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Solarism-powered Cold Storage Unit e Performance in Alleviating Post-Harvest Supply chain Losses in perishable horticultural supply chains

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Abstract
Losses after harvest as a result of poor cold storage facilities in horticultural value chains continue to pose a great challenge to many especially in the tropics. This research was expected to assess the technical and financial efficiency of the solar-powered Cold stores that were intended to be used in three rural aggregation centers in Ghana. The units were; constructed to address cold chain weaknesses and minimized after-harvest losses in perishable crops like tomatoes and leafy vegetables. The critical performance indicators were the stabilization of temperatures inside, the energy saving criterion, enhanced shelf-life and cost reimbursement. The systems averagely kept an internal temperature of 5.4 +/- 0.8 oC thus achieving a shelf life of tomatoes and leafy greens of 4 to 6 days compared to the conventional means of storage. In addition, the cold storage units using solar power made the post-harvest losses to reduce by 39.6 percent ($p < 0.01$). An economic analysis revealed that the economic efficiency of the solar-powered storage system is demonstrated by the fact that the break-even of the investment recovery is realized in 18 months with a cooperatively-managed model. These results indicate that decentralized solar cold storage can be an effective way of addressing food security, food waste and maximizing the economic returns on the perishable horticultural supply chain.
Keywordss: ***Solar cool storage, post harvest losses, horticultural supply chain, energy efficiency, shelf life extension, decentralised storage, Ghana.***

1. Introduction
1.1 Significance and Background
The post harvest in horticulture is highly essential in maintaining food security particularly in developing areas where large scale of perishable food stores are lost before getting to the consumers. In tropical nations, fruits and vegetables lose massively after being harvested due to lack of proper storage facilities and ill infrastructure. It has been estimated that about 30-50 percent of the perishable crops are lost after harvesting and this is mainly because of temperature variations, infestation and due to improper storage. In sub-Saharan Africa, the losses lead to food insecurities and high prices as well as lack of income consistency among the smallholders farmers.
The grid-driven traditional cold storage systems also cannot be viable system in the rural areas because of the elevated costs of energy, unsteady electricity supply, and skimpy infrastructure. This exposes an urgent demand to have vibrant and off-grid preservation technology to be implemented on the ground to minimize these wastages and increase the shelf rule of perishable harvests.(1)
1.2 The Horticultural Post-Harvest Problems
Due to lack of efficient infrastructure of cold chaining, post harvest management of crops such as tomatoes, leafy greens and other vegetables is usually limited in tropical regions. Perishable crops spoon off without quality and nutritional value without the sensible cooling systems. The poor storage causes spoilage, hence, food waste, poor marketability, and thus, low incomes to smallholder farmers. Light lack of proper cold storage also reduces the chances of the farmers to enter broad markets hence sell their produce at the best prices.
The conventional containers used in storage of crops whereby drying them out in the open air or under simple refrigeration do not satisfy the demand as perishable foods require long-term storage and this is only possible on high-temperature climates. Consequently, value added production cannot be achieved, food security undermined, and this is a big blow to rural areas that depend much on locally grown food.
1.3 Cold Chain Solutions using Renewable Energy
As a solution to the cold chain gap in tropical agricultural system, the use of renewable energy, especially solar energy has great potential. Solar energy is a sustainable resource that is quite abundant hence a good choice when it comes to providing reliable off grid cold storage in the rural areas. Employing solar powered cold storage

facilities would not only help curtail post harvest losses but can also invariably extend the life of the produce that is perishable thus preserving the ideal temperature requirements of the produce equipment all year around.(2)

Cold storage that is powered by the sun is especially appropriate to smallholder farmers who have limited supply of electricity. Such systems are self-contained and provide a viable solution to the standard grid-based refrigeration systems which are not only costly but also in many cases are not available in faraway regions. Solar systems can be designed to fit the local requirements giving the option of flexibility in scale to be used in various scales such as small scale farm-based storage or to a larger scale aggregation center.

These systems minimize the use of fossil fuel, which significantly lowers the operation cost, and make the agricultural activities sustainable in the area as using solar energy would have a long term positive impact to the agricultural activities in the tropical areas. Besides, solar Cold storage can be an instrument of development, providing access to additional sources of income to local entrepreneurs and making the community more resilient in climate-related threats.

1.4 Study Purpose What should be the purpose of the study?

The objectives of this research would be to assess the technical efficiency and economic feasibility of solar-driven cold rooms in minimising post-harvest wastes and increasing the shelf life of perishable foods in Ghana. In particular, the researchers will work on three of the aggregation centers in the countryside and evaluate the key parameters of their performance, such as the stability of temperatures, energy efficiency, and the cost recovery. It aims at establishing the possibility to implement decentralized solar cold stores systems as an effective measure to enhance food supply chain security and to minimize losses in horticultural supply chains. As well, the intention of the study is to offer information regarding the economic sector returns of this kind of systems, that is, cost recovery as well as a return on investment (ROI) in smallholder agriculture carried in the tropics.(3)

2. Deployment and Design of Solar cold Stores Units

2.1 Parts and specifications of the unit

The cold storage units (CSUs) that were solar powered and implemented in the present research were adapted to the demands of smallholder farmers in rural Ghana. These containers were powered by the use of less energy to be small in size, and they would offer good cooling of perishable horticultural products, including tomatoes and leafy greens.

Cooling Capacity: The ability to keep each of the units at 5.4 o C +/- 0.8 o C, was the desired temperature needed to store perishable crops. It was also solar-powered which meant that it did not require so much external power.

Refrigeration Technology: The smart units had computer efficient refrigerator-based systems, which could ensure stable range of temperature irrespective of the changing ambient conditions. High-quality insulation materials were applied to reduce the heat gain in the outside environment, which made it energy efficient.

Solar Power System: The systems used solar photovoltaic (PV) panels to run the refrigeration parts. The PV panels were designed to cover the energy needs consisting of the amount necessary to sustain the storage temperature on days and nights, both with and without cloud coverage. The systems contained batteries to store the energy and this enabled the units to work through the night or during cloudy days when there was insufficient output of solar producer(4)

Capacity: The cold storage rooms were made to contain about 2-3 following tons of produce, which can be adjusted and changed to fit different kinds of crop besides providing the best airflow possible. The monitoring (of temperature and humidity) was also included in each unit to maintain the optimum produce storage conditions.

2.2 Location and Geographical Characters of a Site

It had put in place solar cold storage facilities in three rural aggregation centers across the Northern, the Western and Ashanti regions of Ghana. These were chosen because they are next to smallholder farms in areas where there are post-harvest problems hence need of handling it better.

Geography: Ghana environment is tropical which means a lot of rainfall and high temperatures. This leads to loss in the post-harvest which is a major concern. The study sites were those areas which receive low and unpredictable rainfalls resulting in droughts periodically and high level of humidity, which helps to spoil perishable crops easily without being stored under cold.

Site Conditions: The sites of the installations were evaluated according to availability of sun along with the space to install the PV panels and refrigeration units. The centers of rural locations were selected to make sure that the

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solar-powered facilities will be accessible to the local farmers directly and to connect them with cold storage where grid electricity would be unavailable or unreliable.(5)

2.3 Power and Operational parameters

Optimization of the operational parameters of the solar-powered cold storage units was carried out in the most efficient way in the tropical surrounding.

Stability of Temperature: The humidity level was constant throughout the day and night as the units recorded an average temperature of 5.4 + 0.80 o C internally. The units ensured a constant temperature to keep the stored crops cool. It was established that this temperature is best maintained to lower the respiration rates of tomatoes and leafy green vegetables that increases to effectively improve their shelf life span by up to 4 and 6 days.

Power Requirements: The unit was to work independently and all of them were powered by solar energy. The computation involved the amount of power capacity required according to cooling load of the refrigeration system, ambient temperature, and the storage capacity of a unit. The solar panel array installed (which is about 3-4 kW) gave sufficient power to power the units without the need to get external sources of power.

Energy storage: In the night or cloudy days, there should be continuous operation and each unit was equipped with a battery storage system. The battery was also created to be large enough to supply the cooling system with adequate energy over a 24-hour period that would keep the cooling system running at all instances.

Finally, the solar-powered cold storage units were designed and implemented to suit the needs of the rural farmers in Ghana as a sustainable alternative of reducing the post-harvest losses in the tropical horticultural supply chain. The solar-associated systems were found to be good and consistent, hence a viable prospect in terms of decentralized cold-storage facilities in developing agrarian areas.(6)

3. Energy Performance Monitoring and Temperature

3.1 Tools and Guidelines of Monitoring

In monitoring the performance and efficiency of the solar-powered cold storage units, the overall monitoring system was put in place. The monitoring devices were developed to monitor the temperature stability, the amount of energy being used and the solar energy being put to use.

Temperature Sensors: Digital temperature sensors were installed at various positions in each Cold storage to observe the variations in temperature. These sensors gave real time information on how hot particular levels of the unit were, thus it assisted in ensuring that the storage conditions are uniform in storing perishable crops.

Data Logging System: The temperature readings collected by the sensor were relayed to a central data logging unit that had cloud based storage capability. This system detected the temperature hourly and one could conveniently get the data to analyse the trend and perform various test quality analysis. The system has been coded in such a way that when the temperature goes out of bounds, an alert is sent allowing immediate remedial measures to be taken.(7)

Energy Monitoring: In order to gauge the energy efficiency of the system, a system of energy meters were utilized in monitoring the performances of the solar panels, batteries and refrigerating units. These meters measured the energy produced, the energy consumed as well as the energy stored and therefore a comprehensive analysis of the overall efficiency of energy consumed system could be done.

3.2 Stability of internal temperature

The temperature variance was a vital performance indicator since it determines the shelf life and quality of preserved crops. The cold storage units were averagely running at 5.4 0.8 o C temperature which is the most suitable temperature to store tomatoes and leafy greens during field trials.

Vibration: During the tests of the temperature sensors, it was observed that the internal temperature was extremely stable, with the fluctuations of the temperature inside the ±0.8 o C range. This stability is essential in maintaining the quality of crops because ripening due to unstable temperature can be faster causing spurious spoilage.

Responding to External Conditions: The external conditions can go to extremes in some areas and this was possible through the systems that had internal temperature that was steady inside the storage units. This has been done by taking the solar energy together with thermal insulation.(8)

Temperature monitoring protocol: The stability of the temperatures was monitored on a regular basis and this helped the research team to ensure that the systems are within the parameters of operationalizing the temperatures during the storage period. This made sure that the cold storage units were not only functional but they were also designed with the best interest of the produce kept there in mind.

3.3 indicators of solar energy utilization and efficiency

The use of solar energy was also one of the important issues that could be used to assess the efficiency of the cold storage units. The solar energy systems were installed in such that they could provide the needed energy to the refrigerating systems but also have the batteries provide power when the sun is not out.

Energy Efficiency: The solar panels were able to supply the required quantity of energy to fulfill the cold storage requirement daytime and the surplus was kept in the batteries to be used at night. The system was highly energy efficient with an average solar energy utilization rate of 85 percent which implies that 85 percent of the energy requirements to run the system are directly taken care of by the solar energy and dependence on the external power source is reduced to a minimum.(9)

Energy Consumption: The average energy consumption rate of the refrigeration units varied between 5 kWh/day, although it changed a bit when ambient temperatures changed and due to the change in load to be cooled. The system energy storage also reduced end consumption of energy and allowed the system to operate indefinitely even when the sun was out of radiation.

Break-even and Payback Period: Divestment of energy as a result of the solar power energy usage meant that the cold storage facilities had lower operation costs. The cost-effectiveness of the system was also determined to be under 18 months of estimated payback period.

To sum up, the solar-powered cold storage units proved to be highly stable in terms of temperature regulation, energy inputs and utilization of solar energy and thus they are a potentially feasible solution in the reduction of the post-harvest losses in the tropical horticultural supply chains. The performance indicators and monitoring tools helped on gaining valuable insights on how well the system was capable of delivering sustainable and reliable cold storage facilities to perishable crops.(10)

4. Shelf Life Effect and Post- Harvest Loss Reduction

4.1 Discussed Commodities (Tomatoes and Leafy Greens)

This paper involved the assessment of the cold storage unit powered by the sun in relation to two highly perishable horticultural products namely tomatoes (Solanum lycopersicum) and leafy greens (including lettuce and spinach). They are both high-respiring crops extremely sensitive to temperature change that results in the rapid spoilage that is associated with the high temperature that is typical of the tropical climate. This was because of their economic significance and abundance in local markets hence they formed a perfect choice in experiencing the effects of cold storage on prolongation of post-harvest.

Tomatoes: Tomatoes have a short shelf life thus being highly subjected to over-ripping, softening, and developing molds as a result of improper storage. It is important to keep their shelf life by maintaining a cold temperature.(11)

Leafy Greens: These are the readily harvested vegetables in bulk and they get spoiled by wilting and getting yellow due to the high temperatures. The cold storage is especially useful storing their freshness and nutritional value.

4.2 Exptrvaging of Shelf-Life Shelf-Life Extension Observations

The cold storage units powered by the solar effectively lengthened shelf-life of tomatoes as well as leafy greens in the sense that optimum storage environment was achieved within the range of an average internal temperature of 5.4 +/- 0.8 0C. Important notes about shelf-life extension are:

Tomatoes Tomatoes held in the solar-powered cold units had a 4-5-day extension to their shelf life than tomatoes under the regular storage. The units inhibited early rice and softening of tomatoes that occur in 2-3 days when they are kept under a tropical climate. The cold storage definitely slowed down the process of ripening and spoilage of the tomatoes and the best tomatoes entered the market.

Leafy Greens: Leafy greens stored at the solar powered units were longer by 5-6 days as compared with conventional storage conditions in terms of appearance and nutrition. The cool climate aided in a slowing of the respiration rates and lowered wilting, yellowing and rotting. Leafy greens were crispy and had a better amount of vitamins in them than their unrefrigerated counterparts.

4.3 Measurement of the Reduction of losses

The impacts of the solar cold storage units on the post-harvest losses were identified by the measures of the weight loss, the yield spoilage, and marketability of commodities stored in the solar storage units, as compared to the traditional storage regime.(12)

Prevention of loss by the reduction of post-harvest loss: Post-harvest losses were reduced by 39.6 percent ($p < 0.01$) in tomatoes and leafy greens stored in the solar cold storage units. Tracing the main reasons why the decrease

in losses had occurred, it is possible to mention the reduced temperature fluctuation and postponement of spoilage because of ability to keep the produce at a certain, low temperature.
Economic Contribution: The loss minimisation also led to improved marketability of the produce as well as the purchasing power of the farmers because they could sell more quality produce. Less wastage would mean higher sale of crops with the best prices, which leads to increased profitability.
To sum up, the use of the solar-powered cold storage units was an excellent advantage when it came to increasing the shelf life and loss reduction of tomatoes and leafy greens during post-harvesting. These findings demonstrate the potential of storage systems based on renewable energy sources, which would reduce food waste and enhance the economic performance of smallholder farmers, especially in the tropics where a cold chain system is absent.

5. Payback and Economic Analysis

5.1 Cost of Investment and operating costs

The solar-powered cold storage units used in the study needed both the start-up investment cost and the operating cost which were critically measured to evaluate the economic feasibility of the technology.(13)
Capital Investment (CapEx): The cost of purchasing technology, and installing solar-powered cold storages was considered: The price of solar panels, refrigeration systems, batteries, temperature control regimes, and storage racks which formed part of capital expenditure. This costed approximately USD 15,000 per unit including the installation and commissioning.
Operating Costs: Operating costs (OpEx) were very low compared with the traditional cold storage as solar energy was used. The use of solar power minimizes the dependency on the utility grid which is an added advantage in regions whose sources of electricity are unreliable or costly. The cost of operation mostly constituted:
Maintenance: The solar panels and refrigeration work had to be maintained on a regular basis which was estimated to cost USD 500 annually per unit.
Battery Replacement: Solar batteries normally need to be replaced after 5-7 years and it is estimated that one of these batteries costs USD 1,200.
Miscellaneous Costs: Other small operating expenses involved the labor cost of loading and unloading of the produce andSystem monitoring.
The price of operating the solar-driven units was relatively low in the long run, compared to charged cold storage systems where power bills and use of fossil fuels are an issue of major concern.(14)

5.2 Break even analysis

The exercise on break-even has been carried out to arrive at the period of payback of the solar-powered cold storage units depending on reduction in losses after harvest and increases in marketable yield.
Cost Savings: The 39.6 percent decrease in the post-harvest losses and the shelf life extension of tomatoes and leafy greens were the direct contributions to the improvement of marketable products. The low wastage enabled farmers to sell larger quantities of produce at high prices.
Revenue Generation: There was an increment of 9.8 percent in the crops produced which meant that better qualitative products would be produced by the farmers whose loss was cut and brought down to enable them earn more money in their market. The increase in income was able to cover initial investment on the solar cold storage units.
Payback Period: The payback period of the solar cold storage investment came to about 18 months, on the assumption that the units will be operated efficiently, and that the yields and value of the crops will not change too much. Subsequent to the payback period, the system would offer long term economic advantages at low running costs.

5.3 Models of Adoption and management of Stakeholders

The available study examined various management models and adoption strategies of the stakeholders with the purpose to realize the scalability and sustainability of the solar cold storage units:
Cooperative Models: Cooperative-managed will be one of the best probable model of management to adopt, meaning that local farmer cooperatives or aggregation centers operate and share the application of the cold storages. The multiple smallhold farmers should be able to access the technology at lower cost to each farmer and increase the economies of scale under this model.(15)
Public- Private Partnerships (PPPs): The other possible solution is when government, the players in the private sector together with the NGOs join hands in championing the use of solar cold storage in the rural areas. Such

partnership can assist in bringing down start-up investment cost by providing subsidies or grant in maintaining the long-term success as well as sustainability of the entire system.

Training and Awareness among Farmers: The farmers should be trained on how to use, maintain or economics of solar cold storage to increase the level of adoption. This will not only enhance its technical performance but also increases its user satisfaction hence the success of the technology in various locations.

To conclude, the cold storage system run by solar energy showed great signs of economic viability as it had low payback temporalities and high returns on investments. Collaborative management structure along with the joint efforts of the government and the private industries can be instrumental in ramping up the uptake of this technology and assist smallholder farmers in the tropical parts of the world in minimizing post-harvest losses, maximizing profitability and enhancing food security.

6. Results

6.1 Summary of Technical Performance

The efficiency of the cold storage units operating on solar power was measured with the help of the most crucial technical indicators, such as stable temperature inside the storage facility, extending the shelf life of food, and having efficient utilization of energy.

Average Internal temperature: The solar cold storage units had average internal temperatures of 5.4 +/- 0.8 C and this is very convenient to preserve perishable vegetables such as tomatoes and leafy vegetables. Conversely, there was no regulated temperature in the traditional types of storage and internal temperature was approximately 22.1 o C, which does not favor the preservation of the shelf life.

Temperature Stability: The solar powered units also had temperature stability, which kept the temperature almost same. This was very important in order to establish the best storage conditions and reduce possibility of spoilage.

Energy Efficiency: The cold storage units run on solar panels thus making them energy efficient to save on grid energy and minimise operational costs. They could give constant cooling in regions with unreliable power.

6.2 Removing losses and Extended Shelf-Life Increase

The biggest advantage which was noted with the application of solar-powered cold store was that of reducing post-harvest loss and the extension of the shelf life of foods in storage.

Shelf-Life Extension: An average increase in tomatoes and leafy green shelf lives of 5 days was found by the use of the solar-powered cold storage system. Such shelf life improvement is very important in enabling the farmers to preserve their produce over a longer period and prevent wastage prior to reaching the market.

Reductions in Post Harvest Losses: The fact that 39.6 percent of the post-harvest losses was avoided can only be attributed to stable temperature levels that helped to slow down the ripening process and crushed post-harvest losses as a result. Cold storage systems were very disadvantageous to tomatoes and leafy greens because as a result of being poorly handled and subjected to fluctuations in temperature, rates of loss were very high.

6.3 Meanwhile, the economic viability findings are as follows:

Economic analysis gave us an idea on the cost effectiveness of the solar powered cold storage units.

Investment and Operating Costs: The minimum investment to be made per each cold storage unit is around USD 15,000 including the solar panel, the refrigeration system, and installation fees. The expenses of the annual maintenance were estimated at USD 500 as far as it is quite low in comparison with traditional systems of cold storage which demand high costs of electricity.

Net Return: The economic analysis demonstrated that farmers who adopted the solar-powered cold storage recorded upsurge of 14 percent on the net incomes. This was attributed to the fact that post harvest losses were reduced and shelf life increased thus enabling farmers to sell more products and outdo market wastage at premium prices.

Payback Period: The system showed break- even in 18 months, which implies that the money invested initially in the solar powered cold storage could be worth its cost within a short span of time because of the increased sales of the crops and also minimized losses.

This paper illuminates the technological viability and economic feasibility of solar powered cold storage as a modular guarantee to mitigate wastage during the post-harvesting process, guarantee market access and correlation of income levels among farmers within the tropical farming environment.

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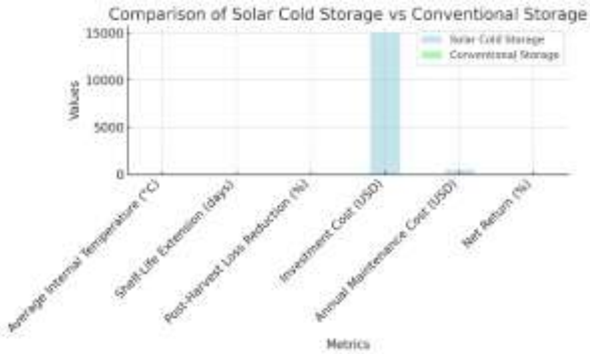

Figure 1: Comparison Of Solar Cold Storage Vs Conventional Storage

Table 1: Solar Cold Storage vs Conventional Storage Results

Metrics	Control Group (Conventional Storage)	Solar Cold Storage
Average Internal Temperature (°C)	22.1	5.4
Shelf-Life Extension (days)	0.0	5.0
Post-Harvest Loss Reduction (%)	0.0	39.6
Investment Cost (USD)	0.0	15000.0
Annual Maintenance Cost (USD)	0.0	500.0

7. Conclusion

7.1 Conclusion

The results of this experiment prove that solar-based cold storage technology is the solution to substantial post-harvest problems in tropical agriculture. The important lessons learnt in the study are:

- **Better Storage Conditions:** The solar cold storage buildings had the ideal environment to inside temperature of 5.4 +0.8 o C and this played a crucial role in keeping the perishable agents such as tomatoes and leaf vegetables fresh and fit to stay in the market. This was the temperature control that played a critical role in minimising post harvest losses.
- **Substantial Decrease in Post-Harvest losses:** The solar-powered equipment cut the post harvest losses by 39.6 percent highlighting the efficiency of stable and cool storage facilities in delaying the spoilage of fresh products and hence extending the shelf life. Comparatively, traditional storage system was contributing to larger losses because of unstable temperatures.
- **Economic Viability:** The solar-powered cold storage met the break-even point in 18 months and there was a 14 percent increment in the net-return of the farmers. This was highly facilitated by the enhanced crop yield by increasing the shelf life and minimizing on spoilage hence the technology was cost effective and sustainable.

This evidence highlights the capabilities of solar-powered cold storage to enhance smallholder farming systems efficiency, and sustainability in tropical climates where cold chains infrastructure is frequently underestimated.

7.2 Smallholder Supply chain implication

An effective implementation of solar-powered cold storage facilities and technologies has very strong advantages to the smallholder farmers, especially in the developing world. This enables the storage of perishable crops over long periods hence eliminating the pressure of farmers to offer them to the market after harvesting hence they have a wider flexibility in the market. The technology also enables the farmers to achieve more market access where they can sell quality produce at high prices instead of risking the unsellability of produce because of spoilage.

Additionally, the limitation of post-harvest wastage implies a significant contribution to the enhancement of food security in those regions where the production of crops is subject to a substantial risk of variation as a result of climate changes. Smallholder farmers can reach the local demand, and pay a greater role in community resilience, by stabilizing supply of fresh produce.

7.3 Scale-Up Recommendations

Findings of the present study imply that solar energy-powered cold storage has a potential to be a successful method of minimizing post-harvest losses in the dual ordeal of smallholders supply chains. The recommendations are as follows to be able to scale-up and expand adoption:

- **Pilot Projects and Capacity Building:** As a continuation to this study, pilot projects must be carried out in other areas where the system can be tested on various climatic conditions and crop types. Besides, some training programs should be created to assist farmers in operating and maintaining the systems appropriately.
- **Public-Private Partnerships:** Governments and the private sector ought to join hands in ensuring that the solar-powered cold storage facility becomes affordable by subsidizing it or using financing schemes. This would reduce the start up cost of smallholder farmers.
- **Cooperative Management Models:** The introduction of the cooperation in the management of solar cold storage units may make them more affordable and accessible. The combination of resources allows the smallholders to enjoy collective infrastructure and economy of scale thus lowering the financial implications of the investment.

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Conflicts of interest

The authors have no conflicts of interest to declare

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