Jordan HortiFuture - Exploring opportunities for postharvest cooling technologies at farm level

A review of low-cost cooling technologies appropriate to farm-level application in Jordan

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Contents

Abbreviation

AC	Advance Consulting
AC	Air conditioner
ECC	Evaporative Cooling Chamber
FLW	Food Loss and Waste
JHF	Jordan HortiFuture
MIT	Massachusetts Institute of Technology
N	Newton, absolute unit of force in the International System of Units
RH	Relative humidity
USD	Dollar USA
WCDI	Wageningen Centre for Development and Innovation
WFBR	Wageningen Food and Biobased Research

1 Introduction

Background
JordanHortiFuture (JHF) is a three-year horticulture sector development programme (September 2021 - December 2024) in Jordan, supported by the Netherlands Ministry of Foreign Affairs (MoFA) through the Embassy of the Kingdom of the Netherlands (EKN) in Amman, Jordan. The programme is conducted by a consortium consisting of Mercy Corps (lead), Wageningen University & Research, and Advance Consulting.

JHF aims to improve the income opportunities and longer-term resilience of smallholder farmers in Balqa, Irbid, and Ajloun governorates with a series of intervention and activities to strengthen the horticulture sector. To achieve this, the potential and feasibility of proven and promising evaporative cooling technologies currently being tested and implemented in other countries (i.e., Kenya) were explored, to contribute to the reduction of post-harvest losses in the fresh fruit & vegetable value chain in Jordan. The programme will contextualize the lessons, findings and technologies to the situation in Jordan.

The literature review was conducted within the context of the JordanHortiFuture (JHF) programme. The objective was to gather information from the literature to lead up to and prepare for the design of a pilot to test and validate the potential for farm-level cooling technologies in Jordan. These technologies should contribute to reducing post-harvest losses, maintaining the quality of fresh horticultural produce, and improving farmers' competitive market positions.

Wageningen Food and Biobased Research (WFBR) was commissioned to lead and conduct both the literature review and pilot testing of potential cooling technologies, in collaboration with and support from University of Nairobi (Faculty of Agriculture, Department of Plant Science and Crop Protection), in particular in the person of Dr. Jane Ambuko, selected for her extensive research experience gained into low-cost cooling technologies for farmers in Kenya. Other JHF implementing partners are Wageningen Centre for Development Innovation and Advance Consulting.

Food loss and waste in Jordan
In recent years, Jordan's national food-security strategy has reported significant increases in food loss and waste (FLW) during the import, production, export and consumption of perishable and nutrient-dense food products (Al-Hunaifat, 2021). Although little data are available on food losses for different value chains and produce groups, it has been estimated that 22% of all locally produced fruits and vegetables are lost along the various value chain nodes. Specific data on the loss percentages occurring at specific points within the value chain are unavailable.

FLW not only constitute a loss of profit for farmers and others in the value chain, higher food prices, and a loss of valuable food resources for human consumption, but also have significant side effects on the food system, especially with regard to valuable resources going to waste. In Jordan, where water is scarce, FLW has a multiplied effect of inefficient use of land, water and energy resources[1], higher opportunity costs, and increased greenhouse gas emissions, in addition to unnecessary financial costs for producers, traders, retailers and consumers.

The issue of food waste at the consumer level has been taken-up in national policy debates, resulting in a national flagship project supported by the Ministry of Agriculture: "The No Food Waste Initiative"[2]. Nevertheless, the contentious issue of food loss (loss of agricultural produce generated during production, storage, transportation, and sale) has not received the same attention. This direct loss of food for human consumption and related loss in economic profits can be accredited to a variety of issues including: the lack of necessary infrastructure, technologies, and protocols to handle, store and transport perishable food

[1] Energy costs make up 15% to 22% of total production costs in Jordan (Khader et al., 2019)
[2] https://jordan.un.org/en/238977-ministry-agriculture-wfp-and-fao-launch-food-waste-management-enabler-initiative

products between farms and central markets. For perishable produce such as fruit and vegetables, poor harvest, handling and storage practices can lead to significant quantitative and qualitative losses.

Cold chain management entails the application of a combination of postharvest best practices and applicable technologies to maintain optimal temperatures during storage and transport. Proper cold chain management entails handling produce at optimal low temperatures from harvest to end-user availability. This is critical for quality preservation and reduction of FLW in fruits and vegetables Therefore, cold chain development has the potential to play an essential part in Jordan's food security, food safety, and agricultural development strategy by mitigating and reducing food losses while safeguarding food quality and safety. To effectively address this complex food system challenge, structural investments are needed to increase awareness regarding the potential of cold chain technologies to implement good agricultural practices and mitigate and reduce food loss.

The purpose of this technology review study is summarize information about low-cost cooling technologies that significantly impact quality preservation, providing insights for future pilot tests. This to ensure that farmers can achieve benefits even with a limited investment. Effective investments should warrant the establishment of "End-to-End" cold chains from farm-level through to central market and distribution points. To ensure an effective cold chain, it is essential to avoid cold intermittency at any point. Therefore, partial investments in cold chain development which only affect one segment of the chain will only partly result in FLW reduction outcomes. Cooling down the produce at the farm is a significant starting point when developing a new cold chain as the first miles after harvest are often the most critical. Effective food loss-reducing strategies must include investments in cooling technologies and practices suitable for farm-level precooling, handling, and storage, as well as investments in cooling technologies for transit facilities such as transportation trucks, aggregation points and large-scale storage houses.

To advance cold chain research and innovation in Jordan's horticultural sector, the JHF programme will conduct several pilot activities to test and validate cooling technologies suitable for precooling and small-scale aggregation. These technologies will be piloted in three selected supply chains, across distinct locations with varying agro-climatic conditions. First-mile cooling technologies which form the focus of these pilots are viewed as a critical component of an integrated cold chain strategy, designed to connect seamlessly with larger-scale cooling facilities at centralized storage hubs.

In this literature review, we examine cooling technologies with potential applications for smallholder horticulture, focusing on those that can contribute to reduce FLW at the farm level first mile of the cold chain. Cold storage technologies in horticultural value chains can be categorized into zero-energy options which do not make use of energy- usually electricity-, and into options using energy. The latter can be either on-grid, using electricity from the available grid, or off-grid where energy is locally generated and used not making use of the grid. All categories are relevant to smallholder horticulture and have to be carefully assessed to ensure their suitability and appropriateness within the specific contextual factors.

Guiding questions for cooling method selection

To identify the most suitable and appropriate technology for piloting in Jordan, the following questions will guide this technology review:

- How long will the produce be stored and how much volume of produce will be stored?
  - The cooling facility design will be influenced by the volume of crops that need to be stored, and the time that they need to be stored.
- What is the main purpose of cooling?
  - The need for cooling will be different if it is to cool down the core temperature of the freshly harvested produce at the farm while waiting for transport, keep unsold produce overnight or for a few weeks, or a wait for better prices.
- Does the structure of the cooling facility offer a protection against pest and animals?
  - Pest entrance in the facility could lead to fruit damage.
- Is the produce that is stored sensitive to ethylene?
  - An accumulation of ethylene could affect the ripeness of the produce.
- In the case of evaporative cooling, what is the local water availability and water cost?

- A low water availability or high costs could render specific cooling technologies inefficient and not cost effective.

- In the case of evaporative cooling, is the technology suitable for the prevailing climatic conditions?
  - For the evaporative cooler to be effective, certain climatic conditions have to be met. .
  - A dry environment, with a low relative humidity, is preferable for the water to evaporate and by the same fact, lower the air temperature in the evaporative cooler.
- In the case of evaporative cooling, is the harvesting season corresponding to the appropriate climatic conditions?
  - An overlap, timewise, is needed to be able to use the evaporative cooler.
- In the case of on-grid cooling solutions, what is the electricity cost?
  - The lower the energy cost, to more cost-effective is the cooling.

Review organisation

Chapter 2 starts with an explanation of the basic principles of evaporative cooling, followed by potentially suitable crops for this technology, the environmental conditions required for it to be effective, and its underlying construction principles. Chapter 3 provides an overview of the different types of direct evaporative coolers available, categorised into passive and active systems. Chapter 4 presents a low-cost non-evaporative on-grid cooling technology, consisting of a cold room refrigerated by an air-conditioner and controlled by the Coolbot™ technology. In addition to technical aspects and feasibility, socio-economic conditions for potential users of a new technology are also critical to consider. While an in-depth exploration of these aspects is beyond the scope of this initial literature review, these are important considerations for the pilot phase. Therefore, Chapter 5 presents several key socio-economic questions that should be addressed during the pilot implementation. Finally Chapter 6 discusses the selection of the most appropriate technology for the Jordanian context, based on insights from this literature review and other experiences. These will then be piloted at farm level in Jordan as part of the JHF programme. For the pilot results, consult Cloutier *et al*, 2025..

2 Evaporative cooling

2.1 Principles of evaporative cooling

Evaporative cooling is based on the principle of heat transfer where heat in the surrounding air is absorbed by water held in a medium and then evaporated, resulting in a cooling effect. Evaporative cooling systems can be direct, indirect or hybrid. In direct systems, hot air is in direct contact with water. In indirect systems, water and air are separated by a surface (Omer et. al. 2015). Direct evaporative cooling systems are the simplest and have been in use for centuries; cooling is achieved by converting sensible heat to latent heat of vaporization. In direct systems, cooling is achieved when warm air is either naturally moving or forced over a medium holding water (Figure 1). Examples of these media include charcoal, sand, hessian (a think and rough fabric used for making sacks,) and other inert materials that can retain water. Natural air movement is known as passive evaporative cooling, in contrast to active systems where external force is used to accelerate the air movement, such as a fan.

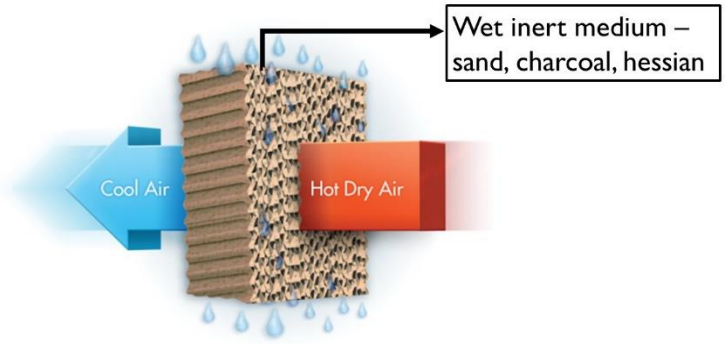

Figure 1. Illustration of the principle of evaporative cooling.

(Source: https://portacool.com/how-does-evaporative-cooling-work/)

Water evaporating from these media "consumes" heat energy from the surrounding environment thereby causing a cooling effect. In addition, as the hot and dry air blows over the wet media, it carries humid air into the chamber. The effectiveness of an evaporative cooling chamber depends on daily and seasonal variation in ambient temperature and humidity which can vary significantly across geographical locations, seasons, and time of day.

A temperature reduction of about 5 - 10 °C compared to the ambient temperature with a high relative humidity (> 80%) can be achieved under the proper climatic conditions; in certain situations, a reduction of 15 °C can be achieved. The relative humidity (RH) inside the evaporative cooling chambers is equally passive and dependent on the time of day and surrounding conditions. Evaporation is reduced during cooler times of the day and cooler seasons, and therefore the difference in RH inside the coolers and ambient conditions is minimal.

The range of temperature reduction is related to the difference between the ambient temperature (dry bulb) and the wet bulb temperature. The wet bulb temperature is measured with a wet cloth on the thermometer at ambient temperature. When RH is 100%, the dry and wet bulb temperatures are the same. The larger the difference between the two, the lower the RH. As the water capacity to evaporate is dependent on the RH, the lower the RH, the higher the evaporative potential is, and thus, the larger temperature depression (temperature reduction of the air) can be achieved. To calculate the cooling efficiency the temperature depression in the facility is divided by the difference between the dry and wet bulb temperature. The higher the result, the more efficient the cooling method:

Cooling efficiency coefficient = (Ambient T°C – Interior T°C)/(dry bulb T °C- wet bulb T°C)

For example, if the dry bulb temperature (ambient temperature) is 32.2 °C and the wet bulb temperature is 21.1 °C and the dry bulb temperature in the cooling facility (interior temperature) is 22.4 °C, then the cooling efficiency coefficient is 0.88 (or 88%), or:

0.88 = (32.2-22.4)/(32.2-21.1)

The modified conditions inside the evaporative cooling chambers are especially beneficial for those crop commodities prone to water loss, a key factor contributing to postharvest losses. In most fruits and vegetables, a water loss of 5% - 10% of their initial weight renders them unmarketable due to wilting and shrivelling. Additionally, excessive water loss is associated with loss of water-soluble vitamins such as vitamin C (Ambuko *et al* 2017). Therefore, reducing water loss prevents both loss of saleable weight and qualitative losses in fruits and vegetables.

2.2 Application of evaporative cooling: suitable crops

Examples of vegetables and fruits that benefit from evaporative cooling include tomato, eggplant, leafy greens, pepper, and okra (Verploegen *et al*., 2018), cucumber, chilli, bean, peas, carrots, cabbage, beetroot, avocado (Verploegen *et al*., 2019), mango, banana (Defraeye, 2023), and leafy greens (Ambuko *et al*. 2018 and Verploegen *et al*., 2019). Evaporative cooling is inappropriate for commodities such as onion, coffee, millet, garlic, maize, meat, dairy products, grains, and dried products because of their sensitivity to high humidity/moisture. They absorb the excess humidity in the evaporative cooling chambers, which can lead to rotting or moulding.

Table 1. Short list of produce suited and not suited for postharvest evaporative cooling storage.

Produce suitable for postharvest evaporative cooling storage		**Products not suitable for postharvest evaporative cooling storage**
Avocado	Leafy greens	Coffee
Green banana	Okra	Garlic
Beans	Mango	Maize
Beetroot	Peas	Meat
Cabbage	Pepper	Millet
Carrots	Tomato	Dairy
Chili		Dry onions
Cucumber		Potatoes (need to be cured first)*
Eggplant		Other dry produces

Source: Author's elaboration

*Potato could be stored in an evaporative cooler specially made for it after being cured. The effect on the quality is only visible after 6 months of storage compared to the traditional farmer's practices (Gulandaz, 2017), which is too long for the purpose of this project.

There is evidence of evaporative cooling application to reduce water/weight loss, preserve quality, and extend the shelf life of perishable fruits and vegetables. After three days of storage a 10% weight loss was observed for carrots and cabbage, 15% for French beans, 30% for (chili) peppers (Verploegen, 2019).

Results from an experiment by Verploegen (2019) show the effect of different types of evaporative coolers (ECC using either straw, sack or bricks) on eggplants, tomatoes, hot peppers, and okras (Table 2). The type of evaporative cooler influences the shelf life. For eggplants, tomato and okra, the shelf life was found to be extended the most in a Brick ECC, whereas hot peppers had the longest shelf life in a sack ECC system (Verploegen, 2019) (Table 2). The brick ECC provided a more stable low temperature and a high relative humidity creating a more suitable environment for the stored produce. Moreover, this type of ECC offers a protection agains pests and animals. Finally, the watering frequency varied from once per day to 7 days whereas the other ECC types required watering 1 to 3 times a day.

Table 2. Examples of shelf life of different produce in evaporative cooling chambers (ECC) compared to optimal storage conditions.

Vegetables		Reported shelf life (days)[a]		Optimal storage conditions			
	Ambient condition	Straw ECC	Sack ECC	Brick ECC	Temperature (°C)	Relative Humidity (%)	Shelf life
Eggplant	3[f]	8 +/- 3	9 +/- 2	10 +/- 3	12	90-95	12-16[G] days
Tomato	7[c]	6+/-1	7+/-1	8+/-2	18-22	90-95	7-21 days
Hot pepper	1-2[d]	14 +/- 9	12 +/- 5	10 +/- 5	0-10	60-70	3-5 weeks [G]
Okra	2-3[e]	5 +/- 1	7+/-1	7+/-1	7-10	90-95	7-10 days

[b] The shelf life listed is under the optimal storage conditions listed (McGregor, 1989 in Verploegen et al, 2018)
[C] Ambient conditions: 20-25 °C, 70-90 % RH (Narsin et al, 2008)
[d] According to the results of the pilot experiment of this project, ambient 30-45 °C
[e] 32.7 +/- 2.5 °C, 72.5 +/- 5% RH, Aksin et al, 2014
[f] 20 +/- 1 °C, 52-54 %RH, Sudhir et al, 2016
[G] : Kader et al, 2002
Source: Adaptation of Verploegen et al, 2018

The second experiment by Ambuko (2017) on leafy vegetables using zero-energy brick cooler (ZEBC) and the evaporative charcoal cooler (ECC) compared to ambient conditions (Table 3). Leafy vegetables have a short shelf life of just 24 hours (or less) under ambient room conditions. Ambuko (2017) determined the effectiveness of evaporative cooling in preserving quality and extending the shelf life of leafy amaranth vegetables, revealing that after five days of storage, vegetables stored at ambient room conditions had lost almost half (48%) of their initial weight. In comparison, those stored in the zero-energy brick cooler (ZEBC) and the evaporative charcoal cooler (ECC) lost only 11% and 7% of the initial weight, respectively (Ambuko *et al*. 2018). The leafy vegetables also retained higher levels of vitamin C, an indicator of quality deterioration, at 12.6 and 13.4 mg/100g fresh weight for ZEBC and ECC respectively, compared to those stored at ambient air temperature (8.4 mg/100g of fresh weight). These figures represent 65%, 69% and 43% retention of the initial vitamin C content (19.5 mg/100g fresh weight) under ZEBC, ECC and ambient room conditions, respectively.

Table 3. Physiological weight loss (% of the initial weight) in amaranth vegetables (amaranth spp.) stored in the zero-energy brick cooler (ZEBC) and evaporative charcoal cooler (ECC), and under ambient room conditions.

Storage options	Storage time (days)		
	2	5	8
ZEBC	6.4a	10.5b	16.2a
ECC	5.6a	6.7b	16.9a
Ambient conditions	5.6a	57.6a	-
Significance	Non-significant	*	Non-significant

*Means withing each column followed by different letters differ significantly at p < 0.05., *Significant different at p < 0.05.*
Table adapted from Ambuko et al., 20217

2.3 Climatic conditions need for evaporative cooling

When selecting a potential cooling technologies, the climatic conditions must be taken into account. If evaporative cooling is selected, the climatic conditions is of the most importance affective the performance of this technology. Indeed, evaporative cooling is most effective in dry and arid climates characterized by low to moderate humidity and high temperatures. In climates or seasons with high humidity, evaporative capacity is lower due to the air saturation and reduced capacity to absorb moisture. The greater the temperature difference between the surrounding air and evaporating water, the higher the cooling effect. Therefore climates/seasons with temperatures above 25^0C are better suited for direct evaporative cooing technologies. Evaporative cooling only lowers the ambient temperature to the wet-bulb temperature therefore if the wet

bulb temperature is the same as the dry temperature, there is no net evaporation of water in air, preventing a cooling effect. An evaporative cooling decision making tool according to the climatic condition is available[3].

Moreover, an overlap of seasonal weather conditions is needed for evaporative cooling and crop harvesting . The evaporative cooling potential for different global locations can be found in the database[4]. The Jordanian data for maximal temperature depression of evaporative cooling technologies in April is 5.0-7.5 °C, and for July to October 5.0-10.0 °C depending on the specific location (Figure 2). It is questionnable whether the evaporative cooling potential is sufficient to cool the produce when considering the field heat. As the relative humidity is higher than 40% between November and April, the period when the evaporative cooler could be applied is significantly reduced. Figure 2 zooms in on the Jordan Valley and Aljoun in January (upper left), April (upper right), July (lower left), and October (lower right) with a colour filter showing the temperature depression potential where yellow offers the greatest potential and blue the least.

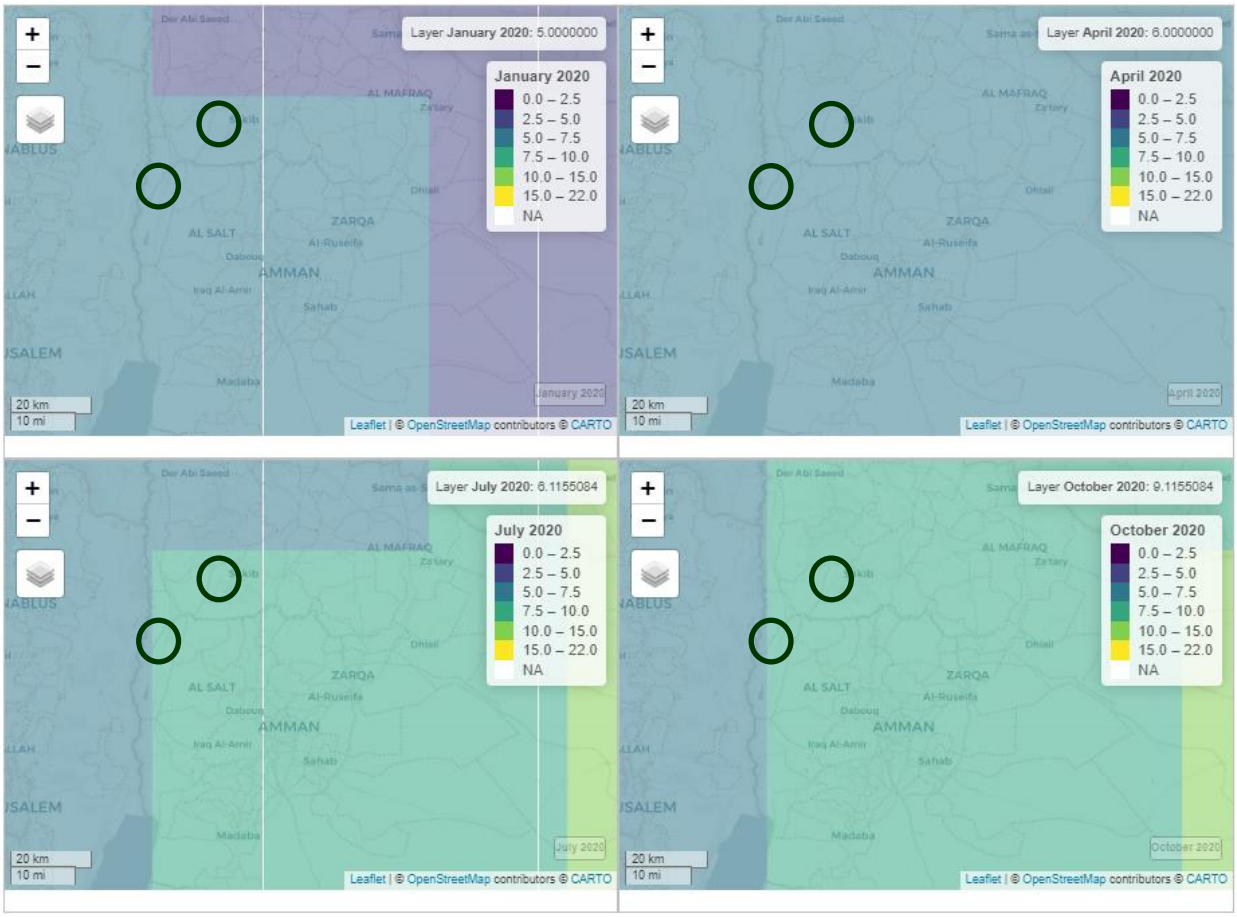

Figure 2. The maximal temperature depression (in °C) due to evaporative cooling for 4 seasons in Jordan. Source: World (empasimbiosys.github.io). The circles show the pilot locations.

[3] https://d-lab.mit.edu/resources/publications/evaporative-cooling-decision-making-tool
[4] https://empasimbiosys.github.io/evapo_cooling_map/

2.4 Overview of different construction types of evaporative coolers

The main types of evaporative coolers discussed in section 3 are presented in Table 4

Table 4. Summary of the characteristics of the presented evaporative cooling methods.

Method	Test Location	Passive/ active	Cost (USD/m3)	Capacity (m3)	ΔT day(°C)	ΔT nigh (°C)	Energy use	Material	Watering	Reference
Nylon walls evaporative cooling	New Delhi, India	Passive	444	9	-14	+3	Grid, battery or solar for the pump	Nylon	Via a pump	(Chopra et al., 2022)
Charcoal passive cooling (ECC)	Kenya	Passive	195	0.6	-3 to -13	n/a	0	Charcoal, pillar, chicken wire		(Manyozo, 2018)
Charcoal blanket passive cooling		Passive		0.6	-2 to 3	n/a	0	Charcoal, pilar, blanket		Defraeye and Onwude, 2022
ECC Straw	India	Passive	62-200	0.25-4 (4-7 field crates)	-5.4 (30-50 RH%)	n/a	0	wood and nails or screws for a frame, straw to cover the surfaces of the ECC and rope or twine to secure the straw	1-3 times/day	(Verploegen, 2018)
ECC brick	India	Passive	88-280	0.25-4 (4-7 field crates)	-5.8 (80-100 RH%)	n/a	0	enough for two layers of brick around the sides and bottom of the ECC (typically, 400-800 bricks), sand to fill the space between the two brick walls, and a cover for the top of the ECC made of wood and straw or cloth	Once per 1-7 days	(Verploegen, 2018)
ECC sack	India	Passive	62-200	0.25-4 (4-7 field crates)	-2.6 (10-30RH%)	n/a	0	wood and nails or screws for a frame, sack to cover the surfaces of the ECC, and rope or twine to secure the sack	1-3 times/day	(Verploegen, 2018)
Zero-energy brick cooler (ZEBC)	Kenya	Passive		2.4	- 9	+5	0	Brick, sand, pipes, tank		Ambuko, Wanjiru et al, 2017
Forced-air evaporative cooling chamber (MIT-model)	Gujarat, India	Active	810-1,500	10	Summer: -16 Winter: -11	n/a	Grid, battery or solar for the pump and fans	Ship container, cellulose evaporative pad in aluminium frame	With a plumbing system	MITD-Lab

Source: Author's own elaboration

3 Passive and Active evaporative cooling

3.1 Introduction

Evaporative coolers can be divided into two main systems: direct and indirect (Kapilan et al., 2023). The direct system involves direct contact of the water with the air, increasing the relative humidity of the cooling facility. In comparison, indirect systems do not contribute to an increase in relative humidity (RH). Since high relative humidity is crucial for most crops during storage, direct systems thus offer an additional advantage over indirect systems. Additionally, air movement in evaporative cooling can be managed either naturally (passive evaporative cooling) or with fan assistance (active evaporative cooling). Due to the RH advantage, this section focuses on direct evaporative cooling systems, both passive and active.

3.2 Passive evaporative cooling

Passive evaporative cooling uses a wall made of porous material where water is added either from the top or the bottom of the structure. The air circulation (natural convection or wind) moves the cooled air via the evaporation of the contained water without the help of fans, there is no need for power. We present a selection of passive-evaporative cooling methods, their pilots and results in the following section.

3.2.1 Nylon wall cooler (NWC)

This type of evaporative cooling uses nylon cloth on painted steel mesh walls (Figure 3). The nylon is wetted with a garden dripline with 2 L of filtered water per hour. A 2,000 L water tank is placed 1 m above the dripline. The structure's pillars and ceiling are concrete. The roof is made of panels at an angle of 23 degrees from the horizontal. The investment needed for this cooler structure is around USD 4,000, 40-60% less costly than a Brick-sand-brick (BSB) wall (Chopra and Beaudry, 2018). Operational costs are minimal, with a low initial investment and low energy demand during operation. The structure measures 3 m wide, 3 m deep by 3 m high and uses 2L/h. The test was in New Delhi (Chopra et al., 2022).

Results show that this type of cooler cools more rapidly and to a greater extent compared to BSB due to lower thermal mass and higher thermal transmittance (Chopra and Beaudry, 2018). The mean temperature decrease compared to ambient temperature (daytime) is 14 °C. The mean temperature difference compared to ambient temperature (nighttime) is 3 °C warmer in the evaporative cooler due to nighttime elevated humidity. Over a 24h-period, the temperature difference is 5 °C, however with a reduction in maximum daytime temperature from 40 °C to 28 °C there is a significant impact on produce quality (Chopra et al., 2022) (Figure 4).

Figure 3. Pusa EC room (3 x 3x 3 m) built in Indian Agricultural Research Institute (IARI), New Delhi. Complete structure with nylon (aramid) felt walls (left) and internal structure showing painted steel mesh (right), which provides support for the fabric walls and the autoclaved aerated concrete covered pillars, ceiling, and floor (Chopra et al., 2022).

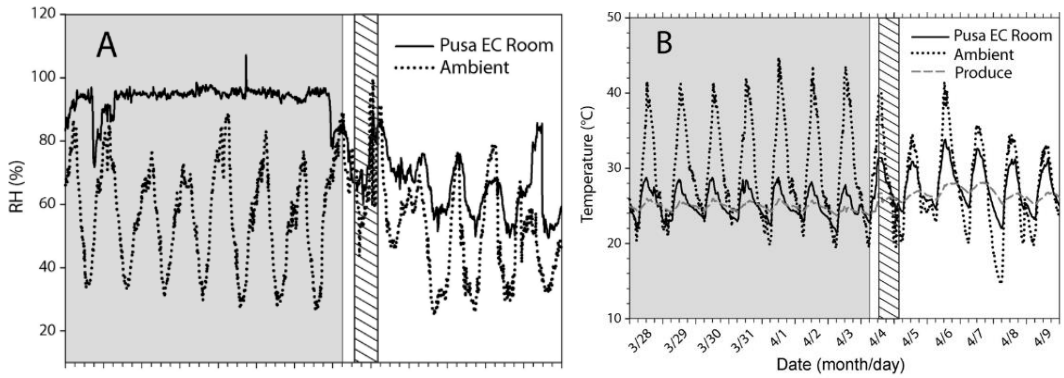

Figure 4. Temperature (A) and RH profile (B) in Pusa EC room (3 x 3 x 3 m) and in the ambient environment taken at 15-min intervals over a representative 13-day period from 28 March to 9 April 2017 om Delhi, India. Simulated produce refers to 1000kg of polyethylene terephthalate bottles filled with water. The shaded area indicates periods when the outer nylon felt fabric were wetted. The non-shaded area indicates periods when water was withheld from the nylon felt. The diagonal pattern indicates a rain event beginning on the evening of 4 April thought the morning of 5 April 2017. (Chopra et al., 2022).

3.2.2 Evaporative charcoal coolers (ECC)

The walls of a charcoal passive cooler can be manufactured on a large-scale using metal wiring and charcoal, or on smaller scale with charcoal-filled blankets (Figure 5).

Figure 5. Example of a charcoal passive cooler made of chicken wire filled with charcoal.

(Source: University of Nairobi, 2024)

3.2.2.1 Small scale: Charcoal cooling blanket (CCB)

Pilots of passive evaporative cooling using a charcoal cooling blanket were conducted in Switzerland. The blanket is adapted for small-scale cooling with a construction size of 1.5x 1 x 0.4 m (Figure 6). The blanket used to make the facility can be used throughout the supply chain and can be adapted for small scale farmers. When tested, this method reduced the temperature by 5 °C in a moderately humid environment with an RH% at 85-95%. For more information[5]

[5] https://www.empa.ch/web/simbiosys/charcoal-cooling-blanket; https://engrxiv.org/preprint/view/2221/4386

Figure 6. Visualisation of a charcoal cooling blanket.

(source: A scalable, simple evaporative charcoal blanket for food preservation, YouTube presentation)

The operational environmental impact (CO2eq. emission) is 200 times lower than that of a similar-sized commercial refrigeration unit for a 14-day storage unit for the same temperature settings. In other words, the carbon footprint of this technology is 15 kg CO_2 eq./m^2 (Defraeye, et al. 2022). Water use is weather dependant, and the specific water quantity required was not specified.

During a field experiment in Switzerland using a 600L blanket cooler, the temperature was lowered by 2-3 °C compared to outside air temperature in sub-optimal weather conditions. Thus we expect the temperature depression in an optimal weather condition, warmer and dry than in Switzerland, to achieve better results. This technique is a promising application for an on-farm, low budget, cold storage unit. The unit can easily be made by the farmer with readily available materials.

The specific advantages of this method are:

- The charcoal blanket reduces any expertise needed to construct and operate the evaporative cooler and can be used by a wider range of people.
- It reduces the costs of microscale cooling facilities compared to larger structures.
- The structure is light (charcoal density 200-600 kg/m3), and the charcoal blanket is mobile.

3.2.2.2 Evaporative charcoal cooler (ECC)

In this system, charcoal is the inert medium that holds the water to be evaporated to achieve cooling. The charcoal is sandwiched between a double wall which is commonly made from wire mesh. There are various adaptations of the ECC in terms of the materials used in its construction. The most common version is made of a double wall of chicken wire mesh or expanded aluminium mesh secured by a frame made of wood or aluminium (Figure 7). The standard size walk-in ECC is 4m X 4m and about 2m high. This unit can be manufactured for approximately USD 5,000 – 7,000 depending on the availability of construction materials (Amwoka, 2021). The structure has a capacity of 4-5 tons of fresh produce packed in 250 standard bread crates.

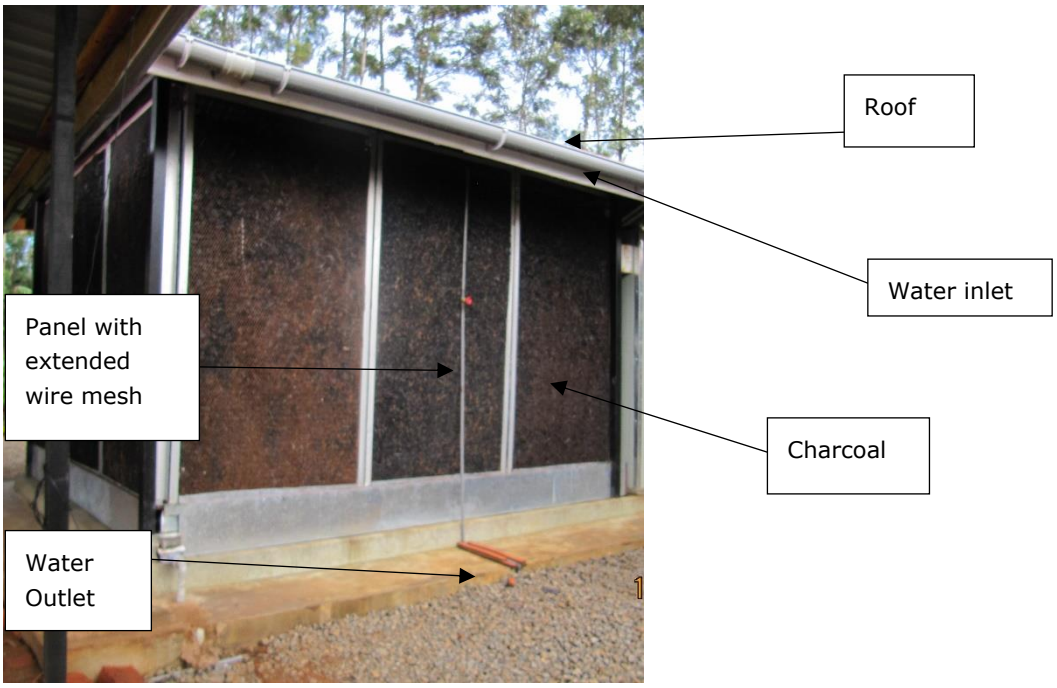

Figure 7. Evaporative Charcoal Cooler (ECC) with expanded aluminium wire mesh filled with charcoal and an aluminium frame.

Source: Ambuko, 2024

A smaller version measuring 1.232 m x 0.6m x 0.85 m and made from chicken wire mesh and a wooden frame costs USD 123.1 in Malawi (Manyozo, 2018). The 4m x 4m ECC can achieve temperatures between 0 to 15°C lower than ambient air temperatures and an RH between 65 – 95%, depending on the time of day and season (Ambuko et al. 2018; Amwoka, 2021). The smaller ECC achieved a decrease in temperature between 3 to 13 °C with an RH of 91 to 95%.

This test was run using tomato; after 24 days of storage the tomatoes in the ECC lost about 8-10% of their weight compared to about 20-25% at ambient temperature. Under ambient conditions, tomato firmness decreased to about 25N after 24 days compared to about 50 N under ECC conditions, with a harvest firmness of about 60N. Vitamin C levels were also higher under ECC than under ambient conditions.

A variation of charcoal designed for regions experiencing extreme temperatures (>40°C) was conceptualized by the University of Nairobi research team with a charcoal-filled expanded mesh encased in fibreglass. The fibreglass walls both enhances durability and gives the charcoal cooler a finer finish so it is easy to maintain and clean. The standard walk-in charcoal cooler (4m X 4m) uses about 500L water per day. By installing a recycling system, it is possible to catch and reuse between 25% and 50% of the water (personal communication Duncan, 2024).

Figure 8. Improved evaporative charcoal cooler (ECC) (left), examples of crop storage in the ECC (right). *Source: University of Nairobi, 2024.*

3.2.3 Straw, sack and brick evaporative chamber cooler (ECC)

Other types of passive evaporative cooling were piloted in Mali (Verploegen et al, 2018) using either straw, burlap sacks, or bricks (Figure 10). Comparing the results of the three materials, the brick evaporative chamber cooler (ECC) offers better conditions for crop storage; the temperature depression was greater while maintaining a higher RH. For the best results, the following operating conditions are required: low humidity level (< 40%), high temperature (daily > 25 °C) with access to clean water in a shady and well-ventilated location.

List of materials for constructing each type of ECC:
Straw ECC: wood and nails/screws for a frame, straw to cover the surfaces of the ECC, and rope or twine to secure the straw
Sack ECC: wood and nails/screws for a frame, sack to cover the surfaces of the ECC, and rope or twine to secure the sack
Brick ECC: enough for two layers of brick around the sides and bottom of the ECC (typically, 400-800 bricks), sand to fill the space between the two brick walls, and a cover for the top of the ECC made of wood and straw or cloth

Figure 9. Evaporative cooling chamber using (left) straw, (middle) sacks, and (right) bricks.
Source, Verploegen et al, 2018

The pilot respondents reported that the brick ECC provided high cooling effectiveness, protection from animals and insects, and ease of watering (Table 5); only the materials access and affordability were rated lower. The sack ECC was rated medium as the cooling effectiveness was better than the straw ECC. Brick evaporative cooling provided the most stable low temperature and a high RH% (Verploegen, 2018) and refilling was easier due to the layer of sand containing the water. Moreover, the EECs constructed with straw and sacks offered less protection against pests (Verploegen, 2018).

Table 5. Comparison of three types of evaporative coolers.

Evaporative cooling device	Average temperature decrease (°C)	Interior humidity range*	Minimum watering frequency	Protection from animals and insects	Storage volume (L)	Cost (USD)
ECC (straw)	5.4	30-50	1-3 times/day	No	250-4,000	50-250
ECC (sack)	2.6	10-30	1-3 times/day	No	250-4,000	50-250
ECC (brick)	5.8	80-100	Once/1-7 days	Yes	500-5,000	70-350

*For the date provided, the ambient relative humidity was less than 40% and the average daily ambient temperature was between 29 °C and 37 °C

Source: Verploegen et al, 2018

The condition variation in the evaporative coolers compared to the ambient conditions is more stable with the most stable environment observed in the brick ECC (Figure 11).

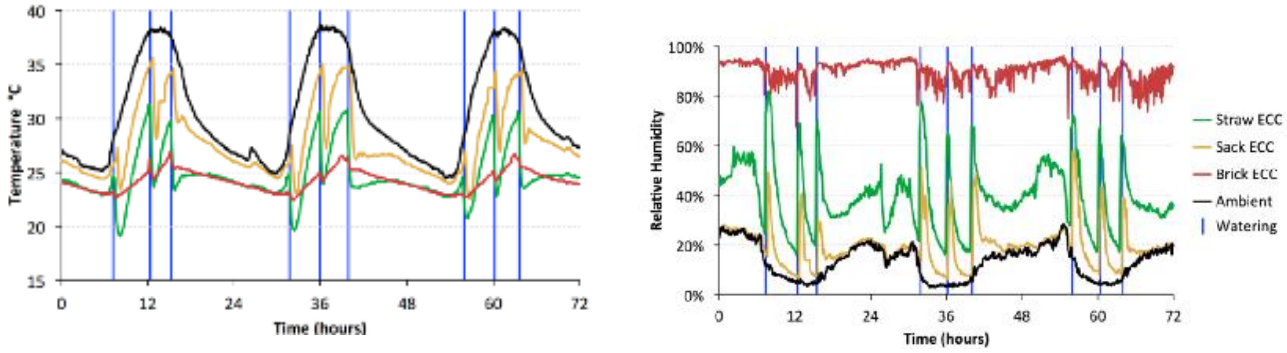

Figure 10. Typical internal daily temperature (left) and relative humidity (right) with watering for all three types of ECCs, and the ambient temperature measured by the independent sensors to the ECCs represented by the block line. A decrease in temperature can be observed at the time of watering for each of the ECCs as indicated by the vertical blue lines.

Source: Verploegen et al, 2018

3.2.4 Zero energy brick cooler (ZBEC)

Ambuko and Wanjiru *et al* (2017) tested the zero-energy brick cooler (ZBEC)r in Kenya. It was made of a double-brick-walled chamber filled with sand, with an aluminium frame providing greater structure stability. The structure had a capacity of 16 crates (2.2 m x 2.0m x 0.6m). The sand is wetted by a dripline and the evaporative effect is supported by passive airflow.

Compared to the charcoal ECC, the ZEBC cools less, but daytime temperatures are more stable. With an ambient temperature between 15.3 – 29.0 °C and an RH% of 46-97% (Figure 11), the temperatures in the ZEBC were around 20 °C and an RH% of 100%. The conditions were stable regardless of the time of the day. However, more fluctuation was observed with temperatures varying between 15.5 – 20.5 °C with an RH% of 75-100%. The produce stayed fresh for 3-5 days longer than under ambient conditions. The more stable conditions under ZEBC did not directly translate into better produce quality.

Similar results were found in Rwanda and Burkina Faso (Verploegen, 2019). In these cases, a brick and mortar structure was used with a solid wooden cover. An average interior humidity > 95% was measured and a stable air temperature with a reduction in daily temperature fluctuations from 10-20 °C each day to less than 4 °C. The daily peak temperatures were reduced by 7-15 °C, avoiding peak temperatures above 30 °C. The shelf-life increased two to four times compared to ambient conditions for specific crops.

In these pilot studies, points of attention mentioned were the fungal contamination from the sides of the inner clay surfaces. In addition, observations were made about the durability and structural strength of the structure. With a structure higher than 1.5 m, wall reinforcement should be used such as wood, a wireframe, or mortar. Worth noting is that it is important to build the ZEBC in the shade.

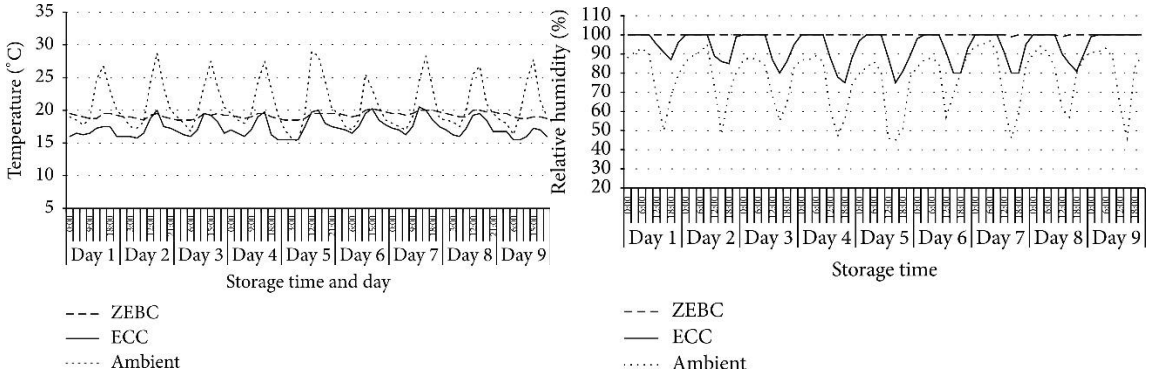

Figure 11 Changes in temperature (left) and RH (right) in the zero-energy brick cooler (ZEBC), evaporative charcoal cooler (ECC), and ambient room conditions storing Leafy Amaranth.

Source: Ambuko et al., 2017

3.3 Active evaporative cooling

3.3.1 Forced-air evaporative cooling chamber using shipping container

An innovative design of an evaporative cooling technology was developed by the MIT-Lab team (Verploegen *et al*., 2022) using a shipping container (Figure 13). A mid-section is created with the means of sliding doors. Industrial fans pushing the outside air into the container (large reg arrow), directed through wetted carton pads (small red arrows). The cooler air flows downwards through the produce, lowering its temperature. The air warms up and rises along the container's sides and leaves the container (orange arrows). Electricity to power the fans can be derived either from the grid or a built-in solar panel[6].

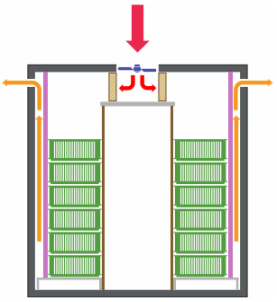

Figure 12. A head-on cross-sectional schematic of the airflow through the chamber.

Source: MITD-Lab, 2023

This technology offers several advantages. It upcycles material by using a reefer container. Compared to conventional refrigeration technologies it is affordable, with costs between USD 8,100 - 15,000 and lower operational costs are, only 25% of the energy is needed. The capacity of the reefer is 168 crates, which is sufficient for a small cooperative to store produce.

Tests were completed in India (Gujarat) where summer temperatures of 42 °C were reduced to 26 °C in the reefer, with 95%RH (Verploegen *et al*., 2022). During the winter, temperatures of 35 °C were reduced to 24 °C. The vegetables tested stayed fresh for up to 6 days. After two days, for the vegetables stored in the reefer, waste was reduced 13% to 50% (Table 6Table 3), with an average ambient dry bulb and RH of 33 °C and 45%, compared to an in-chamber average of 26 °C and RH of 87%.

Table 6. Percentage of produce spoiled after 2 days of storage in the active evaporative chamber operating at 50% capacity factor compared to the control conditions (ambient conditions).

Vegetable	Control (%)*	Reefer chamber (%)	Improvement (%)
Alfalfa	50	17	33
Coriander	70	20	50
Cucumber	30	15	15
Cabbage	15	2	13
Cauliflower	18	2	16
Eggplant	38	12	26
Tomatoes	50	10	40
Chili pepper	17	5	22
Ladyfingers	20	1	19
Ridge gourd	30	8	22
Papaya	24	8	16
Spinach	60	20	40

*Under ambient conditions

Source: Verploegen et al, 2022

[6] For more information: https://www.cooling-chamber.mit.edu; https://www.cooling-chamber.mit.edu/chamber-designs

Tests conducted in Kenya (Kibwezi) showed an average in-chamber dry-bulb temperature of 17.5 °C with a maximum ambient temperature of 33.4 °C. The in-chamber RH it was 91% compared to the ambient RH of 56% (Figure 13). The average evaporative cooling efficiency was 82% (Verploegen *et al.*, 2022). The net water use was between 200-250 L/day, with excess water collected and re-used (Verploegen, personal communication, 2024). The project partners were Solar Freeze (Kenya) and Hunnarshala Foundation (India).

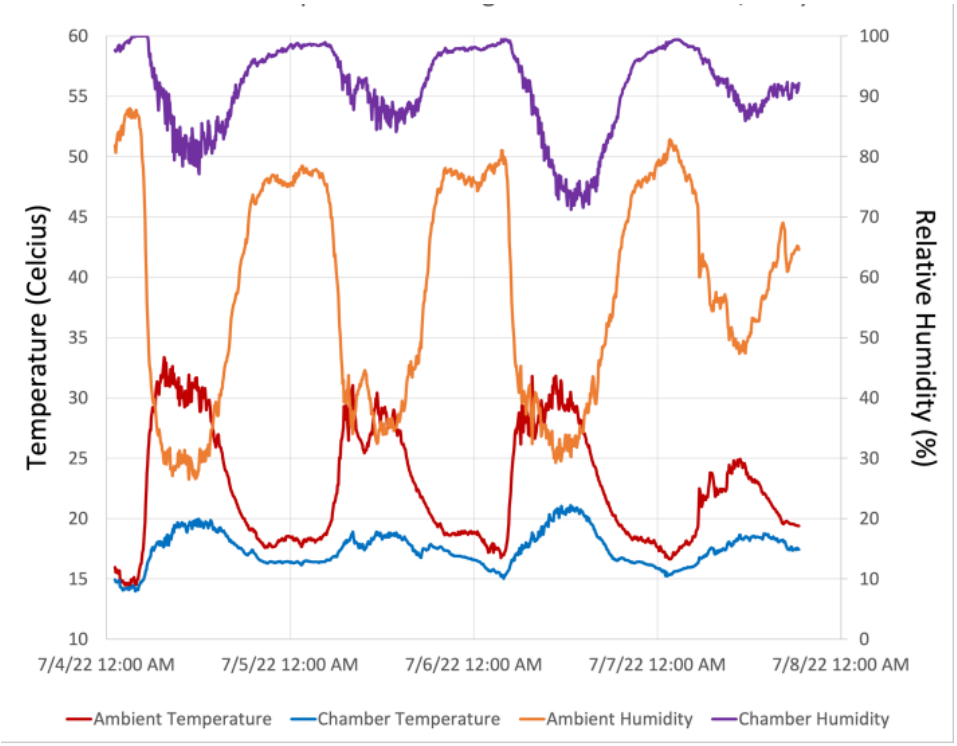

Figure 13. Forced-air evaporative cooling chamber in Kibwezi, Kenya.

Source: Verploegen *et al*, 2022

4 The CoolBot™: an alternative low-cost cooling solution

The Coolbot™ was invented by the small-scale farmers, Kate and Ron Khosla, in the state of New York in the United States of America[7]. Not finding an affordable cooling solution at the farm, they decided to develop their own in collaboration with Cornell University. Since 2006, they have sold more than 125,000 Coolbot™ all around the world.

A Coolbot™ cold room is a walk-in structure that serves as a low-cost alternative to a conventional cold room. It has three main components: a compatible air conditioner, a CoolBot™ controller, and an insulated room (Figure 16). The CoolBot™ is an electronic gadget which upon connection to a compatible air conditioner (AC) (LG 24,000 BTU), it overrides the thermostat and causes the AC to achieve temperatures lower than the set temperatures (about 160C). Without the Coolbot™ controller, at lower than the set temperature, ice would form on the evaporator coils and require defrosting. The cost of a 4m x 4m can range from USD 5,000 – 8,000 depending on the availability of the three components and the level of sophistication. A conventional cold room of the same size and capacity can cost upwards of USD 10,000 (Karithi, 2016; Kitinoja, 2013).

Figure 15. Cold room with an air-conditioning and CoolBot™ (left) and air-conditioner and CoolBot™ (back box with pink lights) (right).

Unlike the evaporative cooling systems described in Section 3, the Coolbot™ serves as a control unit where an appropriate temperature can be set for the stored produce. The Coolbot™ cold room has been used in several studies for fruits and vegetables where the set temperatures are achieved and maintained, with temperatures as low as 4 °C (Ambuko *et al*, 2018). For example, Ambuko *et al* (2018) showed that the set suitable temperature for cold storage of mango fruits (12±2 °C) was achieved and maintained for a 45-day storage period in Kenya when running during the day only (Figure 1Figure 1).

[7] https://www.storeitcold.com/our-story/

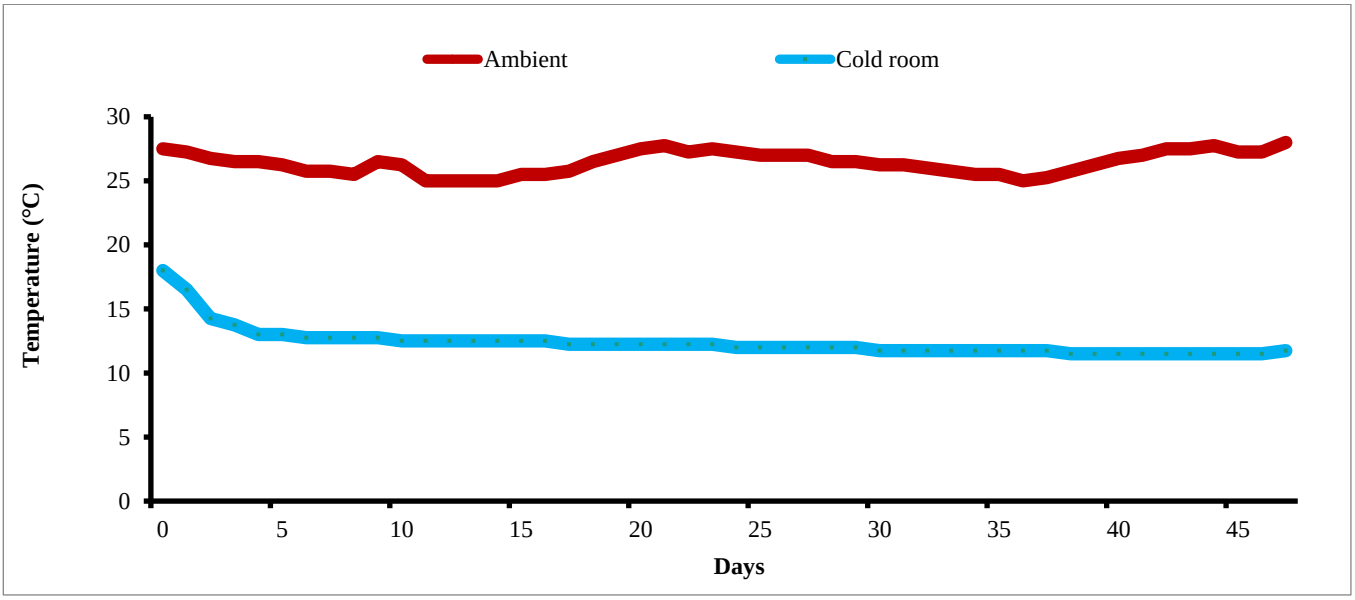

Figure 16. Temperatures inside a CoolBot^{tm} cold room vs ambient conditions over a 45-day storage period in Kenya.

Source: Ambuko et al, 2018

Other studies report that an RH of 60 – 85% can be achieved inside the Coolbot™ cold room. Coupled with other best practices for cold chain management, under these conditions, a shelf life of 30 – 35 days compared to 12 days at ambient conditions was achieved for various mango varieties (Amwoka *et al*. 2021).

The Coolbot™ cold room requires electricity to power the AC and the Coolbot™ gadget, and therefore it is best suited for areas with reliable electricity power. However, solar power can be used if sufficient to run the AC. Because ofits effective cooling, at the right storage temperature the produce shelf life can be extended significantly. Therefore, it can be applied for temporary storage as produce awaits daily or weekly markets. It can also be applied for longer term storage should the market price for produce ibe low. It also works in cases where individual farmers aggregate small volumes to meet quanties required by target markets. The technology can also be used by buyers or local markets to store produce, reducing FLW and increasing sales flexibility. For longer term storage of high value produce, it is advisable to combine cold storage with other synergistic technolgies such as modified atmoshpere packaging (MAP) or waxing. The shelf life depends on several factors such as the type of crop, the quality after harvest, and market requirements for ripening stage.

The cold room using a Coolbot™ has several advantages when compared to evaporative cooling systems The temperature can be set to a required temperature, as long as it is above 4 °C. It requires no water, except for cleaning and maintenance. It offers protection against pests as it is well-closed, while allowing marketing flexibility of the stored produce. However, it is best suitable for region having access to the grid or where the use of solar panels is accessible and where solar radiation is abundant.
Disadvantages are electricity costs, the limited RH management, and the environmental impact due to a low recyclability and lifespan and disposal issues. The profitability of the facility depends significantly on the cost of electricity. The system has no mechanism for managing RH, which is critical for the quality of stored commodities. The recyclability of the construction materials is limited, with key components such as the air conditioning (AC) system needing replacement every 10–15 years. The lifespan of the cold room is estimated at 20–30 years. Proper disposal is a challenge, especially in Jordan, raising concerns about the sustainable disposal of the facility after its lifespan.

5 Investigation points for selection of cooling method

The feasibility and effectiveness of a specific cooling technology depends on multiple factors. The technical suitability of any specific cooling technology needs to take into account the specific environment in which it will operate, the specific crops to be stored, the specific market for which the crops are destined, the total volume of crops to be stored, and the expected period of storage required. Beyond technical suitability, socio-economic factors can also influence the final feasibility and acceptability of a cooling technology. The acceptation of cooling technology by its potential users depends on its user friendliness, the initial investment costs, maintenance costs, operational costs, and ultimately the return on investment.
Before selecting a specific cooling technology, it is essential to address critical questions regarding who will use the facility, how it will be utilized, and why it is needed. Any investment in a cooling facility should be guided by a clear business case, ensuring that the costs are calculated, the benefits are evident, and the associated risks are assessed. To achieve this, stakeholders must define their mission and objectives for marketing their crops, identify their target markets, and determine the best approach to supplying those markets. To ensure socio-economic aspects are considered and incorporated, Table 7 lists of investigation points to be addressed:

Table7. Investigation points to be addressed for selecting an appropriate cooling technology.

Investigation points
The scale of use of the cooling facility
The intended market - local, regional, national, international The investment capacity
The selected crop for cooling
The optimal target temperature for the crop
The harvest issues to be resolved by cooling
The mean goal to be achieved
The user's expectations
Long or short term use: - If short term is there pre-harvest activities that could take place to reduce the need for cooling? - Prolong shelf-life of produce with 1 to 3 days to enable supply to the market few days after harvesting (logistic issues, price levels, negotiation power)
The water/electricity availability around the farm; if available a cost review
Options for farmers to share the cooling facility
For the chosen cooling method assessment of costs, required operational knowledge, availability of spare parts
Market prices for the produce and the added value after cooling
Other factors for consideration: Average temperature per month per projected area of use Maximum day temperature per month per projected area of use Average RH per month per projected area of use

Following completion of the business case, the optimal choice of cooling facilities can be made.

6 Selecting feasible cooling technologies for a pilot study in Jordan

This literature review was conducted with the objective of gathering information on the feasibility of low-cost cooling technologies for the Jordanian horticultural sector. The insights gained are to be used for the design of pilot studies to be conducted within the context of the JHF programme. The pilot studies will test and validate the effectivity, feasibility and return on investment of these different cooling technologies. This will allow JHF to evaluate the potential of farm-level cooling technologies to reduce post-harvest losses, while maintaining the quality of fresh produce and improving farmers' competitive positions.

This review of feasible cooling technologies in the Jordanian context and its horticultural sector included an exploratory field trip to Kenya. We visited two commercial organisations experienced with low-cost cooling technologies, as well as the University of Nairobi. One of the commercial organisations was a cooperative, cooling mangoes from local farmers using a charcoal evaporative cooler. The other was a company renting cooled space using the MIT-ECC. At the University of Nairobi, several cooling options are being researched and tested: the brick-ECC, the charcoal-ECC, and the cold room using an AC and a Coolbot™.

The pilot studies to be conducted within the JHF context focusses on cooling table grapes in Ajloun and cooling tomatoes and hot peppers in the Jordan Valley. These crops are sensitive to water loss, causing shrivelling and quality deterioration, therefore we hypothesize that an on-farm cold storage near the harvest location will maintain produce quality, especially in a warm climate. The pilot studies will replicate a situation where fresh produce is stored for a short period of time, on or near the farm, before being transported to the wholesale market in Amman.

In Table 8, the main features of the different cooling systems described in this paper are summarised, with a conclusion on their appropriateness for use in Jordan.

Table 8. Suitability overview of different types of cooling methods for the Jordanian context.

Type of facility	Cost	Electricity use	Pest protection	Water use	Relative humidity	Temperature depression	Material availability	Sustainability*	Conclusion for suitability
Brick ECC	Low	Non	Low	High	High	Low-medium	Medium	Medium	Low
Charcoal ECC	Low	None	Low	High	Medium-high	Low-medium	Low	Medium	Low
Straw ECC	Low	Non	Low	High	Low	Low	High	High	Low
Active evaporative cooler (MIT model)	Medium	Low	Medium	Low	Medium-high	Medium-high	Medium	Medium	Medium
Cold room with CoolBot™	Medium	Medium-high	High	Very low	High	High	High	Very low	High

*Sustainability was estimated by the authors. A full life-cycle assessment is needed to make precise conclusions. The straw-ECC scored low as all material are available locally and all compostable after use. Brick and charcoal ECC scored medium as the fabrication of the raw material is energy-consuming, but can be up-cycled and use for other purposes after use. The active evaporative cooler scored medium as it is up-recycling part of the material. However, none of the material is compostable after use, some material are easily recyclable, while others are poorly recyclable or not recyclable. Finally, the material of cold room with a CoolBot™ are energy-consuming to produce and poorly to not recyclable after use.

Considering the low investment capacity of the farmers, a low-cost cooling solution is required. At the same time, the cooling technology has to offer sufficient cooling capacity in the warm Jordanian conditions. For the case of tomatoes, the targeted optimal storage temperatures are 10-12 °C. For the case of hot peppers the optimal storage temperatures are 7.5 °C, and for grapes, 0 °C. These low temperatures cannot be reached or maintained using evaporative cooling, one of the low-cost options. Based on the climatic conditions in Ajloun and Jordan Valley, evaporative cooling cannot offer sufficient cooling capacity as the difference between the dry and wet bulb temperatures is too small, while the RH is too high. In addition, a mismatch was found between the climatic conditions required to effectively use the evaporative cooler and the peak periods of the harvesting seasons. During the harvesting season, the humidity level is too high offering an insufficient cooling effect on the produce. This condition results in a situation where the evaporative cooling technology can only be used effectively for six months which coincide with those when the least number of crops are harvested. Furthermore, the existing water scarcity in Jordan justifies the choice of a cooling technology that utilizes the least water. That is not the case for the evaporative cooling options. Based on the generated insights, these type of cooling options are thus not considered appropriate for the pilot studies.
In contrast, the Coolbot™ cold room offers ease of use and availability of the AC with a cooling potential that can overcome the climatological restrictions that affect the suitability and viability of evaporative cooling technologies. Except for maintenance (cleaning), no water is required. The cold room with a Coolbot™ can be used year-round for all types of produce to be stored above 4 °C; the adjustable temperature settings are suitable for a wide range of crops. The closed doors offer protection against pests and animals. The investment costs for a Coolbot™ cold room are lower than those of the MIT-ECC (USD 5,000 compared to 8,000) and also lower than the investment costs of a conventional refrigeration system/ cold room. The Coolbot™ cold room option offers the advantage of ease of use, local availability of parts, local knowledge for assembly, and low maintenance costs. The pilot report provides a more detailed explanation of the motivations for the selection of this specific type of cooling for the pilot studies,

Possible disadvantages of using a Coolbot™ cold room facility are the effect on profitability as this is partly determined by the cost of electricity. Moreover, the Coolbot™ cold room has no means of RH management. Further research is needed to gather data on RH in a Coolbot™ cold room, and its effect on the stored commodities. Finally, the environmental impact must be considered as the Coolbot™'s recyclability is low. As the AC will have to be changed after 10 to 15 years and the cold room itself after 20-30 years, the owner will need to make sure the material can be brought to a recycling centre. To address these drawbacks, it may be useful to investigate renewable energy solutions to reduce electricity dependency and design options for including RH management, Moreover, the use of recycled or more sustainable construction materials should be explored, together with strategies for sustainable end-of-life disposal, in collaboration with local recycling initiatives.

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