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Review Article

Decentralized solar-powered cooling systems for fresh fruit and vegetables to reduce post-harvest losses in developing regions: a review

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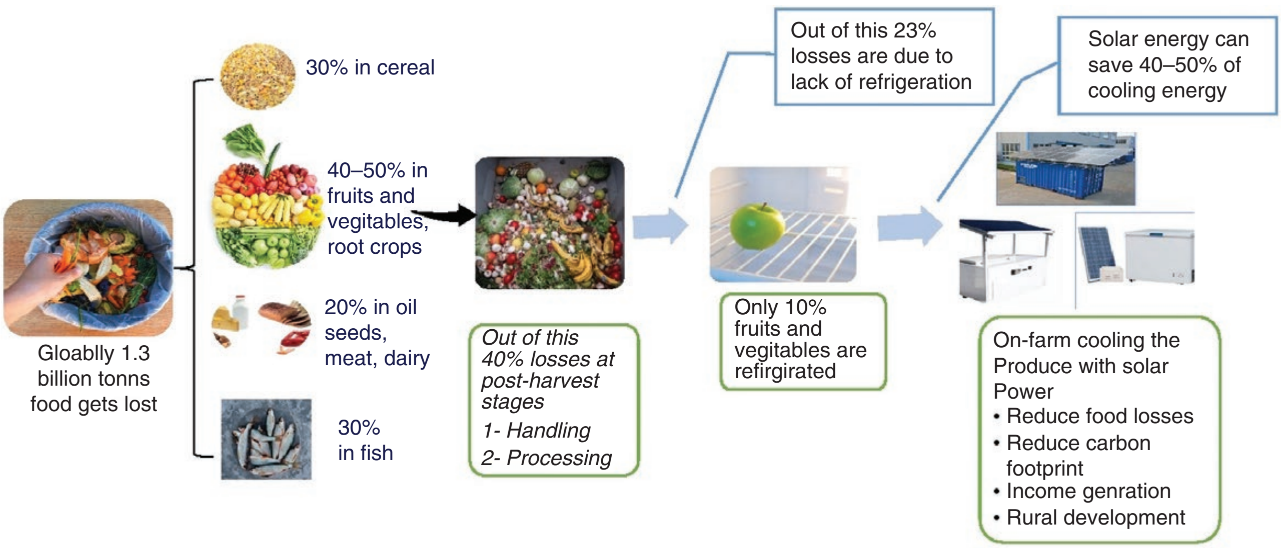
Abstract

The availability of on-farm storage and processing is a critical challenge facing small farmers, which hinders agricultural productivity. Thirty per cent of the food produced globally is lost after harvest, with the proportion being exceptionally high in low- and middle-income countries due to a lack of on-farm handling and storage facilities. Conventional cold-storage solutions have not taken off at the smallholder level, mainly due to a lack of availability and access to reliable grid electricity. Therefore, off-grid decentralized solar-powered cold-storage units can play a vital role in preserving the produce at production sites and enhancing livelihood and rural development with a minimal carbon footprint. To maintain low temperatures at every step of the agricultural value chain, known as the 'cold chain', several technology vendors aim to improve the shelf life and user benefit. Small-scale farmers, which account for two-thirds of all food losses, are another group they focus on. This study examines the existing situation, importance and potential opportunities of decentralized cold-storage systems for fresh fruit and vegetables. In addition to economic, social, technological and environmental limitations, this study examines the triumphs and challenges of incorporating solar-energy-powered cold storage into developing communities. Although the private sector, NGOs and some government agencies are working to promote decentralized cold-storage facilities, relatively little has been done so far to have a significant influence on post-harvest losses and food security. There are still knowledge gaps on decentralized cold-storage facilities. The primary operational constraint is the economic situation of end users and the lack of financing alternatives for smallholder farmers.

Graphical Abstract



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Introduction

With a rapidly growing population, food and energy requirements will increase by 35–56% between 2010 and 2050 [1]. Although the population growth rate for 2007–50 is estimated to be lower (50%) than the rate from 1963 to 2007, high growth rates are still expected in developing regions of the world such as East and Southeast Asia and sub-Saharan Africa, which already suffer from food insecurity [2]. Global food production has gradually increased due to technological advancement [3]; however, post-harvest losses remain significantly high. These losses are due to weight loss, nutritional loss and quality deterioration of the product [4]. Depending on the product, area and economy, post-harvest losses in the food supply chain vary greatly. In the case of developing countries, a large proportion is lost, particularly in the case of perishable products such as fruit and vegetables, due to the lack of agricultural handling and storage facilities. On the contrary, in developed countries, food losses are high on the consumer side and low in the mid-supply chain due to the availability of better infrastructure to manage products [5].

Given the perishable nature of fruit and vegetables, the need for timely storage is of primary importance, as not all harvested products are consumed immediately. The lack of cold-storage facilities is one of the leading causes of massive post-harvest losses in highly perishable produce such as tomatoes, negatively affecting farmers' livelihoods and the economic contribution of the sector [6]. Decentralized sustainable energy solutions for on-farm cooling systems and storage can play a crucial role in addressing this challenge, especially in underdeveloped nations where losses are incredibly high at this stage of the supply chain. Current estimates suggest that post-harvest losses in fruit and vegetables are 30–50% in Africa [7], 20–44% in South Asia [8] and >40% in Latin America [9]. Various socio-economic and infrastructural factors directly affect post-harvest fruit and vegetable losses in developing countries at the production level, the handling and the transportation levels, and retail and wholesale levels [10], as shown in Figs 1 and 2 [11].

Drying and cooling are standard methods to store horticultural products safely [12]. However, the drying process alters the taste, colour and texture of the product, whereas fresh food can be kept in cold conditions without deterioration or shrinkage. Fruit and vegetable rotting begins shortly after harvest; therefore, farmers must sell their produce at a low price to traders and collectors who cannot store it themselves. A standard cold-storage system requires a significant amount of energy, which limits its applicability to smallholder farms in developing countries. Furthermore, commercial cold-storage warehouses are centralized, increasing producers' transportation expenses [13].

Rural communities in underdeveloped nations are more susceptible to climate shocks due to a lack of cold-storage facilities, which also causes more food loss. For example, in sub-Saharan Africa, food losses between harvest and processing are responsible for 37% of the region's food waste. Insufficient energy supply in rural areas, where most food is produced, causes disproportionately large losses. Therefore, decentralized cold storage can significantly help reduce post-harvest losses at production sites and generate income and secure livelihoods in rural communities in developing countries [13]. Solar energy is a viable solution in developing countries, especially in tropical and subtropical regions in Asia, Africa and Latin America. These areas receive a large amount of solar radiation all year round—an average of 4–7 kWh/m^2d, giving an energy amount of 19 MJ over the year [14]. The solar energy potentials in various tropical and subtropical regions of the world are shown in Fig. 3. It shows that developing countries have a higher potential to receive enough solar energy to meet their demands than developed countries due to their geographical location.

It can be observed that the sunniest locations in the world are found in Africa. Theoretically, concentrated solar power and photovoltaic (PV) energy in Africa are estimated to be 470 and 660 petawatt hours (PWh), respectively. The co-occurrence of solar radiation and cooling requirements makes it a desirable energy source that might reduce energy consumption for cooling processes by ≤40–50% [15]. Therefore, solar energy would be a

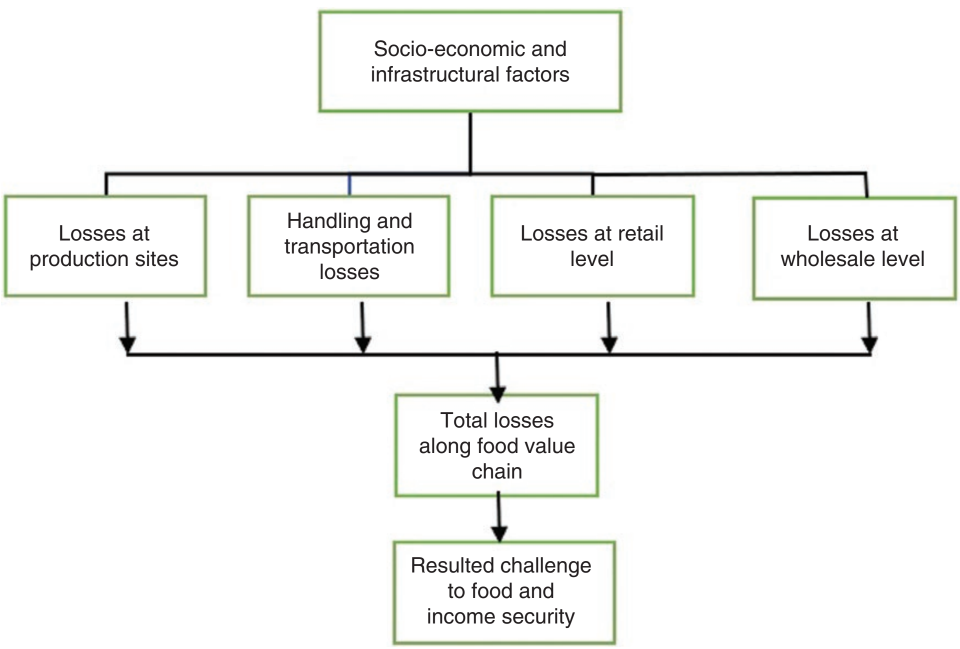

Fig. 1: Impact of socio-economic and infrastructural factors on post-harvest losses of fruit and vegetables. Figure adapted from Khurshid *et al.* [9].

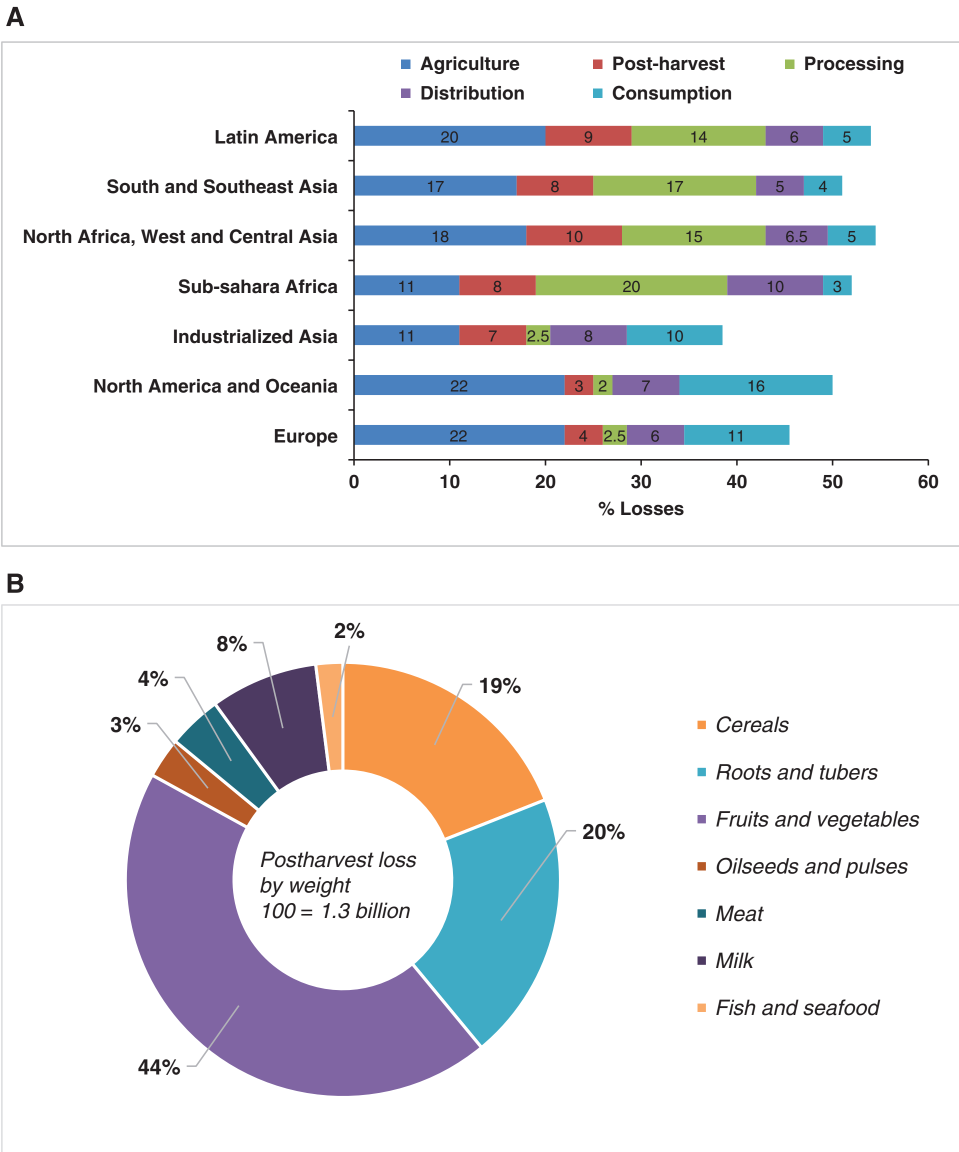

Fig. 2: (a) Distribution of losses at various stages of the supply chain of fruit and vegetables in different regions of the world and (b) share of global post-harvest losses by commodities. Image adapted from Jose Graziano da Silva [11].

great alternative to the traditional grid system for operating cold-storage units in rural and remote areas.

The size of the global solar-powered cold-storage market is expected to reach US$254 billion by 2027, expanding at a compound annual growth rate of 13% during the forecast period (Maximise Market Research Pvt Ltd 2021). The need of the hour is to invest in low-cost, decentralized cold-storage systems. Post-harvest technologies that are close to the farm gate or designed to meet the needs of small farmers have the potential to increase farmer incomes and decrease food loss simultaneously. Efforts have been made to use solar energy for cooling in the forms of solar-thermal energy [16], solar photovoltaic (SPV) [17, 18], solar-hybrid [13, 19] and solar-hybrid energy storage with biomass heat [20]. To maintain the predetermined storage temperature in a solar cold-storage unit, solar energy is captured and employed in a thermally driven chilling process. The application of solar cooling to perishable horticultural produce presents technical and operational issues, and it is crucial to control operational conditions to reduce the risk of product deterioration. One of the major constraints in the utilization of solar cooling in terms of economy and the environment is that stand-alone solar cooling systems are costly due to the size of the battery backup [21]. Furthermore, the lack of knowledge regarding solar-powered cold-storage solutions impedes their future implementation [22]. Second, concerns from solar experts about high installation and deployment costs are exacerbated by additional market constraints, such as low purchasing power from potential customers and limited financing of renewable-energy projects for local solar service providers. The social-cultural contexts and market conditions in different regions can prevent the eventual adoption of solar-powered cold-storage solutions. However, it is predicted that solar electric cooling will require less cost in 2030 due to cost-saving advancements in PV technology and the high COP (coefficient of performance) of vapour-compression refrigeration systems. Although solar cooling is considered promising for building cooling and centralized commercial uses, its decentralized applications in agriculture can play a vital role in addressing food security challenges in developing countries.

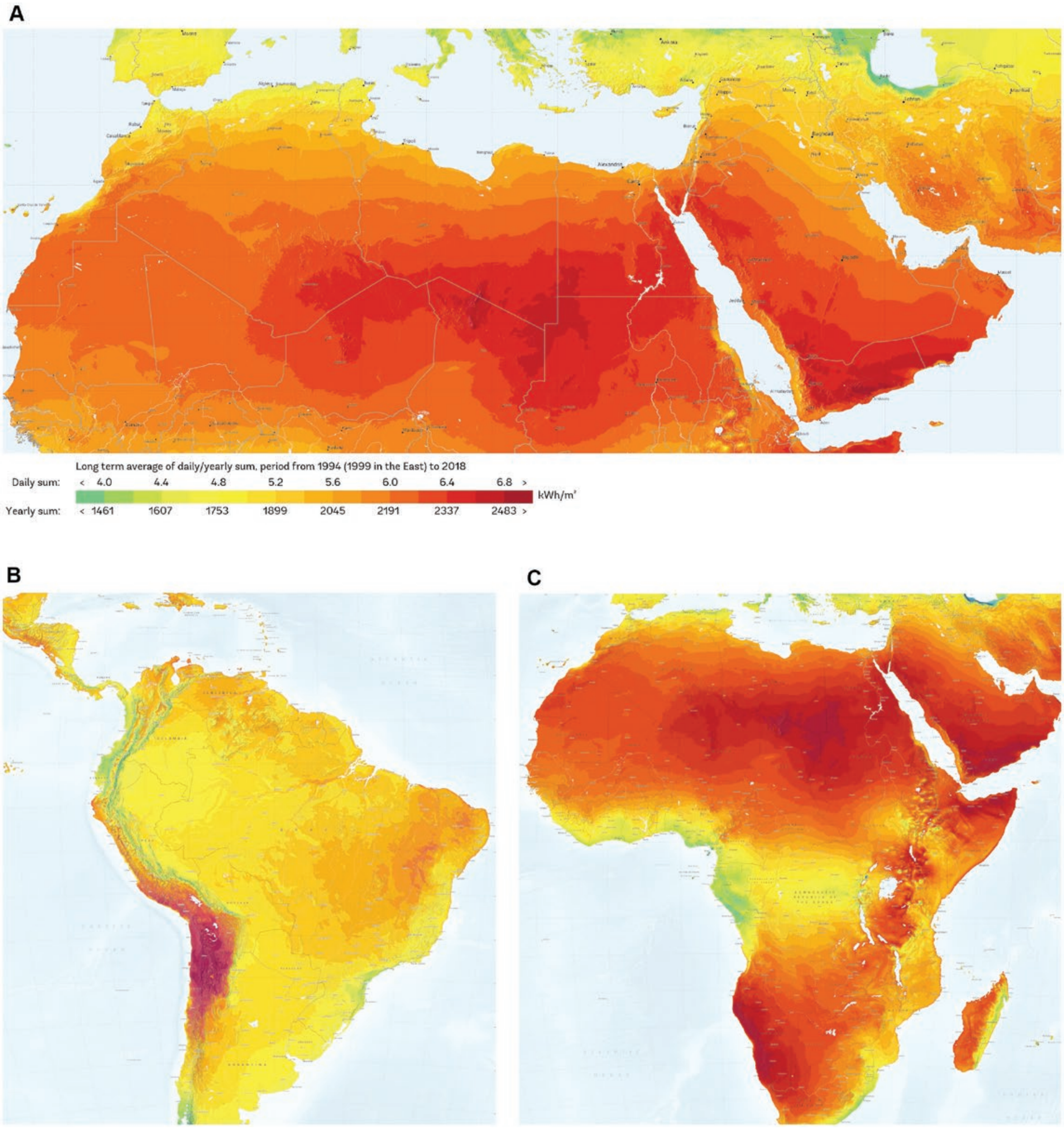

Fig. 3: Global horizontal irradiation. (a) Middle East and North Africa; (b) Latin America and the Caribbean; (c) sub-Saharan Africa. Source: Solargis, 2022 https://solargis.com/maps-and-gis-data/download.

Considering the relevance of reducing post-harvest losses by using solar energy to store perishable fruit and vegetables on time, it turns into a need to know the pattern and scale of solar cooling techniques across the world, especially in developing countries, and identify its potential and a viable way forward for its promotion. Solar-based sustainable storage technological interventions may play a vital role in addressing product handling and storage at production sites. In the past, there have been attempts to develop and disseminate solar cooling technologies for farming communities in developing countries. There is no collected information on the efficacy and state of these technologies, together with potential obstacles and chances of successful deployment. This study provides an overview of the interventions, adoption and scalability of decentralized solar cooling technology for various horticultural products in developing countries, as well as implementation challenges in terms of technical, social, economic and environmental factors. The rest of the paper is structured as follows. Section 1 presents classifications of solar cooling; Section 2 highlights the importance of this technology; Section 3 discusses successful case studies in Asia, Africa and Latin America; Section 4 presents potential operational constraints and opportunities; and Section 5 concludes the study.

1 Low-technology solar-powered cooling options

The food chain has become increasingly dependent on refrigeration. It is used in the food supply chain from processing to retailing to end users in homes [23]. Solar energy can be used for cooling through solar-thermal and PV modes [24]. A solar-thermal-driven system is more energy-efficient than a PV-powered system due to its higher solar-thermal efficiency (>40%) than PV panels (efficiency 10–20%) [25]. The cooling process is highly energy-intensive and involves a unit operation that requires a reliable supply of electricity. Small-scale farmers in developing regions typically lack access to reliable grid electricity, so a decentralized off-grid system can be of benefit. Table 1 summarizes the low-technology options that are feasible for small-scale farming operations [26].

Four established cooling techniques are used to obtain cooling making use of solar energy: vapour compression, sorption cooling (including absorption and adsorption), evaporative cooling and ejector cooling.

1.1 Vapour compression

This refrigeration system consists of a compressor, a condenser, an expansion valve and an evaporator, which are arranged in a closed loop to transform the refrigerant (working medium) into various thermodynamic states for the exchange of heat from the space to be cooled [27]. Normally, ammonia gas is used as a refrigerant because of its low cost and high efficiency. During food storage, both the chilling (>0°C) and freezing (<0°C) processes are used to inhibit microbial and chemical activities. Although vapour-compression refrigeration is commonly used and a mature technology, it creates vibration and noise as a result of the operations of components.

1.2 Sorption cooling

Another type of refrigeration is thermally driven sorption cooling and a thermal compressor (sorbent) is used instead of a vapour compressor [22]. Principally, this system can be classified as 'adsorption' (sorbent in solid form) or 'absorption' (sorbent is in liquid form) in its working. As the system is thermally driven, this type of cooling is attractive when solar plants or solar heat collectors are used when the power supply is insufficient and costly.

1.3 Evaporating cooling

In these cooling systems, machines evaporate liquid (commonly water) to get the effect of refrigeration. During the evaporation process, the temperature of the substrate decreases as a result of the removal of thermal energy [28]. Such devices are used for air conditioning. Evaporative cooling can be further subdivided into direct, indirect and a combination of both, depending on the nature of use. In the case of the direct evaporation method, the liquid evaporates directly from its source into the air and extracts heat energy from the space to cool down. But this process can increase humidity in the space. When the liquid to be evaporated is not in direct contact with the environment to be cooled, indirect evaporation can be utilized as an alternative to prevent such circumstances. In the stream channel of a heat exchanger, where water evaporates, the air flowing in the neighbouring channel is cooled. Evaporative cooling does not require solar energy directly; however, solar-thermal energy can be used to heat the substrate surface (which contains water) to enhance the rate of evaporation. Through evaporative cooling, the air cools and circulates in the space; thus it is further classified as forced air cooling achieved by forcing the cold air to flow all around the product [29]. A fan is used to create a pressure gradient, and the rate of cooling and uniformity of the temperature of the room are used to gauge the effectiveness of the fan. The arrangement of stored products in the storage chamber is particularly important to ensure proper circulation of cool air. In addition, various other factors affect cooling rates such as product size and shape, bulk storage or packed, thermal properties, final desired temperature, flow rate, relative humidity, carton vent area and temperature [30].

1.4 Ejector refrigeration

An ejector refrigeration system works on the principle of the venturi effect for cooling. It is a thermally driven technology in which a fluid is directed through a nozzle-type ejector [22]. Compared with a vapour-compression system, its efficiency is very low due to low COP, but on the other hand, it is simple in design and has no moving parts. Its main advantage is that it can easily use solar energy or exhaust/waste heat of >80°C—so-called solar ejector cooling. Solar ejector cooling devices range from small and simple-to-use machines to complex devices for industrial applications [15, 16].

2 Importance of solar-powered cold storage

The significance of using solar cold storage for fruit and vegetables and its impact on the rural community have been described in four subsections, i.e. product quality, economic value, environmental impacts and social aspects.

2.1 Product quality

Fruit and vegetables start to deteriorate just after harvest. Therefore, handling at the production sites is important to reduce post-harvest losses. The lack of storage and processing facilities at the farm level contributes significantly (10–40%) to the overall losses of produced perishables. For safe storage, temperature and humidity are the two main operating parameters that must be controlled.

Table 1: Cooling technology options for small-scale farmers in developing regions

Cooling technology	Description	Temperature range	Energy options
Passive or evaporative cooling	Operates in areas of dry and low humidity	10–25°C	No fuel (does not require electricity); architectural measures (shade creation, fountains, etc.)
Absorption refrigeration	Thermal-driven technology	<10°C	Solar; kerosene
Refrigerators (vapour compression)	Electricity-driven and, therefore, dependent on reliable electricity supply	0°C	Grid; diesel; renewable sources (hydro, solar, batteries, etc.)

Temperature should be lowered to an appropriate level to increase the shelf life of the product, as it directly affects the rates of biochemical activities [31]. The temperature and rate of respiration are directly proportional; therefore, the higher the temperature, the more the product will degrade. As a result, the storage temperature is controlled according to the thermal load. Second, maintaining the required relative humidity (RH%) during storage is complicated. High relative humidity is necessary during storage to prevent softening, juiciness and wilting and to maintain the saleable weight, taste, flavour, appearance and nutritional content of the product [32]. Factors that affect higher rates of moisture loss (or weight loss) include the storage of damaged products, immature harvested fruit and vegetables, and high surface-to-volume ratio of the product, such as leafy vegetables. Therefore, storage conditions with a hot temperature, low humidity and high airflow would increase the moisture-loss rate. The operating condition that does not cause chilling injury to fresh produce is the most suitable and any variation from the recommended condition is detrimental. Depending upon the type of product to be stored, pretreatment, initial temperature, etc., storage conditions vary for fruit and vegetables. Yahaya and Mardiyya [33] summarized the storage conditions for many fruit and vegetables. Combining a controlled atmosphere with refrigeration is another strategy to reduce food quality changes including softening, yellowing and other issues because it slows respiratory processes [32]. Furthermore, the storage environment can be changed by changing the ventilation rate, using a gas absorber (i.e. potassium permanganate) or using activated charcoal.

2.2 Economic value

According to estimates, production systems receive 95% of global financing for research and development in the agricultural sector, while post-harvest systems receive the remaining 5%. This disproportionality results in enormous post-harvest 'technology gaps' and 'skill gaps', especially in developing countries [4, 28]. It is estimated that <10% of all perishable foods is currently refrigerated, even though post-harvest losses add up to 30% of food production worldwide [1, 3, 4]. In addition to giving farmers the opportunity to boost their income, cold storage also contributes to a decrease in overall post-harvest losses. The importance of pre-cooling and cold storage is critical in tropical and subtropical regions, which may require considerable energy due to hot and humid climates. So, economically, there are two aspects to generate income: one is the decentralized storage of products to reduce losses and the second is the energy-efficient storage technologies to reduce operational costs.

In developing countries, the distribution and supply of electricity in rural areas are not reliable, so the provision of cold-storage facilities is often terrible. This simply leads to the waste of a huge quantity of fruit and vegetables, and even affects the local market for these products with price fluctuation [34]. Introducing sustainable cold-storage technologies for off-grid and weak-grid markets can facilitate farmers, processors, distributors and retailers to take advantage of price fluctuations in the market. Gopal [35] described a company, Ecofrost, in India, that provides decentralized solar-powered cold-storage facilities to farmers. Currently, the units are operating on 35 000 farms, potentially saving 35 000 tonnes of perishables from going to waste. At the same time, these modules have generated 100 million kWh of clean energy. The cold chain requires investment, particularly in pre-cooling and transport refrigeration equipment. This could cut India's perishable food loss by 76% and CO_2 emissions by 16% [36]. Similarly, a report by the Renewable Energy and Energy Efficiency Partnership [37], which develops financing mechanisms to strengthen markets in low- and middle-income countries, estimates that the market potential of solar-powered cold-storage units in Uganda can reduce post-harvest losses by 30% and increase the shelf life by 50%. It is estimated that a farmer can get a benefit of €5250 annually for renting 1 m^3 of cold space. With more of the harvest available for sale, small-scale farmers can increase their income by 25% annually. The cold chain is the key to tackling the loss of perishable products. In this regard, it is predicted that if developing nations implemented refrigeration technology on a par with that in developed economies, around a quarter of all food waste in these nations could be eliminated [38].

2.3 Environmental impacts

FLW (food loss and waste) is a significant driver of climate change. The current estimate suggests that FLW is responsible for ~4.4 Gt of CO_2-eq per year, accounting for 8–10% of global anthropogenic greenhouse gas (GHG) emissions [38, 39]. According to the United Nations Food and Agriculture Organization (FAO), 1.3 billion tonnes of food are lost or wasted annually worldwide—one-third of total food production [40]. These levels of FLW account for 30% of the world's agricultural land and 38% of the total energy consumption of global food systems. It is possible to meet the growing demand for food and to slow down climate change by reducing these enormous volumes of FLW and improving the energy effectiveness of our food post-harvest systems. Sustainable Development Goal (SDG) 12.3 of the United Nations emphasizes the interdependencies of reducing FLW to reduce GHG emissions and mitigate against further climate change while setting a clear goal of halving food waste by 2030. The Paris Agreement (2015) on climate change action also recognized the links between climate change, food production systems and food security. Furthermore, FLW undermines the resilience and adaptation strategies for climate change that were implemented during the production stage and causes volatility in food prices, particularly in the most vulnerable regions.

FLW could be reduced in such a situation by using climate-smart post-harvest agriculture technology, where solar-powered cold storage can be one of the change-making forces. The cooling process for cold storage requires a consistent and stable source of power, which is often supplied by the grid, diesel generators and mechanical turbines. To replace kerosene or gas-powered cooling equipment, PV-powered refrigerators were first introduced for medical uses in impoverished nations. Compared with kerosene refrigerators or diesel generators, solar cooling has the potential to have lower operating costs and a longer life. Despite the fact that solar and kerosene refrigerators have nearly equal life-cycle costs, solar cooling equipment is chosen because of its reliability and environmentally favourable features. Farmers that use solar cold-storage technology in agriculture are moving away from diesel-powered cooling machines, helping to reduce environmental pollution. The Renewable Energy and Energy Efficiency Partnership [37] estimated the potential of solar cold storage for perishables in Uganda and found that despite improving agricultural production (reducing post-harvest losses), solar cold storage will be able to save >100 000 tonnes (equivalent) of CO_2 emissions a year by 2030; this avoids GHG emissions.

2.4 Social aspects

Solar energy is increasingly being used by rural areas around the world that are being impacted by climate change. The adoption of solar energy is facilitated by the availability of funding options. With the high level of GHG emissions, many governments have taken initiatives to switch from fossil fuels to renewable energy. Such initiatives include energy policies and incentives for investors [41]. In 2015, renewable energy resources contributed ~19.3% of total global energy consumption [42]. Regarding employment opportunities, the renewable-energy sector employed 9.8 million people in 2016, most of them in Asia, mainly China, which represents 62% [43]. In this regard, solar energy and biofuels created more jobs. Adoption of solar energy can also improve human health by reducing GHG emissions, which cause various diseases such as cardiovascular morbidity, non-allergic respiratory-tract problems and cancer [44].

Therefore, the market potential for solar-powered cold-storage units, centralized or decentralized, is enormous. This is because solar energy has enormous potential, as does the need to reduce post-harvest losses, the need for cooling to extend product shelf life and the type of cooling system to be used. A market research company named Transparency Market Research describes the market potential of solar cold storage, which is mainly based on regional and end users along with key drivers, as shown in Fig. 4 [45].

3 Case studies

As mentioned previously, applications of solar-thermal and SPV technologies are gaining popularity due to the existing scenario of post-harvest losses in fruit and vegetables and the need for sustainable decentralized cold-storage facilities. This section contains research on solar-powered cooling systems to reduce food losses at the farm gate that was done in various developing regions of the world.

3.1 Asia

Most of the countries in Asia depend heavily on agriculture, where 40–60% of the population are connected to this sector for livelihood [46]. On average, 10–40% of fruit and vegetables are lost at various stages of harvesting, storage and processing. For example, India, which is one of the largest producers of fruit and vegetables, has an enormous potential to use solar energy in food handling and processing, as the annual solar radiation is 1200–2300 kW/m^2 [47]. For India, where 20–30% of produce is lost after harvest due to the lack of adjacent cold-storage facilities, cooling as a service is highly important. Regular electricity is needed to operate cold-storage facilities; however, grid electricity in rural locations is frequently unstable. A solution is provided by solar-powered cold-storage systems; however, due to the high initial cost, farmers have not embraced these systems widely. Eltawil and Samuel [48] developed a SPV-powered cooling unit (0.18 TR, metric tonnes refrigeration) for the storage of potatoes under different operating conditions for 5 months. The size of the cold-storage structure was 2.5 m^3, and the storage temperature and relative humidity were kept at 283.13 K and 86%, respectively. Taking into account a weight loss of 6%, the storage cost for a 1-kg product was calculated to be Rs. 9.02/kg (US$1 = 46 Rs.) using solar energy compared with the total cost that occurred using electricity (7.66 Rs./kg) and a petrol–kerosene generator (14.63 Rs./kg).

Due to their focus on storing a particular item, most cold-storage facilities in poor nations go largely unused for a considerable part of a year. Basu and Ganguly [49] reported on a conceptual design of a cold-storage unit powered by both solar-thermal and SPV energy. The cooling condition inside the storage chamber was maintained by using a water–lithium–bromide-based absorption unit. Thermal analyses based on energy and exergy were performed to find out the number of thermal collectors and PV modules under the climatic conditions of Kolkata, India. It was found that 45 parabolic trough collectors and 225 PV modules could meet the energy demand throughout the year for multi-commodity storage with a payback period of 6.22 years. This demonstrates the technical and economical viability of storing several commodities using solar energy in underdeveloped nations [50]. In another study, De and Ganguly [51] performed an environmental analysis for the same system considering four products (potato, olive, grapefruit and multi-commodity storage). Compared with the other three storage options, it was found that the use of solar energy for the storage of potatoes could reduce CO_2 emissions by 421 tonnes.

Sadi and Arabkoohsar [52] conducted a techno-economic analysis of a decentralized solar cold-storage unit used to preserve horticultural produce in a hot and humid climate. The type of

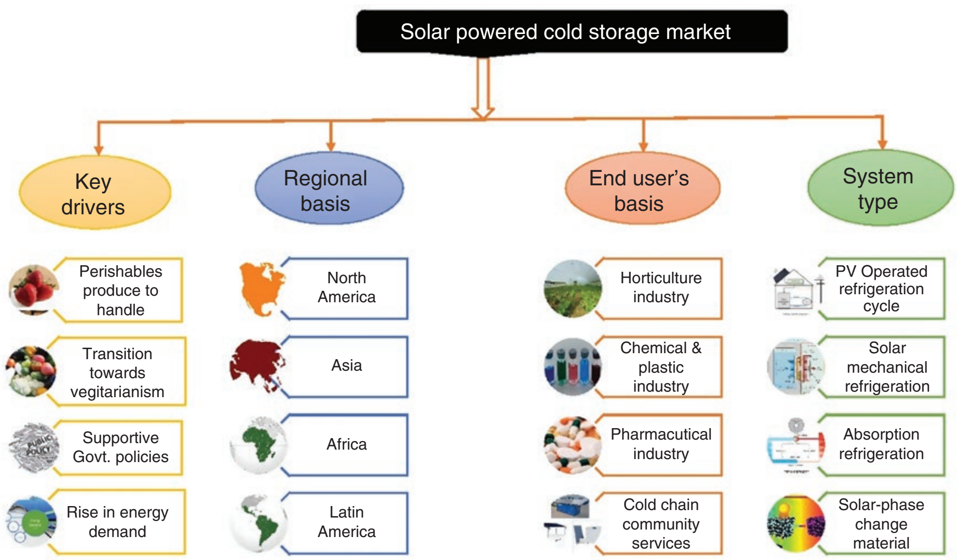

Fig. 4: Parameters for the market potential of solar-powered cold-storage facilities. Adapted from Transparency Market Research [45]).

solar collector was evaluated to deliver the 5 TR in annual cooling load that was needed for the storage of the sample product, potatoes. It was found that when 20 tonnes of potatoes were kept, the system integrated with an evacuated-tube collector produced the highest economic results with a payback period of 11 years. Furthermore, it was also estimated that CO_2 emissions were reduced by ≤53% compared with a gas-powered chiller (absorption). Prasad [53] introduced a solar cold-storage unit named a Solar Cool ColdShed™ for small farmers and traders in Telangana and Andhra Pradesh, India. It was a mobile solar-powered system that could keep goods locally at temperatures ranging from 3°C to –20°C in ≤45°C of ambient temperature. The size of the cold-storage room was 10.6 m^3 and it could hold 3–5 MT of food products.

Solar-hybrid cold-storage devices have also been found to maintain an energy supply during varying solar radiation hours. Bharj and Kumar [54] designed and developed a low-power air-conditioning system using PV modules for small area refrigeration. In another study, Kumar and Bharj [55] developed a solar-hybrid mobile multipurpose cold-storage system. The developed system ran on grid power at night and when it was cloudy, and solar power throughout the day. Inside the cold-storage cabin, panels made of phase-change material (PCM) were installed to provide cooling even when there was no electricity. As soon as the evaporator coil cooled, the PCM absorbed the energy. Depending on the ambient conditions, the PCM released the stored cooling during the power-off period to keep the cabin temperature up to –8°C for ~7–8 hours. Panja and Ganguly [54] proposed a solar–biomass-powered hybrid refrigeration unit with the intention of providing a favourable cooling condition throughout the year, regardless of weather conditions. The model was developed and solved in Engineering Equation Solver for the location of New Delhi (28°35’ N, 77°12’ E) and the results were validated with a reference study. India has a sizable market for the provision of cold-storage facilities, but access to financing continues to be a barrier to widespread adoption of the technology. However, off-grid technologies have additional advantages to address market opportunity. These advantages include a smaller carbon footprint and more reasonably priced fruit for the consumer, which will directly result in financial savings, better nutrition and better health.

Similarly, in China, the use of PCM has also been reported for maintaining cold-storage conditions. For the transportation of fruit and vegetables, Xu *et al.* [56] developed a polyethene cold-storage plate loaded with a thermal storage substance to maintain a temperature of 5–8°C. The sodium polyacrylate and multiwalled carbon nanotubes (MWCNTs) used in the thermal storage material were contained in a vacuum-insulated box. The results demonstrated that the material was capable of maintaining cold conditions inside the box for 87 hours. Changjiang *et al.* [57] reported a cold-storage structure with its walls filled with a PCM of high latent heat density (water/ice) to maintain the cooling conditions. The unit was experimentally tested and simulated. The thermal resistance of the wall was altered by the installation of a PCM layer, resulting in less power being utilized.

In Pakistan, many vegetables (40 types) and fruit (21 types) are produced due to favourable agricultural climatic conditions, but losses are high. The Pakistan Agriculture and Cold Chain Development Project was funded by Winrock International (https://winrock.org/) and it aimed to build a better cold-storage facility for the area. The project provided technical facility and a grant to modernize the Safina Cold Store storage facility in Quetta City for farmers to store their fruit such as apples, grapes and pomegranates before they were transferred to market. The expanded facility had many advantages, which improved the market by boosting farmers' income by 40%. Munir *et al.* [14] developed a solar-hybrid (solar–grid) cold-storage unit for on-farm preservation of perishables. The size of the cold-storage chamber was 21.84 m^3 and it could store 2 tonnes of product. For cooling, a 2-tonne vapour-compression refrigeration unit powered by a 5-kWp PV system was installed. Three cooling pads were used inside the storage chamber as a thermal backup for cooling (–4°C to 4°C). The potatoes were stored for 3 months and performance parameters were recorded. It was found that 15 kWh of energy was consumed, of which 70% (10.5 kWh) was provided by solar energy and 30% (4.3 kWh) was taken from the grid. A similar solar cold-storage system was reported by Amjad *et al.* [58] but it was for a large storage capacity (10 tonnes). Second, the installed 10-kWp solar system was grid-tied, i.e. the system continued to produce power even when there was no storage, and this energy could be used for other farm operations. The average value of the COP for the installed refrigeration unit (3.5 tonnes) was calculated to be 3.95.

The People, Energy and Environment Development Association (PEEDA), which promotes sustainable development, was funded by WISIONS (https://wisions.net) in Nepal to improve the lives of the individual and the rural community. PEEDA carried out a programme to increase farmers' agricultural output by lowering post-harvest losses. Because local markets are far from the producing side and mountains in Nepal make small-scale fruit and vegetable farming possible, there is a significant post-harvest loss. PEEDA introduced mobile solar energy-powered cold-storage units in Dolakha District (Nepal). As a community service, the first unit allowed all farmers to keep their food and sell it in large quantities, rather than individually selling it in tiny amounts. It was concluded that 50% of food loss could be reduced with an employment opportunity for the maintenance and running of the units.

The Philippine agricultural industry suffers from a high level of post-harvest losses, similar to other developing nations. Such losses can range between 20% and 40% for a single high-value fruit and vegetable crop. The agriculture department has introduced solar-powered cold-storage facilities with an agreement with Ecofrost, an Indian-based company providing on-farm solar cold storage on farms. With a maximum power point tracking effectiveness of 99.5%, the device could deliver improved production efficiency. Low maintenance and no operating expenses were needed for the storage of 5 tonnes of perishables at 2°C. The technology could deliver a battery-free backup of 30 hours, for instance, in the form of a PCM. Smallholder farmers will be assisted in increasing their revenue and preserving their products as a result [59].

3.2 Africa

According to the Rockefeller Foundation, in 2021, post-harvest losses in fruit and vegetables were recorded to almost double in Africa, which could be related to the COVID-19 pandemic, which affected many agricultural-based economies. Such a high increase in post-harvest losses has a direct impact on the income and food security of smallholders in Africa. Relatively, a higher investment has been made in tackling post-harvest losses of grains and cereal crops, although investment is significantly lacking in the horticultural sector, particularly fruit and vegetables. Most small-scale farmers lose ≤60% of their post-harvest tomato crops in certain regions of Africa due to the lack of cold-storage facilities [6]. The lack of access to cold-storage facilities, as elsewhere in Africa, is one of the main reasons why newly harvested tomatoes rot so quickly in Tanzania. According to studies, most small-scale producers use ineffective storage techniques, which can result in post-harvest tomato losses of 20–50% [60]. Solar-powered cold-storage technologies (SPCSTs) have gained widespread acceptance in recent years as a vital infrastructure to stop post-harvest losses of fresh produce, especially for small-scale farmers who live off the grid [61]. In Nigeria and, more recently, Kenya and Rwanda, it is estimated that only a small percentage of small-scale farmers have access to SPCSTs, leaving the vast majority of these farmers without access to effective storage facilities to prevent FLW.

In Nigeria, due to poor storage conditions at production sites, almost half of the fruit and vegetables are never consumed. Adekoyejo Kuye (Project Lead, Manamuz Electric Ltd, https://www.manamuz.com/) said that '[t]he cool solution to Africa's burning problem' is the provision of sustainable cold-storage infrastructures. The agricultural sector needs to fill its energy supply shortages. The company (Manamuz Electric) designed and developed a solar-powered cold-chain facility and transport system. The Coldbox Store unit has operating parameters that are tailored for the supply chain for perishable agricultural products in Africa. The facility serves as a direct interface between vendors and growers. The company aims to ensure access to affordable, sustainable and clean energy (SDG 7) and to reduce poverty and hunger (SDG 1, 2). Similarly, Nnaemeka C. Ikegwuonu (CEO, ColdHubs, https://www.coldhubs.com/) developed a walk-in cold-storage structure for 24 hours of cold storage of perishables. Insulating panels measuring 120 mm are used in the cold room to reduce cooling losses. ColdHubs is a facility where growers can store their products for a maximum of 21 days for a set fee of US$0.50 per food crate per day. It is situated in significant production and consumption locations. Until now, the company has provided services to 3517 stakeholders with its 24 units. It is also worth mentioning here that these 24 units saved 20 400 tonnes of food in 2019.

Hiroyuki *et al*. [62] conducted a project funded by the Japanese government to increase livelihood in north-east Nigeria. This region is one of the largest producers of horticultural commodities. In this project, seven solar-powered cold-storage units were installed, each having a storage capacity of 3 tonnes of horticultural products. Each unit was integrated with a 5.6-kW PV system. The results of the project revealed a large increase in product sales and user profit together with a decrease in the percentage of product loss that happened without cold storage. This demonstrates that solar energy, especially in underdeveloped countries, can be one of the practical energy sources to decrease post-harvest losses and generate cash by increasing the shelf life of harvested products. The problem of post-harvest losses in Nigeria, which directly results in a 25% income loss for 93 million small farmers, can be greatly helped by off-grid cold-storage facilities.

In Kenya, post-harvest losses of fruit and vegetables are estimated to be 40–50% [63]. According to the Kenyan National Bureau of Statistics (KNBS), $1.5 billion worth of food went to waste in 2017. Dysmus Kisilu established an agri-tech company named Solar Freeze (https://www.solarfreeze.co.ke/data) that helps farmers who do not have access to better roads and electricity connections to reduce post-harvest losses. In Kenya, 3000 women farmers were employed by Solar Freeze facilities, which reduced losses by 50%. Another commercial cold-storage unit in Kenya with facilities throughout the country is called FreshBox. It can hold 2 tonnes of fruit and vegetables. A retailer has the ability to increase revenue by 25% and store 30–40 kg of fruit and vegetables for $0.50/crate/day as a rental service.

A number of initiatives have been launched by the FAO to encourage investment in the food value chains of developing countries. The market potential for solar cold storage is predicted to be US$6 150 000, according to an FAO evaluation in Rwanda. The evaluation focused on the nation's goal of exporting 46 000 tonnes of horticultural goods by 2024. Like many other African countries, Uganda's economy is mainly dependent on the agriculture sector, which lacks significant investment in the agro-processing industries primarily due to insufficient and unreliable energy in rural areas. In Uganda, Station Energy has introduced a solar-driven cold-storage unit under project REEP [37]; the adoption of these cold-storage units was a success among agricultural co-operatives and farmer groups. Similarly, another company, Madraam Engineers Limited, developed a solar cold-storage facility to store freshly harvested citrus in Amuria District, in the eastern region of Uganda [64]. The primary goal of the facility was to decrease post-harvest citrus losses during the height of the harvest by utilizing the copious solar radiation of the region. The constructed unit operated under two different model types. The first was for farmers who wanted to sell their products directly to customers but did not have access to storage facilities. In this case, they could store the goods for Shs. 460 per kg each fortnight. This took care of 30% of the installed capacity of the solar cold-storage facility. The second approach was for the business to purchase the produce from farmers and then sell it on the market after sorting, preserving and packing it. It would take ~70% of the entire storage space.

Precoppe and Rees [65] developed a solar-powered environmentally controlled sweet potato curing chamber (temperature of 28°C and relative humidity of 85%) and a storage chamber (15°C and relative humidity of 85%) with a capacity of 5 tonnes of roots in Kenya. Instead of relying on imported goods and spare parts, the design made use of locally produced components and parts to make it simple to repair and maintain the chamber. To achieve the desired temperature and humidity, a normal air conditioner was used after making the necessary adjustments. Two axial fans were used for ventilation, allowing cold and moist air to continuously flow through the sweet potatoes. Airflow distribution has been evaluated using computational fluid dynamics (Fig. 5).

3.3 Latin America

Food losses post-harvest to retail in Latin America and the Caribbean have been estimated to be 20% of the world, while the region accounts for only 9% of the world population. The FAO report, *The State of Food and Agriculture 2019*, found that these food losses resulted in 16% of the global carbon footprint, 9% of the land footprint and 5% of the water footprint [66]. The absence of suitable cold-storage facilities, which are essential to reduce both qualitative and quantitative FLW losses, is one of the main causes of these losses.

Chile established the National Committee for the Prevention and Reduction of Food Loss and Waste in 2017 to streamline and co-ordinate initiatives to prevent food losses. Argentina started a similar national programme in 2015 with the collaboration of >80 public and private organizations to develop a national network to reduce food losses at various stages of its supply chain. The InterAmerican Development Bank established a platform in collaboration with organizations like the FAO, the Forum on Goods of Consumption, the Global Network of Food Banks, IBM

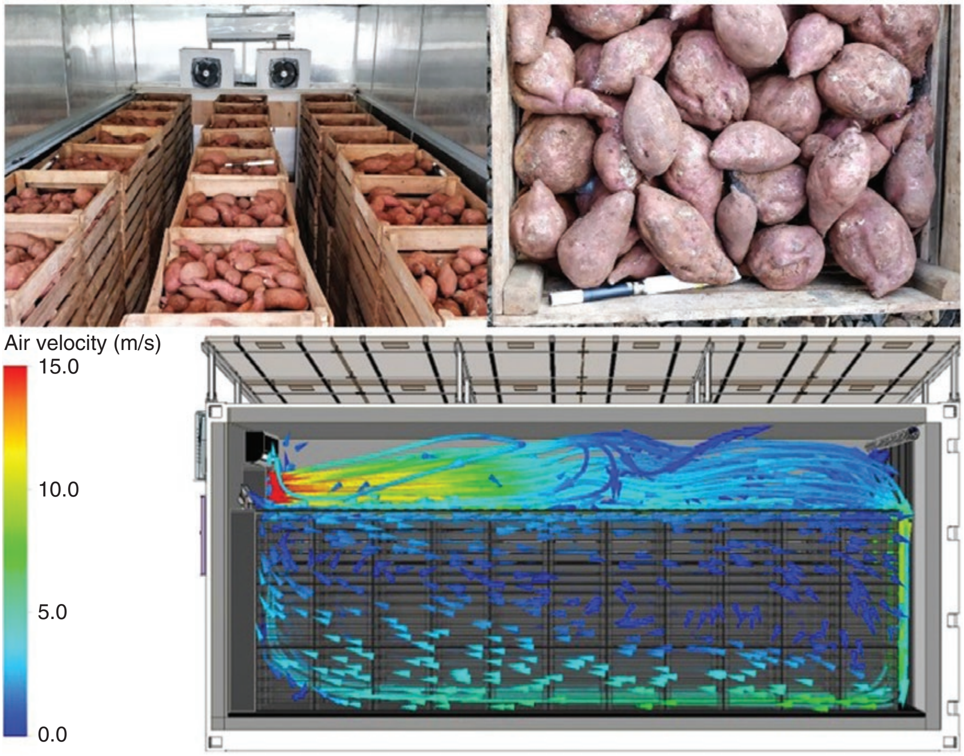

Fig. 5: Internal airflow analysis of the solar cooling unit using computational fluid dynamics (CFD). For the CFD analysis, mesh quality: minimum orthogonal quality = 2.01750e-01 maximum aspect ratio = 2.47855e+01. Mesh size: number of cells = 787 927, number of faces = 4 229 523, number of nodes = 2 920 898. Authors' own analysis, image credit: Marcelo Precoppe.

and other businesses to promote post-harvest interventions and innovations in the region.

The Semi-Arid Renewable Energy Committee (CERSA) promoted the use of solar energy in a rural district in Sousa, Brazil to generate electricity for rural development. The installed maximum capacity of 142 PV panels was 46.1 kW and they were able to generate ~6700 kWh per month. The system provided semi-arid regions of Brazil with market-related economic choices in addition to affordable clean energy for a variety of uses, such as cold-storage warehouses [67].

Table 2 lists the many types of solar-powered cold-storage units that have been tested or are now in use for the storage of agricultural produce. The cold-storage units include solar-thermal-powered, SPV-powered, solar-thermal–PV-powered, solar–biogas-driven and solar-thermal using PCM.

In Fig. 6, an analysis of all the publications used for this paper is presented. It shows the distribution of publications according to the energy source technology. It is clear that solar PV and hybrid systems seem to be of most interest to researchers and practitioners. Fig. 7 provides a year-by-year trend in the number of publications. The trends show that the research and development work on renewable-energy-based cooling systems has increased considerably in the last two decades.

4 Operational constraints and opportunities

Technology vendors target a variety of consumer segments and cold storage has many different applications in rural areas. The number of employees that each group has as well as their access to equipment, land and energy differ throughout cold-chain marketplaces. Smallholder farmers often cultivate <2 hectares of land and have a limited number of production-enhancing resources. They frequently plant labour-intensive, low-value crops using basic farming techniques, since they cannot get financing. This places limitations on the sales prices of cold-chain items and financing alternatives for small farmers [78].

According to studies, the negative opinion of stored products may result from a lack of exposure to high-quality processed foods, price considerations, the underdevelopment of the food processing sector and cultural factors [79]. The main obstacle is getting economical, field-based cold-storage facilities. Rutta [22] conducted a study to identify the challenges that prevent the adoption and deployment of SPCSTs in Tanzania. Semi-structured interviews and focus group discussions were used to explore farmers' opinions on solar technology for cooling and the barriers preventing its use. According to the findings, there is a lack of customer preference for non-refrigerated goods, high investment prices, low paying capacity among farmers and limited awareness as barriers to the implementation of solar-powered cold-storage technology. To overcome these obstacles, policies and programmes must be supported that encourage and maintain investment in cold-storage technologies and increase the affordability through flexible payment options. To ensure the successful deployment and uptake of SPCSTs, which are currently unknown and out of reach for many in Tanzania and throughout Africa, it is important to take into account a number of issues. The assessment of these barriers offers valuable information to decision makers involved in post-harvest agriculture and renewable-energy programmes in Africa.

Most smallholder farmers in sub-Saharan Africa lack access to cold-storage facilities because they cannot get electricity. The problem is that, almost always, cooling depends on having access to a consistent and reasonably priced supply of

Table 2: Types of solar-powered cold-storage systems for the storage of horticultural products

Application/ technologies	Product	Location	Storage temperature (°C)	Cold-storage specifications	Refrigeration type	Energy source	Reference
Solar cold storage for food products (conceptual study)	Potatoes	Kolkata, India	10	Dimensions: 20 × 10 × 5 m = 1000 m^3	Air-cooled H_2O–LiBr absorption system, selected for 24-hour operation	Solar-thermal and photovoltaic (165 modules of 150 W, along with 50 FPCs of dimension: 2 × 0.98 m)	[49]
Solar-assisted multi-commodity cold storage	Potatoes, olives, grapefruits	Kolkata, India	8 8 10	20 × 10 × 5 m	Lithium bromide–water absorption system	Solar-thermal–PV-based (46 PTCs and 275 SPV modules of 150 Wp)	[50]
Solar-hybrid cold-storage integrated double-effect vapour-absorption system	Potatoes, olives, grapefruits	Kolkata, India	10	20 TR	Double-effect VAR system	Solar-thermal–PV-based hybrid power system (45 PTCs of 5.8 m^2 of aperture area along with 225 PV modules of 150 Wp)	[51]
Solar-assisted cooling chamber	Apples	Istanbul	0 to –4	1-m^3 prototype	Vapour-compression refrigeration	SPV collector; 300 W	[68]
Portable solar-powered cold-storage room		Telangana, India	3 to –20	Cold-storage room is 10.6 m^3 and it can hold 3–5 MT	Vapour-compression refrigeration system	SPV	[53]
Solar-hybrid low-power refrigeration unit	Multipurpose cold storage	India	–8	1.5 tonnes	Low-power vapour-compression refrigeration	SPV	[55]
PV-powered refrigeration facility	Milk	Spain	0 to –4	450-L tank	Vapour-compression refrigeration system	SPV (2.5 KW SPV system built with 20 120-W panels)	[69]
Vapour-compression cooling system powered by SPV array	Potatoes	New Delhi, India		2.50-m^3 double walls store structure	Vapour-compression cooling system	SPV (14 modules, each 490 W)	[48]
PV-powered cold-storage unit	Fruit, vegetables, fish	India	–2	21 m^3, designed to store 10 tonnes of product	Vapour-compression refrigeration system (1 tonne)	SPV (134, each 30-W peak)	[70]
Solar-assisted ocean thermal energy conversion (OTEC) cycle for power generation and fishery cold-storage refrigeration	Fruit, vegetables, fish	China	4			OTEC-based solar-assisted combined power and refrigeration cycle	[71]
Solar–biomass hybrid cold storage-cum-power generation system	Potatoes	New Delhi, India	10		LiBr-H_2O vapour-absorption refrigeration system	Solar-thermal and biomass (15 kW, ~5 TR) vapour-absorption machine coupled with a 50-kW biomass gasifier system)	[72]
Off-grid cold-storage system integrated with an auxiliary heater	Potatoes	India	5	225 mm (wall), 200 mm (roof), 200 mm (floor)	Solar-thermal cooling	Different types of solar collectors; cooling load is 5 TR	[52]

Table 2. Continued

Application/ technologies	Product	Location	Storage temperature (°C)	Cold-storage specifications	Refrigeration type	Energy source	Reference
Energy saving with total energy system for cold storage	Fruit, vegetables	Italy	2	1250 m^3	Vapour-compression refrigerating machine and absorption system	Thermomechanical generating unit (total energy system cogeneration unit–IC gas-powered engine producing 300 kW)	[72]
SPV-driven thermoelectric cooler system for cold-storage application	Food, vaccines, milk products	Sohna, Haryana, Delhi, India	10–15	Small cold-storage box of 3 litres	Thermoelectric cooler system	SPV (single crystalline solar cell PV panel, with power rating of 168 Wp)	[73]
Solar-powered movable cold storage	Fruit, vegetables	India	5	1.83 × 1.34 × 1.98 m = 4.85 m^3	Movable refrigerated storage structure	Solar PV (eight solar panels of 210 Wp)	[74]
Solar-powered cold storage	Fruit, vegetables	Nigeria	7	3 tonnes of storage	Vapour-compression refrigerating unit	SPV 5.6-kW PV	[75]
Solar-hybrid (solar–grid) cold-storage unit	Fruit, vegetables	Pakistan	–4 to 4	21.84 m^3, 2 TR	Vapour-compression refrigerating unit	SPV–grid 5-kWp PV	[14]
Solar-hybrid (solar–grid) cold-storage unit	Sweet potatoes	Kenya	15 at 85% RH	5 tonnes, 6 m long, 2.4 m wide, 2.6 m high	Vapour-compression refrigeration system	SPV–grid 5-kWp PV	[63]
Solar-hybrid mobile multipurpose cold-storage system	Fish, meat, vegetables, drinks	India	–8	0.42 × 0.42 × 0.54 m = 0.0953m^3	Vapour-compression refrigeration, electric circuit for controlling conditions	SPV–PCM, 4 panels, 500 W each	[76]
Solar-powered cold-storage warehouse using a phase-change material	Oranges	Nigeria	1	Warehouse: common building bricks (150–290 mm thickness)	Absorbent refrigeration	Solar energy thermal storage system (PCM)	[77]
Phase-change material-based cold-storage house	Fruit, vegetables	China	5	2000 × 1200 × 1400 mm	Heat-transfer resistance is 21.6 kJ	Solar energy thermal storage system (water/ice–PCM layer)	[18]
Solar cold-storage box with nanocomposite PCM	Yoghurt, vegetables	China	–5 to 8		The latent heat value of the PCM was 334.4 kJ/kg	Solar energy thermal storage system (nanocomposite PCM)	[56]

FPC, flat-plate collector; PTC, parabolic trough collector; IC, internal combustion; VAR, vapour absorption refrigeration.

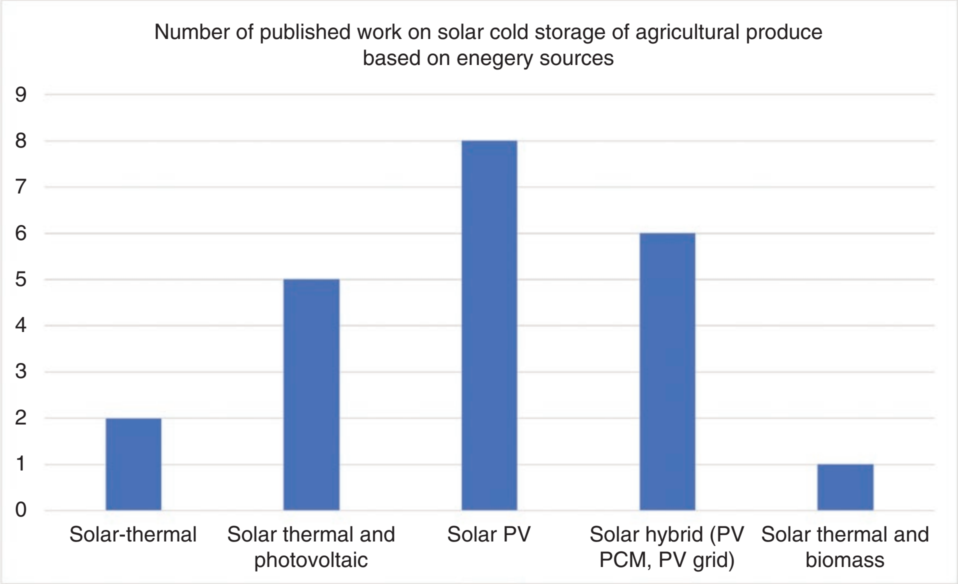

Fig. 6: Number of published works reported on decentralized solar cold-storage facilities based on the energy sources deployed

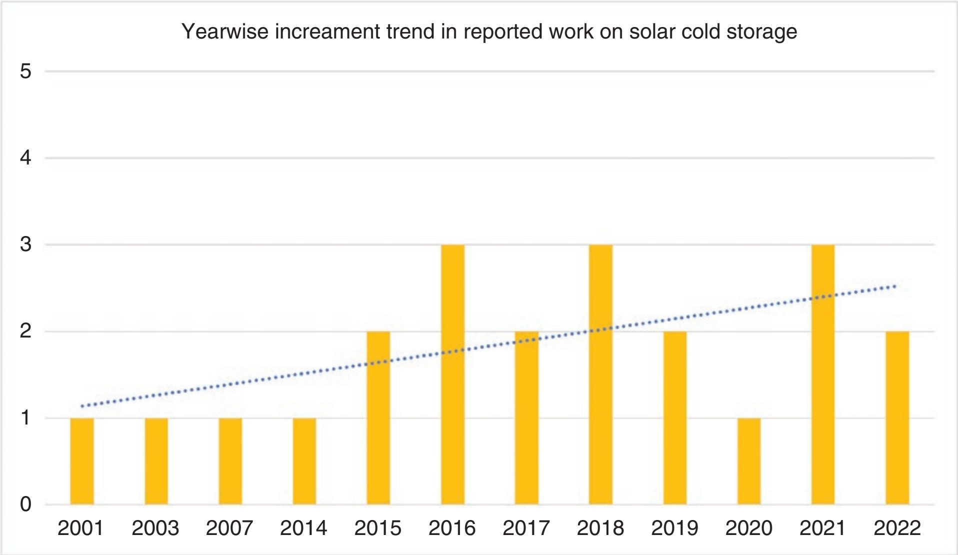

Fig. 7: Year-wise number of published works reported on decentralized solar cold-storage facilities

electricity or diesel fuel, both of which are frequently absent or practically non-existent in developing countries, especially in rural areas where energy security is a serious problem [38]. Most developing nations in Asia and Africa continue to have poor rates of rural electrification: 65% in China and East Africa, 75% in Latin America, 87% in the Middle East, 53% in South Asia and 18% in sub-Saharan Africa [80]. This opens up the possibility of using solar energy for distributed cooling. To reduce food waste at the post-harvest stage of the food value chain, improved storage and processing technologies can be adopted more quickly with access to energy.

It is challenging to precisely determine how much food loss can be avoided by increasing access to electricity because there is a dearth of reliable and consistent data on post-harvest losses in underdeveloped countries [81]. There is a huge potential for solar energy that can be transformed into rural livelihood through food handling and processing practices. According to [82], 70 nations have good PV conditions, with a long-term daily solar power potential averaging or exceeding 4.5 kWh/kWp. Countries in the Middle East, North Africa and sub-Saharan Africa dominate this category, accompanied by Afghanistan, Argentina, Australia, Chile, Iran, Mexico, Mongolia, Pakistan, Peru and many countries in the Pacific and Atlantic. The change in the global food chain is incorporating cooling technology more and more. Offering such cooling technology in under-developed areas such as north-east Nigeria, where access to a traditional source of grid electricity has generally remained unavailable, has become more economically feasible in recent years due to the steadily falling cost of off-grid solar energy [75]. The financing options for renewable-energy projects have expanded greatly during the last 10 years. The portfolio of investments in renewable energy and other environmentally friendly technologies has increased greatly at the World Bank and other multilateral finance organizations.

In the global food chain, the Asia-Pacific area supplies 19% of all food and 31% of all agricultural exports and imports. The demand for agricultural and food products and resources is increasing across Asia as a result of the region's largest and fastest-growing population. In this market, a solar-powered cold-storage device might revolutionize the industry [83]. Similarly, high production and import of agricultural products in the Middle East and Africa are made possible by water-efficient irrigation systems and increasing food demand, which can be attributed to the rising demand for the global solar-powered cold-storage market.

A key social risk linked to solar energy technologies is socio-cultural unfamiliarity with technologies and hesitancy to try new possibilities of solar technology [84]. The societal consequences such as reducing food waste, increasing local farmer income, reducing malnutrition and creating jobs for women can be achieved using sustainable cooling technology, but end users must be motivated to do so (ColdHubs, https://www.coldhubs.com/). Various operational issues in terms of economic, social, technical and local environment are involved in the successful deployment of solar cold-storage facilities at farms along with potential opportunities for success as summarized in Table 3.

It should be noted that, in order to make the most of these opportunities, it is important that the systems to be well designed, well maintained and operated by trained professionals. Data on the most prevalent constraints have been examined in the studies stated above. For this, the records were gathered, duplicates eliminated and the papers or reported work were vetted to eliminate anything not specifically connected to decentralized solar cold-storage systems. Of nine selected studies, each constraint received two marks if it was mentioned as the primary constraint of the study and one mark if it was mentioned as a partially dominant constraint. Fig. 8 shows that the economic constraint has been reported to be the dominant constraint followed by the technical constraint.

5 Conclusions

In developing regions, the most important factor causing post-harvest losses in fruit and vegetables is their bulk storage at

Table 3: Operation of solar-powered cold-storage systems for horticultural products: limitations and prospects

Operational constraints	**Economic**	**High initial cost**	**A solar-powered cold-storage system has a higher overall cost than a conventional cold-storage system by 30% to 50%. The lack of domestic manufacturing facilities for solar hardware devices is the major cause of this high price**	**[22, 85–87]**
		End user affordability	When such facilities are introduced to the local community, farmers face a significant barrier in terms of affordability to adopt and employ solar-powered cold-storage technology.	
		Energy enterpriser	There is a lack of access to funding and equity for renewable-energy companies that want to support these farmers' growth	
		Uncompetitive market	The adoption of decentralized off-grid cold storage has also been hampered by an uncompetitive market. Because most of these systems are developed, operated and maintained by private companies, it is critical that the government to collaborate with the private sector to remove market obstacles.	[36]
	Technical	Energy-intensive process	Compared to other clean energy technologies, such as solar house lighting, agroprocessing and water pumping, cold-storage equipment runs almost continuously and needs more energy availability. The chillers for smallholder farmers are 50 to 250% more expensive than the solar irrigation pumps.	[86, 88, 89]
		Intermittent nature of solar energy	The intermittent nature of solar energy is a major concern. Because of its irregular behaviour, solar energy is not regarded as a reliable source of energy and so is not a good choice for continuous power delivery	[86, 90]
		Battery backup	Solar cooling in the form of a stand-alone system is expensive due to the large size of battery backup. These batteries need to be replaced every 3–5 years, contributing 30–40% of the total cost	[21, 87, 91]
		Distribution	Since sustainable energy technologies are still in their infancy, farmers have only a few options for distributors that can provide installation, parts and servicing. There is a lack of skilled manpower	[84, 92]
	Social	Fresh food preference	Experts and farmers believe that the desire of the customer for fresh produce (non-refrigerated fruit and vegetables) could pose a significant barrier to the widespread adoption of cold storage	[22, 93]
		Sceptical behaviour	Before it leaves the farm gate, a sizable portion of the harvest produced by smallholder farmers is lost to spoilage. However, they frequently have doubts about the necessity for cold storage and the viability of using clean energy to operate farm equipment	[88]
		Lack of awareness	Agriculturalists are unaware of the diversity of new technologies that could be useful to them, especially renewable-energy-based technologies	[79]
		Scattered community	Energy businesses have challenges due to remote and scattered rural communities, which are often very poor	

Table 3. Continued

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		Uncompetitive market	The adoption of decentralized off-grid cold storage has also been hampered by an uncompetitive market. Because most of these systems are developed, operated and maintained by private companies, it is critical that the government to collaborate with the private sector to remove market obstacles.	[36]
	Environmental	Data availability	Geographical location has a significant impact on solar energy. So, without detailed feasibility assessments, solar systems cannot be installed. It is also challenging in developing regions to obtain accurate environmental data, which are essential for utilizing solar energy	[86]
Opportunities for success	Demand for leafy foods	The transition to vegetarianism across the world has increased the demand for fruit and vegetables. To meet the demand, the existing losses in the field can be reduced through decentralized storage facilities		
	Energy demand	The exploration of new energy sources has increased as a result of an increase in energy demand around the world. This will probably propel the market for solar-powered cold storage Cooling is the most efficient approach to reducing the rate of spoilage; however, implementing cold storage in rural areas of developing nations has a more serious problem because of the absence of consistent electricity		[36]
	Need for food value chain	Lack of adequate cold storage is a bottleneck in many developing nations that results in food losses through biological deterioration and jeopardizes farmer income. Perishable goods, including fruit, vegetables and dairy, have very high food loss rates due to improper cold storage. For sustained nutrition, there must be a functional food value chain. This aspect triggers the need for decentralized handling of food		[52]
	Short payback period	Farmers do not have access to financing for upfront payments to purchase the system; off-grid solar makes the system capital demanding. However, the short payback period (<2 years) creates a compelling business case, and if farmers have access to the financing facility, the cold chain might be more widely used in rural areas		[85]
	Agricultural development	One of the most significant factors influencing the growth of the solar-powered cold-storage industry is agricultural development. A third of agricultural production is lost due to deterioration. Farmers can reduce produce waste and improve storage quality with solar-powered cold storage, which has ultimately led to a rise in demand for this type of facility		[83]
	Business model	The affordability issue can be solved with a smart business plan that satisfies consumer demands and is within their price range. Implementing suitable payment plans could convince many low-income people to accept solar items that they consider to be very expensive Promoting regulations such as reducing import taxes on components of solar technology would be essential for expanding the market and attracting additional solar service providers to offer and implement solar technologies Instead of selling refrigerated equipment, innovators can develop business strategies that offer chilling as a service. By eliminating the requirement for consumer financing, chilling services would allow customers to pay for the chilling equipment only when it is actually used		[36, 84]
	Awareness of technology	It is vital to inform potential users about the financial advantages of using solar-powered cold-storage technology and to promote and increase knowledge of these advantages. Before deployment, it would be essential to raise public awareness and educate consumers about solar-powered cold-storage solutions in order to promote demand and uptake for such technologies among other market segments besides farmers		[86, 90],

production sites and then transportation to long-distance markets in a non-refrigerant environment. There is a dire need to handle the horticultural produce safely at production sites. Various public and private sectors are working to use solar energy for cold storage. Despite the dire need for this sustainable technology, the viability of the cold-storage infrastructure becomes difficult due to fragmented farming practices in developing countries leading to poverty.

Solar-powered cooling can play a vital role in addressing the challenge of food security through decentralized storage of horticultural commodities. It not only helps in the reduction of FLW, but also supports green economic growth by

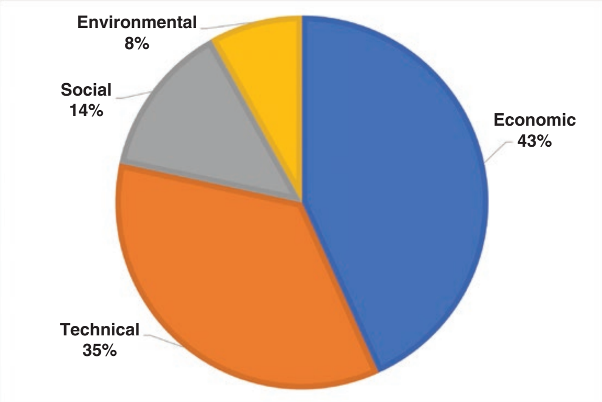

Fig. 8: Percentage of prevailing operational constraints for the successful deployment of decentralized cold-storage facilities in developing regions

reducing GHG emissions. In this regard, Asia, particularly India, has done more work than Africa and other developing regions. The lack of cold-storage facilities in rural areas is related to operational challenges caused by inconsistent grid supply and the difficulty in obtaining financing for the construction of solar-powered cold-storage systems. The key barrier faced in the uptake of such systems is the high upfront cost. These obstacles need to be overcome, such as providing affordable finance to farmers and incentivizing stakeholders. Possible solutions include the development of adequate technology to meet the needs of cold storage, creative finance to make cold-storage systems affordable and a supportive business/enterprise/market environment to enable the successful deployment of the solutions.

Moreover, the following recommendations have been conceived from the study:

- Governments must pass specific legislation to promote the use of renewable energy for cooling throughout the entire agri-food supply chain to improve the confidence of consumers and financial institutions.
- To make cooling solutions available to small-scale farms, stakeholders (public, corporate and financial institutions) must simultaneously encourage financial innovation such as blended finance.
- In addition, effective co-operation and communication between key players and agricultural organizations such as extension departments should be accelerated through an effective training programme on the importance of off-grid solar technologies.
- Most regions have a sizable cold-storage capacity, but it is primarily devoted to the long-term preservation of particular crops, such as potatoes. Instead, small-capacity decentralized cold-storage facilities are needed in or near villages. These short-term transitional storage facilities would assist small and marginal farmers by allowing them to store their horticulture products during times of surplus or when the produce cannot be transported to demand centres due to any limitations or disruptions.
- Analysing the technical and economic applicability in a particular country or location, as well as the size at which it would work, is a crucial step before adopting it. This is essential since the cost of storage, value-added and processing technology or infrastructure varies greatly depending on the level of local skill and the level of development of the nation.

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Data availability

The data sets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflict of interest statement

The authors declare no conflict of interests.

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