

Portable Solar-Powered Cold Storage Box for Post-Harvest Preservation of Agricultural Produce

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Abstract — Post-harvest losses of vegetables, fruits, milk, and flowers constitute a significant economic challenge for small and marginal farmers, especially during the interval between harvesting and sale when produce is exposed to heat without cooling support. Village-level cold storage facilities are limited, and conventional compressor-based cold chains are often prohibitively expensive and reliant on grid electricity, making them unsuitable for small-scale rural applications. This paper introduces a Portable Solar-Powered Cold Storage Box designed to address this gap through an off-grid, renewable energy-based cooling system. The system utilizes a solar panel to charge a battery via a charge controller; the stored energy powers a thermoelectric (Peltier) module that cools an insulated chamber. A microcontroller equipped with a temperature sensor implements a duty-cycle control loop to maintain the target temperature and optimize energy usage. This paper details the system architecture, operational workflow, hardware and software components, advanced design strategies for differentiation, anticipated performance, advantages, limitations, and the potential for micro, small, and medium enterprise (MSME) adoption.

Keywords — Solar Energy, Peltier Cooling, Post-Harvest Loss, Portable Cold Storage, IoT Monitoring, Renewable Energy, MSME.

I. INTRODUCTION

Agriculture is a fundamental component of the rural economy in India; however, a considerable proportion of harvested produce fails to reach consumers in a marketable state. Small and marginal farmers often harvest vegetables, fruits, flowers, and milk early in the morning and must travel several hours to reach local markets or collection centers. During this period, exposure to heat accelerates respiration and microbial spoilage, resulting in a loss of freshness, weight, and market value prior to sale. Conventional cold-chain infrastructure is not designed for this scale of operation, as compressor-based cold rooms require a stable grid connection and substantial capital investment, both of which are generally unattainable for village-level enterprises.

The real gap is not that farmers are unaware of spoilage; it is that no affordable, off-grid cooling option exists between the field and the market. Solar energy, being abundant and freely available in most agrarian regions of India, offers a natural way to close that gap. This paper proposes a *Portable Solar Cold Storage Box* that uses photovoltaic energy to power a thermoelectric cooling unit, enabling farmers to preserve produce quality during transport and short-term storage without relying on the grid or fossil fuels.

II. PROBLEM STATEMENT

Produce transport and short-term storage at the farm level today is still largely unmanaged – there is no cooling once the crop leaves the field, and the wait for transport or a buyer is treated as unavoidable dead time. This works acceptably for a short walk to a nearby stall, but it is not adequate against a multi-hour journey under the sun, which

is common in rural marketing chains. The result is that:

- Produce spoils before reaching the market due to heat exposure in transit.
- Village-level cold storage is largely unavailable or unaffordable.
- Farmers are forced to sell quickly at distress prices to avoid total loss.
- Post-harvest food waste directly reduces farm household income.

What is missing is a portable, low-cost, energy-independent cooling unit that can travel with the produce rather than requiring the produce to travel to a fixed cold store.

III. LITERATURE REVIEW

Solar-assisted cold storage for agricultural produce is an active area of applied research. Field datasets on solar-powered produce cooling under tropical conditions confirm that photovoltaic systems can sustain usable cooling loads in off-grid rural settings [1]. Hybrid portable solar cold storage designs aimed at vegetables and fruits in remote areas have been evaluated for their preservation performance [2], and broader reviews of decentralized solar-powered cooling for fresh produce highlight its potential to reduce post-harvest losses across developing regions [3]. Thermoelectric (Peltier) modules driven by solar power have separately been explored for small-load applications such as vaccine storage [4] and low-cost vegetable/fruit coolers [5, 7], while recent work has proposed low-cost solar-powered cold storage systems specifically for agricultural products [6]. Across this literature, a consistent theme emerges: solar-Peltier systems are well

suited to small, portable cooling loads, but efficiency and product-specific performance improve considerably when combined with better insulation, phase-change thermal storage, or smart duty-cycle control – the gap this paper’s design strategies (Section VII) are intended to address.

IV. PROPOSED SYSTEM

The proposed system is a portable, insulated cold storage box powered entirely by solar energy. A photovoltaic panel charges a rechargeable battery through a solar charge controller; the stored energy drives a thermoelectric (Peltier) cooling module that lowers the internal temperature of the insulated chamber. A microcontroller (ESP32/Arduino) with a temperature sensor continuously monitors internal conditions and runs a duty-cycle control loop, switching the cooling module on only when needed so that battery energy is conserved rather than drained by continuous operation. The enclosure is mounted on wheels for single-person portability between the field, transport vehicle, and market.

V. METHODOLOGY / IMPLEMENTATION

- A solar panel and charge controller are installed to continuously harvest and regulate energy into a rechargeable battery.
- A temperature sensor is placed inside the insulated chamber to continuously report internal conditions to the microcontroller.
- The microcontroller compares the reading against a target threshold and switches the Peltier module on when the chamber is too warm, and off once the target is reached, forming a closed control loop.
- A heat sink and cooling fan dissipate heat from the hot side of the Peltier module so cooling efficiency is maintained.
- An optional LCD/OLED display shows live temperature and battery status; optional Wi-Fi logging records temperature history for quality assurance.
- Multi-layer insulation (Section VII-B) reduces heat ingress so the cooling module needs to run for a smaller fraction of each cycle.

VI. BLOCK DIAGRAM OF THE PROPOSED SYSTEM

Fig. 1 shows the overall block diagram of the system, illustrating the energy flow from the solar panel to the cooling chamber and the sensor feedback loop used for temperature regulation.

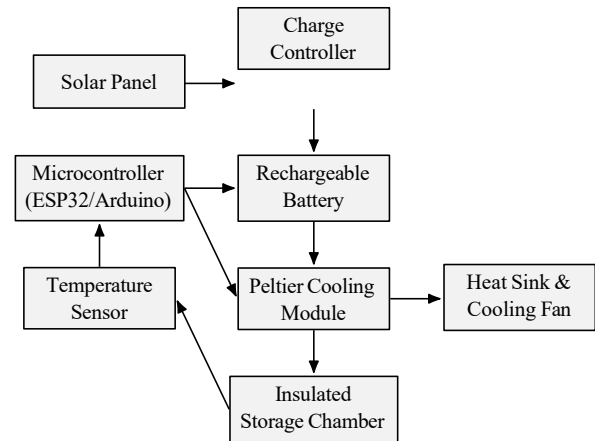


Figure 1: Block diagram of the portable solar cold storage system.

Solar & Power Layer

The solar panel and charge controller continuously harvest and regulate energy into the rechargeable battery, which is the sole power source for the system.

Sensing Layer

A temperature sensor inside the chamber continuously reports internal conditions to the microcontroller.

Control Layer

The microcontroller runs the duty-cycle logic that activates the Peltier module and logs data for optional display/IoT reporting.

Cooling Layer

The Peltier module, heat sink/fan and insulated chamber together produce and retain the cooling effect.

VII. WORKING DIAGRAM (FLOWCHART)

Fig. 2 shows the working flow of the temperature-controlled cooling cycle, from monitoring through cooling activation and back to standby.

As shown in Fig. 2, the sensor layer continuously feeds temperature data to the microcontroller. If the chamber is within the target range, the cooling module is kept off to conserve battery energy; once the temperature drifts above the threshold, the module is activated until the target is restored, after which the system logs the reading and resumes monitoring in a continuous loop.

VIII. COMPONENTS USED

Hardware:

- Solar Panel and Solar Charge Controller
- Rechargeable Battery
- Peltier (Thermoelectric) Cooling Module
- Heat Sink and Cooling Fan

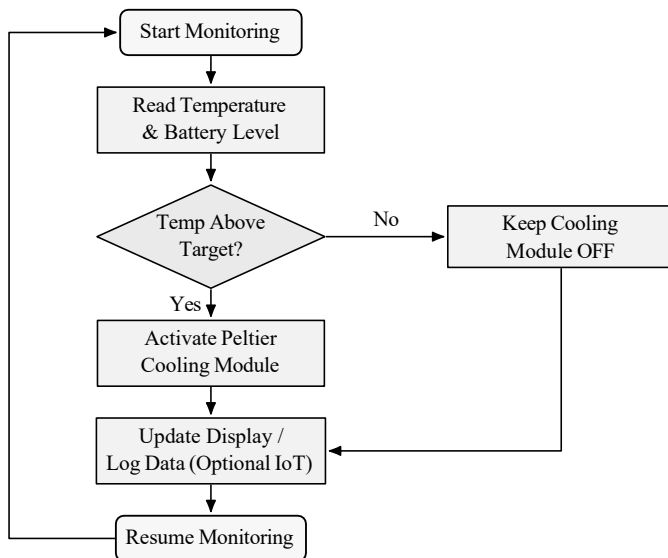


Figure 2: Working flow of the temperature-controlled cooling cycle.

- Microcontroller – ESP32 / Arduino (optional Wi-Fi)
- Temperature Sensor (e.g., DS18B20/DHT11)
- LCD / OLED Display (optional)
- Multi-Layer Thermal Insulation
- Portable Insulated Box with Wheels

Software:

- Arduino IDE / embedded C++ firmware
- Duty-cycle temperature control algorithm
- Optional cloud/IoT dashboard for data logging

IX. ADVANCED DESIGN STRATEGIES FOR DIFFERENTIATION

A plain solar-Peltier cooler is technically simple but not very efficient for larger loads, so the following strategies are proposed to strengthen originality and efficiency for MSME and patent consideration.

A. Modular, Produce-Specific Cooling

Interchangeable internal trays with a microcontroller-based profile selector let the target temperature/humidity be adapted for vegetables, fruits, dairy or flowers.

B. Advanced Passive Insulation

Vacuum insulation panels or aerogel sheets combined with a reflective outer layer cut heat ingress, letting a smaller solar panel and battery achieve the same performance.

C. Hybrid Cooling

Pairing the Peltier/solar-electric unit with pre-frozen Phase Change Materials, or evaporative cooling pads in low-humidity regions, reduces battery drain by adding passive thermal storage.

D. Smart Energy Management

The ESP32 duty-cycle controller, battery/temperature display and optional Wi-Fi logging conserve energy and support quality-assurance record-keeping for FPOs and cooperatives.

X. ANTICIPATED PERFORMANCE

As this design is at the MSME prototype-proposal stage, formal load-testing has not yet been carried out; anticipated performance is instead grounded in the solar-Peltier and hybrid-cooling literature reviewed in Section III. Field evaluations of comparable solar-powered produce coolers report meaningfully slower spoilage and better retained produce quality relative to uncooled transport under tropical conditions [1, 2], and duty-cycle-controlled Peltier systems are consistently reported to draw less battery energy than continuously-run units for the same target temperature. Incorporating hybrid PCM-assisted cooling and improved passive insulation (Section VII) is expected to further reduce the electrical cooling load, allowing a smaller solar panel and battery to maintain performance across a full transport cycle. Prototype fabrication and field trials are planned as the next stage of this work to quantify these gains directly.

XI. ADVANTAGES

- Reduces post-harvest spoilage during transport and short-term storage.
- Fully solar-powered – no grid dependence, suited to off-grid villages.
- Portable and low-cost compared to compressor-based cold rooms.
- Smart duty-cycle control conserves battery energy automatically.
- Modular and hybrid-cooling options allow adaptation to different produce types.

XII. LIMITATIONS

- Peltier modules are less energy-efficient than compressor cooling for larger loads.
- Cooling performance depends on adequate daily sunlight for battery charging.
- Advanced insulation (VIP/aerogel) and PCM materials add to prototype cost.
- Requires periodic battery maintenance/replacement for sustained use.

XIII. CONCLUSION

The Portable Solar Cold Storage Box offers a practical, low-cost, and energy-independent approach to reducing post-harvest losses among small and marginal farmers, directly supporting SDG 2, SDG 7, SDG 9, SDG 12, and SDG 13. While the base solar-Peltier configuration is technically straightforward, the proposed enhancements – modular produce-specific cooling, hybrid PCM-assisted cooling, advanced passive insulation and smart energy management – provide meaningful differentiation for MSME funding and future patent consideration, with clear revenue paths through unit sales, maintenance and seasonal rental to farmers, FPOs and cooperatives. Future work will involve prototype fabrication and field testing of cooling performance under real transportation conditions.

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