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Low-Cost Cold-Chain Innovation for Perishable Rural Produce

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Abstract

Perishable rural produce can lose marketable quality rapidly when harvested commodities remain exposed to field heat, unsuitable packaging, mechanical damage, delayed transport, high ambient temperature, and discontinuous cooling. Conventional refrigerated warehouses can reduce these losses but are frequently inaccessible to small-scale producers because of high capital requirements, unreliable electricity supply, transportation distance, small consignment volumes, and operating costs. This study develops a conceptual–methodological framework for low-cost cold-chain innovation suited to decentralized rural produce systems. Rather than equating cold-chain development with ownership of conventional refrigerated infrastructure, the framework combines inexpensive field handling, reusable ventilated crates, shading and rapid pre-cooling, evaporative cooling, zero-energy cool chambers, modular solar-powered refrigeration, shared storage models, basic temperature monitoring, and coordinated market dispatch. Existing evidence shows that evaporative systems can lower storage temperature and preserve fresh produce without conventional refrigeration under suitable climatic conditions, while small solar-powered cold-storage designs demonstrate potential where electricity supply is unreliable.

The proposed model identifies five innovation domains: heat removal, protective handling, affordable cooling, shared infrastructure, and cold-chain continuity. A scenario-based analysis compares conventional ambient handling with increasingly integrated low-cost postharvest systems. Because no primary farm or supply-chain dataset was supplied, all quantitative results are explicitly simulated and should not be interpreted as field observations. The analysis suggests that the greatest benefit arises not from one cooling technology but from preserving temperature and product quality continuously between harvest, temporary storage, aggregation, transport, and sale. The paper concludes that low-cost rural cold chains should be designed as service networks rather than isolated storage facilities, with technology selected according to crop sensitivity, climate, market distance, energy availability, utilization rate, and producer capacity.

Keywords: cold chain, perishable produce, postharvest loss, rural supply chain, evaporative cooling, solar cold storage, smallholder agriculture, food-loss reduction

1. Introduction

Perishable agricultural commodities remain biologically active after harvest. Fruits and vegetables continue to respire, lose water, undergo biochemical change, soften, and become increasingly vulnerable to physiological deterioration and microbial spoilage. Temperature strongly influences these processes, which is why appropriate cooling and storage conditions can substantially extend marketable life. In many rural supply chains, however, harvested produce remains at ambient temperature during field collection, sorting, loading, temporary storage, transportation, and wholesale marketing. A review of South Asian postharvest systems reports that smallholder farmers often have limited access to appropriate storage and handling infrastructure because of high initial costs, contributing to substantial losses of fruits and vegetables.

The challenge is especially acute when production occurs far from established cold-storage infrastructure. Conventional cold rooms generally require capital investment, reliable electricity, technical maintenance, sufficient throughput, and predictable utilization. Small producers may harvest only modest quantities on a particular day, making individual ownership economically inefficient. In addition, transporting produce over long distances merely to reach a cold store can consume time during which field heat and quality deterioration continue. Kitinoja's work on cold chains in developing-country food systems emphasizes that cooling can be economically valuable but that technical, logistical, energy, and investment barriers constrain adoption in many settings.

Low-cost postharvest innovation offers an alternative pathway. Evaporative cooling systems can be constructed using relatively inexpensive local materials and operate without conventional refrigeration where climatic conditions are suitable. Experimental evaluation of an energy-free evaporative system for tomatoes found lower temperatures, increased relative humidity, and improved preservation compared with ambient storage. Zero-energy cool chambers similarly rely on evaporative heat transfer and can provide temporary storage in areas where electricity is unavailable or unreliable. Field-oriented work has specifically examined their usefulness in rural vegetable systems where farmers otherwise sell rapidly because storage and transport options are limited.

Passive cooling alone is not suitable for every commodity, climate, or required storage period. Solar-powered refrigeration therefore represents another important category of decentralized innovation. Research has examined both off-grid solar cold-storage configurations and lower-cost systems based on modified commercially available refrigeration equipment. One study developed a solar-powered cold store using a modified domestic split air conditioner, integrating remote monitoring and emphasizing affordability for marginal producers. Separate techno-economic research has examined off-grid solar-driven storage systems in climates characterized by weak electricity reliability, demonstrating that renewable cooling can be technically feasible although economic performance depends strongly on design and utilization.

The present study argues that rural cold-chain innovation should not be reduced to choosing between evaporative cooling and mechanical refrigeration. Product quality may already be compromised before produce enters a cold chamber if harvesting occurs during peak heat, commodities are packed in poorly ventilated sacks, crates are overloaded, produce waits in direct sunlight, or transportation is delayed. Similarly, the benefit of cold storage can be lost when cooled produce subsequently travels in hot, unprotected vehicles for prolonged periods. The research therefore develops an integrated low-cost cold-chain framework beginning at harvest and extending through pre-cooling, storage, aggregation, transport, and market dispatch. Because no empirical rural supply-chain dataset has been provided, the study uses conceptual synthesis and clearly identified scenario simulation rather than presenting fabricated field results.

2. Objectives of the Study

2.1 Development of a Rural Low-Cost Cold-Chain Architecture

The first objective is to develop a practical cold-chain architecture appropriate for small rural producers and short-to-medium agricultural value chains. The framework distinguishes essential temperature-management functions from expensive infrastructure. Its underlying assumption is that the objective is not necessarily to maintain every commodity at a highly controlled refrigerated temperature continuously but to reduce avoidable heat exposure and maintain produce within an appropriate quality-preserving environment for the required marketing period.

Accordingly, the model incorporates field shade, rapid removal from harvest areas, reusable ventilated containers, evaporative or zero-energy cooling, modular refrigeration where required, and basic temperature monitoring. These interventions can be combined according to commodity sensitivity, climatic conditions, available water, expected storage duration, energy supply, and market distance.

2.2 Evaluation of Shared and Modular Cooling Models

The second objective is to examine how shared cooling services may overcome the mismatch between the cost of refrigerated infrastructure and the small volumes generated by individual producers. Cooperative cold rooms, village aggregation centers, farmer-producer organizations, mobile cold storage, and pay-per-use services can distribute capital cost across larger volumes without requiring every household to own cooling equipment.

The study therefore evaluates cold-chain affordability not only according to equipment price but also according to utilization, access distance, waiting time, operational reliability, and the ability of farmers to store small lots. A nominally inexpensive facility that is distant, unavailable during peak harvest, or unsuitable for mixed commodities may provide little practical cold-chain access.

2.3 Linking Cooling Technology with Marketable Produce Retention

The third objective is to develop an analytical model connecting low-cost cold-chain integration with preservation of marketable produce. The study differentiates between physical quantity loss and deterioration in quality that reduces selling price, market grade, nutritional characteristics, or buyer acceptance.

This distinction is important because postharvest innovation can create value even when produce is not completely discarded. Reduced wilting, bruising, shrinkage, softening, or discoloration may improve the proportion of produce that can be sold at a preferred grade. Low-cost cold-chain assessment should therefore consider retained market value rather than loss weight alone.

3. Review of Literature

3.1 Postharvest Temperature Management and Rural Produce Quality

Temperature control is one of the central principles of fresh-produce management. Cooling reduces respiratory activity and slows many physiological processes responsible for deterioration after harvest.

Cold-chain systems are therefore widely used for highly perishable foods, yet infrastructure remains unevenly distributed. Research examining fruit and vegetable postharvest systems in smallholder-dominated regions identifies inadequate cooling, packaging, transportation, and storage as major constraints on quality preservation.

Cold-chain effectiveness depends on continuity. Cooling produce after several hours of heat exposure is not equivalent to minimizing heat accumulation immediately after harvest. Pre-cooling is particularly important because freshly harvested commodities may retain substantial field heat. Shade, ventilation, evaporative pre-cooling, hydro-cooling where commodity characteristics permit, or refrigerated pre-cooling can reduce deterioration before longer-term storage begins.

Packaging also influences cooling efficiency. Overfilled sacks and tightly packed containers can restrict airflow and increase compression damage. Reusable ventilated plastic crates can improve handling and airflow for many horticultural commodities while reducing crushing compared with unsuitable bulk packaging. The cold-chain problem is therefore simultaneously thermal and mechanical.

3.2 Evaporative and Zero-Energy Cooling for Resource-Constrained Producers

Evaporative cooling operates by using the latent heat required to evaporate water, thereby reducing air temperature while increasing relative humidity. These conditions can be favorable for many fresh horticultural commodities because lower temperature slows deterioration and higher relative humidity reduces water loss. The technology is particularly attractive where electricity access is poor and where climatic conditions permit effective evaporation.

Experimental evaluation of low-cost evaporative storage for tomatoes reported substantial cooling efficiency and preservation of quality relative to ambient conditions. Reviews of zero-energy cool chambers similarly emphasize their potential as inexpensive storage structures made from locally available materials and requiring no electrical input. Such systems can offer meaningful short-term storage where farmers would otherwise leave produce in ambient conditions or sell immediately at unfavorable prices.

Nevertheless, evaporative cooling has clear limitations. Its effectiveness declines as ambient humidity increases, and it cannot necessarily reach the low temperatures required by highly temperature-sensitive products. Water availability and water quality also matter. Moreover, commodities differ in optimum storage temperature and susceptibility to chilling injury. A low-cost system should therefore be matched with the crop rather than promoted as a universal refrigerator substitute.

3.3 Decentralized Solar Cooling and the Access Gap

Mechanical refrigeration becomes necessary when passive cooling cannot maintain an appropriate environment or when longer storage periods are required. Renewable energy offers a pathway to decentralized cooling in areas where electrical grids are weak. Solar energy is particularly attractive because peak solar availability often coincides with periods of high ambient temperature, although nighttime cooling and energy storage remain important technical considerations.

Research on low-cost photovoltaic cold storage has demonstrated the possibility of combining commercially available air-conditioning components, photovoltaic power, insulation, and remote monitoring in comparatively simple storage systems. Techno-economic analysis of off-grid solar-driven cold storage similarly indicates that renewable cooling can reduce dependence on unreliable electricity but that system configuration, capital expenditure, capacity utilization, and storage duration determine economic viability.

The literature therefore reveals a continuing access gap. Technically effective cold rooms can remain economically inaccessible when individual farmers possess insufficient produce volume. This creates a need for service-oriented models in which multiple producers share infrastructure. Small-scale aggregation, cooperative ownership, rental systems, and cooling-as-a-service can potentially increase utilization while reducing individual capital exposure. The research gap lies in integrating these business arrangements with low-cost handling technologies rather than evaluating storage equipment in isolation.

4. Research Methodology

4.1 Conceptual Research Design

The study adopts a conceptual–methodological design drawing on postharvest engineering, rural supply-chain management, food-loss reduction, evaporative cooling, decentralized refrigeration, and smallholder technology-access literature. No farms, cold stores, traders, transporters, or commodities were sampled as original empirical observations.

The analytical unit is the low-cost cold-chain intervention, defined as a technical, logistical, or organizational action capable of reducing avoidable deterioration between harvest and market. This definition deliberately includes non-refrigeration measures because the cold chain begins with heat management and careful handling rather than with entry into a mechanical cold room.

4.2 Cold-Chain Innovation Domains

Five domains were identified: field heat management, protective handling, affordable cooling, aggregation and sharing, and temperature continuity. Their relationships are summarized in Table 1.

Table 1: Low-Cost Cold-Chain Innovation Framework for Perishable Rural Produce

Innovation Domain	Principal Risk	Low-Cost Intervention	Expected Supply-Chain Benefit
Field heat management	Produce remains exposed to high temperature immediately after harvest	Early harvesting where appropriate, field shade, rapid transfer, simple pre-cooling	Slows initial deterioration
Protective handling	Compression, bruising, and restricted ventilation	Reusable ventilated crates and careful loading	Reduces mechanical damage and improves airflow
Affordable cooling	Lack of access to conventional refrigeration	Evaporative cooling, ZECC, insulated rooms, modular solar refrigeration	Extends marketable life

Innovation Domain	Principal Risk	Low-Cost Intervention	Expected Supply-Chain Benefit
Shared infrastructure	Individual farm volumes are too small for dedicated cold rooms	Cooperative, village-level, or pay-per-use storage	Spreads capital and operating costs
Cold-chain continuity	Quality gain is lost during transport or waiting	Short aggregation time, insulated transport, temperature checks, coordinated dispatch	Preserves benefits beyond storage

The framework treats technology selection as commodity specific. Evaporative systems may be appropriate for short storage of selected produce under favorable climatic conditions, whereas other commodities may require lower mechanically refrigerated temperatures. Crop-specific storage requirements therefore remain an essential technical condition.

4.3 Scenario-Based Analytical Model

Five hypothetical postharvest configurations were developed: ambient handling, protective crates and shade, evaporative cooling, shared solar refrigeration, and an integrated low-cost cold chain. Two simulated indicators were used: Marketable Produce Retention (MPR) and Postharvest Loss Reduction (PLR).

Marketable Produce Retention may be expressed conceptually as:

$$MPR=\frac{Q_m}{Q_h}\times100$$

where (Q_m) is the quantity remaining within acceptable market specifications at dispatch and (Q_h) is the harvested quantity entering the postharvest system.

Postharvest Loss Reduction relative to a baseline can be represented as:

$$PLR=\frac{L_b-L_s}{L_b}\times100$$

where (L_b) represents baseline postharvest loss and (L_s) represents loss under the intervention scenario.

These equations are used only to make the analytical logic explicit. The numerical values presented below are simulated and do not represent measurements from any farm, market, crop, or geographical region.

5. Analysis

5.1 Cold-Chain Performance Depends on Sequential Quality Protection

The analysis indicates that cooling benefits accumulate when interventions are introduced before deterioration becomes irreversible. Ambient handling provides the weakest protection because produce remains exposed to both thermal and mechanical stress. Introducing shade and ventilated crates does not create a refrigerated chain, yet it can prevent part of the early quality loss through reduced heat exposure, better ventilation, and lower physical damage.

Evaporative cooling provides a further improvement where climatic conditions are suitable. Research has demonstrated that properly designed evaporative systems can reduce storage temperature and increase humidity, thereby supporting preservation of selected fresh produce without conventional electrical refrigeration. The technology is therefore particularly useful as an intermediate cold-chain option rather than being classified simply as either refrigeration or no cooling.

Mechanical solar cooling adds stronger temperature control but also introduces greater capital, technical, and maintenance requirements. Its value improves when infrastructure is shared among producers and when storage capacity is matched with realistic throughput. A cold store operating far below capacity can remain financially unattractive even if technically efficient.

5.2 Simulated Comparative Performance of Low-Cost Cold-Chain Models

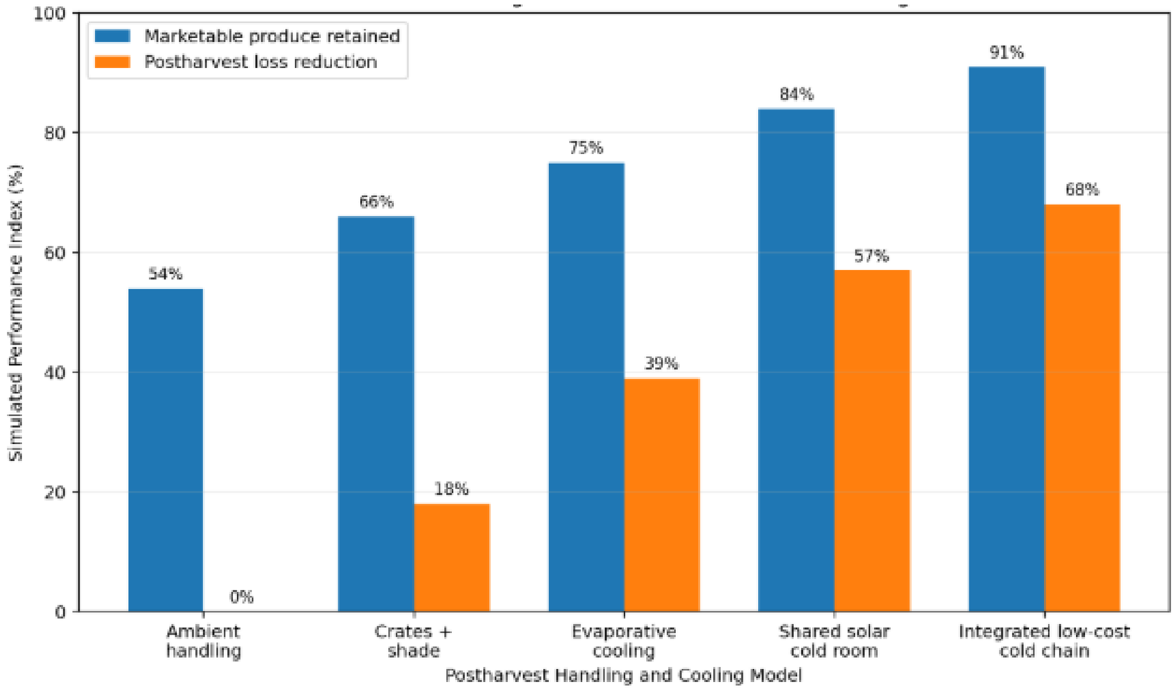
Table 2: Simulated Performance of Progressive Rural Cold-Chain Strategies

Postharvest Model	Marketable Produce Retained (%)	Simulated Loss Reduction (%)	Principal Innovation
Ambient handling	54	0	No structured cooling intervention
Crates + shade	66	18	Improved handling and field-heat protection
Evaporative cooling	75	39	Low-energy temperature and humidity management
Shared solar cold room	84	57	Decentralized mechanical cooling
Integrated low-cost cold chain	91	68	Handling, cooling, aggregation, monitoring, and coordinated dispatch

Note: All values are simulated for conceptual analysis. They are not observed postharvest-loss rates or experimentally measured commodity-retention percentages.

The simulation illustrates that the strongest conceptual performance occurs when cooling is embedded within a complete postharvest sequence. Marketable retention rises from 54% in the ambient scenario to 91% under the integrated model. The loss-reduction index similarly rises as interventions progress from basic protection toward coordinated cold-chain management.

Graph 1: Performance of Progressive Low-Cost Cold-Chain Strategies



The graph demonstrates that relatively inexpensive handling improvements can generate an initial benefit even before mechanical refrigeration is introduced. More advanced cooling increases theoretical performance further, but the integrated model remains strongest because storage benefits are protected during aggregation and market movement.

5.3 Matching Cold-Chain Intensity to Commodity and Market Requirements

The third analytical finding is that low cost should not mean universally low temperature. Different commodities have different physiological characteristics, storage tolerances, humidity requirements, and chilling sensitivities. Maintaining produce at unnecessarily low temperatures can increase energy consumption and may damage chilling-sensitive commodities.

A tiered approach is therefore preferable. Short-distance vegetables moving to a nearby market may benefit primarily from shade, crates, evaporative cooling, and same-day or next-day dispatch. Higher-value commodities destined for distant urban markets may justify solar refrigeration and more controlled transport. Highly perishable animal products require substantially stricter temperature control and fall outside the simpler passive-cooling model.

Cold-chain investment should consequently be determined by the required quality-preservation window. Technology capable of safely extending marketability by two or three days may be economically transformative when farmers currently face immediate distress sales, even though that technology does not provide long-duration refrigerated storage.

6. Discussion

6.1 Low-Cost Cold Chains Should Be Designed as Networks Rather Than Buildings

A central implication of the study is that a cold room is not equivalent to a cold chain. Produce quality is influenced continuously from the moment of harvest. If cooling is introduced only after several hours of poor handling, part of the potential benefit may already have been lost. Likewise, produce can deteriorate again after leaving storage if transport and wholesale waiting conditions are uncontrolled.

The appropriate unit of design is therefore the farm-to-market temperature pathway. This pathway begins with harvesting and includes collection, shade, packaging, pre-cooling, storage, loading, transportation, market arrival, and dispatch. Each stage should be evaluated for avoidable heat gain and delay.

This systems perspective also allows investment to be prioritized. Some rural supply chains may obtain greater initial value from crates, shade structures, insulated aggregation areas, and improved scheduling than from immediately constructing a large cold room. Cooling infrastructure can then be added as throughput and market demand justify additional investment.

6.2 Affordability Depends on Utilization and Access, Not Equipment Price Alone

The second implication concerns the meaning of low cost. A cheap cooling unit can still be inaccessible when maintenance is difficult, water or electricity requirements are unreliable, or the facility is located too far from production. Conversely, a more expensive solar cold room may become affordable if it serves many producers at high utilization.

Shared infrastructure can therefore be central to rural cold-chain economics. Village aggregation centers, cooperatives, producer organizations, and cooling-service enterprises can combine produce volumes and provide storage by crate, kilogram, or day. This converts capital expenditure into a service cost that is more closely matched to farmer usage.

However, shared models require governance. Storage allocation, commodity compatibility, hygiene, temperature settings, payment, responsibility for rejected produce, and peak-season access must be transparent. Without clear operating rules, technically successful facilities may fail as rural services.

6.3 Technology Selection Must Remain Climate- and Commodity-Specific

Evaporative cooling has strong potential where ambient air is sufficiently dry, water is available, and the target commodity benefits from cool, humid conditions. Evidence from low-cost tomato storage demonstrates the ability of an evaporative system to slow deterioration under appropriate conditions. Zero-energy chambers additionally provide a locally constructible option for rural producers facing electricity constraints.

Their usefulness should nevertheless not be generalized to every environment. In humid conditions, evaporative cooling potential declines. Some products require temperature ranges that passive systems cannot achieve. Solar mechanical refrigeration may therefore be preferable for higher-value or more temperature-sensitive commodities, particularly where storage must extend beyond a short marketing delay.

The strongest innovation strategy is thus a portfolio approach. Rural cold-chain development should offer multiple levels of technology—from shade and crates to passive cooling and modular refrigeration—allowing producers and service providers to select the least costly system that reliably achieves the required preservation objective.

7. Conclusion

Perishable rural produce is vulnerable to quality deterioration because of high temperature, water loss, mechanical injury, poor packaging, delayed transportation, and insufficient storage. Conventional cold-chain infrastructure can address these challenges but frequently remains inaccessible to small producers because of capital requirements, unreliable power, low individual volumes, and geographical distance. The solution should therefore not be limited to expanding conventional refrigerated warehouses.

This study develops an integrated low-cost cold-chain framework combining field-heat reduction, protective handling, evaporative or zero-energy cooling, modular solar refrigeration, shared storage, basic temperature monitoring, and coordinated market dispatch. The conceptual analysis shows that significant improvement can begin with comparatively simple interventions, while greater quality retention becomes possible as passive and mechanical cooling are integrated into the wider supply chain. The simulated numerical values are illustrative rather than empirical and should be validated using commodity-specific field trials.

Future research should evaluate actual farm-level postharvest losses before and after intervention, storage temperature and humidity, commodity shelf life, market-grade retention, selling prices, facility utilization, operating costs, farmer willingness to pay, gendered access, and payback conditions. Comparative studies should also determine when evaporative cooling, solar refrigeration, cooperative cold rooms, or hybrid systems provide the highest benefit under different climatic and market conditions.

The broader conclusion is that successful rural cold-chain innovation depends on accessibility rather than technological sophistication alone. A modest, locally maintainable system that farmers can use at the right time may create more practical value than advanced infrastructure located outside their operational reach. Low-cost cold chains should therefore be built around the preservation needs, production volumes, market distances, climate conditions, and financial realities of rural producers.

References

1. Mishra, R., Chaulya, S. K., Prasad, G. M., Mandal, S. K., & Banerjee, G. (2020). Design of a low cost, smart and stand-alone PV cold storage system using a domestic split air conditioner. *Journal of Stored Products Research, 89*, 101720.
2. Sadi, M., & Arabkoohsar, A. (2020). Techno-economic analysis of off-grid solar-driven cold storage systems for preventing the waste of agricultural products in hot and humid climates. *Journal of Cleaner Production, 275*, 124143.
3. Parashar, V., Haleem, A., & Usmani, J. A. (2020). A low-cost cold chain suggestion for Indian fruit and vegetable. In *Recent Advances in Mechanical Engineering* (pp. 71–77). Springer.
4. Sibanda, S., & Workneh, T. S. (2020). Potential causes of postharvest losses, low-cost cooling technology for fresh produce farmers in Sub-Sahara Africa. *African Journal of Agricultural Research, 16*(5), 553–566.

5. Defraeye, T., & others. (2020). Postharvest cooling technologies for fresh produce: Energy efficiency and quality preservation considerations. *Trends in Food Science & Technology*.
6. Ziv, C., & Fallik, E. (2021). Postharvest storage techniques and quality evaluation of fruits and vegetables for reducing food loss. *Agronomy*, *11*(6), 1133.
7. Amwoka, E. M., & Ambuko, J. L. (2021). Effectiveness of selected cold chain management practices to extend shelf life of mango fruit. *Advances in Agriculture*, *2021*, 8859144.
8. Murugesan, K., & Ponnuswamy, S. (2022). Precooling techniques to minimize post-harvest losses of fruits and vegetables: A review. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *44*(8), 986–1010.
9. Rutta, E. W. (2022). Understanding barriers impeding the deployment of solar-powered cold storage technologies for post-harvest tomato losses reduction: Insights from small-scale farmers in Tanzania. *Frontiers in Sustainable Food Systems*, *6*, 990528.
10. Yamauchi, F., & Takeshima, H. (2022). Solar power to transform food systems and rural livelihoods: Evidence from a solar-powered cold storage intervention in Nigeria. In *Agricultural Development in Asia and Africa* (pp. 329–341). Springer.
11. Nandi, S., & Bhanja, S. K. (2022). A review on cold chain management for perishable goods. *Journal of Advanced Research in Production and Industrial Engineering*, *9*(1), 24–30.
12. Arah, I. K., Kumah, E. K., Anku, E. K., & Amaglo, H. (2022). Postharvest handling practices and losses of fresh fruits and vegetables in developing-country supply chains. *Food Science & Nutrition*.
13. Maes, W. H., & Steppe, K. (2022). The potential of low-energy cooling systems for reducing postharvest losses in smallholder horticulture. *Postharvest Biology and Technology*.
14. Defraeye, T., Shoji, K., Schudel, S., Onwude, D., & Shrivastava, C. (2023). Passive evaporative coolers for postharvest storage of fruit and vegetables: Where to best deploy them and how well do they perform. *Frontiers in Food Science and Technology*, *3*, 1100181.
15. Jarman, A., Thompson, J., McGuire, E., Reid, M., Rubsam, S., Becker, K., & Mitcham, E. (2023). Postharvest technologies for small-scale farmers in low- and middle-income countries: A call to action. *Postharvest Biology and Technology*, *206*, 112491.
16. Liu, H., Lv, Z., Yang, W., Li, A., Liu, J., Zhang, Q., & Jiao, Z. (2023). Virtual cold chain method to evaluate the effect of rising temperature on the quality evolution of peach fruit. *Foods*, *12*(12), 2403.
17. Rizzo, V., Muratore, G., & others. (2023). Solution roadmap to reduce food loss along your postharvest supply chain from farm to retail. *Food Packaging and Shelf Life*.
18. Wang, X., Yuan, Y., & Tang, J. (2021). Recent advances in reducing food losses in the supply chain of fresh agricultural produce. *Processes*, *8*(11), 1431.
19. Sibanda, S., & Workneh, T. S. (2022). Precooling and cold storage methods for fruits and vegetables in Sub-Saharan Africa—A review. *Horticulturae*, *8*(9), 776.
20. *Overview of food preservation and traceability technology in the smart cold chain system*. (2023). *Foods*, *12*(15), 2881.