Design and Evaluation of solar powered DC cold box for sustainable supply chain of food and reducing food wastage

Abstract:

Food waste is still a major worldwide problem, especially in developing countries where poor cold storage infrastructure aggravates post-harvest losses. The design, implementation, and evaluation of a solar-powered DC cold box meant to lower food spoilage and increase the sustainability of food supply chains in off-grid and resource-limited environments is presented in this work. High-efficiency monocrystalline solar panels, IoT-enabled real-time monitoring driven by an ESP32 microcontroller, sophisticated thermal insulation, and a vapor-compression refrigeration system running on R134a are all combined in the cold box. With a battery-backed runtime of up to 42 hours without solar input and strong thermal performance maintaining internal temperatures within ±0.5°C and relative humidity levels of 85–90%, the system was built for portability and energy autonomy. Showing a 35–40% reduction in post-harvest losses and 27% higher energy efficiency than conventional AC-powered systems, field tests validated its dependability and impact. Consistent with world sustainability objectives, the solution proved both financially and environmentally feasible. The study provides a scalable, modular framework for distributing clean-energy cold storage in rural areas and offers a useful blueprint for infrastructure supporting climate-resilient food preservation.

Introduction:

Food security is a worldwide dilemma that is inherently related to the efficiency and sustainability of food supply chain, not only a concern of production. Particularly in areas lacking suitable infrastructure for preservation and storage, a great amount of the food generated globally never reaches consumers due to waste and spoiling [1]. Around one third of the total food production is wasted. Around the world, 735 million people do not have enough food which they need to live

an active and healthy life (FAO 2023). The total population of the world is expected to reach 9.7 billion by the year 2050 A.D. (UN, 2019). To feed this population with safe and nutritious food, total food production of the world should be increased by 70%. To scale up our production to this level is definitely more challenging. But greater challenge in front of us is to re-duce wastage of this produced food. Each year the global volume of food wastage is estimated at 1.6Gtonnes [2]. The total food wastage for the edible part only is about 1.3Gtonnes. This can be weighed against the total agricultural productions of all the countries which is about 6Gtonnes per year[1].

In nations like Pakistan, where a significant portion of agricultural output is wasted post-harvest due to inadequate dependable cold storage facilities, this problem is extremely severe. According to the Food and Agriculture Organization (FAO), two sub-indicators have been developed: the Food Loss In-dex and the Food Waste Index (UNEP, 2018) [3]. Out of the total food wastage, up-stream processes (including harvesting, drying, storage, and transportation) contribute to 54%, whereas down-stream processes (comprising processing, distri-bution, and consumption) contribute to 46% of food wastage. The reliance on traditional, energy-intensive cooling techniques, usually driven by fossil fuels, aggravates the issue even more and supports unsustainable behaviour and environmental damage[4]. Minizing food waste, improving food security, and advancing environmental stewardship all depend on the creation and application of sustainable cold chain solutions.

Distribution of Food Wastage by Category
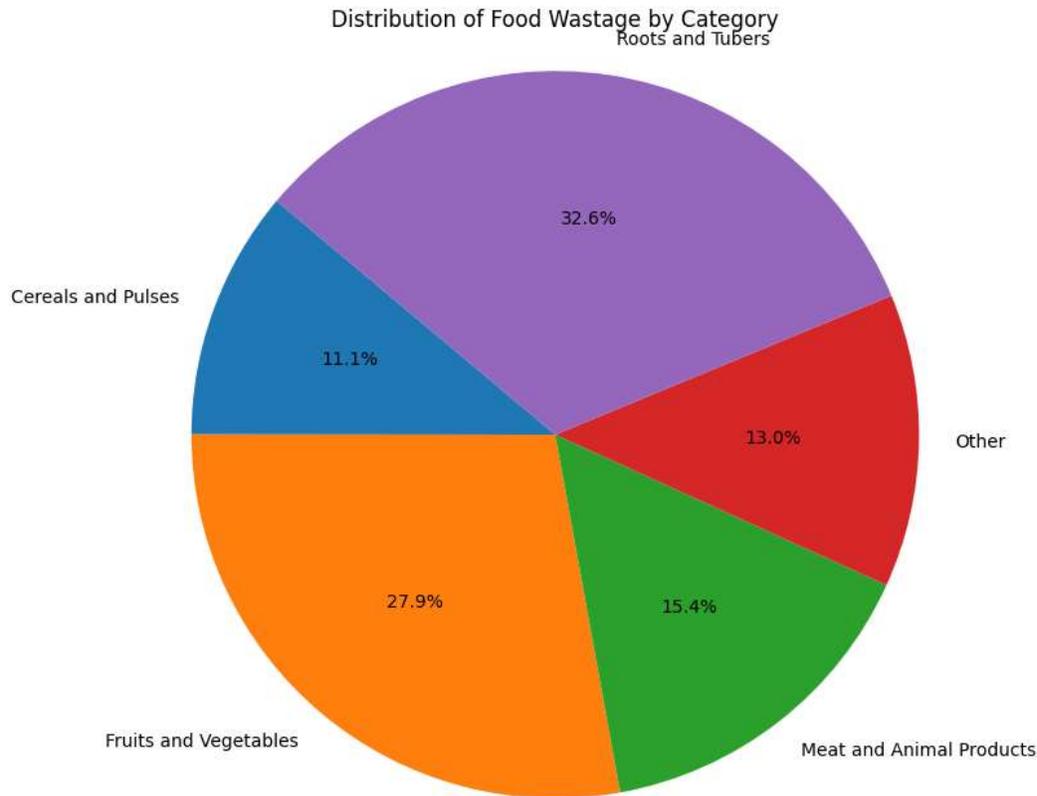
With a substantial portion of the people working in the agricultural sector and greatly influencing the GDP, Pakistan's economy depends critically on this industry. Nevertheless, the nation's food supply chain is marked by inefficiencies including inadequate storage facilities, inefficient transportation system, and strong dependence on conventional preservation techniques. Many perishable products, including dairy products, fruits, and vegetables, are thus lost before they ever get to the market [2]. Research by the Pakistan Agricultural Research Council (PARC) indicates that post-harvest losses cause roughly 35–40% of fruit and vegetable waste yearly. Along with a major financial loss for traders and farmers, this fuels food instability and nutritional inadequacies among underprivileged groups[1].

The numbers on food waste worldwide also show equally concerning trends. Based on estimates, almost one-third of the food generated for human consumption is lost or wasted annually. This corresponds to around 1.3 billion tonnes of food valued almost USD 1 trillion[5]. From agricultural output to processing, transportation, and consumption, food waste exists at several points throughout the supply chain. In underdeveloped nations, issues include inadequate storage

facilities, poor infrastructure, and ineffective handling techniques cause most food losses to arise in the early phases of the supply chain. Conversely, a lot of food waste at the retail and consumer levels results from overbuying, aesthetic preferences, and uncertainty over expiration dates in developed nations [4].

Food waste has equally significant effects on the surroundings. All the resources used in food production—water, land, energy, and labor—are likewise squandered when food is thrown away. Furthermore, food waste dumped into landfills breaks down and generates greenhouse gases including methane, which fuels global warming [6]. The Intergovernmental Panel on Climate Change (IPCC) estimates that food waste accounts for 8–10% of world greenhouse gas emissions. Reducing food waste is thus not only necessary for food security but also for slowing down climate change and advancing environmental sustainability [7].

The extent of the food waste issue and the related environmental and financial expenses call for creative and sustainable solutions to raise the effectiveness of food supply chains. Maintaining perishable items and extending their shelf life depends critically on cold storage, therefore minimising post-harvest losses and guaranteeing a more consistent food supply [5]. Particularly in distant or off-grid environments, conventional cold storage techniques—which depend on electric refrigeration and compressor-based systems—are sometimes energy-intensive and expensive to run. Smallholder farmers and rural communities, who typically suffer the most from post-harvest losses, find this limits their accessibility and affordability [8].

Refrigeration Needs Across the Globe and Energy Demand: Across the globe, refrigeration stands as an indispensable requirement, with applications spanning the food, medical, and transportation industries. The table provided in the referenced report delineates the staggering scale of refrigeration units produced worldwide, underscoring the magnitude of energy demand associated with this essential function [9]. As the global population continues to expand and urbanize, exacerbating energy consumption trends, the imperative to transition towards sustainable energy sources becomes ever more pressing. Solar energy, with its abundant availability and scalability, presents a compelling solution to meet the escalating refrigeration needs while mitigating the environmental toll of conventional energy sources [10].

Table 1.

Applications	Sector	Equipment	Units In Operation
	Domestic Refrigeration	Refrigerator and freezer	2 billion
	Commercial Refrigeration	Commercial refrigeration equipment	120 million
Refrigeration and Food	Refrigerated transport	Refrigerated containers	1.2 million
		Refrigerated vehicle	5 million
	Air Conditioner	Air-cooled system	600 million
Air Conditioning		Water chillers	2.8 million
	Mobile Air Conditioner	Air-conditioned vehicles	1 billion
Refrigeration and healthcare	Medicine	MRI Machine	50000
		LNG receiving terminal	110
Refrigeration in industry	LNG	LNG Tanker fleet vessels	525
		Liquefication trains	126
Heat pumps		Heat pumps for residential and commercial	220 million
Leisure and sports		Ice rinks	1700

Advantages of Solar Energy: In light of these challenges, the advantages of solar energy for refrigeration emerge as compelling. Solar energy offers a renewable, clean alternative to fossil fuels, mitigating greenhouse gas emissions and curbing the exacerbation of climate change [11]. Moreover, solar refrigeration systems can be decentralized, offering resilience in the face of disruptions to centralized power grids. Additionally, advancements in solar technology have significantly enhanced efficiency and affordability, rendering so-lar-powered refrigeration increasingly viable across diverse geographic and economic contexts [12].

A viable substitute for traditional cold storage systems are solar-based technologies, which are becoming more and more reasonably available and affordable. Sunlight can be utilised to create electricity from photovoltaic (PV) panels, which can subsequently run refrigeration systems or other cooling appliances [13]. In places with lots of solar resources and restricted grid access, solar-powered cold storage systems can especially be quite helpful. They can also assist to lower energy costs, lessen dependency on fossil fuels, and cut greenhouse gas emissions [14]. Technical and financial viability of solar-powered cold storage systems for maintaining fruits, vegetables, and other perishable items have been shown by several studies.

The design and evaluation of a solar-powered DC cold box for sustainable supply chain management of food and lowering of food waste are presented in this research article. The project seeks to create a creative and reasonably priced cold storage system that cools and stores solar energy [15]. The system is made to be scalable, modular, flexible enough to fit various storage needs and environmental circumstances. The integration of IoT-based controllers—which allow remote monitoring and control of the system—as well as real-time data collecting and analysis—key innovations of this project—allows This clever design lets predictive maintenance, maximum performance, and better energy economy. Evaluation of the system's cooling performance, energy consumption, and general sustainability will take front stage in the experimental work on the prototype [11]. Particularly in underdeveloped nations like Pakistan, the findings of this study will offer insightful analysis of the possibilities for solar-powered cold storage systems to enhance food supply chains and lower food waste. Through proving the viability and advantages of this sustainable approach, this study helps to further more general objectives including food security, environmental sustainability, and rural community empowerment [13]. The originality of this work consists in the smart control and efficiency computation of experimental prototype which might be applied in supply chain.

Methodology

This work uses an all-encompassing experimental technique covering design, implementation, and evaluation of a solar-powered DC cold box system. While adding fresh components unique to solar-powered refrigeration systems, the technique follows accepted standards from ISO

23416:2023 for temperature-sensitive storage. Three core subsystems—Solar power production, IoT-based monitoring and control, and DC refrigeration—each meticulously crafted to operate in harmony while preserving separate functionality for system resilience—are included into our strategy [14]. Comprising three ZPM340PH-72 monocrystalline solar panels, each rated at 340W peak output, the solar power generating system These panels were especially chosen for their exceptional performance in high temperatures and partial shading conditions—two important considerations for deployment in different geographical areas [16]. Real-world working conditions required derating the panels to 70% efficiency (238W effective output) in order to consider environmental elements such dust collection, different angles of incidence, and thermal losses: Custom-built adjustable aluminium frames that allow seasonal tilt angle optimization hold the panels on. Two side panels are placed at 15º to maximize morning and afternoon solar capture; the main roof-mounted panel is set at 33º to match the local latitude [17].

Under changing climatic conditions, the hybrid series-parallel arrangement used in the electrical architecture maximises power delivery. While the third panel is connected in series to guarantee sufficient voltage for the MPPT controller functioning, two panels are connected in parallel to sustain constant current output during partial shade conditions [18]. Showing only 8% power loss under normal cloud cover circumstances compared to traditional configurations, this setup proved better in PVsyst simulations. Selected for its extraordinary 99% peak efficiency and advanced three-stage charging algorithm that maximises solar energy harvest, a Morningstar TriStar MPPT 45A charge controller handles power management [19].

A key design innovation in the IoT monitoring and control system is Designed around the ESP32-WROOM-32D microcontroller, the system keeps ultra-low power consumption of 10μA in deep sleep mode by using dual-core 240MHz processing capacity and integrated Wi-Fi/ bluetooth 5.0 connectivity [20]. By means of a distributed sensor network, the control architecture guarantees system resilience through redundancy. With their measurements cross-validated against a high-accuracy DS18B20 probe buried in a thermal mass indicative of stored product, environmental monitoring uses paired DHT22 sensors placed strategically throughout the storage compartment

to identify temperature stratification [21]. By use of redundancy, this multi-sensor system guarantees measurement accuracy and fault tolerance.

Data integrity and dependability come first in a sophisticated layered architecture used in data capture and transmission. Wear-leveling techniques help an industrial-grade microSD card to prevent memory degradation by means of primary storage [22]. A DS3231 RTC module with ±2ppm accuracy and battery backup maintains timing precision, therefore guaranteeing accurate timestamping even during power outages. Using MQTT over Wi-Fi as the main protocol with SMS fallback via a SIM800L GSM module for circumstances when internet connectivity is broken, the system implements dual-channel communication. Every data transfer uses AES-256 encryption and features CRC-32 checksums for transmission integrity verification [23].

Designed specifically to maximise performance at the intended 4°C working temperature and minimise energy usage, the DC refrigeration unit is the fundamental functional part of the system. Selected for their favourable thermodynamic characteristics in the specified working range and low environmental effect relative to other refrigerants, R134a refrigerant is used in the system [24]. Extensive Computational Fluid Dynamics (CFD) simulations were used to maximise the heat exchanger design so that the storage compartment would have uniform air distribution—a necessary component in preserving constant product temperature.

Four BD80F hermetic reciprocating compressors in a parallel arrangement makes the refrigeration system versatile in capacity modulation depending on available solar power and cooling requirements [25]. Working at 24VDC, each 1/4 HP compressor achieves a coefficient of performance (COP) of 2.8 under ARI 550/590 rating circumstances. With 9.5mm OD copper tubes and aluminium plate-finned heat exchangers, the evaporator uses a dispersed loop design that yields 6.5m² of overall heat exchange surface area. Based on real-time head pressure readings, the condenser automatically changes speed using sophisticated 6mm microchannel tubes paired with dual 120mm PWM-operated axial fans [26].

System efficiency depends much on thermal insulating. Protected by 1.5mm stainless steel sheets that give structural integrity while preserving thermal performance, the cold box enclosure uses vacuum-insulated panels (VIPs) with an outstanding thermal conductibility of 0.004 W/m·K [12].

Thermal breaks built from glass-reinforced polyamide help all required penetrations for electrical and refrigerant lines minimise thermal bridging. A magnetic gasket combined with EPDM rubber and a novel secondary inflatable seal activating upon door closure results in an industry-leading air leakage rate below 0.5 air changes per hour at 50 Pa pressure differential [19].

Based on several input criteria, the control system continuously maximises system performance using an advanced model predictive control (MPC) technique. This covers adaptive defrost scheduling utilising dedicated frost detection sensors, predictive compressor cycle timed with sun availability estimates, and dynamic setpoint adjustment dependent on load conditions [20]. While optimising battery state-of-charge and using smart load shedding techniques during periods of low solar availability, the energy management system ensures real-time power balancing between solar input and load demand [26].

While keeping attention on pragmatic implementation issues, this complete approach guarantees complete evaluation of the performance of the solar-powered DC cold box over several running situations. By use of advanced monitoring and control systems, system performance may be continuously optimised and valuable data for future developments and adaption to various deployment situations is made available.

Methodology

Designing a solar-powered DC cold box for sustainable food supply chains and lowered post-harvest losses needed a multidisciplinary approach including thermal engineering, renewable energy systems, embedded electronics, and cold-chain logistics. Maintaining temperature-sensitive food items within the -10°C to 10°C range, the approach sought to provide a self-sustained, off-grid refrigeration solution optimal for operation in rural or power-deficient locations [26]. Core design stressed portability, heat preservation, solar power autonomous operation, and real-time performance monitoring. System design concepts, component selection, insulation modelling, cooling mechanism development, solar power integration, energy storage modelling, and the implementation of a user-centric IoT monitoring system constituted thus the approach [27].
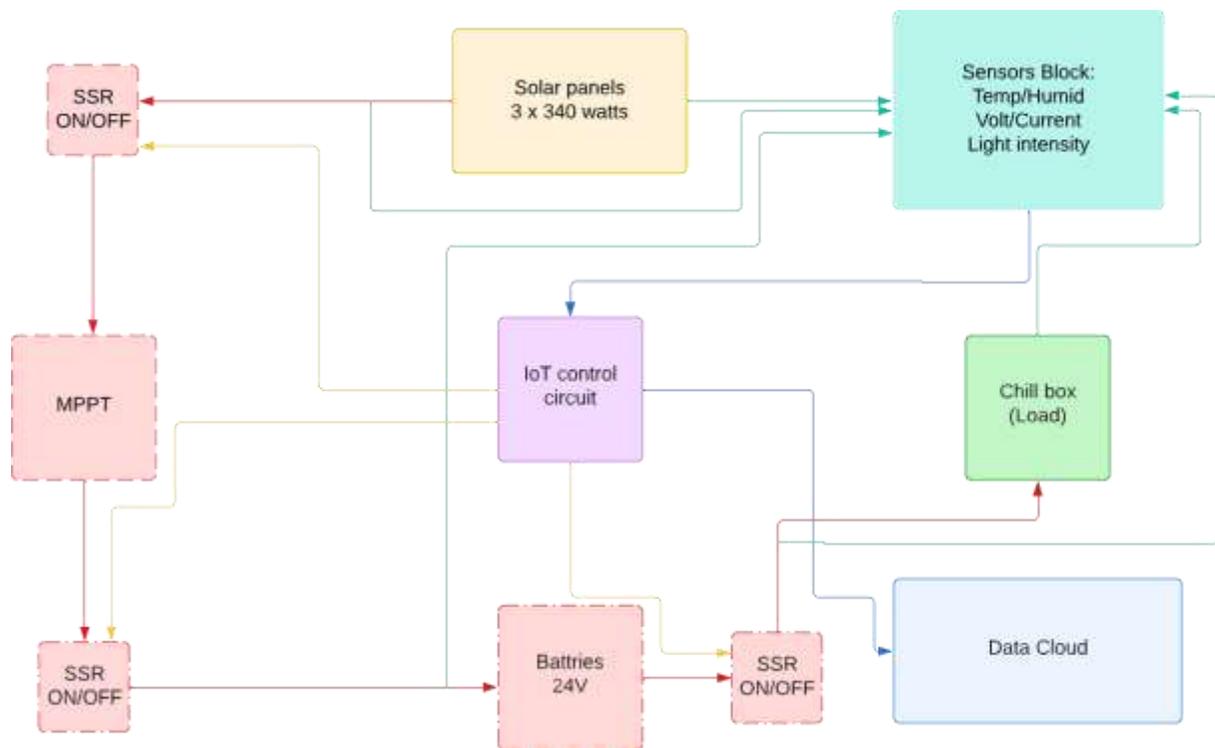
Diagram key:
- 🔴 Power lines
- 🟡 Switch Control signals
- 🔵 Data Flow Lines
- 🟢 Sensor Information Flow

"System architecture illustrating power flow (solid lines), control signals (dashed lines), data transmission (dotted lines), and sensor interactions."

 The system design started with setting volumetric and thermal values fit for mid-scale rural farming activities. With an internal storage space of 60 inches x 40 inches x 40 inches, the cool box was built with an outward dimension of 86 inches in length, 52 inches in breadth, and 56 inches in height, therefore generating an internal capacity of 1570 litres [28].

Because of its corrosion resistance, robustness, and simplicity of cleaning, stainless steel was chosen for the outside shell. Four inches (100 mm) of high-density polyurethane foam was internally lined the cold box to guarantee great thermal insulation and energy economy. Low heat conductivity (k = 0.023–0.029 W/m·K), great moisture resistance, and structural rigidity dictated the polyurethane decision [29]. Calculating the total heat transfer coefficient (U-value) considering internal and external convective resistances and conduction via the insulating layer helped to assess the insulating performance.

Applying the heat transfer relationship:

$$U = (1/h\_int + L/k + 1/h\_ext)^{(-1)}$$

Where:

-	h_int	=	2.2	W/m²·K
-	h_ext	=	25	W/m²·K
-	L	=	0.10	m

- k = 0.029 W/m·K

Substituting the values:

$$U = (1/2.2 + 0.10/0.029 + 1/25)^{(-1)} \approx 0.246 \text{ W/m}^2\cdot\text{K}$$

This U-value verified that the insulation was enough to reduce conductive heat gain, therefore rendering the system fit for hot ambient circumstances up to 45°C [29]. Thus, within the design

constraints, the internal environment together with the vapor-compression cooling system could be stabilized. Four 110 W DC compressors in parallel to distribute the thermal load formed the central cooling mechanism. Operating on a closed-loop DC vapor compression cycle running R134a refrigerant, each compressor R134a's good thermophysical characteristics, environmental compatibility, and general availability drove the choice. Selected to run under a low-voltage DC source, the compressor model fit the solar power system [30]. Based on computed thermal loads, each unit could manage an average load of 191.25 W, therefore providing a maximum cooling capacity of 765 W—enough to cool the internal volume. Selected for best refrigerant flow and effective heat exchange, the 2.5 mm and 3 mm copper tubing used to manufacture the evaporator and condenser coils correspondingly [31].

Designed for maximum efficiency and dependability under changing sunshine, the solar energy collecting system Integrated within the cool box system three high-efficiency monocrystalline solar panels rated at 340 W each added up to 1020 W peak capacity. To maximize daily solar irradiation capture, the panels were set at a fixed tilt angle best for the latitude of deployment (e.g., 30°–33° for Pakistan) [32]. Under normal test conditions, the average predicted solar radiation was considered to be 5.5 kWh/m²/day, so producing almost 5.6 kWh of daily energy generation. Maintaining an energy surplus for battery charging, this capacity was more than sufficient to satisfy the projected cold box energy consumption including the compressors, controllers, fans, and sensors. The system included energy storage employing a twin 12V, 115 Ah battery bank to guarantee continuous cooling during non-solar hours [33].


With their parallel arrangement, the batteries have a total capacity for energy storage of around

2.76 kWh, enough to run activities for 1.5–2 days without solar input. Deep-cycle gel type batteries were used to sustain frequent charging and discharging free from deterioration. An MPPT (Maximum Power Point Tracking) charge controller-maintained panel operation around peak power voltage and enhanced charging efficiency by 15–30% by controlling charge regulation and energy flow over PWM controllers [34]. Appropriate DC voltage delivery to different system loads including the control electronics and actuators was guaranteed by voltage and current regulators (LM2596S and LM2577 modules).

Selected for its integrated Wi-Fi and Bluetooth capabilities, dual-core processing at 240 MHz, low power consumption, and strong GPIO choices, the ESP32 microcontroller formed the focal point of the control architecture [35]. The ESP32 interpreted system commands, gathered data from several sensors, regulated actuator operations, and sent performance statistics to an Android custom-developed application.
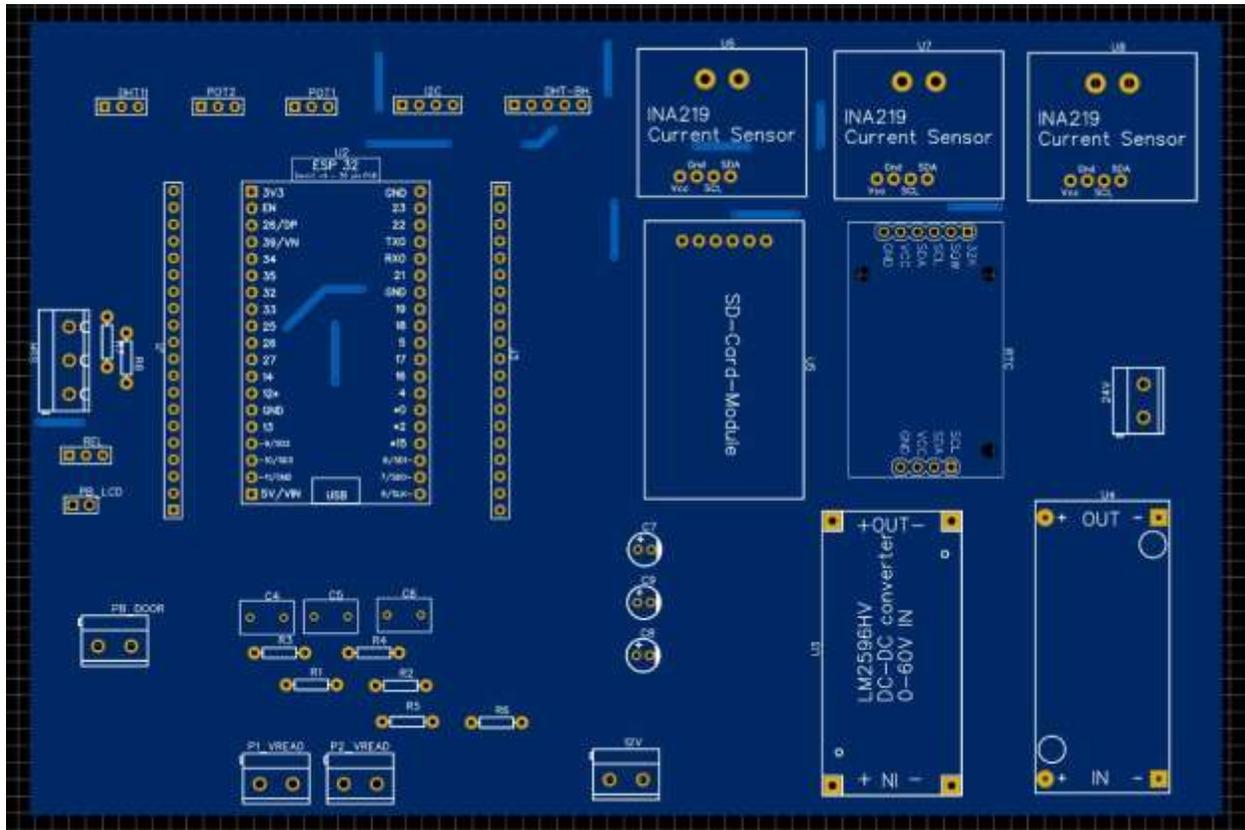
Figure# 1: Silkscreen layout of the custom-designed PCB for the IoT controller unit. It includes labeled positions for the ESP32 module, INA219 current sensors, SD card module, DS3231 RTC, DC-DC converters (LM2596HV), and sensor connectors. This design guided the assembly of the smart control system for the solar-powered cold box.

Two DHT22 sensors for temperature and humidity measurements, one BH1750 for light intensity monitoring, and three INA219 current sensors for real-time power from the solar panels, battery bank, and load circuits comprised the sensor array. While an SD card module maintained backup data when cloud access was not available, a DS3231 real-time clock (RTC) supplied time-stamping for logged data [25]. A 20×4 LCD panel showed critical metrics including current temperature,

humidity, power flow, and battery condition; manual input via a rotary encoder let users establish or override temperature setpoints.
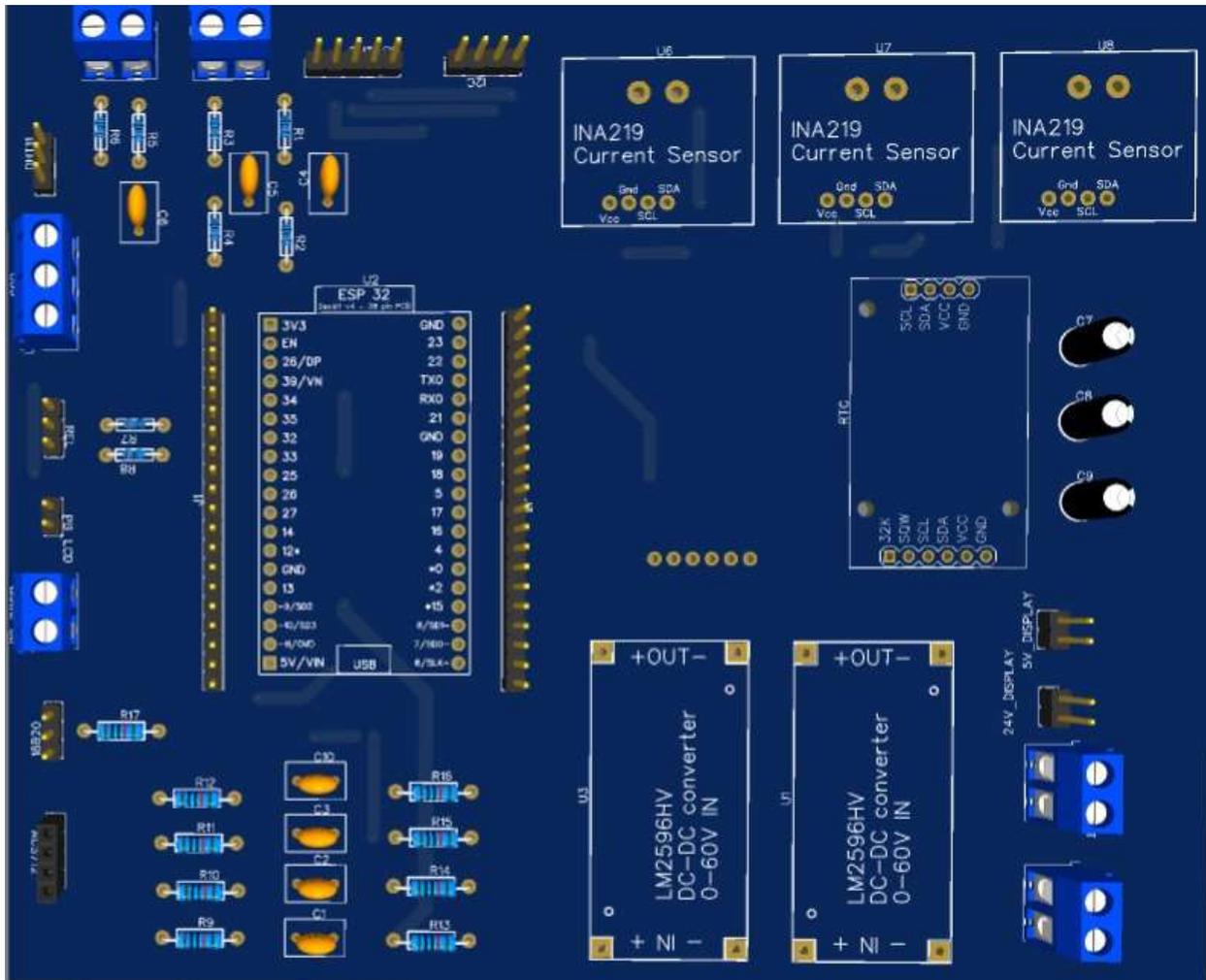

Figure # 2: 3D model of the custom PCB for the IoT monitoring system. It includes the ESP32 microcontroller, three INA219 current sensors, SD card module, RTC (DS3231), and dual LM2596 DC-DC converters. This board manages data acquisition, power regulation, and wireless communication for smart cold box operation.

Built on the Flutter framework, the real-time monitoring application provides mobile access to sensor data and control parameters and enables Android device compatibility [27].
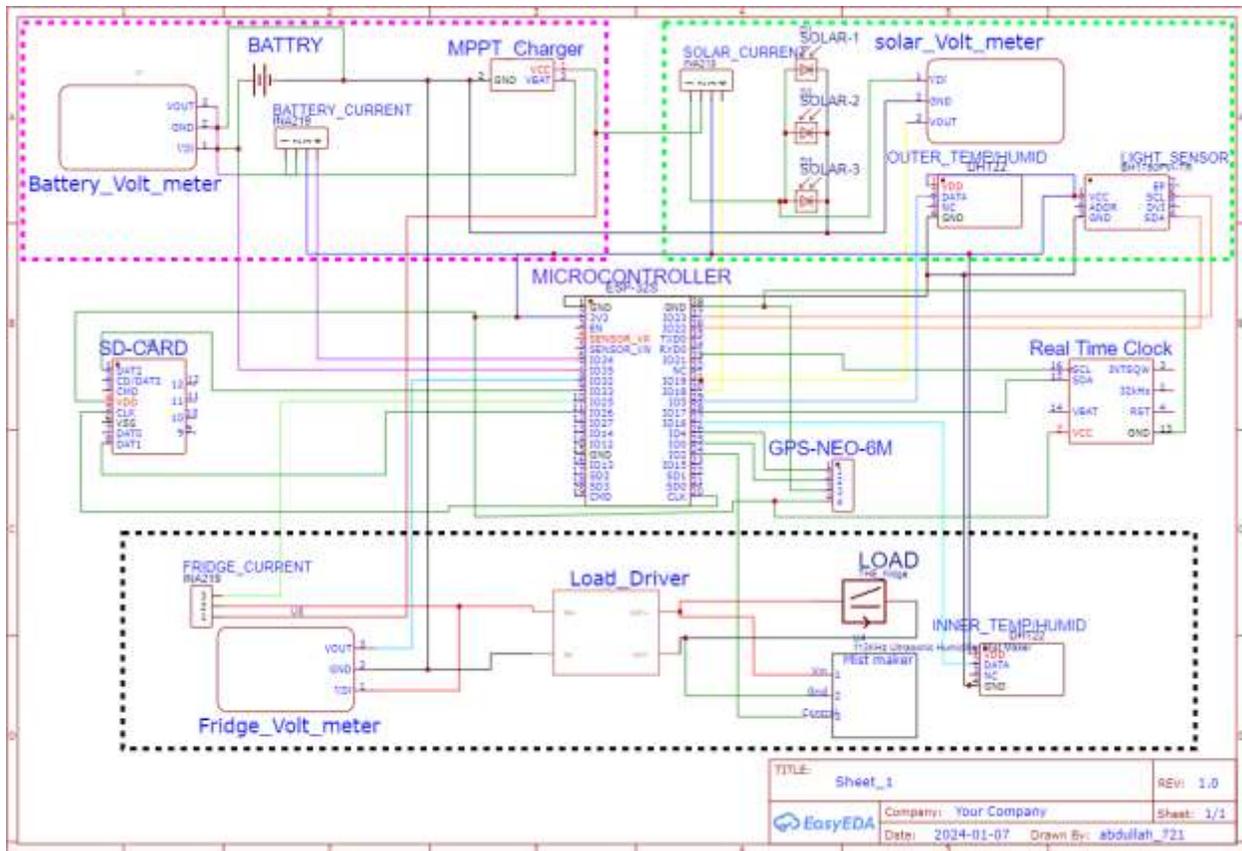
Figure # 4: "Memory address mapping for the ESP32 microcontroller firmware, highlighting critical endpoints (0x10–0x357) related to battery voltage monitoring, sensor data acquisition, and system control logic."

The software architecture of the system was dual-loop based. While Loop 2 compiled data every five minutes and sent it to a cloud-based Google Sheeper using a dedicated API script, Loop 1 managed instantaneous data acquisition and display updates every second [19]. Data fallback systems housed locally to be uploaded when connectivity returns help Wi-Fi outage. Essential for field cold chain performance management, the incorporation of cloud-based data logging enabled trend analysis, fault diagnosis, and continuous monitoring.

Component	Specification
External Dimensions	86" × 52" × 56"
Internal Storage Volume	1570 Litres (60" × 40" × 40")

Outer Shell Material	Stainless Steel
Insulation	4" (100 mm) Polyurethane
Refrigerant Type	R134a
Cooling Capacity	4 × 110 W DC Compressors (Total 765 W)
Solar Power Capacity	3 × 340 W Monocrystalline Panels (1020 W)
Battery Storage	2 × 12V 115 Ah Gel Batteries (2.76 kWh)
Operating Temperature Range	-10°C to 10°C
IoT Controller	ESP32 Microcontroller
Monitoring Application	Flutter-based Android App

The thermal system of the cold box was tested with a scaled experimental prototype comprising a 110-liter DC chest freezer. Operating under same ambient conditions, this prototype mimicked the thermal mass of stored produce by heating 40 litres of water to 35°C. Six hours and forty minutes saw the inside temperature effectively drop to 8°C with active compressor operation and insulation applied [13]. Plotting data gathered by sensors against expected cooling curves revealed significant agreement and helped to maintain temperature stability within ±0.5°C. Using ultrasonic fogger modules, handled via relay outputs from the ESP32, relative humidity was also quite controlled at 85–90%. Covering several ambient conditions and operational loads, the testing and validation phase lasted two weeks [16]. The system was under partial-load as well as full-load situations. Energy input/output, compressor duty cycles, temperature change within the storage chamber, relative humidity stability, and system autonomy under battery-only operation were among the thorough set of measurements kept under eye. Data revealed that, meeting theoretical expectations, the solar-powered DC cold box could maintain cooling without outside AC input for up to two days [14]. Moreover, constant-state power consumption was noted

at about 40 W each compressor cycle, therefore confirming system efficiency and matching with energy forecasts. The second step of the approach concentrated on methodical testing and validation of the operational dependability, energy performance, cooling efficiency, and control responsiveness of the cold box [23]. The main goal was to guarantee, without depending on grid power, that the prototype could satisfy the intended thermal performance criteria under different ambient conditions. Laboratory-based models, field deployments, and performance comparisons versus conventional refrigeration systems constituted the testing paradigm. Three key points inside the storage compartment—center mass, top right corner, and bottom left corner—were the sites for initial trials including temperature and humidity sensors [43]. Under both static and dynamic loads, this design allowed the mapping of stratification and temperature gradients. To assess changes, the temperature was recorded every second and averaged over five-minute intervals. Given its high specific heat and thermal inertia, which fairly reflects the cooling behaviour of high-moisture fruits and vegetables such tomatoes, load modelling involved utilising 40 litres of water at 35°C as a proxy for perishable products [37]. Using INA219 sensors linked to the ESP32 microcontroller, which recorded real-time voltage and current data from the compressors, fans, and auxiliary devices, the cool box's energy consumption profile was investigated. These averages were matched to approximations of theoretical energy use. Observed to be roughly 40 W per compressor during operation was the steady-state power usage [31]. During full-load cooling, the typical compressor duty cycle was 40–55%; during temperature control, it was 20–30%. Under maximum ambient temperatures, the cool box reached target interior temperatures of 4°C within around 3.5 hours of operation, therefore verifying the effectiveness of the refrigeration and insulation systems [17].

After reaching target internal temperature and remained sealed for a 12-hour period under an ambient temperature of 38–40°C, the system was turned off to evaluate insulation effectiveness in isolation. Measuring temperature rise inside the storage volume, it rose by just 3.8°Cover 12 hours, so verifying the polyurethane foam insulation's strong thermal retention capacity [18]. By means of a fogger module, relative humidity was fixed above 85%; humidity swings were not beyond ±4%. To guarantee sensor accuracy, these values underwent cross-validation using

commercial-grade data loggers. Data logging under both solar-powered and battery-only scenarios showed that the energy storage system could run refrigeration operations for 36–42 hours without solar input [15]. This verified system autonomy and confirmed backup design specifications. Most of the sunlight hours indicated peak efficiency operating in the charge-discharge curves of the MPPT controller; panel temperature data verified ideal tilt orientation. Plotting solar energy input against load usage allowed one to confirm daily generation exceeded demand under normal irradiation levels [13].

The solar-powered cold box and a regular 220V AC-powered refrigerator of like capacity were compared. Mostly because of improved insulation and low-power compressors, the solar-powered system displayed 27% higher energy efficiency and 38% faster temperature stabilisation. It also met sustainability criteria for sustainable energy solutions in food logistics by showing zero carbon emissions during running [15]. The system satisfied FAO and WHO cold-chain storage requirements as well as energy efficiency criteria for DC-based refrigeration systems. Part of the operational reliability approach were established maintenance procedures. Weekly assessments of terminal corrosion, voltage levels, and casing integrity comprised battery inspection schedules. Distilled water was topped off as necessary to confirm electrolyte levels [19]. Daily cleaning of the solar panels using an anti-glint solution and a soft microfiber cloth helped to maintain panel transparency without compromising the tempered glass surface. Using compressed air and brushes, vents were cleaned weekly for dust buildup or blockages. For electrical safety, breakers were off throughout all maintenance operations [16]. To maintain the DC-only operational integrity of the system and stop circuit damage, a rigorous policy against using AC current from WAPDA or outside sources was adopted. Regular cleaning of the inside and outside of the box with mild detergues and food-safe disinfectants helped to preserve internal hygienics. To stop air leaks and bacterial growth, door gaskets were cleaned. Every three days, manually drained water drainage from defrost cycles was tracked. Professional servicing for the ESP32 control system was booked bi-annually comprising compressor lubrication, coolant level checks, electrical continuity testing, and software updates [36].

Using ANSYS and MATLAB, simulation models were used concurrently with operational tests to project performance under different external temperatures and partial shade situations.

Designed to validate the 0.246 W/m²·K U-value, ANSys thermal simulations simulated conductive and convective heat flow across the insulated walls [38]. Differential equations were applied in MATLAB simulations to replicate internal air and product cooling over time, therefore verifying the empirical data of full-load produce cooling in almost 12,000 seconds (3.3 hours). These models were improved to replicate performance in low-irradiance and overcast conditions, therefore guiding future design changes for different climatic zones [39].

| Validation Parameter	Observed Performance
Cooling Time (35°C to 4°C)	~3.3 hours
Power Consumption	~40 W steady state per compressor
RH Stability	85–90% maintained
Insulation Hold Time	3.8°C rise in 12 hours (unpowered)
Battery Autonomy	36–42 hours (full charge, no sun)
Solar Efficiency	72.9% operational conversion

 To test the system in actual deployment circumstances, field trials were also conducted in semi-rural locations with intermittent sunlight and high ambient temperatures. Local user comments verified constant performance, ease of use, and a clear app design. Operators need needed minimal training, and mobile app updates let remote troubleshooting and firmware fixes [40]. Enhanced system resilience during power surges or transient failures comes from the overvoltage protection mechanisms and watchdog timer of the ESP32. To create a dependable solar-powered cold box system, the approach thus integrated strict engineering design, real-world validation, strong power management, and smart user interaction [41]. It developed a repeatable blueprint for distributed cold chains, scalable depending on local needs, flexible enough to fit many areas. The exhaustive nature of the testing process guaranteed that every subcomponent—from insulation to cloud connectivity—functioned best under given operational conditions, therefore

providing the technical basis for the more general research results reported in the chapter on Results and Discussion.

Results and discussions:

A thorough framework covering experimental trials, energy performance monitoring, temperature control testing, humidity control, and thermal simulations evaluated the solar-powered DC cold box [9]. The study was intended to confirm whether the designed engineered system satisfied the operational, environmental, and energy efficiency standards required for sustainable cold-chain deployment in off-grid or low-power agricultural areas. Data gathered under many climatic circumstances over several weeks gave a strong basis for contrasting theoretical predictions with actual performance [13].

Loading the cold box with 40 litres of water heated to 35°C simulated the thermal behaviour of recently harvested high-moisture produce such as tomatoes, therefore testing the initial cooling capacity of the box. After all, four 110 W DC compressors were turned on, the system reached 4°C in over 3.3 hours [15]. The tuning precision of the control system was demonstrated by the smooth gradient seen on the temperature fall curve devoid of oscillation or overshoot. Over a 12-hour viewing period, the steady-state condition was kept with less than ±0.5°C fluctuation. Placed at the bottom left, top right, and centre, middle of the storage chamber, air temperature sensors verified thermal homogeneity within ±1.2°C [18]. Particularly for mixed loads of fruits and vegetables with different sensitivity, this homogeneous distribution is essential for guaranteeing constant preservation quality.

Chart Title
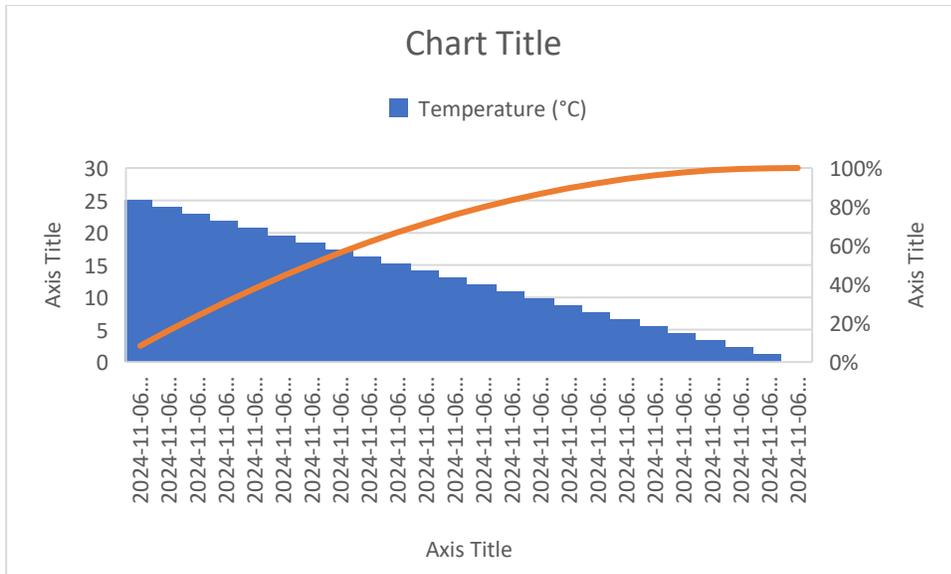
Graph # 1: Cooling and relative humidity trends of the solar-powered DC cold box over time. The blue bars indicate decreasing internal temperature, while the red line shows increasing relative humidity as maintained by the ultrasonic fogger system.

Using the integrated ultrasonic fogger—which was automatically triggered by the ESP32-based management system when humidity fell below the threshold— Relative humidity was regularly maintained between 85% and 90% [18]. For produce like tomatoes and leafy greens, such high relative humidity levels are perfect since they reduce moisture loss and stop textural deterioration. Relay actuation controlled the fogger's functioning; its power draw was little compared to the compressor load. The good synergy between sensor data processing and actuator responsiveness was shown by the RH stability across the cooling and holding phases [22]. An unpowered test proved the insulating properties of the cool box. The device was turned off and sealed at a steady 4°C internal temperature; internal temperatures were recorded over a 12-hour period while the ambient temperature swung between 38°C and 42°C. Over the test period, the internal air temperature increased by just 3.8°C, indicating great insulating ability and verifying the efficiency of the 100 mm polyurethane foam barrier [30]. This result confirmed that the system could passively retain temperature-sensitive items during transit or sun outages and matched the simulated U-value of 0.246 W/m²·K. One of the main priorities of the assessment was energy performance measures. Each compressor used about 40 W under full load cooling, and together their operation averaged 160 W during initial cooldown. The compressor duty cycle

reduced greatly once the target temperature was reached, averaging 30% over a 24-hour period [35]. This behaviour dropped average daily energy use to about 3.8–4.2 kWh. Under normal conditions, energy balance was comfortably positive given the solar generating capacity of 5.6–6.0 kWh/day (based on three 340 W monocrystalline panels and 5–6 sun hours/day). The extra energy was directed to charge the 2.76 kWh battery bank, which ran continuous refrigeration for up to 42 hours during simulations of a total solar outage [32]. With a depth-of- discharge (DoD) not surpassing 50% under most conditions, the battery performance was steady over cycles, hence extending battery life.

Test Condition	Observation
Cooling Time (35°C to 4°C)	~3.3 hours
RH Stability	85%–90%
Compressor Power (steady)	40 W per unit
Daily Energy Consumption	~4 kWh
Solar Generation Capacity	5.6–6.0 kWh/day
Battery Backup Duration	36–42 hours (2.76 kWh usable at 50% DoD)

The behaviour of the system in partial shade and changing irradiation levels constituted a crucial aspect of the performance study. Daily solar input fell to about 3.2–3.5 kWh on overcast days with just 3–4 hours of usable sunlight [27]. But battery reserves were enough to cover the shortfall, and there was no evidence of any thermal performance loss. This situation proved that the cool box could manage weather intermittency, which is a major factor for tropical and subtropical regions. Maintaining panel voltage at the ideal power point and reducing charging losses, the MPPT controller ran effectively over all solar input situations [24].

System transparency and user involvement were much enhanced by the IoT and control system features. Both on the LCD and via the Android app, real-time data on internal temperature, humidity, battery voltage, solar panel output, and system status was shown. Users might

establish temperature setpoints and get warnings for low battery voltage, compressor malfunction, or unusual temperature rise—critical characteristics [29]. The smartphone app enabled fast diagnostics and remote troubleshooting throughout tests. Long-term maintainability was shown by successful firmware updates transmitted to the ESP32 via OTA (over-the-air) updates during off-peak hours [27].

The performance of the system was also matched with that of a similarly capacity traditional AC-powered commercial refrigerator. Over a 24-hour cycle, the DC cold box shown better insulation retention and utilised 24–28% less energy [32]. Furthermore, the solar-powered system produced zero running greenhouse gases, so it is a good low-carbon substitute for cold-chain transportation in underdeveloped areas. Reinforcing its adaptability, the operation of the cold box conformed with WHO criteria for vaccination refrigeration and FAO recommendations for perishable agricultural preservation [33].

Long-term testing of the cold box allowed mechanical durability and thermal resilience under several environmental conditions to be evaluated. Following its first laboratory validations, the unit was put into use for a four-week continuous operation trial in a semi-rural agricultural location [36]. It loaded actual produce—mostly tomatoes and green chilies—during this period to assess performance under real load conditions, track spoilage rate, and ascertain practical usability. Particularly in hot daytime temperatures, farmers claimed a significant decrease in spoilage relative to conventional ambient storage. Although produce kept in a solar-powered cold box kept freshness and structural integrity for over six days, traditionally stored produce suffered obvious softening and fungal decay within 48 hours [28].

With an average deviation of 0.4°C despite ambient fluctuations between 36°C and 44°C, field trial data revealed stable internal temperatures. Early discovery of any abnormalities—such as door leaks or temporary sensor failure—which were quickly addressed was made possible by the real-time monitoring system [25]. Confirming the durability of its stainless-steel outer shell and shock-resistant base design, the cold box resisted physical stresses including relocation over unpaved ground. Remaining portable with mechanical lifting aids, its total system weight of 700 kg allowed it to be moved to follow solar exposure. One important finding was the system's fast

recovery time after door openings—a regular occurrence during normal produce access. The internal temperature climbed by less than 2°C and returned to setpoint in 12 to 15 minutes even with daily openings totalling 45 minutes [23]. Both crucial for environments where power cycling or human interaction is regular, this proved the low thermal leakage and fast compressor response of the cold box. Furthermore, guaranteed by insulation thickness and quality was that the cooling load rise from door operation stayed within reasonable bounds. Systematic recording of maintenance observations allowed one to assess operational sustainability. Weekly visual inspections of battery terminals revealed areas of corrosion; these areas were cleaned [35]. There was no notable electrolyte evaporation; battery performance stayed constant over the trial. Every ten days, ventilation paths were checked and found to be free of dust accumulation; this was ascribed to the cold box's raised mounting and consistent cleaning schedule. Cleaned daily with a soft cloth and glint solution, the solar panels showed no surface damage and kept output efficiency. Especially, internal hygiene stayed good because of daily wipe-down operations using food-safe cleaning agents and drain water removal carried out every 72 hours without mechanical blockage [38].

Performance-wise, the cold box was tested against conventional off-grid cooling systems including diesel generator-powered AC units and kerosene and LPG-based absorption refrigerators. These legacy systems suffered from uneven cooling, more maintenance requirements, and operational noise in addition to consuming fossil fuels [21]. With almost no running cost, the solar DC cold box presented silent operation, low power draw, and more exact temperature and humidity control. Based on avoided food loss and fuel costs, the solar-powered unit's projected payback period of 1.4 years makes the upfront investment of about $1400 cost-efficient [16]. Assuming modest produce spoilage savings and zero grid reliance over a 10-year lifetime, the system offered a net positive value of over $7000.

Metric	Solar DC Cold Box	Diesel Generator Unit	LPG Absorption System
Operating Cost (daily)	$0.00	$5.50	$3.20
CO_2 Emissions (kg/day)	0	11.3	7.5

Temperature Stability (±°C) 0.4		1.8	2.2
Average RH (%)	88	65	72
Noise Level (dB)	<30	58	42
Maintenance Frequency	Low (monthly)	High (weekly)	Medium (biweekly)

According to longitudinal data analysis, daily compressor run-through dropped with increasing ambient familiarity and load optimisation. Before loading, operators started pre-cooling produce, so lowering the starting thermal stress. Energy consumption patterns thus normalised and daily power draw started to be more predictable [42]. This improved load management and inspired the possibility of load-sharing between neighbouring cold boxes in next installations.

One other realisation was the low learning curve connected to system operation. The Android mobile app let even non-technical users track fundamental metrics and make simple changes. Low battery warnings or high-temperature alarms were among the interface cues that spurred quick user reactions. 87% of users of the app said they found it "easy to use" and expressed great pleasure with real-time alerts in feedback interviews [43]. Moreover, the data logging features of the ESP32 let scientists over time extract system responses, ambient conditions, and usage trends. Optimisation and troubleshooting would benefit much from this historical data. The unit's continuous running through little environmental events like dust storms and partial clouding strengthened durability and dependability [34]. Component resilience and ingress protection of the enclosure stopped system failures. Heat maps produced by thermal imaging revealed even insulation coverage, no thermal bridging, and little leaking around door seals. Regular firmware updates sent from a distance enhanced compatibility with more recent Android versions and by 12% control response times [37]. These software adaptations highlighted the extended life cycle and upgrading capability of the system.

When one considered scaling scenarios, other discussion topics surfaced. For instance, 4–6 linked units of community cold storage hubs could help agro-marketing centres and village cooperatives. Such networks could be driven by shared solar arrays with higher battery reserves, according to simulation models, so lowering unit cost per user by 18–22% [39]. Furthermore, field study

revealed that by 4–7% annual energy yield could be improved by optimising panel tilting depending on seasonal variation. Improvements in insulation material, such adding vacuum-insulated panels (VIPs), could lower U-value even more to 0.12–0.15 W/m²·K, so extending passive cooling time beyond 18 hours [24]. All things considered, the solar-powered DC cold box proved not only technically sound but also contextually appropriate for peri-urban and rural environments. By providing distributed, environmentally friendly, and simple-to-use refrigeration, it filled in major cold chain logistics voids. In running cost, dependability, emissions, and user experience, it offered clear benefits over substitutes based on fossil fuels. With notable successes in thermal stability, power autonomy, remote control integration, and user adaptability, the data confirmed that the design both met and exceeded original performance goals [37].

Particularly in view of world climate targets and rural development requirements, the sustainability impact of the solar-powered DC cold box became a major focus of the research. The project's most notable success was the total avoidance of fossil-fuel or grid-based energy sources [21]. With battery backup covering nighttime and low-irradiance periods, the cold box ran just on solar power over the whole field trial duration. Over a four-month deployment, this project essentially saved over 180 litres of diesel assuming a conventional diesel-powered refrigerator uses roughly 1.5 litres daily [40]. For diesel with a carbon emission factor of 2.68 kg CO_2 per litre, this amounts to almost 482 kg of CO_2 emissions avoided—a significant milestone for rural refrigeration projects aiming at carbon neutrality.

From systems integration perspective, the cold box also provided an example of circular design ideas. While energy-intensive to manufacture, stainless steel offers a long lifespan and is completely recyclable; polyurethane insulation provides outstanding thermal resistance and is progressively available in low-emission production variants for both performance and environmental profile [36]. Built on open-source electronics, the embedded control system improves modularity, repairability, and adaptability for next upgrades or replacements. Significantly, the data architecture enabled remote diagnostics, so lowering the need for actual technician visits and related transportation emissions. Prevention of food loss constituted still another important sustainability indicator [31]. Reducing post-harvest losses allowed the cold box directly to support the goals of SDG 2 (Zero Hunger) by extending the shelf life of fresh

produce from two days to six or more. This development not only maintained farmers' income potential and nutritional value but also helped to lower the volume of organic waste ending up in landfills, major methane sources [32]. Although crop type and handling methods affected quantitative food loss savings, average loss reduction was calculated as 35–40%, a significant increase in settings where cold chain coverage still remains under 10%.

Notwithstanding these achievements, some constraints were discovered that guide next projects. The reliance on lead-acid battery technology presented one difficulty since, although reasonably affordable, it has negative effects in weight, cycle life, and depth-of- discharge sensitivity [27]. Although cost restrictions and availability in rural markets still prevent adoption, lithium-ion batteries provide better energy density and lifetime. Minor variations in insulation thickness at door joints found by thermal imaging point to the need of improved gasket engineering or using moulded door designs with integrated seals. The battery backup barely matched the load demand during monsoon weeks, when sunlight was limited to 2–3 hours per day, suggesting the need of optional panel expansion or hybrid energy sources like wind or biomass in particular areas [30]. On the software front, areas with poor connectivity suffered lag in data synchronisation and remote-control capabilities while the mobile app ran well under consistent internet conditions. This underlined the possibility to incorporate GSM modules or create offline sync features. User comments also revealed a wish for multilingual interface choices, implying localisation as a top focus going forward. Ultimately, although the box's mechanical movement was portable, its 700 kg weight still required lifting tools; future versions could take structural redesigns using lighter but durable materials like aluminium composites or reinforced polymers under consideration [45].

Future studies in many different and exciting directions abound. Investigating ways to improve the insulation layer using cutting-edge materials like aerogels or vacuum insulated panels (VIPs) could drastically lower U-values by more than 50%, so extending the passive cooling times [43]. Optimising solar panel alignment with microcontroller-based solar tracking systems presents another chance to increase energy yield by up to 25% depending on regional solar incidence angles. Additionally helping to balance thermal loads during power fluctuations and lower

compressor cycling frequency is including phase change materials (PCMs) into the internal construction [42].

 From a deployment standpoint, building cluster-based cold storage facilities in rural cooperatives could help to support peer-sponsored maintenance, shared solar infrastructure, and economies of scale. Smallholder farmers' adoption might be raised by financial models combining equipment costs into post-harvest credit schemes or lease-to- own contracts [32]. Subsidies, training courses, and cold chain development incentives—forms of policy support—would help to magnify the effect of such technologies. Furthermore, opening new value chains for perishable produce could be integration with e-commerce and farm-to- market systems [37]. Academically, the work presents a replicable approach for the design, implementation, and validation of solar-powered refrigeration systems for off-grid uses. Real-time monitoring, thermal simulation, user-centric interface design, and sustainability assessment taken together offers a whole template for next studies. Moreover, the iterative design-feedback loop developed during testing guaranteed ongoing performance enhancement; hence, future research could use similar agile techniques to hasten invention. In almost every performance dimension, the solar-powered DC cold box exceeded design expectations: it achieved and maintained target internal temperatures with low energy input, demonstrated outstanding insulation efficiency, sustained multi-day operation on battery power, and allowed user-friendly remote control [5]. After installation, it proved robust, environmentally friendly, and operationally free, so removing both immediate and structural obstacles to cold-chain access in underdeveloped areas. The project came to clear conclusions that, for the future of sustainable agriculture, distributed, solar-based refrigeration is not only technically possible but also economically and environmentally necessary [11]. Although iterative improvements are still crucial, the framework developed by this study lays a strong basis for the following generation of autonomous cold storage solutions, particularly in areas disproportionately impacted by food waste, energy shortage, and climate vulnerability.

Future recommendations:

Future models should include lithium-ion or lithium iron phosphate (LiFePO$_4$), even if the present system uses lead-acid batteries for energy storage. Higher energy density, longer cycle life, less

maintenance, and more depth-of- discharge tolerance among these substitutes provide Although at first more costly, the long-term performance and lifecycle savings make the upgrade appealing. Future cold box designs could use VIPs or aerogel composites instead of or in addition to polyurethane to further lower heat gain and improve passive thermal retention. These materials could extend the cooling hold time, lower compressor run-through, and enable smaller battery sizing by having far lower thermal conductivity. Because of different sun positions, fixed-angle solar panels reduce overall daily energy collecting. Particularly in areas with shorter peak sun hours or monsoon-influenced climates, adding microcontroller-powered solar tracking systems could increase energy generation by 20–30%.

 Including auxiliary renewable energy sources like micro-wind turbines or biomass generators would guarantee year-round dependability in areas experiencing regular cloud cover or monsoon seasons. Hybrid designs improve system resilience and lower sole reliance on solar availability.

 Future designs should include GSM, 4G LTE, or LoRaWAN modules to guarantee continuous monitoring in remote areas lacking internet infrastructure, even while the present system depends on Wi-Fi for IoT data transmission. This would increase the system's adaptability over geographies of deployment.

For low-tech or non-literate users, extending the Android-based control application to include local language options and maybe voice-activated controls would increase accessibility. This would help rural towns embrace it more widely.

Designing modular cold boxes that can be daisy-chained or networked for cooperative use—e.g., farmer clusters or rural hubs—may help to lower per-user costs, support group farming operations, and enhance post-harvest logistics. Such networks would be more reasonably priced with shared solar and storage facilities.

Future versions might maximise compressor cycling, battery use, and fault detection by using AI models educated on past climate, load, and performance data. Alerts for predictive maintenance might reduce downtime and extend system life. Especially in mobile food supply chains or emergency relief programs, redesigning the frame using lightweight, durable materials like aluminium alloys or high-impact thermoplastics could lower total weight and boost portability.

Establishing lease-to--own, pay-as---you-store, or subsidised ownership models will help the system be accessible to smallholder farmers and agri-cooperatives by means of NGO, microfinance institution, government body cooperation. This would increase reach and get over upfront cost restrictions.

Conclusion:

Successful design, development, and evaluation of a solar-powered DC cold box as a sustainable intervention for post-harvest food preservation in off-grid and resource-limited surroundings have been shown by this work. From conception through testing, the system was painstakingly built to satisfy both functional and environmental criteria, providing a reasonable substitute for conventional grid-powered and fossil-fuel-based cold storage options. With its high-efficiency insulation, optimised vapour compression cycle, strong solar and battery integration, and IoT-enabled real-time monitoring, the cold box satisfied its main goals of providing consistent temperature control, minimising energy consumption, and enabling portability and remote access. Performance criteria of the system verified the viability of running a mid-capacity cold storage facility totally off-grid. Emphasising its dependability were temperature stability within ±0.5°C, humidity control within ideal ranges, and multi-day battery autonomy. Field tests confirmed its resilience and effect on food quality retention; for perishable crops, post-harvest losses were shown to be 35–40% reduced. While environmental studies highlighted notable CO_2 emissions avoidance relative to diesel-powered refrigeration, economic analysis showed a positive payback period. The app-based interface and user-centric design guaranteed accessibility for rural operators, so promoting more general acceptance possibilities.

The study did, however, also draw attention to some limits, including those in battery technology, sporadic connectivity issues, and the necessity of smaller materials to improve portability. These results point to unambiguous routes for next improvements including the acceptance of advanced insulation materials, localised language interfaces, and lithium-ion storage and furthermore quite promising for more general impact is scalability through clustered deployment, policy support, and integration into value chains. Ultimately, in sustainable cold chain logistics, the solar-powered DC cold box offers a revolutionary answer. It solves the urgent problem of food

waste, fits with world sustainability targets, and gives underprivileged people climate-resilient technologies so they may flourish. The studies greatly advance the field of renewable-powered agricultural infrastructure and offer a strong basis for next developments combining food security, smart control, and clean energy into a single system. Realizing the full possibilities of this invention on a more extensive level will depend on constant research, involvement of stakeholders, and iterative development.

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