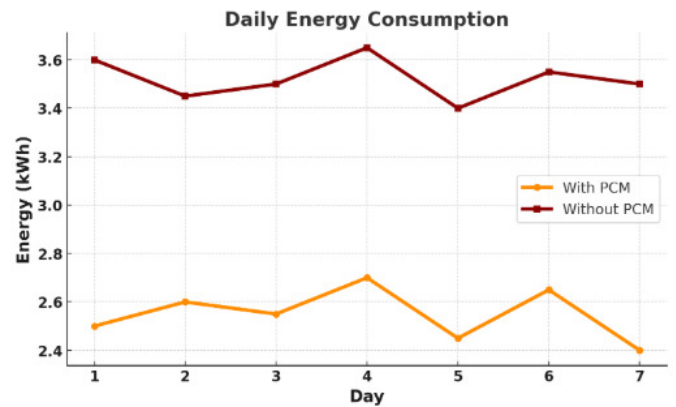


Fig. 3. Daily energy consumption comparison between cold storage with PCM integration and without PCM.

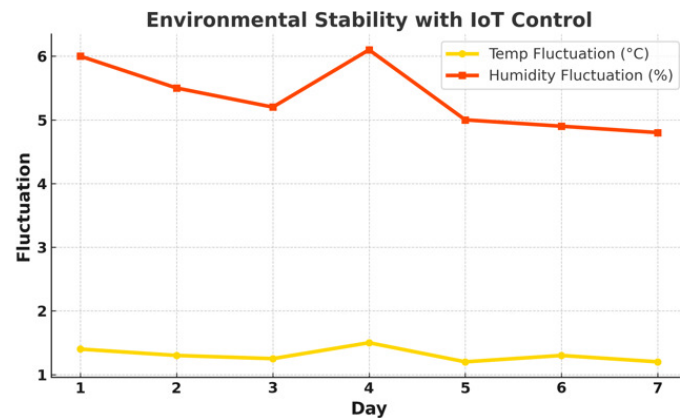


Fig. 4. Environmental stability of the cold chamber maintained through IoT control.

C. Shelf Life Extension and Loss Reduction

The system increased the production longevity. Tomatoes that are typically spoiled within 2 days under ambient conditions were preserved for up to 6 days in the cold-storage chamber. Mangoes lasted up to 8 days, and spinach retained freshness for up to 4 days (versus 1 day without storage). These extensions reduced the immediate post-harvest waste and enabled farmers to time the sales at more favorable market prices.

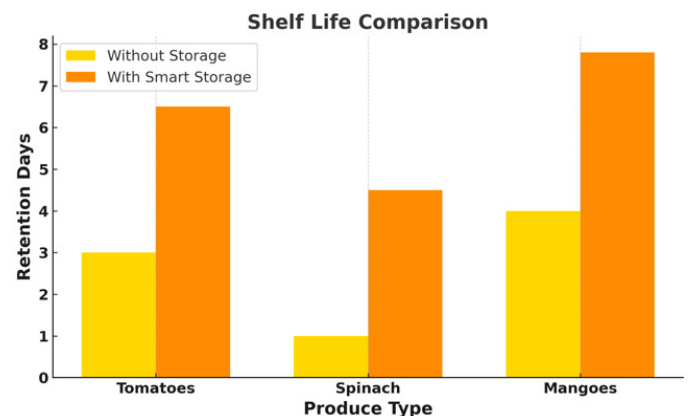


Fig. 5. Shelf life comparison with and without smart cold storage.

D. Economic Analysis

A comparison of the capital and operating expenditures showed that the smart cold-storage unit incurred approximately 45% lower CAPEX and approximately 70% lower OPEX than traditional systems. Over three years, the ROI was estimated at approximately 2.1x, versus approximately 1.2x for the conventional units—nearly doubling the investment return. These gains stem from lower energy use, extended shelf life, and improved market timing.

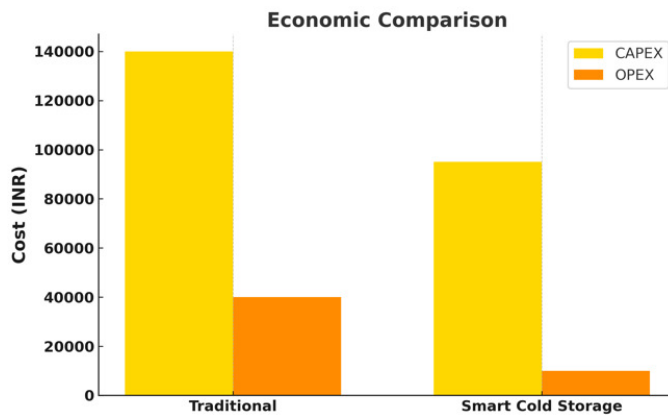


Fig. 6. Comparison of CAPEX and OPEX between traditional and smart cold storage systems

E. Digital Sales Engagement

The farmer adoption during the pilot indicated that 12 of 15 farmers actively used the digital interface, while the remainder preferred traditional methods. Those who used the platform reported an average 22% price increase, attributable to the strategic timing of produce release and direct market access. These outcomes underscore the value of ICT-driven platforms in enhancing the farmer's income through transparency and timely decision-making.

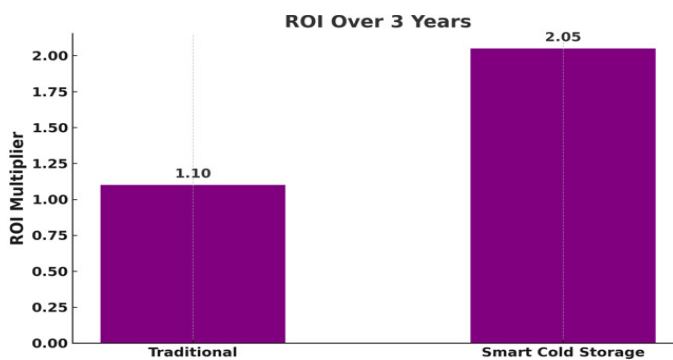


Fig. 7. Three-year ROI multipliers for traditional and smart cold-storage systems.

F. Comparative Analysis of Cold Storage Approaches

Table I summarizes the key differences among traditional storage, ICT-enabled platforms, and the proposed smart cold-storage system. The proposed system combines solar-powered energy efficiency, real-time IoT monitoring, extended shelf life

(up to 8 days), and digital market access, yielding a higher ROI (approximately 2.05x) for smallholder farmers.

TABLE I. COMPARATIVE ANALYSIS OF COLD STORAGE APPROACHES

Parameter	Traditional storage	ICT-enabled platforms	Proposed smart system
Energy source and efficiency	Grid-based, high usage	N/A	Solar + PCM, 28% energy savings
Monitoring and control	Manual or none	Basic market data only	IoT-based with real-time alerts
Shelf life extension	2–3 days	Not applicable	Up to 5–8 days (tomato/mango)
Market access and ROI	Middlemen dependent	Limited pricing tools	Direct-to-market, ~2.05x ROI in 3 yrs

V. CONCLUSION

This paper presented a techno-economic framework for smart cold-storage management tailored to smallholder agricultural communities. The system integrates PV-powered refrigeration, PCM-based thermal buffering, IoT monitoring and control, CA regulation, and a digital marketplace to address the post-harvest losses, limited market access, and energy inefficiency. In a 30-day field deployment in a peri-urban cluster near Dharwad, India, the 200 L prototype extended the shelf life by up to 4x, reduced the daily energy use by approximately 28%, and lowered the operating costs by over 65% relative to the traditional storage. Platform users realized an average 22% price gain by timing releases to demand peaks, with 12 of 15 farmers adopting the interface. While the results are derived from a single-site pilot of modest scale, the approach is scalable, sustainable, and digitally intelligent, offering a practical path to improved food preservation, economic returns, and energy autonomy in resource-constrained settings. Future work will prioritize the traceability integration and predictive spoilage control to further strengthen the quality assurance and market confidence.

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