A Cooling Atlas for preserving fruit and vegetables in low- and middle-income countries

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ABSTRACT

Background. Preserving fruit and vegetables after harvest is especially relevant for low- and middle-income countries (LMIC) for food and nutrient security, reducing poverty, and increasing smallholder farmers' access to markets further afield. Cooling is one of the most impactful postharvest preservation methods, particularly when powered by renewable energy.

Problem. A wide variety of cooling technologies exist, though only a subset is sufficiently advanced to present commercially viable deployment options in LMIC, of which only a smaller subset is widely known. Active cooling based on mechanical vapor compression is often considered the most commonly used solution. However, in LMIC, many structural and case-specific challenges limit their widespread use. Therefore, deploying alternative active and passive cooling technologies from a technical, financial, social, environmental, and political context could be more suitable. However, many active and passive technologies are not well-known and are in limited use.

Solution. By compiling existing options, we raise awareness of these promising cooling solutions for LMIC. These include multiple active cooling, passive cooling, and auxiliary technologies that prevent heat gains or regulate the incoming heat, for example, by thermal heat storage or ventilation.

Results. We discuss the advantages and disadvantages of these existing cooling solutions and the physical processes underpinning how they provide cooling. We have developed a selection matrix for the different technologies according to specific criteria. With that, we created a multifactorial evaluation for the technology spectrum for a certain country that can help stakeholders choose the right technology or a combination of technologies. Key factors here are cost, ease of installation, potential for scalability and adaptability, operation and maintenance, energy supply, energy use and storage, cooling process, cooling performance, suitability for food types, market accessibility, demand, and suitability for adoption by potential producers.

Broader perspective. The Cooling Atlas aims to provide evidence for decision-makers and program implementers to make informed investment and implementation decisions. Our Cooling Atlas encompasses existing relevant cooling solutions for LMIC. Choosing the right cooling technology for a specific value chain and use case should be carefully evaluated before implementation. It should only be a holistic solution to increasing food and nutrition security and safety.

Keywords

refrigeration; high-performing appliances; smallholder farmers; agricultural cold chains; cooling technologies; food preservation; off-grid; rural

1 Introduction

Preserving fresh fruit and vegetables is important to improve food and nutrient security for people who are underfed or even malnourished. More food preserved after harvest can also help subsistence and smallholder farmers increase their income and thus help pull them out of poverty. In addition, food preservation also helps to reduce food losses and waste, as well as the environmental impact of fresh food supply chains, making fresh foods more accessible in remote or underserved areas.

Smallholder farmers with land under 2 hectares globally produce about 30% and 15% of the world's fruit and vegetables, respectively (Ricciardi et al., 2018). These farmers comprise most of the agricultural workforce in several low- and middle-income countries (LMIC), which also partly encompass the Global South. Some examples are Guinea-Bissau (60%), Kenya (54%), India (43%), and Nigeria (35%) (Food Systems Dashboard, 2023). However, the success rate of implementing and using postharvest preservation methods is still too low in these regions, amongst others, due to a mismatch with the aimed market, the type of value chain (Jarman et al., 2023), and the type of crop involved. There are typically four types of value chains for which the need for cooling may differ: (1) the cold chain (fruit and vegetable, roots and tubers, meat, dairy, fish); (2) the dry chain (Bradford et al., 2018) (cereals, oil crops, and pulses); (3) the processed chain involving thermal processing to prolong storage life by canning or drying (e.g., fruit and vegetables or fish); and (4) the ambient chain for all crops and products that can be stored under ambient conditions and sold on the market before spoilage.

Cooling is one of the primary postharvest preservation methods used to maintain product quality after harvest, hence extending the shelf life of fruit and vegetables (Schudel et al., 2023). Typically, combinations of methods are implemented along the supply chain to delay loss of quality, such as to avoid temperature damage, dehydration, physical damage, inadequate sanitation, and associated contamination by pathogens (Jarman et al., 2023). Cooling often plays a key role in the postharvest solution. Moreover, the better the product quality after harvest, the more efficient the cooling effect is in keeping the quality of stored products. Products of insufficient quality will not improve even when stored at low temperatures. Lowering the product temperature below ambient temperature slows down several processes: (1) respiration rate and the associated breakdown of metabolic sugars and heat production, (2) senescence or aging and associated cell death, (3) the development of pathogens, including molds, (4) the ripening process and associated tissue softening, breakdown and sometimes ethylene production, (5) transpiration and associated mass loss. Storage conditions need to be carefully designed and monitored since too-low temperatures can also negatively affect fruit and vegetables, including chilling injury and can impact the design temperature for the remaining cold chain in certain value chains. Cooling can be induced by active or passive cooling. Active cooling implies that cooling relies on an electronic device that uses mechanical or electrical energy to induce cooling, a typical example being a refrigerator. Its counterpart, passive cooling, typically does not rely on external energy sources to induce a cooling effect.

Refrigeration and associated cold chains have become the norm within food chains of most high-income countries (HIC) since the more recognized version emerged around the 1930s. However, the cold chain is limited, fragmented, or nonexistent in the food supply chains of many, if not most, low- and middle-income countries (Onwude et al., 2023), especially in rural off-grid areas with largely unavailable, unaffordable, or unreliable access to electricity. Many recent initiatives have been deployed to promote active cooling of fresh produce in LMIC, including in Asia and several African countries. A typical example of what has been called a 'cold rush' is the small-scale, solar-powered cold storage facilities with a few metric tons of food storage capacity. These facilities cater to the needs of smallholder farmers and their off-takers to preserve harvested fruit and vegetables, expand markets, increase incomes, and avoid food waste through refrigeration. A niche of companies serving these specific markets has emerged, developing such cold stores and/or deploying them with farmer-producer organizations, various aggregators, and farmers. The refrigerated transport afterward is closely linked to farm-level cold storage, which is often further challenging. Issues include poor road infrastructure, particularly in the first mile, and a lack of affordable, refrigerated transport services in rural areas, partly driven by the lack of commercial opportunities and other factors. However, a few cold storage companies have started to provide these services in recognition of the need.

There are several challenges with implementing active cooling widely in LMIC. Restrictions to the widespread use and effective maintenance of refrigeration technology cover areas such as transport, price-variable markets, the utilization rate of the cold store in terms of the capacity that is used, fragmented cold chain infrastructure, remote and challenging locations for operation, seasonality of harvests and access to sufficient agricultural inputs, access to finance for all stakeholders, development, adoption of suitable business models and financing mechanisms, lower access to technical training for installers or operators in rural areas, and regulatory aspects for the export market. The impact of these hurdles remains often hidden as many existing cold chain facilities are now partially subsidized through development programs. These hurdles lead to existing facilities not being used at all or sub-optimally. These so-called 'white elephants' (Oostewechel et al., 2022) lead to high operating costs, less revenue for the cooling companies, lack of maintenance, and low utilization rates, meaning the amount of fruit stored inside relative to the total capacity, and lost investments. In many cases, there is what we can call catastrophic failure of the cold store or chain, leading to complete dysfunction or non-use. These unused cold chain facilities become stranded assets/failed investments due to the subsequently limited or completely negative added value.

However, this 'active' means of cooling technology is not necessarily the most suitable storage option for the targeted market or food product in LMIC, especially regarding local implementation, the product itself (the physiology of some food products is less critical), market perspectives, or financial viability. This problem is depicted schematically in Figure 1 via the relation between the production level of fresh produce versus the market sophistication. The viability range of selected cooling technologies and the type of supply chain (ambient or refrigerated) required for several produce types is also depicted (adjusted from (Oostewechel et al., 2022)). Therefore, other non-active cooling technologies could be more viable for specific use cases, countries, products, and markets. Several reviews and guidelines exist on the identification of suitable active and passive cooling solutions (ASHRAE, 2022; IIFIIR and Efficiency for Access, 2023; Jarman et al., 2023; Kitinoja, 2013; Kitinoja and Thompson, 2010; Makule et al., 2022; Schelle et al., 2023; Teutsch and Kitinoja, 2019; Thompson, 2008). Most of these, however, do not specifically focus on cooling solutions for smallholder farmers in low- and middle-income countries or mainly target active cooling solutions.

This study gives a comprehensive overview of viable cooling technologies for low- and middle-income countries. We call this the 'Cooling Atlas' for fresh produce for LMIC. We aim to help guide researchers, practitioners, non-governmental organizations (NGOs), development partners and finance institutions, policymakers, and government agents to find the best solution (or a combination thereof) for their use case without missing the less obvious technologies. We focus on cooling, which is most accessible to the prevalent small-holder farmer circumstances found in LMIC. We leave out high-tech solutions such as pre-coolers (forced-air, hydro cooling, vacuum cooling) or large-scale cold stores using a controlled atmosphere. We focus on detailing and providing an overview of the physical processes and effectiveness of the various means of actively and passively removing heat rather than on the system's capital and operating costs (CAPEX, OPEX). Although critical, these costs are very specific to the hardware solution and manufacturer.

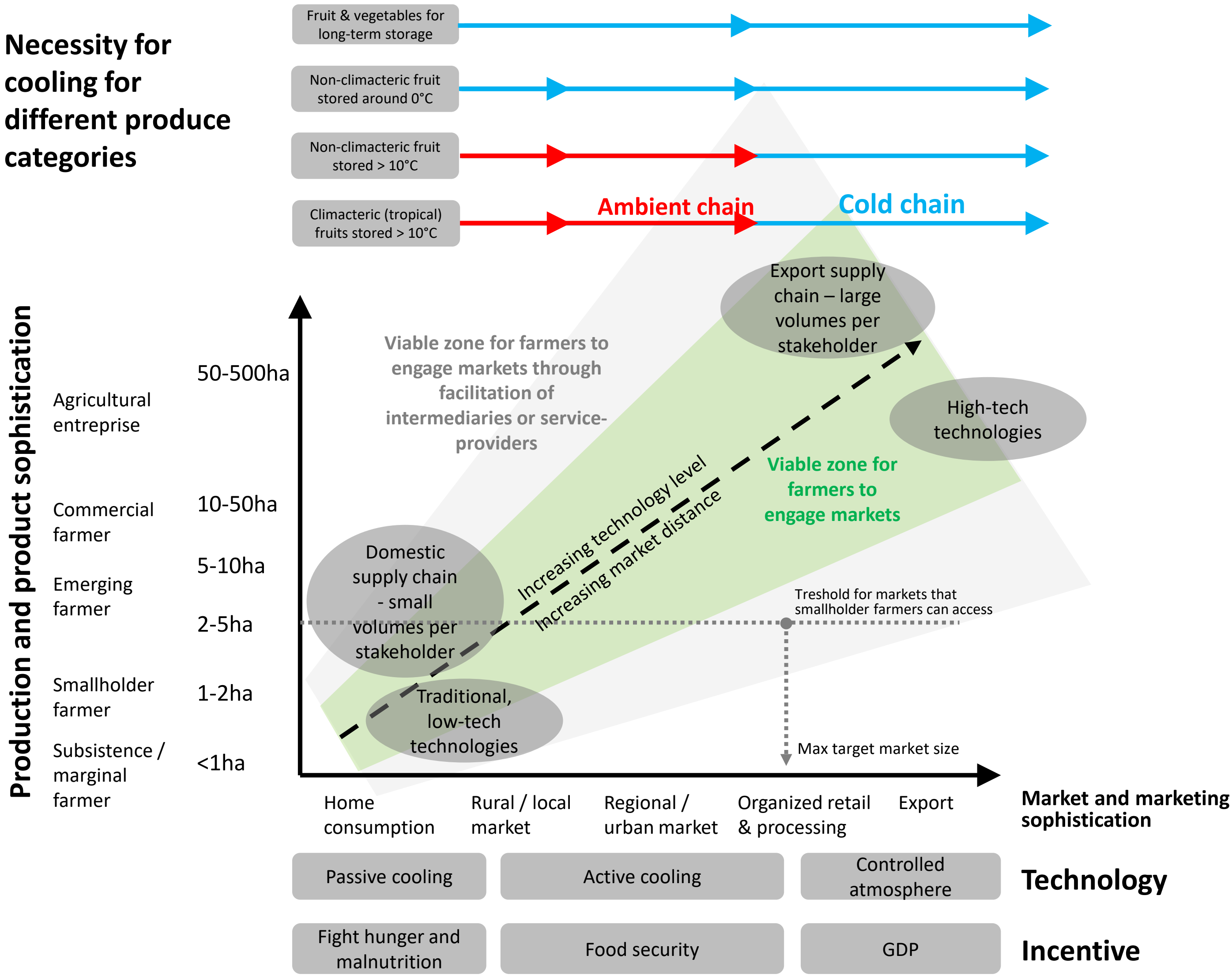

Figure 1. Levels of production and product sophistication of fresh produce versus the market sophistication with an indication of the viability range of selected cooling technologies and the type of the supply chain (ambient or refrigerated) for several produce types (adjusted from (Oostewechel et al., 2022)***). The increase in the viability range when engaging intermediaries is also shown.***

2 Target: what do we want to achieve with cooling, and what are our targets

The targets for the application of cooling need to be defined as they also determine the cooling technology type most apt to be used. In addition, the wanted impact is essential.

<u>Possible impacts that we want to achieve with cooling are:</u>

- Enhance food quality preservation and extend shelf life, thereby reducing the amount of lost and wasted food. The storage period does not always have to be maximized, especially when the products only have to reach the local market (not export or regional markets) within a short period. It is often only needed to store fruit and vegetables until the point of sale at the specific cold store location or nearby markets instead of storing them as long as possible. As a result, lower-tech equipment and solutions are also often viable for local and regional supply chains. Preservation after the point of sale, so the last mile and at-home storage, is also very important in LMIC, as domestic refrigeration is often unavailable. For example, the sales of solar-powered refrigerators in sub-Saharan Africa and South Asia are estimated to reach 0.2% of the serviceable market (Efficiency for Access, 2024). Meanwhile, evaporative cooling solutions, such as the zeer pot or variations, have been proven effective and viable where climatic conditions are suitable but only at the pilot scale, with unknown possibilities for widespread scale and replication (Verploegen, 2024).

- Extend the product availability. The production window is often limited to some weeks, maybe a few months. In this period, product availability is high. Product availability decreases quickly after the production peak without proper preservation, and many unconsumed products are lost or wasted. The farmers may have more food available for consumption or sell to consumers if cooling is available.
- Improve farmer's income. Increasing farmers' income can be achieved through three main strategies: firstly, minimizing economic losses caused by spoiled or deteriorated produce, which farmers might need to sell for a lower price or discard entirely. Secondly, by implementing better quality control measures like cooling, farmers can secure higher prices for produce that meets the required standards, thus increasing profitability. Also, cooling produce instead of traditional methods, such as air drying for fish, can exponentially increase the price received for a given weight and dramatically increase income. Additionally, having a consistent supply of quality produce enhances farmers' bargaining power with buyers, allowing them to negotiate more favorable terms and secure better deals. Reduced losses, controlled quality, and stronger negotiation capacity contribute to a more sustainable and profitable farming model.
- Ensure viable operations of cold room and cold chain assets. Equipment and facilities need to be made available sustainably in terms of providing sufficiently attractive returns on the financial and physical investments to all stakeholders, including suppliers, operators, farmers, and consumers of foodstuffs. The selected location/siting of a cold room will significantly determine the commercial viability of the asset. This needs to be assessed and understood by the commercial players in the supply chain alongside the above-targeted impacts.
- Improved access to markets for smallholder farmers. The application of cooling enables the feasibility of reaching new markets, such as regional or export markets. Without cooling, the farmers are often limited in their ability to sell beyond their immediate, local market. Due to local climatic conditions, other smallholder farmers often grow similar produce, resulting in an influx of produce and an increased supply vs. demand at a given time. This impacts the price per unit that the farmer can secure. By diversifying their access to markets, smallholder farmers have the potential to improve their incomes.

<u>The possible targets and associated use cases for deploying cooling technology are:</u>

- Fast cooling after harvest to start the cold chain as fast as possible. This target is especially relevant for very perishable produce, such as strawberries or leafy greens, but less for resilient produce, such as citrus or pineapple. Fast cooling significantly reduces product loss waste and increases earnings, particularly for sensitive products.
- Spatially uniform cooling of the cargo inside any cooler to have low variability in quality within the cargo. Especially given that many farmers only have a few crates to be stored, variability in refrigerated food preservation within the cold store could be disastrous, as some farmers can be disadvantaged as their product loses more quality than the produce of others. In addition, there is a large variation in the type of products to be stored. Different products from different farmers have different store temperature requirements, complicating the situation even more.
- Temporally stable cooling is relevant to avoid high- or low-temperature damage and large temperature variations, which can hurt product preservation.

<u>Appropriately designed, deployed, and operated cold chain solutions can achieve the following:</u>

- Increased investment in cold storage infrastructure or cold storage (e.g., via suitable business models such as pay-per-use or cooling as a service model) and low needs to be underpinned by capacity-building activities to reach a sufficient expertise level to operate and maintain the system.
- Reduced electricity costs for grid-connected systems and power generation requirements for off-grid systems, in addition to reducing greenhouse gas emissions and carbon footprint through energy-efficient systems. Reducing the cost of systems can also exponentially increase their affordability and, thus, their potential for deployment across a wider variety of use cases and applications.

- Improved reliability time of the entire cold chain to preserve food quality from farm to fork.

Not all targets are relevant for all use cases in LMIC and smallholder-driven supply chains of fruit and vegetables. Note that achieving other targets simultaneously during cold storage is also important since food quality preservation does not only depend on temperature, although it is often the most relevant one. Other important criteria for the technology are:

- Limited dehydration to avoid wilting and shriveling due to excessive mass loss.
- No or little condensation on the food and reduction of very high humidity levels to avoid mold growth. Condensation on cold chamber walls is less of an issue.
- Limit ethylene-sensitive fruit that is exposed to ethylene, such as ethylene-producing fruit, as this will speed up the ripening and decay process and accumulation of ethylene in cold storage rooms.
- Limit mechanical damage during handling and transport after harvest to avoid food loss, decrease the chance of mold infections, and reduce ethylene production. Simple solutions, such as using crates instead of sacks, have been shown to have dramatic benefits.
- Avoid food safety issues due to contamination and growth of micro-organisms.

3 Technologies composing the Cooling Atlas

3.1 The Cooling Atlas

The different cooling technologies relevant to storing fruit and vegetables in LMIC are described. They form the backbone of the Cooling Atlas. They can be, in principle, divided into active and passive cooling solutions as well as auxiliary systems and technologies. Active cooling is assumed to require some kind of electricity source for cooling (e.g., running compressors in the vapor compression cycle) or airflow generation (e.g., using fans for air circulation). Auxiliary systems support the cooling solutions by influencing heat transport and exchange processes from/to and within the storage room through the prevention of heat gains or modulation of heat transport processes. Different active and passive cooling systems and preventive and modulation techniques relevant to cooling are depicted in Figure 2.

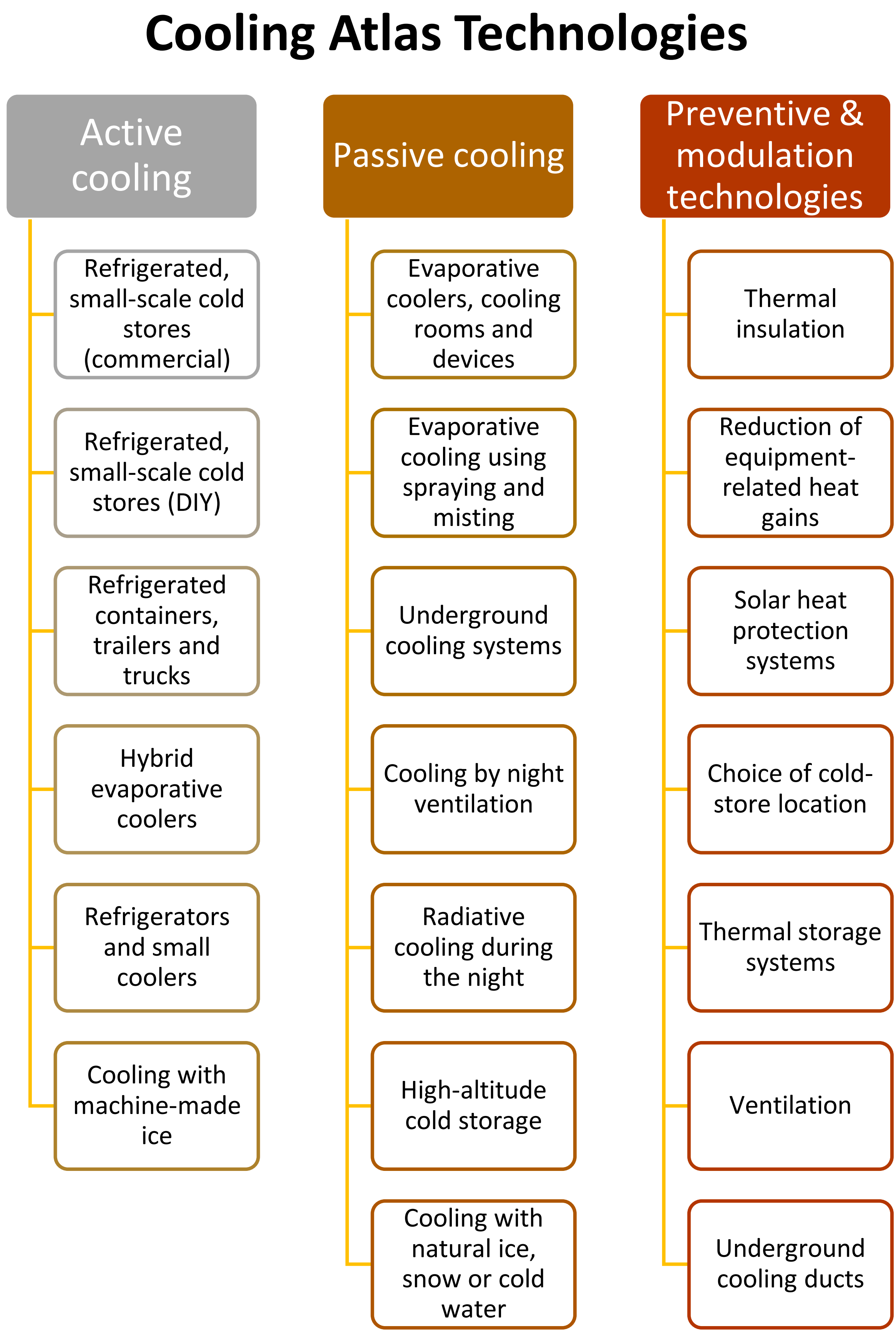

Figure 2. List of active and passive cooling systems, preventive and modulation techniques relevant to cooling, and criteria for choice of the technology. (DIY: do it yourself).

A key disclaimer is that the Cooling Atlas technologies should only be used if cooling justifies the required investment and a viable business model is in place. In other words, guidelines must be followed to determine when to use cooling, in which climate, and what level of cooling is needed.

The cooling solution should match value chain needs, as we should not have cooling in place for a value chain that does not necessarily require cooling. An example is a climacteric fruit, such as mangoes or tomatoes, which can be stored at ambient temperatures if it is destined to be sold within a few days at local markets (Figure 1). In such a case, cooling to the optimal temperature is beneficial but not essential for preserving quality and selling price until the point of sale. The need for cooling and feasibility of cooling investments can be established using a recently developed postharvest assessment method (Oostewechel et al., 2022). The tool offers a holistic approach to assessing postharvest investments' suitability on the logistic, economic, sociocultural, and financial levels. In cases where cooling was defined to be necessary, a set of criteria for the selection of the proper cooling system applies. These include criteria concerning installation, scalability and adaptability, operation and maintenance, energy supply, energy use and storage, cooling process, cooling performance, food products, and the market and producers. It is advised to map these when evaluating one or different cooling options. Such a multifactorial mapping is also presented later (section 4).

Another guidance example is the recently published 'Walk-In Cold Rooms: A Practitioner’s Technical Guide' from the IIFIIR and Efficiency for Access, which is a comprehensive document for specifying, installing, and operating small-scale solar-powered cold rooms (IIFIIR and Efficiency For Access, 2023). It provides 12 essential steps (see Figure 3) for developers, owners, and operators to make an informed decision in their respective areas, starting with whether a walk-in cold room is the right solution for the given context. Tailored for rural and agricultural settings, the Guide supports sustainable storage by preserving produce quality through carefully controlled temperature, humidity, and gas conditions, ensuring economically viable and environmentally-friendly cold storage solutions for horticultural and agricultural produce.

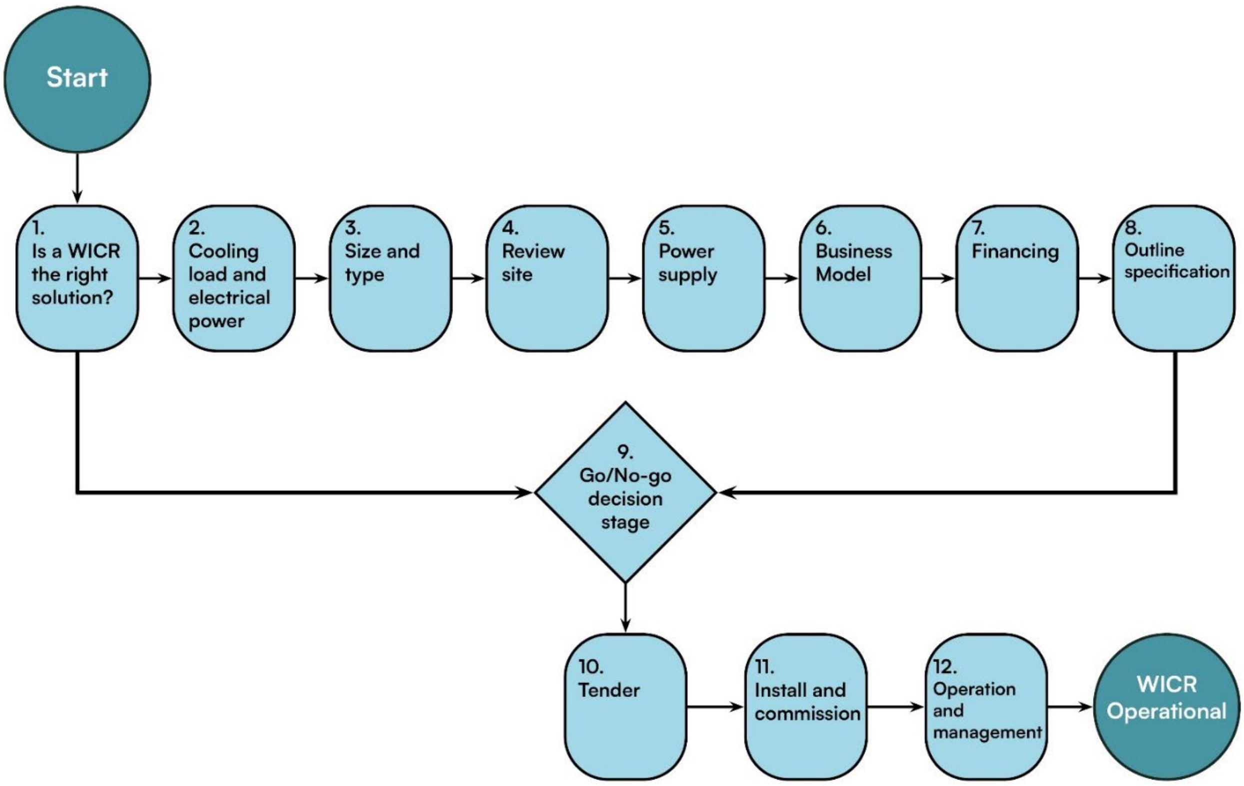

Figure 3. Twelve main steps to specify, design, and operate a solar-powered walk-in cold room to preserve the quality and extend the shelf life of fruit and vegetables (IIFIIR and Efficiency For Access, 2023).

Evaluation criteria for the selection of cooling technologies

Use case: Producers & market	• Producer/farmers: subsistence, smallholder, emerging/intermediate, commercial • Target market: home consumption, local, regional, organized retail, export • Accessibility to market & market demand
Use case: other	• Transportation infrastructure, consumer preferences, export dependencies, competing technologies, climate (change) and crop seasonality, financial accessibility, local availability of materials, policy and legal aspects • Commercial viability (business case) • Local conditions and culture
Installation / Implementation	• Capital cost • Local manufacturing or assembly possible • Dependency on imported materials and parts • Location
Scalability & Adoptability	• Scalability to different sites • Scalability to farm size • Adoptable to different use cases (e.g. rural vs. peri-urban farmers) • Adoptability to multicommodity storage
Operation & Maintenance	• Expertise required to operate • Maintenance frequency, remote monitoring, lifetime of critical components • Availability and proximity of maintenance staff • Availability of spare parts (financial and geographical) • Quality of equipment & warranty
Energy supply	• Energy availability • Energy stability throughout the day & day/night (e.g. photovoltaics) • Cost of required energy supply
Energy use & storage	• Primary power source available (grid dependency, solar PV stand-alone, solar PV microgrid, solar thermal) • Backup power source (diesel generator, grid) • Energy storage (battery, thermal storage) • Energy efficiency
Cooling process	• Refrigeration technology (mechanical, thermoelectric, …) • Cooling time (fast, slow) • Heat transfer mechanism and speed from produce to cooling medium (convection with air or water, contact cooling, …)
Cooling performance	• Temperature reduction • Temperature stability • Humidity control
Food product	• Climacteric, tropical • Climacteric, non tropical • Non-climacteric

Figure 4. Evaluation criteria for technology choice (technologies that are part of the refrigeration unit are indicated in blue).

The physical processes that determine the temperature of the cold storage room are shown in Figure 4, together with passive cooling and auxiliary technologies. These processes will be discussed in more detail in the next sections. It is critical to acknowledge when cooling down perishables that:

- You need to remove the field heat first. Produce typically enters any cooling appliance or facility with remaining heat from the field or transport. The initial cooling is critical to reach the target temperature that needs to be maintained throughout the cold chain.
- You cool in a certain location and microclimate, which will strongly affect the relative distribution of heat loads of any (manufactured or homemade) cold store.
- You do not just cool an inert product: fresh produce is alive, so it respires, breathes, produces heat and ethylene, and loses moisture (IIFIIR and Efficiency For Access, 2023).

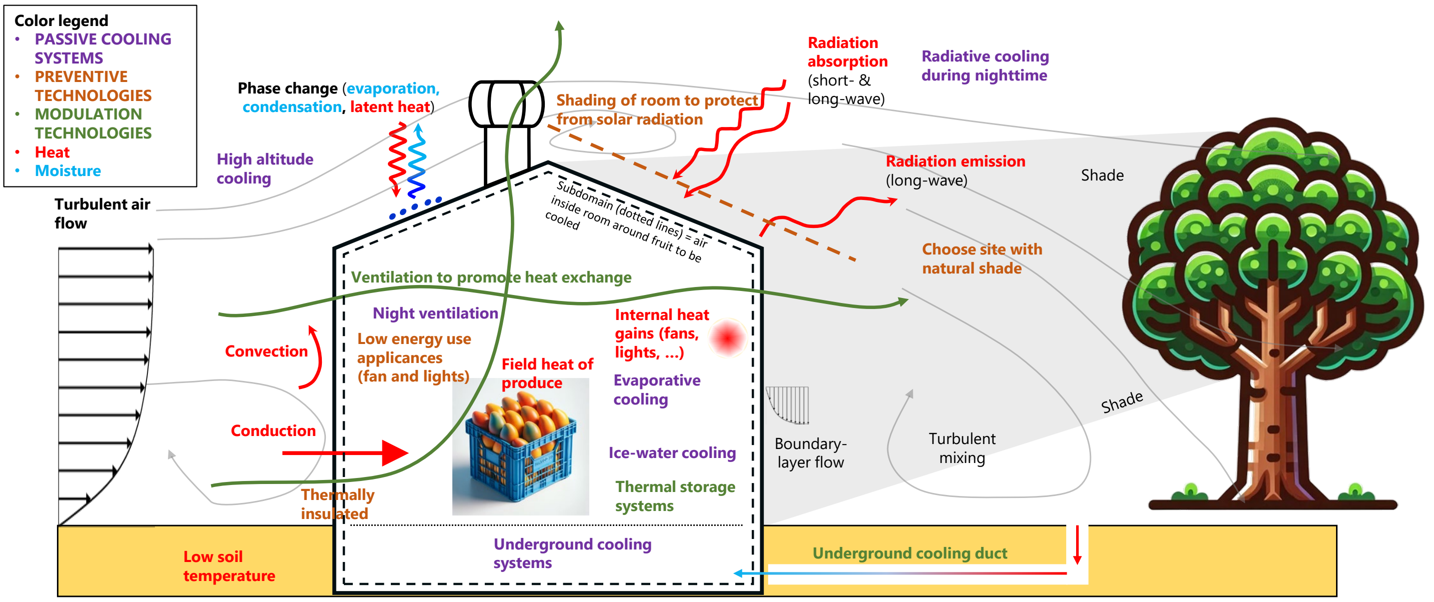

Figure 5. Overview of (1) the physical processes that influence the temperature of the cold storage room; (2) passive cooling technologies in systems for room cooling; and (3) auxiliary technologies for the prevention and modulation of heat transport.

3.2 Active cooling systems

Refrigerated, small-scale cold stores, often known as 'walk-in cold rooms': Commercial systems

Walk-in cold rooms (WICRs) in most LMIC applications are typically locally fabricated, using mostly imported key components of the cooling and power systems (for those designed for stand-alone off-grid applications) combined with locally supplied construction materials for the actual cold room. Some are supplied as prefabricated turn-key 'plug and play' solutions or as partially assembled kits from a growing number of companies. The key elements of a walk-in cold room are the power supply, the cooling generation and channeling system, a means of storing electricity or thermal energy for backup when electricity is not available, the actual cold store itself, and the system control equipment. WICRs can be accessed by customers through various business models implemented by the operators, including rental, pay-as-you-store, aggregator, lease-to-own, upfront payment, and mobile services models (IIFIIR and Efficiency For Access, 2023). The size of a typical WICR for first mile or local market applications in LMIC is usually similar to that of a standard shipping container, for example, 20 feet long by 8 feet wide and 8.5 feet high (Figure 5). WICRs are typically designed to store 2-5 metric tonnes of food and are often solar-powered when deployed in remote or off-grid locations. They include small fans to ensure sufficient airflow of the cooled air from the refrigeration unit, although airspeeds tend to be relatively low. WICRs can be located at various points in the cold chain but typically at the first mile of the farm (production) or the retail market (demand). To ensure consistent cooling in off-grid and unreliable grid areas, energy storage is sometimes provided through thermal storage (using phase change materials), chemical (battery) storage, a backup power generator, or a combination of those. The set temperature of WICRs is typically between 0 and 10 °C. Relative humidity is often monitored but not directly controlled. The installed cost of a 20-foot size, 5-metric-tonne WICR tends to be somewhere between 20,000-50,000 USD, equivalent to 4,000-10,000 USD/tonne.

The advantages of well-designed WICRs are that they provide state-of-the-art cooling to the optimal temperature and the removal of field heat quickly from large amounts of food. The benefit of prefabricated systems, which are also well installed, is that they have been rigorously tested, which avoids the need for the operator to troubleshoot. These cooling units often come with additional software to monitor the cold room, potentially even with additional features such as market price analytics. The disadvantages are that prefabricated WICRs tend to be expensive and often need to be transported and imported into the country of deployment (except for India, where most WICRs are manufactured in-country), which adds to the final cost. Most key components also need to be imported for locally assembled units, and all materials need to be transported to the site. Once installed, WICRs contain expensive equipment that is prone to theft, so protection measures are essential. Some companies deploy the cooling-as-a-service (CaaS) model to make cooling more financially available for farmers or act as an aggregator of produce, typically for export markets.

Further details can be found in the 'Walk-In Cold Rooms, Practitioner's Technical Guide' which provides detailed step-by-step recommendations on how to effectively design, commission, and operate WICRs for fresh produce in off-grid and unreliable grid areas (IIFIIR and Efficiency For Access, 2023).

The following selected companies are mainly active in this field:

- Providers of cooling systems: AfricaGreenTech (Germany), African Mini Grids (USA), Cold Zones (South Africa), Coolcrop (India), Celtic Cooling (The Netherlands), CHDK Technology (India), CT Technologies (Denmark), DGrid Energy (USA), Ecosaras (India), Ecotutu (Nigeria), Ecotech Mali (Mali), Ecozen (India), Eja Ice (Nigeria), Freecold (France), FreshBox (Kenya), Greenpower (Nigeria), Inficold (India), Inspirafarms (UK), Isocool Africa (Zimbabwe), OnlyKem Technology (China), Pluss Advanced Technologies (India), Promethean Power Systems (India), SelfChill (Germany), SolarFreeze (Kenya), Solar Cool (Nigeria), Tan90 Thermal Solutions (India).
- Operators of cold stores: AkoFresh (Ghana), Adili Solar Hubs (Kenya), Baridi (Kenya), Coldhubs (Nigeria), FreezeLink (Ghana), Keep It Cool (Kenya), Koelfresh (India), Munyax.Eco (Rwanda), SokoFresh (Kenya), WeTu (Kenya).

ACTIVE COOLING SYSTEMS

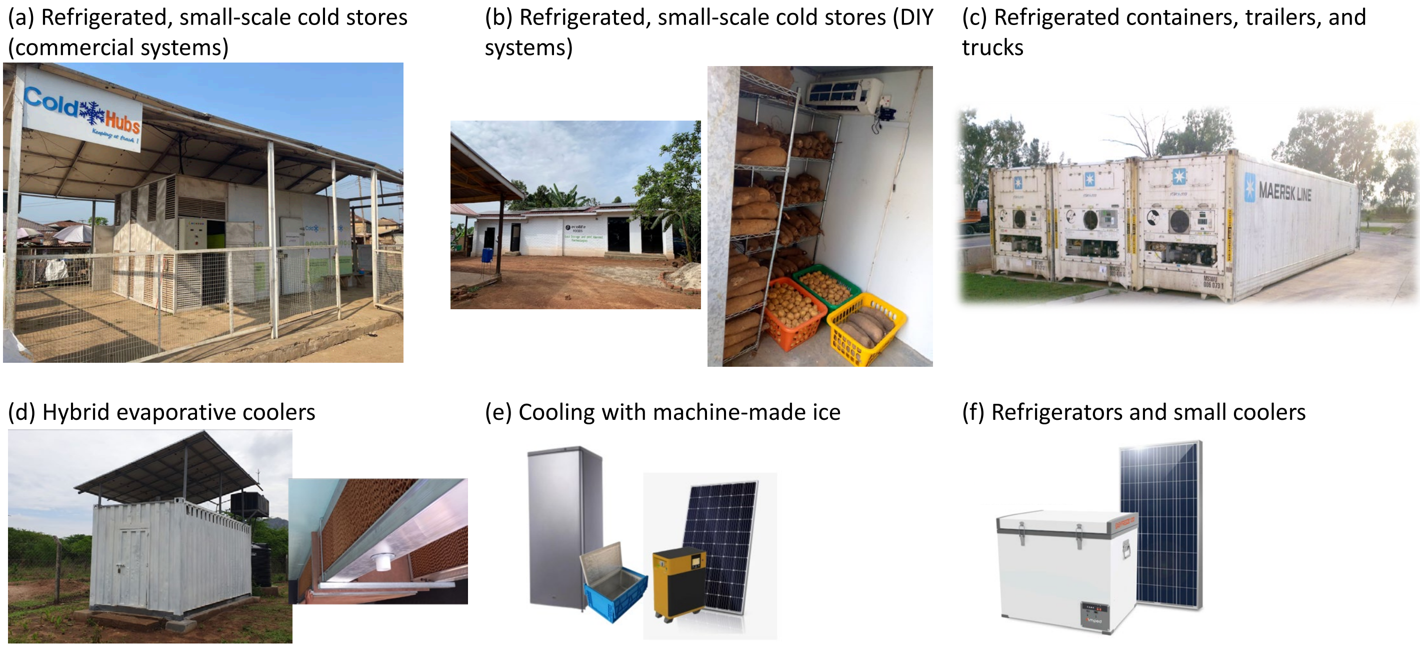

Figure 6. Images and schematics of various active cooling technologies (figures with credits from (a) ColdHubs, (b) Leap Energy and Smart Villages, (c) Thijs Defraeye, (d) Stephen Nyamai (an off-grid forced air evaporative cooling chamber near Kibwezi, Kenya) and Mahavir Acharya (evaporative cooling pads installed in the ceiling of a forced air evaporative cooling chamber near Bhuj, India) from https://www.cooling-chamber.mit.edu/, (e) Village Infrastructure Angels (Efficiency for Access, 2021)***, (f) Amped Innovation 2024 (https://www.ampedinnovation.com/products-solar-freezers)).***

Refrigerated, small-scale cold stores often known as 'walk-in cold rooms': DIY systems

Refrigerated, small-scale cold stores (Do-It-Yourself (DIY) systems) are built by local entrepreneurs, community groups, small companies, or even farmers in HIC and LMIC to preserve produce. Their size is variable but often smaller compared to the commercial systems, and they typically can store a few metric tons of food. The main components are an insulated enclosure or room, a cooling unit, and, if required, additional fans. A popular system used for this is the CoolBot technology (StoreItCold, 2024). This controller can be connected to a normal, commercially available air conditioner unit, which can also be solar-powered. The controller overrides the standard air conditioner's controller, by which the air conditioner keeps running to reach a lower room temperature than envisaged for households or commercial buildings while avoiding freezing. As such, air temperatures of 2 °C can be reached (Karithi Esther, 2016) However, this strongly depends on the room size, insulation level, and number of times the door is opened. Relative humidity monitoring or control is usually not present. The air conditioner's fan generates rather low airflow rates. The cost of a DIY cold room can be around 5,000 USD for a 6 to 8-metric-tonne cold room (Jarman et al., 2023; Kitinoja and Thompson, 2010) or 3,500 USD for a 1-metric-tonne cold room (Karithi Esther, 2016), equivalent to 830-3,500 USD/tonne. When powered by electricity on the grid the main up-front or CAPEX cost comes from the air-conditioning unit and insulating the room, as the controller only costs a few hundred USD. Such CoolBot-equipped cold rooms have already been deployed in several countries, including Nigeria, Bangladesh, Nepal, and Kenya. Although these cold rooms are generally cheaper than walk-in cold stores, the relatively high upfront costs for smallholder farmers make the technology particularly viable for high-value fruits and vegetables.

Key advantages for LMIC are that DIY cold rooms are simple and can be made with locally available or commonly imported components. The main components include materials to insulate a room, an air conditioning unit, and a Coolbot controller. This makes finding spare parts and maintenance service staff relatively straightforward. The Coolbot controller is also brand agnostic, so it can be deployed with all types of air conditioners, even second-hand ones. These systems are also scalable as more air conditioning units can be placed inside the room. Heat removal from the food can also be accelerated by installing additional fans to increase airspeed. The disadvantages are that these systems have a low cooling capacity and low airflow rates, so they cool down the product slowly. In addition, they tend to consume more electricity as they are relatively inefficient due to them being used to reach lower temperatures than the original air conditioning design. Furthermore, these systems involve multiple stakeholders, such as a building contractor for the room, an HVAC (Heating, ventilation, and air conditioning) specialist for the air conditioning unit, the import of the CoolBot controller, and the monitoring system. DIY cold rooms' efficiency, performance, and reliability are significantly more variable than commercial systems.

The following selected companies are active in this field:

- Providers of cooling systems: StoreItCold (USA), global suppliers of conventional air conditioning units
- Operators of cold stores using this technology: Ecolife Foods (Uganda), LeapEnergy (Nigeria)

Refrigerated containers, trailers, and trucks for stationary cooling or cooling during transport

Refrigerated containers, trailers, and trucks can be bought or rented as stationary (but mobile) cooling units or cooling units during transport. They can be described as standardized, insulated enclosures equipped with refrigeration units that can be replaced easily as they only need a power supply or even have their own clip-on generator sets ('gen-sets'). Typically, 20-foot or 40-foot containers are available. Refrigerated trucks and trailers come in different sizes. Produce aggregators frequently use them to serve formal markets like supermarkets or for export. A growing number of local cold room operators supply and operate these, most widely in India, with growth in sub-Saharan African countries such as Kenya and Nigeria. Airflow in refrigerated containers is typically vertical from bottom to top, and in refrigerated trucks, it is from top to bottom. These units are not designed to precool the cargo.

Nevertheless, refrigerated containers could still be used for this purpose if no precooling is available (Defraeye et al., 2016, 2015). The largest 40-foot containers and trailers can hold 20-30 pallets (depending on pallet size) and a maximal loading capacity of about 20 tons. Smaller 20-foot containers could hold 5-10 tonnes. In this case, the containers are assumed to be fully packed, which is typically done for transcontinental transport. If they were used in LMIC, where produce needs to be taken in and out, the total loading capacity would be much less and typically only a few tons as space to walk inside the room needs to be foreseen. Airflow rates are a few 1,000 $m^3 h^{-1}$. The cost for a 20-foot refrigerated container without energy supply systems (e.g., PV panels) is roughly 5,000-7,000 USD. Renting a refrigerated container costs around 1,000 USD per month or less and can be done with suppliers of these containers. An example of where these containers have been used to precool citrus cargo is given in Defraeye et al. (2016). Here, the electricity supply came from the grid.

Key advantages for LMIC are that their design is optimized as millions of these units are operational worldwide, especially across the shipping sector, and they have advanced control software to optimize airflow and cooling, resulting in energy savings. They can also be retrofitted and adjusted to specific needs, for example, by placing racks or additional fans. Containers are also mobile, to some extent, and can be moved elsewhere. The disadvantage is that specialized maintenance staff and parts are typically required. Furthermore, users need to procure and often install their own energy supply if a grid connection is not available, for example, using PV panels.

The following selected companies are active in this field: Daikin, Carrier, Maersk Container Industry, Transicold (USA), and Thermo King.

Refrigerators and small coolers

Refrigerators and small coolers are relatively mature technologies that are readily available off-the-shelf in many, if not most, LMIC, at least in main cities. They also rely on active refrigeration but distinguish themselves by having a much smaller volume than the walk-in units in the previous sections. Some models operate with a variable thermostat, so the user can select between refrigerator or freezer mode or have a separate compartment for each. Due to the size constraints, this product category is limited in its use for horticultural produce applications. It is typically used either at retail for chilling perishables before sale or for chilling and freezing fish within a cold chain. This product category has seen considerable expansion in the number of companies designing units specifically for use in off- and weak-grid applications in LMIC, accompanied by in-built remote monitoring capacity and the ability to sell and use on a pay-as-you-go (PAYG) basis where the operator only pays a down payment accompanied essentially by a rent-to-own model where they pay for the product in small increments between 1 to 3 years. Some companies also pilot the cooling-as-a-service (CaaS) model with their solar-powered refrigerators. The known sales of solar-powered refrigerators from companies self-reporting to the off-grid solar industry association GOGLA have been between five and ten thousand units annually in recent years (GOGLA, 2024).

There are several types available.

- Small cool box (~30-50 L) without active refrigeration, cooling using ice packs.
- Small cool box (~30-50 L) with integrated photovoltaics (PV) and cooling through vapor compression with electrochemical batteries or battery-free via solar direct drive (SDD), or other less common solutions like thermo-electric cooling using a solid-state active heat pump (Peltier device).
- Commercially available refrigerator and/or freezer (~30-600 L) that is powered by the grid, mini-grid, diesel generator, or standalone solar PV panel. Such devices are also used for emergency relief to store food or medical supplies. Users can add thermal storage with ice or water containers.
- Specialist refrigerator and/or freezer (~50- 600 L) that is designed for use in off- and weak-grid circumstances, powered by standalone solar PV panels. The market for productive use in off-grid LMIC is now moving towards the use of thermal 'ice batteries' using phase change materials (PCM). However, the standard lower-cost design relies on using electrochemical batteries for energy storage (conventionally lead acid with component-based systems but with the growing standardization of lithium iron phosphate and LiFePO4 in plug-and-play options). Users can add thermal storage with ice or water containers in all cases.

Key advantages for LMIC are that these are relatively small units that are easy to transport on-site. The disadvantages are their storage capacity is low, and the resulting capital cost per ton of fruit stored is relatively high, particularly for the solar-powered units.

The following selected companies are active in this field, which provide specialist off- or weak-grid refrigerators and/or freezers: Amped Innovation (USA), Devidayal Solar Solutions (India), Ecotutu (Nigeria), EcoZen (India), Eja-Ice (Nigeria), Global Ice Tec (Germany), Koolboks (Nigeria), SelfChill (Germany), Solar Run (China), SunDanzer (USA), SureChill (UK), The Cool Ice Box Company (UK).

Hybrid evaporative coolers

Hybrid evaporative coolers deploy forced airflow to push air through a wetted porous material, such as a wetted pad. The resulting evaporation cools down the air as the latent heat is required for water evaporation. This heat is extracted from the air and the porous material. This technology is a hybrid between passive and active cooling: it uses passive cooling but still requires electricity to power fans to speed up evaporation. However, no active refrigeration is needed. This technology is often used as an alternative for cooling buildings and rooms (Doğramacı and Aydın, 2020; Hindoliya and Mullick, 2006). Active evaporative coolers have recently been applied to refrigerate fruit and vegetables. At the same time, they also humidify the air, which reduces mass loss and maintains several quality aspects of the produce.

The cooling capacity will be limited to the evaporative capacity, which can be calculated according to the air temperature and the relative humidity. Critically, this is not effective in humid climates as the air is already too saturated to create a cooling effect, and it is thus suitable only for dry and hot environments. Evaporative cooling can reduce the ambient temperature up to the wet-bulb temperature. This is the lowest temperature down to which air can be cooled through the evaporation of water in the air at a constant pressure. If the wet bulb temperature is the same as the dry temperature, there is no net evaporation of water in the air, which will prevent any cooling effect. The temperature reduction observed is between 5-15°C below ambient. It is important to consider that the effectivity of any evaporative cooling solution will depend on an overlap of the seasonal weather conditions needed for evaporative cooling and the harvest time of the crops.

An example of a hybrid evaporative cooler would be a refurbished 20-foot shipping container that becomes a forced-airflow evaporative cooling chamber (Verploegen, 2024). Several fans drive air through evaporative cooling pads and can be powered by solar panels, batteries, or the grid. This cool air is channeled vertically through the produce, packed in ventilated packaging. Construction and operation information is open-source (D-LAB, 2024).

Another example is where water is sprayed on fresh produce, and forced ventilation (mechanically driven fans) is used to rapidly evaporate the water convectively. Temperature reductions of roughly 5-15 °C below ambient can typically be reached (Defraeye et al., 2023). The lower limit strongly depends on the wet-bulb temperature, which is the theoretical lower temperature limit. A forced-air evaporative cooling chamber container costs around 8,000-15,000 USD (Adams, 2023), depending on local market conditions and whether it is solar or grid-powered. Note that several off-the-shelf, affordable, small evaporative coolers can be purchased worldwide to provide room cooling. Further research is necessary to determine the applicability of these appliances to provide hybrid cooling solutions.

Key advantages for LMIC are that energy is only needed for the fans and not for active cooling itself, resulting in a considerable reduction in the CAPEX costs. These rooms can be made and maintained much cheaper and simpler in comparison to active cold rooms, although at peak performance, their cooling capability is considerably lower. They also have a dual effect of cooling and humidification. The disadvantage is that the cooling power depends on the outside climate (temperature and humidity), which varies throughout the day and within the seasons. They also require sufficient water to operate, which is not available everywhere or at any time.

The following selected companies are active in this field that provide cooling systems: CoolVeg (USA) and Portacool (USA).

Cooling with machine-made ice

Cooling with machine-made ice to preserve fish is common, but using it for fruit and vegetables is a relatively new concept. When ice is produced by mechanical refrigeration, we consider it part of active cooling technologies since it requires an external energy source. The cold energy is, however, not directly dispersed but in a delayed manner. The produced ice can be used for cooling in the form of ice packs or ice flakes, as an ice bank for room cooling, or to cool water for hydrocooling, for example.

Key advantages are that ice can be produced when energy is available, and ice can be sold for many purposes, such as cooling meat, dairy, fish, medical products, or cold drinks. The key disadvantage is that it is difficult to control the cooling speed temperature. This can cause issues when cooling or chilling sensitive crops or when large amounts of food need to be cooled.

There is a wide range of companies that supply and operate solar-powered ice-making machines. However, the vast majority of them use ice to preserve fish. The use of machine-made ice as a means of thermal storage to cool down fruit and vegetables at above 0°C is further described in the auxiliary systems section 3.4.

3.3 Passive cooling systems

Passive cooling implies that we use low temperatures (i.e., cold energy) to cool down fresh produce by removing or reducing exposure to heat. This can be done in many ways. To identify how we need to ask ourselves where and when we have available air or another fluid or solid at low temperatures so it can then transfer this cold energy to the food (Figure 4):

- using natural or human-made shade to reduce exposure to heat
- when evaporating water
- underground
- in cold air during the night
- in clear skies during the night
- at high altitudes
- when snow/ice or cold water is available

Few of these passive cooling technologies are marketed by companies, and many of them are homemade solutions. An overview of the systems is given in Figure 6.

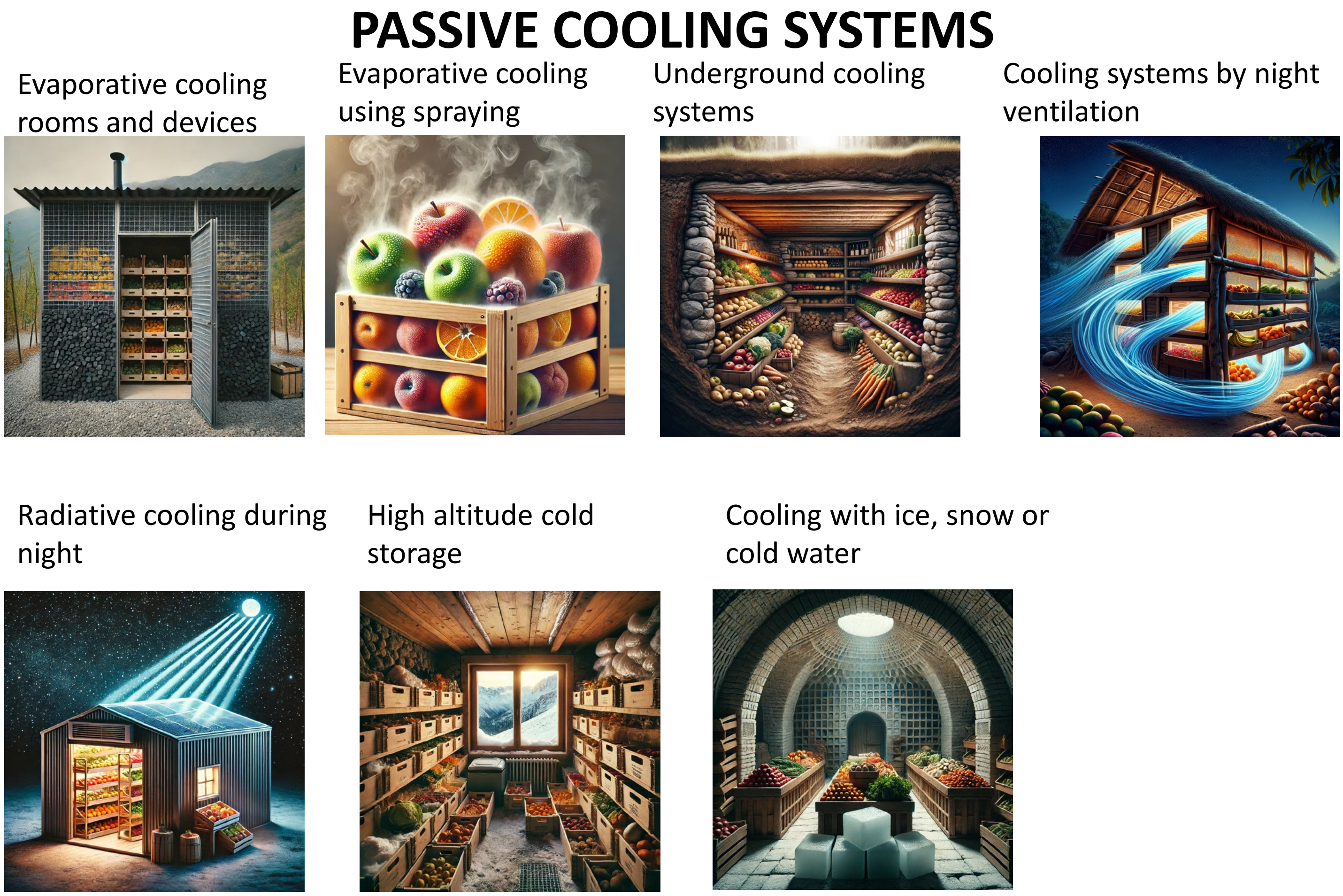

Figure 7. Artistic images of various passive cooling technologies.

Evaporative coolers, cooling rooms, and devices

Passive evaporative cooling rooms and devices work similarly to active evaporative coolers, but they do not have fans enabling airflow. Instead, they rely on wind and natural convection. The walls of these coolers or cooling rooms are built of porous materials that can hold and evaporate water. Typically, charcoal, sand, or sawdust are used as a porous material. Different types and sizes of passive evaporative coolers have been made, ranging from large charcoal rooms or brick coolers ('zero-energy cool chambers – ZECC) down to small charcoal blankets, desert coolers, or clay pot-in-pot coolers (Figure 7). Similar temperature reductions can be reached with active evaporative coolers (5-15 °C, (Defraeye et al., 2023)), depending on the local climate, the porous material, the cooler design, and the wetting frequency of the porous material. The cost of such cold stores is often relatively low as they can be made in-house by the users, but it largely depends on the size of the cooler. ZECC costs range, for example, from 300-600 USD for 100 kg to 4,000 USD for 2 tonnes (Jarman et al., 2023). The costs largely depend on the available materials and size. Note that these evaporative cooling techniques have been used to cool down water (e.g., in clay pots: olla or matka) and buildings. Clay pots are also used to store fruit and vegetables, without cooling, for longer periods of time.

Key advantages are the low cost, the independence of electricity on the grid or solar energy, and the fact that it can serve as a first-mile, small-scale cooling solution at the farm, home, or enterprise. There is also the dual effect of cooling and humidification. The disadvantage is that the cooling power depends on the outside climate (temperature and humidity), which varies throughout the day and within the seasons. They also require sufficient water to operate. The dripping water can also attract wildlife. The use of charcoal might be perceived as negative by stakeholders as it induces deforestation and habitat destruction. This is true for charcoal used for cooking, but charcoal for cooling rooms can be used for many years and later to help fertilize the land. Finally, the training to build and operate these rooms and devices is essential for their success and typically requires hands-on training and funds to pay for and organize its deployment. The required training programs and materials are still rather scarce, although online channels are increasingly used to disseminate technologies among smallholder farmers (AccessAgriculture, 2024; EcoAgTube, 2024; PostharvestOrg, 2024). There are several videos dedicated to evaporative cooling. One company that stimulates the use of clay pot-in-pot and pot-in-dish coolers and has detailed guidelines is the CoolVeg Foundation.

Figure 8. Different types of passive evaporative cooling devices. (credits: (a) Theresa Wittkamp in Kenya, (b) Eric Verploegen (amaranth after 1 day stored in a clay pot cooler (left) and in a plastic basket (right) in Niamey, Nigeria, by CoolVeg (https://www.coolveg.org/clay-pot-coolers)), (c) Charcoal cooler to store fruit and vegetables at a smallholder farm in rural Uganda (photo credit: Jakub Vrba).

Evaporative cooling using spraying and misting

Passive evaporative cooling can also be achieved through sprinkling or misting (clean) water on or over fruit and vegetables and relying on natural convection or wind to evaporate the water. Such spraying can be done manually at certain times with a small bottle and spray nozzle or a garden hose with spray nozzle. Continuous sprinkling can be done using a (homemade) soaker hose. However, as water comes into direct contact with the fruit or vegetables, there is an increased risk of contamination or growth of microorganisms. Care should be taken to ensure the water is clean and the food does not remain wet for too long. The cost to implement these systems is very low. Airflow is essential to accelerate evaporative cooling, so these systems should be applied outdoors in windy conditions or indoors in well-ventilated areas. Advanced misting systems have been implemented at retailers in high-income countries (Contronics, n.d.).

The advantage is that this system can be deployed almost anywhere, by anyone, and on multiple scales (at home, on-farm, or retail). A disadvantage is that clean water is required, while wetting the product may trigger mold infections, and it is difficult to control the cooling process, speed, and uniformity.

Underground cooling systems

Underground cooling systems rely on the temperature underground being often lower than the ambient temperature during summer, and this also fluctuates less throughout the year. If an underground structure, such as a cellar or cave, is used, food can be preserved under more constant temperature conditions. The soil or rock provides insulation. Their size can vary widely. Small root cellars have been constructed, and even single bins or boxes have been placed underground. No equipment is required to cool this way, so it is a passive solution. However, excavation and construction of a safe chamber are required, and proper ventilation is essential to avoid mold growth or ethylene buildup for some crops, which can be done actively or passively. Also, drainage of condensation water is essential. In high-income countries, very large commercial systems in caves exist, storing 1,000 tons of fruit (Melinda, 2024). Also, prefabricated systems are available that just need to be dug in (Groundfridge, 2024).

The temperature reduction that can be achieved is strongly dependent on the location. Soil temperatures are determined by the air temperature and are subject to seasonal and daily variations. These variations reduce with depth, where at 10-15 m, the soil temperature equals the annual mean air temperature. The mean annual air temperature in Europe is around 5-15 °C, depending on the location (Mourshed, 2016). In tropical regions, it is much higher, for example, around 25 °C around the equator. Even when the temperatures are too high to store fresh produce, one should note that the temperature outside is likely to be higher in summer so that underground storage can remove exposure to peak temperatures. The cost of such underground storage facilities is highly dependent on the size and the choice of materials and is similar to building a house or shed of the same size, which can be substantial for some farmers. They can often be homemade using bricks or even bags of sand as walls, but they can also be natural structures like caves. Underground systems are readily applied worldwide. Although they have a high potential, these systems have rarely been applied in LMIC (Kanali et al., 2017). Reasons are not always clear, but they could be the construction cost, cultural attitudes, the risk of flooding in some areas, and the fact that in several LMIC, the soil temperature will still be too high to store fresh produce.

Key advantages for LMIC are that underground storage systems are very straightforward to operate and that temperatures are rather constant compared to passive evaporative coolers. The disadvantage is that these systems can only cool down to a certain temperature. The ground temperature in LMIC is often relatively high for fruit and vegetables, although it is still lower than the outside temperature. As a result, this can make foods decay faster than, for example, in evaporative coolers.

Note that farmers also apply direct underground storage where the food is directly put into the ground, for example, for potatoes or cassava. A pit or trench is dug, after which the potatoes are placed in the pit, often on straw, and then the pit is closed. A similar, but aboveground, system is a field clamp. Here, a pile of potatoes is covered with straw and soil to keep them cool. A proper design and size of the pit or clamps are essential to guarantee good quality, where sufficient ventilation is key to managing heat production by the products.

Cooling by night ventilation

Cooling by night ventilation of the storage room uses colder night temperatures to cool down fruit and vegetables. Such ventilation systems are one of the most important passive cooling strategies for buildings to save energy, including in retail stores (Mylona et al., 2018). The cold air can be used to cool down the food directly. It is essential, of course, that the nighttime air temperatures are lower than the room temperature during a substantial part of the night. Airflow through the (colder) storage room is promoted at night and inhibited during the day by opening and closing vents.

Ventilation can be driven by natural convection using (1) cross ventilation that uses openings on opposite sides of the cold store to allow airflow, which can be enhanced by using wind catchers; (2) stack ventilation that relies on the buoyancy effect, so the rise of warmer air that exists through openings on the top of the cold store and pulls cold outside air through openings at the bottom, which a chimney can promote. Airflow can also be forced by fans that extract the air from the cold store and suck outside air in, or vice versa, that supply cold air inside. Combined mechanical and natural ventilation can also be used. Having the food stored in an insulated enclosure is essential to benefit from night ventilation to avoid excessive heating up during the day. Night ventilation can also be used in combination with thermal storage, where the air cools down material or the cold store's walls so they can store this cold energy (see section 3.4).

The temperature reduction strongly depends on the outside temperatures and the ventilation airflow rate. The outside air temperature should be several degrees Celsius below the product temperature for several hours at night to have a meaningful cooling effect. Air has a very low heat capacity (1,006 J kg^{-1} K^{-1}) and density (1.2 kg m^{-3}), compared to fruit (3,700 J kg^{-1} K^{-1} and 900 kg m^{-3} for apple fruit (Defraeye et al., 2017)). Hence, limited cold energy (measured in Joules) is stored in a cubic meter of air, which means that large airflow exchanges are required to cool down a certain volume of fruit. Additionally, one cannot fully cool down all products due to the thermal inertia of the food.

Given that the storage room is already available, the simplest night cooling systems cost nearly nothing, as manual opening of the ventilation holes can be done in the morning and evening. Key advantages for LMIC are that this is readily implementable in existing storage systems at low cost. The disadvantage is that these systems do not work in certain climates with night temperatures that are higher than envisaged inside the cold store. Furthermore, proper control is essential to start and stop ventilation at the right time.

Radiative cooling during the night

Radiative cooling implies that heat is removed from a structure (storage room) or even the product directly through long-wave (infrared) radiation, driven by the lower temperature of the sky. This cooling effect is typically largest during the night when skies are clear, for dry climates, and when the surface of the roof of the room has a strong thermal (long-wave) emissivity.

Cooling a room

A radiative cooling system for a cold storage room typically includes a roof painted or coated with a high-emissivity material. The heat removed is proportional to the surface area of the emitting surface, so large surfaces are beneficial. Dome-shaped surfaces are also used instead of flat roof surfaces since the surface radiating to the sky is double, for example, with ice houses. Such ice houses are also called yakhchals in the Middle East. Note that if the roof is well insulated, the penetration of the cold energy inside the cold store will be restricted compared to uninsulated storage sheds. If a roof with a heavy structure on the outside of the insulation is placed, however, this material could buffer the heat load from the outside by storing it during the daytime and then cooling it away at night through radiative cooling. This is less practical in several rural settings as heavy roofs (e.g., concrete) also require a heavy support structure. Active radiative cooling systems also exist, typically for buildings, where pumps and heat exchangers are used to cool water in 'radiator' panels, which can subsequently be used for room cooling. The advantages are that such (passive) systems are easy to deploy and mainly involve painting the surface of the roof. The disadvantage is that a large surface exposed to the environment should be available for radiative cooling to work, but this surface will also be heated up during the day by the sun. Passive systems also have the largest impact on uninsulated storage sheds, whereas preferably, one would insulate a storage room to keep the cold inside.

Cooling the fruit

Radiative cooling can also be used to cool the fruit directly. Fruit radiates heat to the sky during the night and is also cooled by the cold air temperatures. Hence, harvesting the fruit at night or in the early morning makes use of the radiative and night ventilation cooling effect to remove heat from the fruit, which then does not need to be removed any more by other cooling means. However, the produce needs to be open to the air and is thus vulnerable to pests, wildlife, or theft, which can be seen as a deterrent to adoption unless the area is secure.

Cooling to produce ice

In some desert climates, including at high altitudes, the temperatures at night drop below the freezing point, amongst others, due to radiative cooling towards the sky. Hence, ice can be created in shallow water pools. Thin layers of ice are formed quickly and can be harvested and stored, for example, in ice houses. These pools are typically protected from the sunlight using a shade wall, providing additional time for harvesting ice during the morning. Such ice production only works in selected areas of the world due to the specific conditions required.

High-altitude cold storage

High-altitude cold storage can be used for cooling as the air temperature decreases linearly at about 6.5 °C with a 1,000 m increase in altitude, and such temperatures are lower throughout the year. As such, storage at a high altitude can be an attractive alternative. Nevertheless, transport to and from the high-altitude storage becomes essential here, where the road and transport infrastructure is often suboptimal in LMIC and labor-intensive. An evaluation needs to be made to determine that the food losses due to transport, such as mechanical damage on roads with potholes, are lower than those when storing food on-site. This storage method also makes sense for longer-term storage, such as potatoes or apple fruit. The cost for this solution is mainly the transport cost and costs for additional hardware to ensure transport without excessive food losses, given that a high-altitude storage solution is available.

The advantages are that it is simple to deploy and provides a rather constant temperature reduction compared to ambient temperature throughout the year. The disadvantage is that it is only viable for long-term storage and that additional transport and handling losses must be accounted for. Temperature control is difficult, and care should be taken so that fruit and vegetables are not damaged by temperatures too cold to induce chilling or freezing injury. A storage shed or other structure is still needed to store the food.

Cooling with ice, snow, or cold water

When water is available in the solid or liquid phase at a lower temperature than the air, it can be used for cooling. Examples are well water or water of rivers. Water from a deep well is roughly equal to the average annual air temperature and similar to the soil temperature. Also, nature-made ice or snow can be used, which does not require active refrigeration to be produced. Although available during winter and at higher altitudes, it must often be stored for a long time to benefit during warmer periods. This can be done, for example, by ice houses or ice pits, such as yakchals. Ice can also be made at night and harvested to be placed in an ice house (see section on radiative cooling). Food can also be stored in pits dug in the snow or the ground, by which it is stored frozen or at near-zero temperatures.

In these cases, water is used to cool via freezing into cold packs for contact cooling, ice banks for air-cooling, or liquid water for hydro cooling. Another application is to store materials with high thermal capacity outside overnight, such as stone, sandbags, or water containers, and use them as cooling elements in an insulated cold room during the day.

A key advantage is that cold water or ice has a large specific heat capacity and density, containing a lot of cold energy. Low temperatures can also be reached. The disadvantage is that cold water, ice, and snow are often not found near areas in LMIC that have excessive food losses due to elevated temperatures. Care should also be taken so that fruit and vegetables are not damaged by temperatures too cold to induce chilling or freezing injury.

3.4 Auxiliary systems that support active and passive cooling

Several auxiliary systems and technologies can support the previously mentioned cooling solutions. These influence several heat transport and exchange processes from/to and within the storage room, such as conduction, convection, radiation, heat storage, and heat production/removal (Figure 4). We discuss mainly those technologies related to cooling but note that other processes also affect the quality of fruit and vegetables, such as transpiration leading to mass loss, ethylene production and sensitivity leading to ripening of the fruit or adjacent fruits, microbiological growth of organisms leading to spoilage, or respiration leading to heat and CO_2 production and mass loss. We split these techniques into preventive and modulation.

Preventive techniques assisting in cooling

Thermal insulation of the enclosure (storage room, cold store, refrigerator, etc.), which is where the fruit and vegetable foods are kept stored, helps keep the cold energy inside and prevents heat from entering the enclosure; for example, the daytime heat gains particularly during the day when ambient temperatures are usually high.

Reduction of equipment-related heat gains inside the room prevents this heat from needing to be removed again. Examples are minimizing fan operation and using more energy-efficient lighting and electronic equipment. Fans, for example, promote air circulation in the room and airflow through the refrigeration unit, but they also produce heat. The less efficient a system is, the more heat it produces.

Solar heat protection systems help to reduce the solar radiation heat gains to the fruit inside the room. The simplest way of doing so is to provide shade. This can also be done by using materials for the room that maximize solar reflectance, such as materials with a high albedo value. An additional shading structure around the room can also help to avoid solar heat gain. The photovoltaic panels in a solar-powered cold storage room already provide additional shading of the room and other shading measures can be implemented to prevent direct solar radiation from heating up the outer walls of the room (IIFIIR and Efficiency for Access, 2023). Apart from protecting the room from solar heat gains, one should also protect the fruit from solar heat gains after harvest, prior to it entering the room. Produce should always be placed in the shade to remove field heat and avoid gaining additional heat that needs to be removed afterward.

The choice of site location can help prevent solar radiative and convective heat loads throughout the storage room. Placing a room where it is sheltered from solar radiation (e.g., by trees), where temperatures are lower (near a forest, water pond, or at higher altitude), or where wind speeds are higher can help keep the structure cooler. The local microclimate needs to be assessed here, including solar radiation, air temperature, humidity, wind speed, and direction.

Modulation techniques assisting in cooling

Thermal storage systems can capture and store cold energy within the room whenever excess from active or passive cooling sources is available and release it later when necessary. There are two ways of doing this: (1) by storing cold energy in materials with a large specific heat capacity and density, such as water, stone, or sand, and (2) by storing cold energy by invoking a phase change, for example by freezing water from liquid to ice or using a phase-change material, after which this energy can be released again. Such materials can also be integrated into solar-powered cold stores to enable cooling during the night. Thermal storage has also been integrated into solar food dryers to ensure higher temperatures for drying overnight. These systems often need to be coupled with ventilation to promote heat dissipation.

Ventilation is not a cooling technique but plays a key role in transferring heat from the product to the environment. Ventilation from within the cold store can be done, typically achieved using fans or natural convection due to air density differences. Next to active airflow generation inside the room, passive airflow with outside air by wind or natural convection can be used. Wind catchers or roof ventilators can amplify the effect of wind (Liu et al., 2024). When done with cold outside air at night, such ventilation can also provide cooling.

Underground cooling ducts can be used to precool the ventilation air entering a room by acting as an earth-to-air heat exchanger since the ground is typically cooler than the outside environment during summer (Figure 4). If this air is also directed above a waterbed, then the air is cooled additionally through evaporation. Such systems are sometimes used for building cooling.

4 Multifactorial selection matrix of the cooling technologies

We have composed a cooling technology selection matrix where different cooling technologies are mapped and can be scored according to multiple criteria (Figure 8). The aim of this 'CoolSel' matrix is to easily compare different cooling technologies for a specific use case and identify the most promising solutions taking into account several criteria simultaneously.

The scoring will differ for each case as some categories of this multifactorial matrix depend on the specific country and supply chain. Figure 8 depicts the matrix template that can be completed for the case being analyzed (therefore, no scoring has been included in the template). This matrix provides a visual evaluation overview of cooling technologies versus these criteria unique to a certain supply chain.

Such an assessment for a specific use case and country can support stakeholders in better choosing the most appropriate cooling technology/ies. However, cooling is often just a part of a combined set of postharvest solutions. In some cases, cooling produce is not even the optimal route to take. Therefore, the recommended first step is always to assess the need for cooling based on a holistic assessment, for example, by applying the postharvest assessment method developed by Wageningen University and Research (Oostewechel et al., 2022). If the use of cooling is indeed needed or provides sufficient added value, then the CoolSel matrix can be deployed to support the selection of the most suitable cooling technology for the specific case.

Technology	Name	Actively-refrigerated, small-scale cold stores (commercial systems)	Actively-refrigerated, small-scale cold stores (DIY systems)	Refrigerated containers and trailers	Actively evaporative coolers	Cooling with machine-made ice	Vacuum evaporation?	Passive evaporative cooling rooms	Passive underground cooling systems	Passive cooling systems by night ventilation	Radiative cooling during night	High altitude cold storage	Cooling with ice, snow or cold water
	Cooling type	Active	Active	Active	Active	Active	Active	Passive	Passive	Passive	Passive	Passive	Passive
1 = positive/low 5 = negative/high													
Goal	Cooling criterion												
	Short term storage												
	Long term storage												
Installation	Capital cost (CAPEX)												
	Local manufacturing or assembly possible												
	Import dependency materials and parts												
	Location: Local												
	Location: Urban												
Scalability & Adoptability	Scalability to different sites												
	Scalability to farm size												
	Adoptable to different use												
Operation & Maintenance	Expertise required to												
	Maintenance frequency												
	Availability and proximity of maintenance staff												
	Spare parts available												
Energy supply	Energy availability												
	Energy stability throughout the day												
Energy use and storage	Primary power source												
	Backup power source												
	Energy storage (battery, thermal)												
	Energy efficiency												
	Grid dependency												
Cooling process	Refrigeration technology												
	Cooling time												
	Transmission of heat from product												
Performance	Temperature reduction												
	Temperature stability												
	Humidity control												
Product	Climacteric - tropical												
	Climacteric - Non tropical												
Market	home consumption												
	local												
	regional												
	organized retail												
	export												
Producer	subsistence												
	smallholder												
	emerging/intermediate												
	commercial												

Figure 9. Cooling technology selection matrix (CoolSel) with scoring for each technology.

5 Conclusions

We mapped a wide range of cooling solutions for preserving fruit and vegetables in low- and middle-income countries. These include active cooling, passive cooling, and auxiliary technologies that provide a preventive or modulation effect. We identified their pros and cons and described the underlying physical processes according to which they work. This Cooling Atlas can help farmers and farming cooperatives, vendors, retailers, aggregators, program implementors, cold chain operators, and policymakers choose the right cooling technology for their specific country and use case, which is part of the value chain they are active in.

We also developed a selection matrix for the different technologies according to 30+ criteria to enable a quantitative comparison. Key factors here are cost, installation, scalability and adoptability, operation and maintenance, energy supply, energy use and storage, cooling process, cooling performance, food product, and the market and producers. The result enables a multifactorial evaluation for each technology tailored to a specific use case. We stress that cooling solutions should be embedded in a more holistic postharvest solution to improve food quality preservation in the value chain. A combination with other solutions along the value chain is essential.

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AUTHOR CONTRIBUTIONS

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly (full paper) to improve the spelling, grammar, and style of the text. No additional original content was generated using these AI-assisted technologies. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication. DALL-E (OpenAI) was used to generate selected images.

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