

A Review of Postharvest Cooling Techniques, Challenges, and Conventional Cold Storage for Fruits and Vegetables Handling in Tropical Climates

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Abstract

Postharvest handling of fruits and vegetables in tropical regions faces significant challenges due to unpredictable weather. This review critically examines the application of conventional cold storage techniques in the postharvest management of tropical horticultural produce, considering the constraints that affect their performance and the environmental factors influencing the storage of tropical fruits and vegetables. Particular attention is given to the technical limitations of these systems when deployed under tropical conditions. The study systematically examined findings from peer-reviewed literature on various conventional cooling applications, offering a comprehensive overview of their performance and limitations. Furthermore, it explores the integration of solar-powered refrigeration systems to enhance energy efficiency and promote technological innovation in off-grid cooling. Findings from this review underscore research gaps and highlight the need to develop advanced, climate-resilient cold storage configurations tailored to the unique challenges of tropical environments. Specifically, integrating solar-powered refrigeration units with thermal energy storage (TES) compartments into conventional cooling systems for the storage of fruits and vegetables.

Keywords:

Cold storage, Fruits and vegetables, Postharvest, Solar-powered cooling, and Tropical climates

Introduction

Postharvest handling of fruits and vegetables in tropical weather conditions of developing countries faces critical challenges due to the interplay of climate change, poor handling practices, energy inefficiency, inadequate storage facilities, harsh ambient temperatures, and inefficient transportation practices. Fruits and Vegetables are vital agricultural products for human consumption, providing vitamins A, C, and K to enhance the human immune system (Irfan et al., 2023). However, fruit and vegetable supply chains in tropical climates are characterised by significant spoilage risks, owing to their sensitivity to harsh handling conditions after harvest, such as high ambient temperatures and low humidity. For most locations with two (2) common seasons (i.e., wet and dry) in Nigeria, Udeh et al. (2024) reported a range of 23.0-40.0 °C and 31-93% for temperature and humidity at the coastal and northern domains, respectively. Additionally, the inadequacy and unreliability of conventional cold storage techniques in the tropics lead to setbacks for the bulk storage of freshly harvested commodities among smallholder farmers. Likewise, the grid electricity to power refrigeration systems, to cater for the cooling demands in rural areas, is unaffordable, causing a severe limitation for farmers. Biologically, due to the sensitivity of fresh fruits and vegetables,

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they require timely conditioning in a low-temperature, high-humidity atmosphere to maintain their market and nutritional qualities (Han et al., 2021). Fruits and vegetables play a crucial role in Nigeria's agriculture, nutrition, and economy.

Major fruits produced include mango, pineapple, and citrus, while vegetables include tomato, okra, and pepper (Ibeawuchi et al., 2015). Despite their importance, farmers face various production and market risks, including short-term deterioration, pest damage, weather instability, and mechanical damage (Fakayode et al., 2012). In order to address these challenges and promote sustainable fruits and vegetables value chain, several interventions have been proposed, such as providing improved varieties and seeds which can be climate resilient (Abd-El-Hamed, 2021), implementation of off-grid cooling systems (Luerssen et al., 2020), introducing evaporative cooling solutions incorporated with thermal energy cooling function, and enhancing market access through plastic crates logistic handling (Takeshima et al., 2023). These are interventions with the potential to modernise the value chain, reduce losses, and improve the resilience of fruits and vegetables. According to Ibeawuchi et al. (2015), further developments in the fruit and vegetable sector in Nigeria have demonstrated inclusive development and improvements to enhance the livelihoods of rural populations, as noted by Takeshima et al. (2023). In Nigeria, for instance, seasonal fluctuations in weather conditions significantly impact the production patterns, quality, and storage of fruits and vegetables, considering the seasonal differences in these commodities, which are further exacerbated by climate variability. In the case of developing economies, limited access to bulk storage infrastructure and unsustainable postharvest handling practices, particularly at the farm and aggregation levels, are serious issues, with non-adherence to quality standards (Yahaya & Mardiyaa, 2019). All these factors lead to substantial economic losses between farm and fork, estimated to be over \$9 billion. The perishability of fruits and vegetables at high ambient temperatures makes them vulnerable to rapid deterioration after harvest (Ariwaodo, 2022). Likewise, microbial infections, coupled with biodiversity interactions of the environment from farm worsened by fungi tolerance to the harsh weather conditions (Sambo et al., 2016); mechanical injuries caused by poor harvesting methods, bulk damage caused by poor road conditions during transportation (Okoli et al., 2015); and inadequate access of rural farmers to sustainable

refrigeration due to high costs and unreliable electricity supply (Rami & Allouhi, 2024). All these factors have exacerbated postharvest losses in the supply chain of fresh fruits and vegetables under tropical climates. Hence, there is a need to explore access to innovative refrigeration and cooling techniques that leverage solar energy applications for the sustainable preservation of fruits and vegetables in tropical climates. Postharvest cooling, deployed to preserve the quality of agricultural products, primarily focuses on temperature management and control. This review examined existing peer-reviewed literature to represent studies on various conventional cooling techniques in tropical climates, analysed factors affecting cold storage utilisation, and explored different design modifications that could enhance the performance efficiency of postharvest cold storage for fruits and vegetables.

Methodology

For this review, Scopus, high-impact journals, and institutional databases publications were explored to assess bibliometric findings on postharvest cooling of perishables in the tropics. The publications reviewed represent a comprehensive repository of peer-reviewed literature, including scientific journals and conference proceedings. These materials were consulted to measure and examine the extent of scholarly work on the subject, given their extensive coverage. The information obtained from online publications was compiled and summarised. Keywords used to filter the search included "evaporative cooling in the tropics," "cold storage," "cooling performance," "fruits and vegetables storage," "solar cooling system", and "energy performance." The search yielded a total of 83 publications, with only one study directly addressing the storage of fruits and vegetables in the tropics. The use of all scientifically based publications as research sources for this review provided a comprehensive foundation for the findings and ensured reliability in this review.

Cold Storage Mechanism

Cold storage for fruits and vegetables involves a process of removing heat, controlling humidity, and regulating air conditions to preserve freshness, quality, and safety, thereby extending the shelf life of these products. Cold storage mechanisms in tropical environments present unique challenges due to the temperature differences at various locations, affecting applications across different concepts. Under a tropical climate, achieving cold storage with a drop in temperature of 5 -10 °C can effectively preserve some,

but not all, perishables, showing a better effect compared to ambient temperature and humidity conditions, making it preferable to freezing, which tends to alter produce properties (Cook et al., 2016). However, cold storage's impact on fresh produce properties can significantly reduce spoilage, delay ripening in climacteric produce, and mitigate microbial infections, among other benefits. The application of solar-powered cold storage systems relies on the mechanism of energy conversion from solar insolation to thermal energy production for ice, which is then used to preserve fruits and vegetables. This mechanism utilises sunshine to enhance the energy efficiency of cooling in remote locations, Luerssen et al. (2020), with the integration of a refrigeration system to advance cold storage facilities. In Solar cooling methods, the solar refrigeration cycle generates the mechanical power required to drive the refrigerator's compressor. The Carnot cycle is the heat exchange cycle considered for this process. In the Carnot cycle, the refrigerant (a fluid) is evaporated at a low temperature and high pressure by heat pump action. A storage tank for ice storage is included in this process to provide low-temperature thermal storage in the form of ice-cold water pumped through a heat exchanger at low pressure, where it is again vaporised to remove heat from a medium. Conversely, tropical and subtropical fruits, when stored at temperatures below 10 °C, tend to suffer from chilling injury, exhibiting symptoms such as pitting, discolouration, and decay, which limits the effectiveness of cold storage (Patel et al., 2016).

Postharvest Losses of Tropical Fruits and Vegetables

The demand for fruits and vegetables as food, combined with post-harvest losses in tropical climates, presents a significant challenge to food and nutrition security. For instance, in countries like Nigeria, where the mean daily ambient temperature ranges between 23-40 °C (Udeh et al., 2024), under such conditions, more than 45-60% losses are recorded in the fruits and vegetables supply chain (SureChain, 2021). In most cases, vegetables alone experience a loss of about 40% (USDA, 2016). However, the primary causes could be attributed to environmental factors, such as harsh weather conditions (high temperatures) (Zheng et al., 2022), which affect the produce's metabolism. Also, micro-organisms, diseases and insect infections from the farm by opportunistic pathogens, mechanical damage during harvest and transportation, inappropriate harvesting and storage techniques

causing further deterioration (Thole et al., 2021; Firdous, 2021), and inadequate packaging and marketing practices (Etefa et al., 2022; SureChain, 2021). In some cases, fungal pathogens which attack fresh produce in the field are easily resistant to the impact of low temperatures, which further causes decay of tropical fruits (Thole et al., 2021). Apart from physiological deterioration, which is typical of fruits under tropical weather conditions (Sibanda & Workneh, 2020), biologically active phytochemicals in fruits tend to attract bacteria and fungi, causing rot or decay, and are susceptible to water loss, resulting in wilting, shrivelling, or darkening (Kitinoja, 2013). Postharvest losses arising from metabolic reactions also result in weight loss and rapid colour change simultaneously as storage temperature fluctuates (Bogdanovská et al., 2019; Abd El-Hamed, 2021). Technically, the method of agronomic practice also plays a crucial role in the susceptibility of fruit and vegetable produce to postharvest losses (Thole et al., 2021). Various techniques to mitigate postharvest losses of fruits among rural and smallholder farmers in the Tropics include the construction of evaporative coolers (Olosunde et al., 2009; Muhammad et al., 2012). However, performance defects due to metrological differences are a challenge (Ibeawuchi et al., 2015). Storage techniques, such as controlled atmosphere, have been recommended for postharvest handling, packaging, transportation, and storage practices in tropical weather (FAO, 2018; Elik et al., 2019). Other key factors contributing to fruit and vegetable losses in the tropics were described by Muhammad et al. (2012), Bolarin & Bosa (2015), and SureChain (2021), including improper handling, inadequate cold chain facilities, and suboptimal packaging methods. Some other key factors responsible for handling fruits and vegetables at preharvest and postharvest stages were highlighted in Figure 1, which informed the mode of cooling applications. The production of tropical fruits and vegetables in remote areas is often affected by a lack of technical know-how in utilising advanced techniques to mitigate postharvest losses (Firdous, 2021). However, Elik et al. (2019) recommended capacity building and practical demonstrations to promote appropriate practices. SureChain (2021) highlighted key innovations for sustainable and market-driven solutions in loss-mitigation techniques across the fruits and vegetables value chain. For farmers, while Olosunde et al. (2016) suggested promoting advanced refrigeration techniques, such as hybrid evaporative cooling systems, small-scale solar-

powered cooling boxes are also considered adaptable to the tropics (Sibanda & Workneh, 2020). Evaporative cooling, a conventional method in tropical climates, is the process by which the temperature of a medium is reduced due to the cooling effect of water evaporation (Okafor, 2017). An evaporative cooling approach using locally sourced materials could significantly reduce the substantial postharvest losses incurred in the fruits and vegetables supply chain under tropical climates by 70% (Elik & Aysar, 2019; FAO,

2022); however, energy performance has been a technical challenge. Biotechnological solutions, such as molecular characterisation, have been developed to reduce pre- and postharvest losses of tropical fruits and vegetables. An approach to advance the local cold storage process was considered by Ariwaodo (2022) & Lip et al. (2022), which together suggested solutions such as refrigerated containers for transporting fruits and vegetable commodities

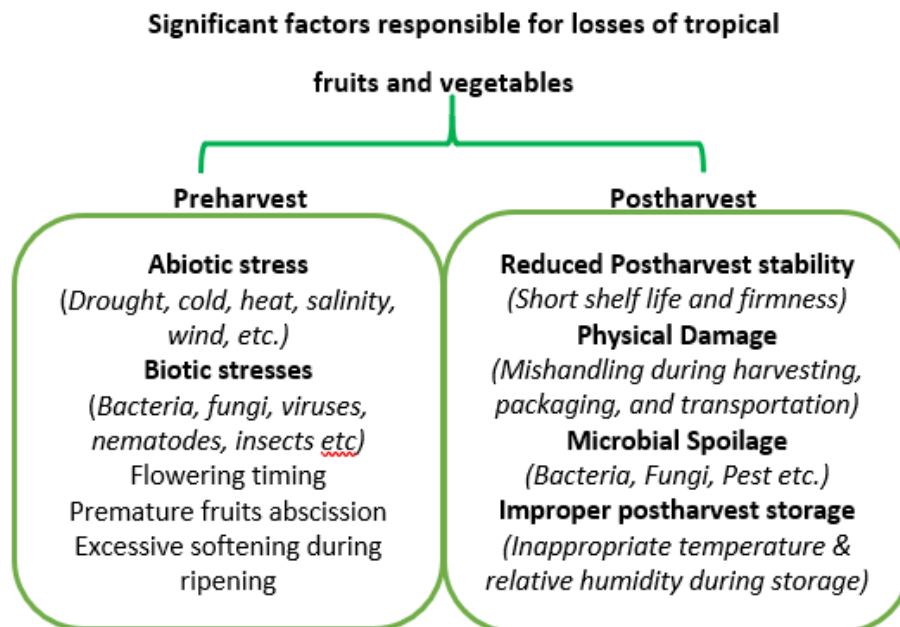


Figure 1. Key factors responsible for losses at preharvest and postharvest (Irfan et al., 2023).

Importance of Cooling to Postharvest Handling of Tropical Fruits.

Effective temperature management plays a crucial role in preserving the quality of fresh fruits and vegetables (Ndukwu et al., 2013). Cooling is a vital process for maintaining the postharvest quality and extending the shelf life of fresh fruits and vegetables in tropical climates (Olosunde et al., 2016; Zainalabidin et al., 2019). Studies have emphasised the importance of temperature control in the process of heat removal from stored bulk fruits and vegetables to retain their quality (Addo et al., 2012). The conventional practices of smallholder farmers in the tropics are more of small-scale production (Sibanda & Workneh, 2020), although characterised by limiting factors such as lack of access to smart cooling techniques, exposing their produce to physiological deterioration, such as rot and spoilage within a short time due to imbalanced temperature (Takeshima et al., 2023). The cultivar and species of most tropical fruits and vegetables also determine susceptibility to decay incidences after harvest, necessitating appropriate storage conditions to

ensure quality retention (Zainalabidin et al., 2019). Postharvest cooling is crucial for maintaining the quality of fresh fruits and vegetables and extending their shelf life in tropical climates (Olosunde et al., 2016). However, chilling effects caused by environmental and storage conditions expose perishable fruits to greater loss of physiological value when stored at very low temperatures (Heyes, 2018; Ariwaodo, 2022). Several studies, such as (Morris, 1982) had focused on the assessment of the effects of chilling injury and its mechanisms on tropical fruits, while some concentrate on shrivelling induced by conventional refrigeration methods as a result of cooling at temperatures below 5 °C (Biswas et al., 2012; Hailu, 2016; Heyes, 2018; Zainalabidin et al., 2019). Conventional refrigeration for cooling is generally expected to enhance the cooling of fresh fruits and vegetables, thereby extending their shelf life; however, managing chilling damage necessitates precise control of temperature and relative humidity (Heyes, 2018; Ogumo et al., 2020). Strategies to mitigate chilling effects include temperature

conditioning by intermittent warming, controlled atmosphere storage, and chemical treatments (Zainalabidin et al., 2019). Cooling systems for fruits and vegetables powered by solar renewable energy, such as stand-alone mini-grids, offer a cost-effective alternative to fossil fuels. Losses of fresh produce, which disproportionately occur in the "few miles" after harvest, could be managed by effective cooling logistics (Dongyu & Francesco, 2021). To enhance shelf life quality, sustainable cooling techniques and facilities for improving postharvest handling are crucial in tropical weather conditions (Liberty et al., 2013). Immediate cooling of fresh produce after harvest can minimise quality losses arising from high ambient temperature gradients, which also affect the continuous physiological changes and metabolic reactions resulting from field heat (Baladhiya & Doshi, 2016). Therefore, managing the physiological changes within a controlled atmosphere, such as a cold room operated with thermal controls, becomes essential for maintaining the quality and extending the shelf life of tropical fruits and vegetables (USDA, 2016; Hailu, 2016).

Overview of Cold Storage and Quality Preservation of Tropical Fruits and Vegetables

The suitability of cold storage for preserving quality and extending the shelf life of fresh tropical fruits was established by Poku et al. (2017) and Zainalabidin et al. (2019). An effective cold storage system better preserves essential postharvest qualities, such as weight, colour, flavour, and firmness, while increasing nutrient retention capability for market acceptance (Majidi et al., 2014). Although the entire cooling process for quality preservation can be energy-intensive, depending on ambient weather conditions (USDA, 2016), it is particularly so in situations where continuous application is required for bulk storage (Rami & Allouhi, 2024). In tropical climates, evaporative cooling solutions have proven to be a promising approach, at least to some extent, compared to conventional air conditioning in rural areas, enabling temperatures to be managed below ambient weather conditions (FAO, 2022). Cold storage deployment in the tropics has leveraged local methods for storing climacteric produce, such as tomatoes, in raffia baskets at the farm level (Akinniran et al., 2020), due to its ability to address both sensible and latent heat loads (Becker et al., 2014). Cold storage by evaporative technique in the tropics is more effective in managing the heat load arising from respiration in fresh fruits and vegetables due to higher ambient

temperature (Pott et al., 2020); whereas, deficiency of the unstable relative humidity has not been adequately addressed for thermal stability using the technique (Yang et al., 2002). The improvement of evaporative cooling through the incorporation of desiccant dehumidification using green materials, such as agricultural waste, was reported by Emdadi et al. (2017). Locally developed structures from earth materials for the construction of evaporative cooling media include pot-in-pot and wall-in-wall models, as studied by Babarinsa & Omodara (2016) and Sunmonu et al. (2016), and the use of absorbent material for a cold room (Olosunde et al., 2009). While the performance of an evaporative cold storage system in the tropical climate could depend on factors such as air (dryer) condition in the outer environment, much attention is given to temperature drop within the cooling medium where produce is stored, thermal properties and water-air exchange efficiency and texture of the earth-wall material at different periods (Poku et al., 2017). According to Yang et al. (2002), incorporating enthalpy exchangers in solid desiccant-based cold storage was said to improve dehumidification potential under subtropical and tropical climates. Remarkably, Oluleye & Boukhanouf (2019) discussed trends in the utilisation of absorption refrigeration and solar photovoltaic systems, suggesting they have a promising advantage for air distribution in tropical climate cooling spaces. The integration of cold rooms in hot weather with solar powered refrigeration and air distribution systems has been assessed for technical, economic and environmental merits (Olosunde et al., 2016); while the conventional refrigeration had gained relevance in cold storage; it is often inaccessible to small-scale farmers for handling of tropical fruits due to cost of acquiring the facility and electricity limitations (Liberty et al., 2013). The localisation of the evaporative cold storage method has emerged as a suitable cooling solution, particularly for rural farmers in hot and dry regions, enabling them to store fresh produce under cool conditions (Poku et al., 2017). To further leverage the abundant solar radiation in the tropical climates, advancing the evaporative cooling techniques by incorporating desiccant and an air distribution unit powered by solar or wind energy has been studied (Sibanda & Workneh, 2020). Other studies have developed models to optimise the performance of solar-powered evaporative cooling systems integrated with thermal absorption components for enhanced cooling performance tailored to tropical climates, aiming to improve the

preservation of fruits and vegetables (Pietruschka, 2010; Boero & Agyenim, 2019; Shahhath et al., 2020).

Conventional Cooling Methods and Postharvest Handling

Conventional cooling methods used in the tropics to extend the shelf life of horticultural produce include refrigerated coolers powered by fossil and grid electrical energy sources, as well as evaporative cooling systems (Ogumo et al., 2020). These techniques, although mostly standard in the tropics, are not always reliable due to the impact of ambient conditions on their performance. Based on the fact that conventional cooling systems are not always the best solution for maintaining the freshness of perishable fruits, due to some resultant effects of storage conditions on the appearance of the stored produce, such as black spots on mangoes (Le et al., 2022). According to Han et al. (2021), vacuum cooling appears to be an effective conventional cooling method for produce like fresh broccoli, which may not be suitable for highly perishable climacteric fruits. Conventional cold storage techniques, such as zero-energy cool chambers, are popular as a local method and affordable for short-term storage of fresh perishables in tropical countries (Pott et al., 2020). However, unstable electricity often limits the functionality of conventional refrigerators' cooling systems, which rely on refrigeration engines, posing a serious challenge.

Additionally, the use of non-eco-friendly refrigerants, often reliant on fossil fuels, is also affected (Maheshwar & Chanakya, 2006). Emerging technologies, such as solar cold storage systems with phase change materials, are being explored (Sarbu & Sebarchievici, 2018), offering benefits in terms of energy efficiency and temperature stability. Different conventional cooling applications in the tropics include transportation with refrigerated vehicles, insulated cooling boxes, and low-temperature packing lines for the distribution of fruits and vegetables (Zhang et al., 2019; Han et al., 2021). The importance of conventional cold chain methods has been further highlighted during the pandemic, particularly for vaccine storage and distribution (Küçük et al., 2023). Due to variations in the weather conditions of the Tropical climate, characterised by unstable ambient temperatures, there is a significant cooling need (Yahia, 2010). Research into conventional refrigerated storage powered by solar energy can significantly minimise energy consumption, shrinkage, chilling effects, and spoilage on sensitive products. This

informed the study by Sibanda & Workneh (2020) on developing indirect cooling using a solar evaporative coolant with minimal refrigeration components (Becker et al., 2014). Technologies such as smart cold boxes and solar-based indirect cooling chambers have been developed to improve access to conventional cooling options, for example, the cold box transport of fruit (Sibanda & Workneh, 2020).

Application of Vapour Compression Refrigeration To Fruit and Vegetable Cooling

Air conditioning, utilising vapour compression refrigeration systems, is adapted for cooling fresh agro-crops during storage (Ogumo et al., 2020). The increasing global demand for cooling has driven significant innovation in suitable refrigeration techniques for the tropical climate food supply chain (Kitinoja, 2013). An increase in cooling needs across the fruits and vegetables supply chain has led to a high reliance on electricity, which is often unstable (Khiro & Boukhanouf, 2024). According to the EforA (2023) report, tropical regions like Nigeria, Mali, Niger, etc., in Sub-Saharan Africa have a cooling deficit of about 3 trillion cubic meters. However, the air conditioner market in tropical Africa is proliferated by fossil and grid-driven mechanical refrigeration systems, which are no longer sustainable (Sakiliba & Hassan, 2020). Therefore, Vapour compression refrigeration systems are energy-intensive machines that pose a potential threat to environmental degradation by increasing greenhouse gas emissions (Khiro & Boukhanouf, 2024). Adaptation of solar-driven vapour compression cooling systems will therefore serve as a suitable replacement to reliance on the alternating current system (Lip et al., 2022). Research to find a suitable postharvest cooling option has increased the focus on innovating for direct current (DC) vapour compression refrigeration units (Mahmood et al., 2021; Ogumo et al., 2020). According to Tarawneh (2013), solar-powered and DC systems are a promising solution to address the energy complexity arising from reliance on fossil fuels, as they reduce emissions and improve access to affordable, clean energy cooling solutions. Mahmood et al. (2021) reviewed the energy performance challenge of the vapour compression system (VCS). They tested the utilisation of a mixture of R134a and LPG with a mass fraction of 28:72 as an alternative refrigerant to R134a. Sidney (2021) and Khiro & Boukhanouf (2024) explored advancements in vapour compression systems utilising R600a. As an eco-friendly refrigerant, isobutane is recognised for its low global warming potential and high energy

efficiency due to moderate suction pressure for evaporation (Akdemir, 2017). Alsagri (2022) evaluated the suitability of a mechanical vapour compression refrigeration cycle powered by photovoltaic solar panels to drive a conventional cooling system in a tropical climate. The study tested its applicability on conventional refrigeration systems to address cooling demands in the tropics, as presented by Kumar & Abhijit (2015). A novel thermo-mechanical vapour compression system developed by Khиро & Boukhanouf (2024) integrated with an ejector and solar-powered compressor showed a 31% reduction in electrical energy consumption and up to 44% improvement in the COP compared to conventional refrigerators. At the same time, solar thermal absorption, adsorption, and desiccant cooling techniques are also advancing, with hybrid configurations for improved energy efficiency (Rahadiyanti, 2017), which aligns with the Sustainable Development Goals of the UN (Dongyu & Francesco, 2021).

Adaptation of Solar-Powered Refrigeration and Cooling

Solar cooling applications offer a sustainable advantage for agro-food preservation in the Tropics. Specifically, to provide a thermal energy-efficient and environmentally friendly system that reduces reliance on the grid, thereby lowering greenhouse gas emissions (Huang & Zheng, 2018; Shahhath et al., 2020). Improved solar cooling has created opportunities for cold storage configurations that can incorporate innovative designs with thermal energy storage adaptation (Tyagi et al., 2012; Wu et al., 2015),

which are particularly applicable to off-grid zones in tropical climates. Due to the challenges with electrical energy in tropical climates of developing nations, solar cooling is becoming increasingly attractive for postharvest applications (Khиро & Boukhanouf, 2024). Solar cooling systems partly use inverters and direct current DC enabled components, either through photovoltaic (PV) panels, a direct current DC battery backup unit or a solar thermal energy reservoir to compensate for energy needs at the off-peak (Ghosal & Mohanty, 2020). Solar cooling machines with vapour compression systems (VCS) for postharvest cooling can be energy-demanding (Jain & Paul, 2020). However, it can offer a sustainable alternative to conventional air conditioning systems, which use high-horsepower heat pumps that are expensive to meet the demands of rural agriculture. Apart from reducing electricity consumption, a limitation of traditional refrigerated cooling systems (Shahhath et al., 2020), this approach will also mitigate the proliferation of hydrocarbon refrigerants, which are hazardous to the ecosystem. A configuration of the DC refrigeration cycle with a heat pump was invented and studied by Alsagri (2022) for thermal energy production and storage, utilising evaporative cooling systems. This configuration leverages solar energy for off-grid cooling. The heat pump configuration is shown in Figure 2, specifically designed to be incorporated and adapted as a low-energy consumption alternative for DC compressors utilising eco-friendly refrigerants (R600a) mounted to solar-powered cooling systems. The refrigeration cycle has the potential to set up a modular, stand-alone solar cooling system for off-grid cooling solutions in tropical climates.

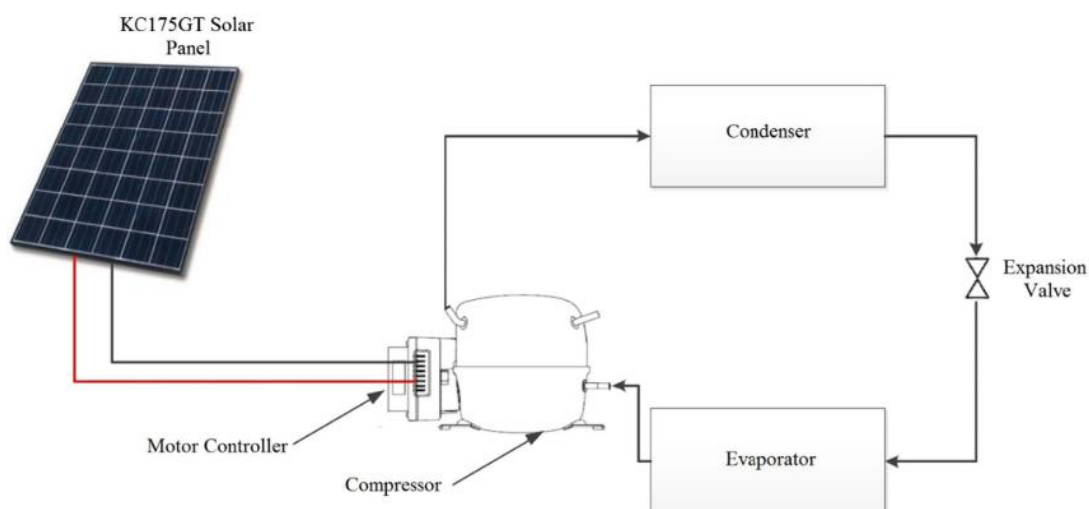


Figure 2. Schematic configuration of DC vapour compression refrigeration cycle powered with a photovoltaic unit. Source: (Alsagri, 2022)

For tropical climates, cooling demands are consistently high, and the adaptation of solar-powered cooling systems for the fruits and vegetables supply chain has been suggested as a promising solution (FAO, 2022). Some of the existing technologies for cold storage in the literature include cooling thermal energy storage (CTES), as discussed in the study; chilled water Storage methods (CWS); and ice thermal storage (ITS), which were compared in the study by Sinha & Karale (2013). The last two were compared to assess their merits for tropical climate applications that rely on solar energy availability. In Nigeria, Sakiliba & Hassan (2020) conducted a case study on solar cooling with inverter technology designed for cold storage and the preservation of fresh fish and meat. Biswas et al. (2020) reported on the utilisation of solar coolers for the Indian climate, considering the animal health value chain, particularly in the storage of vaccines and animal products. The feasibility of a novel twin-circuit (HFC-134a and HC-600a) DC compressor milk chiller with water-based TES operated by solar PV was studied under different climatic conditions in India (Sebastian et al., 2016).

Classifications of cold storage technologies for fruits and vegetables include refrigerated storage, controlled atmosphere (CA) storage, and evaporative cooling systems. Refrigerated storage involves temperature-controlled environments, while CA storage additionally regulates gas composition (Ziv & Fallik, 2021). Evaporative cooling, effective in hot, dry climates, reduces temperature and increases humidity (Alemu, 2022). Recent innovations include solar hybrid systems, which reduce operating costs and emissions, as well as the use of phase change materials for thermal energy storage (Kapilan, 2020). Portable cold storage units, such as refrigerated containers and cold rooms, offer flexibility and employ various cooling methods like compression, absorption, and thermoelectric cooling (Raju et al., 2024). These technologies significantly reduce postharvest losses, with evaporative cooling potentially increasing produce availability by 42-62% (Alemu, 2022). Future trends in cold storage include the integration of renewable energy sources, smart sensors, and Internet of Things technology (Raju et al., 2024). The process of harnessing the abundant solar energy in tropical climates, coupled with the downward challenge of shortening fresh fruit and vegetable shelf life, presents a need to develop sustainable and affordable cooling solutions to address the cooling needs of tropical fruits. This aims to create systems that can effectively ensure nutritional security in perishable commodities under

harsh tropical weather conditions. Hence, promoting the application of solar refrigeration as an alternative to address the significant postharvest challenge in the fruits and vegetables supply/value chain is crucial. Climate-smart storage technologies, such as a complete off-grid system, will offer cold storage solutions to bridge the gap between electrical energy supply and cooling demand, particularly for integrating renewable energy into refrigeration systems (Ikevuje et al., 2023). Some of the innovations include advanced battery storage systems, thermal energy storage systems, and hydrogen storage, which are capable of addressing the intermittent nature of renewable energy (Ikevuje et al., 2023). Emerging thermal storage technologies like ice-storage in water are being explored to address the thermal energy gaps for cooling (Rashid et al., 2023). Other energy storage options for effective cooling in tropical climates encompass various forms, including electrical, chemical, thermal, and electromagnetic, each with unique characteristics tailored to different end-user needs (Eakvanich et al., 2022). The development of these energy conversion techniques can lead to innovative, sustainable energy systems that meet growing global cooling demands, addressing postharvest storage deficiencies for fresh fruits and vegetables in tropical climates. The approach will also address concerns related to climate change and energy security (Acar, 2018; Ikevuje et al., 2023).

Conclusion

This review extensively highlights the experimental and theoretical studies on the use of conventional evaporative coolants in postharvest handling of fruits and vegetables for cold storage in tropical climates. It studied the effect of climate differences on the cooling performance of conventional cooling approaches incorporated with vapour compression refrigeration systems, establishing the need for advancements in utilising thermal energy storage solutions to improve the energy performance of traditional cooling solutions in the tropics. It further describes possible design modifications using different thermal techniques, such as vapour injection to evaporative cooling systems, from the literature accessed. Findings from the literature suggest a limited scope for applying thermal cooling energy conversion methods to postharvest cooling systems for perishable crops. Thus, advancing conventional evaporative cooling methods with innovative hybrid refrigeration techniques requires further research based on the peculiarities of weather conditions in tropical climates, thereby promoting an

integrated cooling approach with affordable solar-powered cooling configurations to meet cooling demands in the fruits and vegetables supply chain under tropical conditions. The low-cost indirect cooling alternative, combined with hybrid refrigerated solar cooling storage, is capable of reducing the loss of fruits and vegetables at various stages of the postharvest chain from approximately 45% to 15% if harnessed.

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