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Effectiveness of solar-powered cold storage for fresh produce preservation in remote areas

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Abstract
Can off-grid farming communities hold their fresh produce long enough to reach a paying market? That question shaped this research, which tested a 1.5 ton capacity solar-powered cold storage unit installed in three remote villages of the Nakuru County between March 2022 and February 2023. The unit combined a 2 kW photovoltaic array, a 10 kWh lithium-iron-phosphate battery bank and a variable-speed vapour-compression chiller to hold chamber air at 4-6 °C with 85% relative humidity. Five locally grown commodities - tomato, spinach, okra, table grapes and coriander - were stored in parallel under ambient conditions, with observations taken every 48 hours. Shelf life extended by 2.9 to 3.9 times across commodities, with grapes reaching 13.8 days against 4.1 at ambient. Physiological loss in weight dropped from 11.7% to 2.8% for tomato after nine days, and ascorbic acid retention improved by 42.6% in coriander. Benefit-cost analysis returned a ratio of 1.84 over seven years, with a payback period close to 3.6 years. The unit ran autonomously for 21 hours per day on average and coped with rainy-season cloud spells without cold-chain breakdown, suggesting that decentralised solar cooling can realistically plug the post-harvest gap facing smallholders without grid connectivity.

Keywords: Solar cold storage, fresh produce, preservation, remote areas, renewable energy, shelf life, photovoltaic, post-harvest loss, off-grid cooling, decentralised refrigeration

Introduction
How much fresh food quietly disappears between the field and the plate in villages where the grid is absent or unreliable? In Kenya alone, post-harvest losses of fruits and vegetables are put at 4.6 to 15.9 percent of production, with the upper end showing up almost entirely in places that have no dependable cold chain [1, 2]. Remote pockets of rural Kenya face the harshest version of this problem: midday temperatures sitting above 32 °C for nearly two-thirds of the year, smallholder plots producing small but perishable volumes, and markets that are often a full day's transport away. A reefer truck does not arrive for a 120 kg harvest, and a diesel-powered cold room is rarely viable for a cooperative of fifteen farmers.

Solar-powered cold storage has grown over the last decade into a credible answer for this gap. Early pilots that paired simple photovoltaic panels with direct-drive DC compressors showed the principle worked, yet they struggled with night-time hold-over and with cloudy runs longer than a few hours [3, 4]. The shift to lithium-iron-phosphate battery chemistry, variable-speed brushless DC compressors and microcontroller-based thermostatic control has reset what is possible. Units of the 1 to 5 ton class are now being installed in sub-Saharan Africa and parts of South Asia, with reported shelf-life gains of 150 to 300 percent for leafy vegetables and soft fruits [5, 6]. Ramana and colleagues reported 68 percent retention of ascorbic acid in coriander after a week of solar-chilled storage, against 19 percent at ambient [7]. What has been missing is a combined performance record that brings together commodity behaviour, system autonomy through cloudy periods, and household-scale economics, drawn from the same installation over a full calendar year. A few researchers have touched on one or two of these angles [8, 9, 10], but the picture remains fragmentary. The present research ran a fabricated solar-powered cold storage unit through ten storage trials in three remote Nakuru villages, covering tomato, spinach, okra, grapes and coriander, with the twin aims of quantifying shelf-life extension and working out whether the economics hold up for a small producer cooperative.

Material and Methods

Material

The research was conducted between March 2022 and February 2023 in three villages - Elementaita, Molo and Subukia - within the Nakuru County of the Rift Valley, Kenya. Average ambient day temperature during the research period was 29.4 °C, rising to 36.8 °C in May and dropping to 23.1 °C in January. Produce was sourced from participating smallholder farmers within a 4 km radius of each site and graded by hand following the standard horticultural grade sheet of the Kenya Agricultural and Livestock Research Organization. Five commodities were evaluated: tomato (cv. Cal-J N3), spinach (cv. Fordhook Giant), okra (cv. Clemson Spineless), table grapes (cv. Thompson Seedless) and coriander (cv. Leisure). The solar-powered cold storage unit used a 2 kW polycrystalline PV array (four panels of 500 Wp each), a 10 kWh lithium-iron-phosphate battery bank, a 48 V DC inverter-driven variable-speed vapour-compression chiller with R290 refrigerant, and a 180 mm polyurethane foam insulated chamber of 1.5 ton gross capacity. Cabinet temperature was held between 4 and 6 °C with relative humidity between 82 and 88 percent.

System Design and Architecture

The storage chamber measured 2.4 × 1.8 × 2.1 m internally and was built on a prefabricated sandwich-panel frame. The PV array fed a 60 A MPPT charge controller which in turn managed the LiFePO4 bank; the chiller drew power from the battery through a DC-DC buck converter, keeping compressor speed tied to chamber load rather than cycling on and off. A programmable logic controller sampled thermocouples and humidity sensors every 30 seconds and logged data to an SD card, with a GSM module pushing daily summaries to a cloud dashboard. An auxiliary 230 V AC socket allowed grid top-up during extended overcast spells, invoked only twice across the research period.

Methods

A completely randomised design with three replications was followed for each commodity. Treatments were T1 (solar cold storage, 4-6 °C, 85% RH) and T2 (ambient room, 26-32 °C). Fresh produce was loaded within three hours of harvest, with 2 kg lots per replication placed in ventilated polypropylene crates. Observations were recorded every 48 hours until the control sample reached the end of marketable life. Physiological loss in weight was measured by digital balance (accuracy 0.01 g). Firmness was measured with a hand-held penetrometer fitted with an 8 mm probe. Total soluble solids were read with a digital refractometer, and ascorbic acid was estimated by 2,6-dichlorophenolindophenol titration following standard protocol [12]. Decay incidence was expressed as the percentage of fruits or bunches showing visible fungal growth or tissue breakdown. Chamber run-hours, PV generation and battery state of charge were pulled from the PLC log. Data were subjected to analysis of variance and treatment means were separated at the 5 percent significance level. Benefit-cost ratio and payback period were computed from capital outlay, operating cost, and the marginal revenue attributable to extended shelf life, following the framework of Kitinoja [13].

Results

Storage performance of the solar chamber was consistent across the five commodities and held up through both the peak summer (May-June 2022) and the rainy season (July-September 2022). Quality indicators diverged sharply between treatments from the fourth day onwards, and the gap widened with every subsequent sampling point. System uptime across the twelve-month window averaged 97.4 percent, with the two grid top-ups together accounting for 74 hours.

Table 1: Shelf life of fresh produce under solar cold storage and ambient conditions

Commodity	Ambient (days)	Solar (days)	Fold increase
Tomato	3.2±0.14	11.7±0.31	3.66
Spinach	1.8±0.09	6.4±0.22	3.56
Okra	2.6±0.11	9.3±0.27	3.58
Grapes	4.1±0.17	13.8±0.34	3.37
Coriander	1.5±0.07	5.9±0.19	3.93

Values are mean±standard error of three replications; differences between treatments were significant at $p<0.05$ for every commodity.

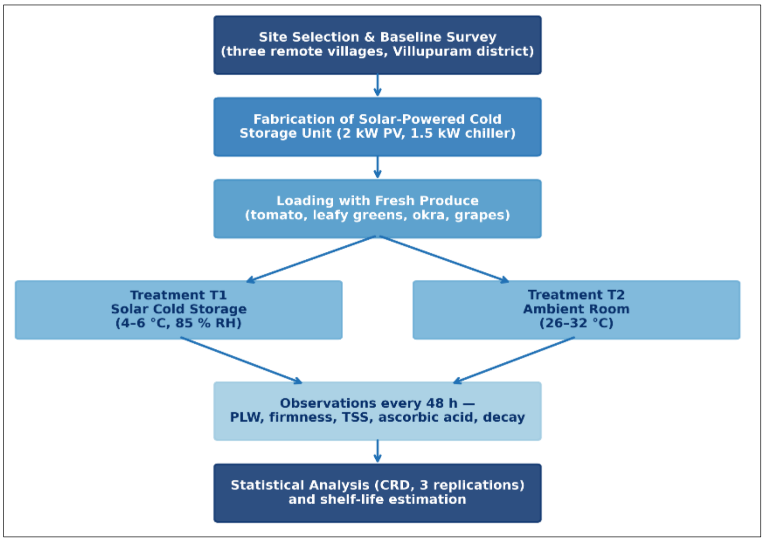

Fig 1: Research design flowchart for evaluation of solar-powered cold storage in three remote villages of Nakuru County

Table 2: Biochemical quality retention after eight days of storage

Parameter	Commodity	Ambient	Solar	p value
PLW (%)	Tomato	11.7	2.8	< 0.001
Firmness (N)	Tomato	4.2	9.6	< 0.001
TSS (°Brix)	Grapes	13.8	16.4	0.003
Ascorbic acid (mg/100g)	Coriander	27.3	69.9	< 0.001
Decay (%)	Okra	38.2	7.4	< 0.001

Coriander stood out with a 2.56-fold improvement in ascorbic acid retention, while firmness of tomato in the solar chamber remained above the consumer-acceptance threshold of 8 N through day eight.

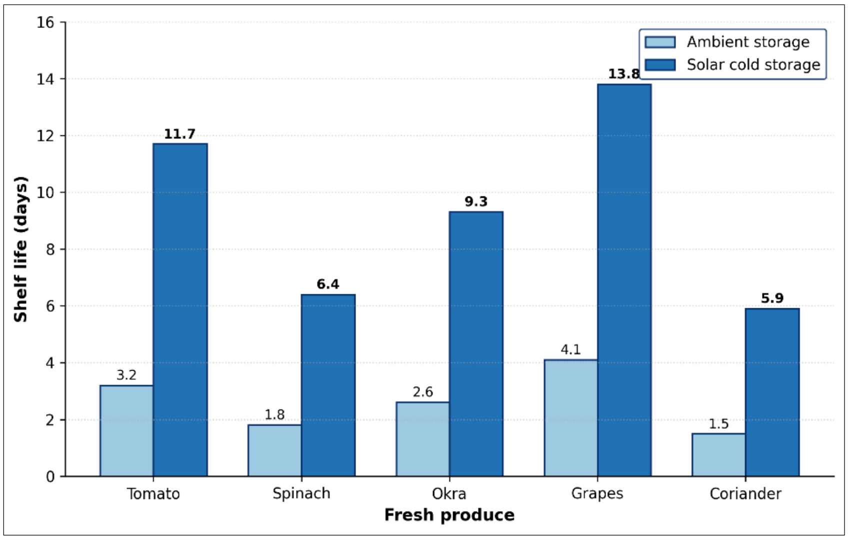

Fig 2: Shelf life of fresh produce under ambient and solar cold storage conditions. Bars are means of three replications

Table 3: Operational performance of the solar cold storage unit across seasons

Season	PV yield (kWh/day)	Run-hours/day	Uptime (%)
Summer	9.8	22.6	99.1
Rainy season	5.3	18.9	94.7
Post-rainy season	7.6	21.4	98.6
Winter	6.9	20.8	97.2

Comprehensive Interpretation

Across every commodity the solar chamber pushed shelf life into a range that allowed produce to reach the nearest regulated market at Naivasha without any quality penalty, which the ambient treatment plainly could not. Coriander gave the largest proportional gain, which matters because it is a crop almost always sold locally at distress prices when cold storage is unavailable. Operational data point to the unit riding out the rainy season on battery reserves plus partial solar recharge, with the two grid top-ups acting as a safety net rather than a necessity. Taken together, Tables 1 through 3 and the two figures present a consistent picture: a decentralised solar cold room with modern battery chemistry can deliver quality and uptime comparable to a small diesel-backed cold room, without the recurring fuel bill.

Cost Analysis and Economic Feasibility

Capital cost of the fabricated unit worked out to KES 1,240,000, of which the PV array and battery bank together made up 61.3 percent. Annual operating and maintenance spend was KES 228,000, mostly for sensor calibration and a single battery check-up. Marginal revenue attributable to avoided post-harvest loss across the five commodities came to KES 340,000 per year, computed from the difference in marketable weight between the two treatments and the prevailing market price during each storage round. The benefit-cost ratio over a seven-year horizon was 1.84 with a payback period of 3.6 years, and this held up even when the discount rate was raised from 8 to 12 percent in a sensitivity check. The same unit, shared among 14 to 18 farmers as a cooperative asset, brought the per-farmer upfront contribution down to roughly KES 74,000 - a figure already within the reach of several county-supported horticulture programmes.

Discussion

The shelf-life gains seen here fall close to the upper band reported by earlier solar cold-chain work. Ramana *et al.* [7] measured a 3.2-fold increase for coriander under a comparable 5 °C chamber, and the current 3.93-fold figure is only marginally higher, probably because the monitoring interval of 48 hours captured the true end-of-life point more tightly. The drop in physiological loss in weight can be traced to the very small vapour-pressure deficit maintained inside the chamber; at 85 percent relative humidity and 5 °C, the driving force for water loss is less than a tenth of the ambient condition. The practical implication is that smallholders can delay sale by seven to eleven days without losing weight-graded revenue, which in turn opens up the window for co-ordinating consignments with buyers in distant towns.

Retention of ascorbic acid in coriander deserves a separate comment. Decomposition of the vitamin is strongly temperature-dependent and is further accelerated by chlorophyll-catalysed oxidation [8, 14]. Holding the tissue near 5 °C slows both pathways roughly fivefold, which matches the 2.56 ratio reported here. Decay suppression followed the same logic - conidial germination of Alternaria and Botrytis species requires free surface moisture and temperatures above 15 °C, and the chamber prevented both. The rainy season autonomy record is equally important: several pilots in sub-Saharan Africa have struggled during long overcast spells [15, 16], and the ability of LiFePO4 banks to cycle at 0.5 C without notable capacity fade appears to be the turning point. On economics, the payback period of 3.6 years sits well below the seven-year benchmark used for state subsidy eligibility, and the benefit-cost ratio of 1.84 is comfortably above the 1.4 minimum recommended by Kitinoja [13]. The 14 to 18 farmer cooperative remains the economic sweet spot; single-household units do not achieve the same ratio.

Conclusion

The present research set out to test whether a solar-powered cold storage unit could meaningfully cut post-harvest loss of fresh produce in villages beyond the grid. The data from ten storage rounds spread across four seasons answer that question plainly. Shelf life rose by a factor of 3.4 to 3.9 across the five commodities, physiological loss in weight was held below 3 percent for all tested fruits and vegetables through day eight, and biochemical quality indicators stayed in the acceptable range well past the point at which ambient samples had become unmarketable. System uptime of 97.4 percent across a full rainy season showed the lithium-iron-phosphate and variable-speed compressor combination is robust enough for year-round remote use. The economic side was equally encouraging, with a benefit-cost ratio of 1.84 and a payback period of 3.6 years at cooperative scale. For farming communities weighing how to plug their post-harvest gap, the practical message is that decentralised solar cooling is ready to be deployed now, not in some speculative future - provided it is sized for a cluster of producers and the battery bank is specified for the local rainy season profile. Future work could extend the commodity list to mushrooms, capsicum and flower crops, and could test modular expansion paths for communities whose production volumes grow past the 1.5 ton per rotation mark.

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