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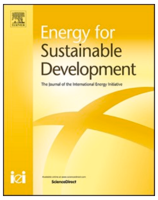

Enhancing postharvest storage in low- and middle-income countries: Evaluation of the passive evaporative cooling blanket for fruits and vegetables

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ABSTRACT

Over 30 % of fruit and vegetables produced in low- and middle-income countries is lost from farm to consumer. To combat this, cooling fresh produce after harvest is vital. Evaporative passive cooling is a viable solution, yet it is underutilized mainly due to complexity, scalability, and affordability issues for smallholder farmers. The passive cooling blanket represents a cleaner alternative to current evaporative coolers that can address these challenges. It is a re-usable textile-based blanket filled with a natural padding material such as sawdust or charcoal. However, its performance in real-world conditions has not been tested so far. This study evaluated the efficacy of two cooling blankets with capacities of 0.06 m^3 and 0.18 m^3 to preserve fresh produce by full-scale outdoor experiments in Kenya. Storage trials on tomato, kale, zucchini, and peas were conducted, comparing the blanket with a traditional charcoal cooler and storage under permanent shade. The blanket effectively lowered air temperature on average by 3–5 °C below ambient, with a maximum reduction of 10 °C during the warmest time of the day. It maintained a constant interior relative humidity of 95 %, which slowed down the wilting of the produce. The cooling efficiency was 70 % during the daytime. The blanket performed slightly better than the traditional large charcoal cooler room in terms of humidity. The quality preservation of the vegetables was improved significantly compared to storage under the shade, reducing postharvest losses by up to 45 %. The combination of cool temperatures and elevated humidity makes this storage method suitable for preserving several fruits or vegetables. A comprehensive cost analysis indicated that the payback period of the blanket is less than three months. Moreover, a survey among smallholder farmers and fruit vendors revealed an extremely high willingness to adopt this blanket. As a result, the passive cooling blanket emerged as a promising and sustainable solution for addressing postharvest storage challenges in low- and middle-income countries.

Introduction

Agricultural production plays a crucial role in improving the livelihoods of many smallholder farmers in low- and middle-income countries. For instance, in Kenya, the sector generates 20 % of the total gross domestic product (GDP) and employs >70 % of the rural population in 2023 (Central Bank of Kenya, 2023; FAO, 2023). However, in Sub-Saharan Africa, postharvest losses are generally high, particularly for fruit and vegetables, with estimates ranging from 30 % to 50 % (FAO, 2025; Armachius & Zikankuba, 2017). The main reasons for these significant losses are the lack of efficient and affordable storage solutions and improper handling practices (Makule et al., 2022). Postharvest loss results in a decrease in farmer's income and reduced access to nutritious food (Verploegen et al., 2018). Moreover, they increase the cost of waste management, contribute to the emission of greenhouse gases, minimize resource conservation, and waste scarce resources used during their production, all of which negatively affect society (Aulakh et al., 2013).

Proper storage conditions are crucial to preserving the quality of fresh produce after harvesting. For most fruits and vegetables, this

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means a cold and sufficiently humid environment to decelerate fruit deterioration, as temperature and humidity are the main drivers for degradation (Onwude et al., 2020, 2023). Lower temperatures help to slow down the rate of spoilage and ripening processes. High relative humidity prevents moisture loss (McGregor, 1989; Onwude et al., 2022). Several initiatives currently promote the access of smallholder farmers or farmer groups to cooling facilities in developing countries (Singh et al., 2018; Sadi et al., 2021; Odeyemi & Ikegwuonu, 2021; Takeshima et al., 2021). Yet, most cold storage techniques depend on electricity, which is not available, affordable, or stable in many rural parts of Sub-Saharan Africa. Consequently, access to affordable and efficient post-harvest storage solutions is often restricted, and farmers living in off-grid areas or with limited financial resources remain underserved (Verploegen et al., 2021).

One key strategy for addressing this challenge involves using evaporative cooling. It is a well-known technology that has been used for centuries to preserve food (Roy & Khardi, 1985). It is considered one of the top 22 investable innovations that can transform food systems in emerging markets (GKI, 2017). Several different designs of passive evaporative coolers exist, for instance, charcoal coolers, brick cooling chambers, or clay pot coolers (Verploegen & Padalino, 2023; Mogannam et al., 2022; Abdul Latif Jameel Water, & Food Systems Lab, MIT, 2023). The underlying physical principle is the same: a porous material in the cooling system (such as charcoal or sand) is kept moist. With the evaporation of the absorbed water, latent heat is extracted from the environment and the produce. Concurrently, this leads to a reduction in temperature of typically 3–10 °C inside the system compared to the ambient temperature and an increase in relative humidity up to 70–100 % (Defraeye et al., 2024). The low temperature and high humidity result in improved storage conditions for the fresh produce stored inside the cooler. In general, the highest cooling effect through evaporation can be reached in regions with hot and dry climates. When ambient humidity is high (above 70 %), the potential for temperature reduction is limited because the maximum possible rate of evaporation decreases (Verploegen et al., 2019).

A considerable number of studies have reported that storage in a passive evaporative cooler preserves fruit quality (e.g., weight, color, firmness, deterioration) and extends the shelf life typically up to 6 days, depending on the produce (Dadhich et al., 2008). Since passive evaporative coolers do not require any energy source, these systems are

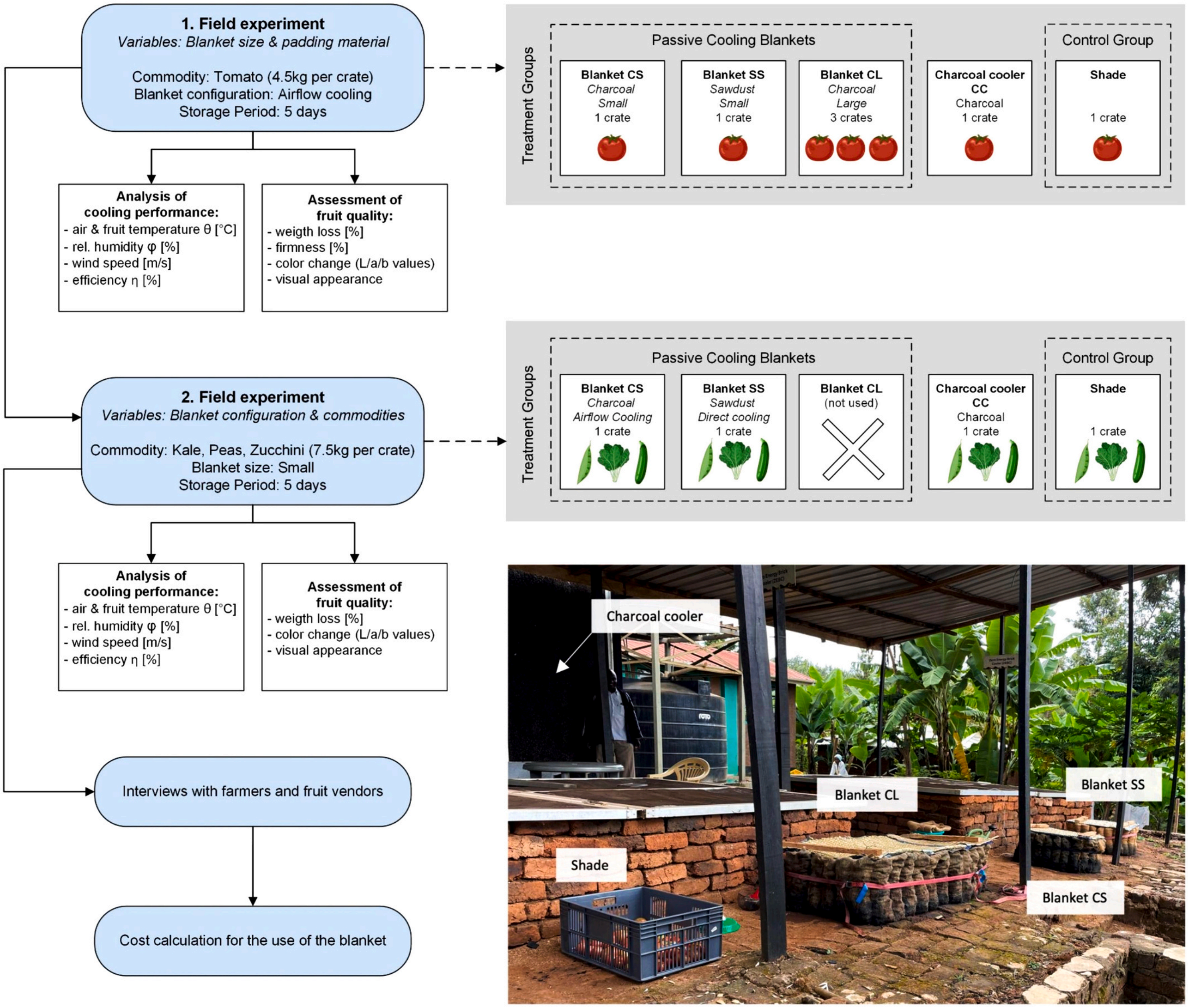

Fig. 1. Overview of the methodology and setup of the different cooling systems at the study location. Three cooling blankets were tested simultaneously (CL = charcoal large, CS = charcoal small, SS = sawdust small) and compared with storage in a large charcoal cooler and shade. Each experiment was replicated once.

particularly beneficial for smallholder or marginal farmers living in remote, off-grid areas. Regardless of the context, the use of natural and simple materials and the lack of energy demand make passive evaporative coolers a cost-effective and sustainable alternative to refrigeration systems (Verploegen et al., 2021). Despite their huge potential, evaporative coolers are rarely deployed. For instance, a study in Kenya revealed that <1 % of the farmers currently use charcoal or sand-and-brick evaporative coolers (Kanali et al., 2017). Major factors limiting the adoption are high capital costs, inappropriate storage capacity, and unavailability of the required materials, as well as the lack of awareness, expertise, and trust (Defraeye et al., 2024).

To address these drawbacks, Defraeye et al. recently developed a novel design for an evaporative cooler: the passive cooling blanket (PCB) (Defraeye et al., 2024). The blanket is re-usable, self-supporting, easy to construct, scalable and made of an air-permeable, sustainable hydrophilic fabric (e.g., burlap) which is filled with charcoal as padding material (Fig. 1). The filled blanket can be wrapped around the box(es) of fruit to be stored or placed over them as a cover. The blanket size can be varied and, thus, adjusted to the user's demand. The charcoal is periodically wetted from the outside. This water evaporates naturally (passively) by extracting energy from the environment in the form of heat. This leads to a reduced temperature of the air and the products stored inside, and thus to the desired cooling effect.

Compared to existing systems, the system stands out due to its scalability, the few materials required, the low material and operational expenses, as well as the simple construction and the fact that it is self-supporting. The initial study found that the blanket successfully reduced the interior temperature by 5 °C below ambient temperature in laboratory experiments. While these results are promising, the performance of the passive cooling blanket has not yet been evaluated in real-world settings under diverse natural conditions, particularly in regions where it would have the most significant impact and will actually be deployed. Such regions include low- and middle-income countries in Sub-Saharan Africa, Asia, and South America (Defraeye et al., 2023). The most promising regions in the world to deploy passive cooling and the months in which the highest cooling effect can be achieved are also depicted in an open-source online map (Simulating Biological Systems Group, 2023).

As a step towards further adaptation of the PCB in these countries where cold storage access is limited, this study aims to quantify the effectiveness of the passive cooling blanket (PCB) in maintaining postharvest quality and reducing losses of fruits and vegetables under real-world conditions in Kenya. The study also evaluates the feasibility and acceptability of the PCB from the perspective of local stakeholders, including smallholder farmers and vendors. Specifically, this study addresses the following research questions: (1) How effective is the passive cooling blanket in preserving the quality and extending the shelf life of fruits and vegetables compared to traditional storage methods (shade storage and charcoal cooling chambers (Verploegen & Padalino, 2023))? (2) How do different padding materials (charcoal vs. sawdust) used in the PCB affect its cooling performance and fruit preservation capability? (3) What are the current needs and perceptions of smallholder farmers and local fruit vendors regarding postharvest storage solutions? (4) What is the potential economic benefit of using the PCB for different stakeholder groups in rural Kenya? By answering these questions, the study provides critical insight into the performance, acceptability, and potential scalability of the PCB as a sustainable postharvest cooling solution in low-income countries. This paper is therefore structured as follows: The first section is the introduction, and then the next section describes the materials and methods used for evaluating the PCB performance and conducting the survey. The paper then goes on to present the results of the storage performance tests and stakeholder feedback, including the economic evaluation of using the cooler in the third section. The last section concludes with recommendations for future work and scaling.

Materials and methods

In two full-scale experiments conducted at a farming cooperative in Karurumo, County of Embu, Kenya (0°28′11.9″ S 37°39′47.4″ E), the performance of the passive cooling blankets to preserve horticultural products was analyzed (Fig. 1). Storage under permanent shade and in a local stationary charcoal cooler of 40 m^3 (*CC*, Fig. 1) served as benchmarks. The latter was built in 2020 by the University of Nairobi in collaboration with MIT's D-Lab (Verploegen & Padalino, 2023). The PCB was piloted in two different sizes (capacity of 0.07 and 0.23 m^3), applications (airflow cooling, direct cooling), and with two padding materials (charcoal, sawdust). Tomato, kale, zucchini, and peas were selected for the experiments. The crops were chosen due to their importance for local farmers during that season and because of their susceptibility to high losses during storage. We ensured that the selected combination of foods was compatible regarding ethylene production and sensitivity (S2 in the supplementary material for further explanation). Beforehand, preliminary experiments were conducted inside a climatic chamber. The findings from the laboratory experiments were used to improve the design and application of the cooling blanket for the subsequent field experiments.

Study area

Karurumo, Kenya is located at 1439 m above sea level and is characterized as Lower Midland 3. The average temperature is 20 °C, ranging from a minimum of 12 °C (July) to a maximum of 30 °C (March). It comes to bimodal rainfall with short rains from October to December and long rains from March to June, with an average of 850–900 mm per annum (Jaetzold et al., 1982). The major crops of the County are tea, coffee, dairy, cassava, and horticultural crops such as tomato (Mujuka et al., 2019; Geoffrey et al., 2014). Due to seasonal patterns in horticultural crop production, different crops are grown and harvested at various times throughout the year. For instance, tomatoes and sometimes kale thrive during the warm months in Karurumo, Kenya, which typically span from June to August. Harvesting usually commences within 2 to 3 months after planting, placing it around September or October. On the other hand, snap peas are typically planted in March and harvested in May or June. Moreover, Karurumo experiences two distinct rainy seasons: a long one and a short one. During the long rainy season, farmers focus on crops that take longer to mature and can be harvested within the same season. An example of such a crop is cassava. In contrast, during the short rainy season, farmers cultivate short-maturity crops like lettuce, spinach, and mint (Willis et al., 2019; Stöber et al., 2017). This strategic approach ensures that a variety of horticultural crops are available year-round. Besides, Karurumo farmers engage in irrigation practices, allowing them to maintain a consistent supply of specific crops throughout the year. From this perspective, evaporative cooling could then be used consistently with no seasonal limitations. This study was conducted in June and July, which corresponds to the coldest time of the year, and when produce such as kale, snap peas and zucchinis were harvested. Thus, testing the technology during a period with a rather low potential temperature reduction due to evaporative cooling makes it possible to demonstrate its effectiveness for the whole year.

Design and construction of the blanket

Three cooling blankets were designed and constructed using burlap textile based on the schematic shown in Fig. 2a. Key engineering parameters were considered to optimize performance, including compartment size, filler material properties, textile permeability, and application configuration, as elaborated below.

Selection criteria

The design of the cooling blanket was guided by multiple

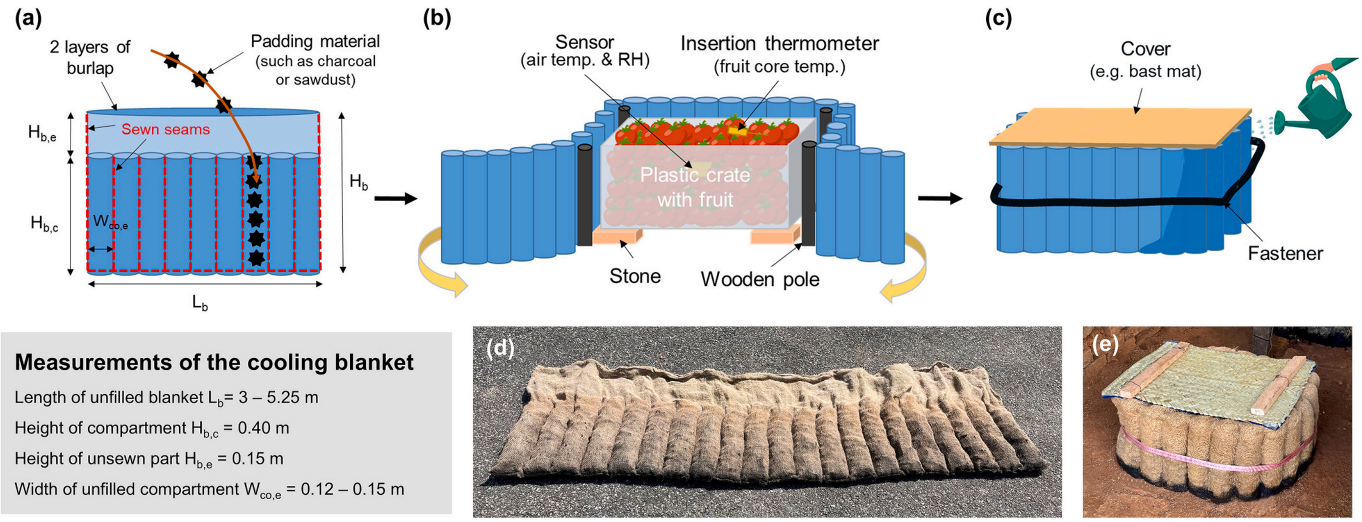

Fig. 2. (a) Technical drawing of the cooling blanket. Each compartment is filled with padding material up to $H_{b,c;}$ (b) Construction of the blanket exemplary for one crate with supportive structures; (c) Assembled blanket covered with a lid and watered for usage; (d) Cooling blanket filled with charcoal; (e) Assembled small cooling blanket filled with sawdust and covered with a bast mat. Images not to scale. RH stands for relative humidity.

performance and usability criteria:

- Cooling efficiency under passive airflow conditions.
- Water-holding capacity (WHC) for extended evaporative action.
- Mechanical stability and ease of handling.
- Cost-effectiveness and local material availability.
- Simplicity of fabrication for replicability.

These criteria were used in the decision matrix (Table 1, Supplementary Material S1) to assess variations in compartment width, filler type, and watering methods. The optimal solution showed a balance between high cooling efficiency, portability, and ease of use.

Fabrication, assembling and filling of the blanket

Blankets were fabricated at Empa by tailoring burlap sheets (180 g/m^2) into longitudinal compartments. The burlap textiles were purchased in Switzerland and sewn manually using thread and needles. Dimensions were chosen to match experimental design constraints. Two small blankets (CS and SS) were sewn into different compartments, following Fig. 2a schematic. At the pilot location in Karurumo, County of Embu, Kenya, the blankets were filled with charcoal and sawdust manually:

- Charcoal was crushed and sieved to retain pieces within 20–50 mm diameter.
- Sawdust was sourced from local sawmills as waste material.

Filling was done using a funnel to ensure uniform distribution, followed by weighing to confirm dry area densities.

Table 1

Characteristics of the different cooling systems tested in the experiments. Storage capacity is shown both in cubic meters (m^3) and in terms of standard vegetable crates (each crate ~0.06 m^3). CS = small charcoal blanket, SS = small sawdust blanket, CL = large charcoal blanket, CC = charcoal cooler.

Cooling system	CS	SS	CL	CC
Main materials	Charcoal, burlap	Sawdust, burlap	Charcoal, burlap	Charcoal, metal
Inner dimensions [m]	0.6 × 0.4 × 0.3	0.6 × 0.4 × 0.3	1.3 × 0.6 × 0.3	4.0 × 4.0 × 2.5
Storage capacity [m^3]	0.07	0.07	0.23	40
Storage capacity [standard crate]	1	1	3	72
Water volume per wetting [l]	5	5	12	Automatic (volume unknown)

Note that in the charcoal cooler, only up to 72 crates are stored in practice (even though it can carry up to 666 creates in principle), due to airflow, stacking limitations, and access space.

Material and design parameters

The length of the blanket (Lb) was 3.0 m for small blankets and 5.25 m for the large blanket, while the compartment width (Wco,e) was 0.12 m (empty) and approx. 0.10 m (filled) for small blankets, and 0.15 m for the large blanket. For all blankets, the height of the compartments was 0.4 m (H_b), with the filled wall thickness (Db) corresponding approximately to the compartment width (so Db ≈ Wco), governed by the caliber of the filler and determines pressure resistance and cooling area. The first small PCB (referred to as *CS*, "Charcoal Small") and the large blanket (CL) were filled with charcoal (caliber 2–5 cm). The second small cooling blanket (SS) was filled with sawdust. Charcoal has a thermal conductivity of 0.07 Wm^{-1} K^{-1} (Eltom & Sayigh, 1994) and sawdust of 0.045 Wm^{-1} K^{-1} (Rojas-Herrera et al., 2024). After filling, the length was reduced to 2.3 m (CS, SS) and 4.2 m for CL, respectively, due to the compartmentalization. Due to the different material densities and filler calibers, the resulting dry weight of the blankets was about 12 kg (CS), 4 kg (SS), and 30 kg for the large one. As such, the area density of the blankets was about 13 kg m^{-2} (CS), 4 kg m^{-2} (SS) and 18 kg m^{-2} (CL). These area densities are critical for understanding the water-holding capacity (WHC), mobility, and mechanical stability. Charcoal-filled blankets had higher weight and WHC, enhancing evaporative cooling, but potentially reducing portability if too thick or densely packed. Sawdust offered reduced weight.

Furthermore, the blankets were used in two cooling configurations:

- Indirect, flow-through cooling where air flows through the blanket wrapped around stacked crates or inside a makeshift cool room, cooling down as it passes through the moistened padding (see Fig. 3 (1)).
- Direct contact cooling where the blanket is placed over ventilated produce crates, allowing heat exchange through direct surface contact and evaporation (Fig. 3 (2)).

The air permeability of the composite system depends on the burlap porosity, charcoal caliber, and packing density. Low air permeability

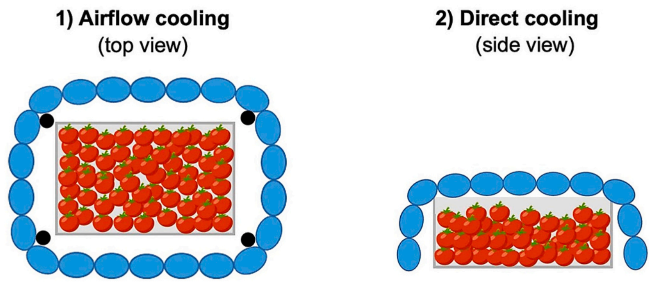

Fig. 3. Operating configurations of the passive cooling blanket (in blue). For airflow cooling wooden poles (black circles) are used to obtain a gap between the blanket and the crate. In the experimental setup, the gap was approx. 4 cm. Illustration not to scale. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reduces internal airflow and thus cooling effectiveness. In this study, compartment width with medium-caliber charcoal provided a suitable trade-off between ease of handling, sufficient cooling, and water absorption. We also design for a minimum air gap of 4 cm between crates and inner wall to allow airflow. Table 1 summarizes the main characteristics of the cooling systems used in the experiments. More details on the construction of the blanket are included in the supplementary material (S1).

Heat and mass transfer considerations

Evaporative cooling in the blanket occurs via latent heat removal from water evaporating into the airflow. The lowest temperature that can be reached theoretically by evaporative cooling is the wet-bulb temperature (T_{wb}), which is mainly dependent on the ambient temperature (dry-bulb temperature, T_{db}) and the relative humidity (LeRoy & Kuehn, 2001). Thereby, higher humidity leads to a higher T_{wb} (closer to T_{db}) and therefore, reduces the temperature depression, which is possible to achieve by evaporation. The wet-bulb temperature was calculated using the iterative approach recently presented by Defraeye et al., which was found to have a smaller error than empirical equations often used (Simulating Biological Systems Group, 2023). Following, the efficiency (η) of an evaporative cooling system is calculated as defined in Eq. (1). T_1 is the air temperature reached inside the cooling system (Doğramacı & Aydın, 2020; Olosunde et al., 2009).

$$\eta = \frac{T_{db} - T_1}{T_{db} - T_{wb}} \times 100\% \quad (\text{with } 0 \leq \eta \leq 100) \tag{1}$$

The amount of water required for the PCB depends on the evaporation rate (E_{vap}), which is influenced primarily by ambient temperature, relative humidity, air velocity, and surface area of the wet blanket and is given by the equation below:

$$E_{vap} = \frac{h_{fg}\, A\, (P_{sat}(T) - P_{air})}{R\, T} \tag{2}$$

where h_{fg} is the latent heat of vaporization of water (approximately 2260 kJ/kg at 100 °C, but varies with temperature), A is surface area (m^2), $P_{sat}(T)$ is the saturation vapour pressure at temperature T, P_{air} is the partial pressure of water vapour in the air, R is the specific gas constant for water vapour (≈461.5 J/kg·K), T is the absolute temperature (K), and E_{vap} is the evaporation rate (~3–5l/m^2/day). Blankets must be rewetted every 1–2 days, depending on ambient conditions.

Field experiments

In the first field experiment, the aim was to compare the performance of the PCB in different sizes as well as the usage of different padding materials (charcoal and sawdust) for postharvest storage of tomatoes. For this purpose, each blanket was used for airflow-driven cooling (see Fig. 3). This means the blankets were wrapped around one standard plastic crate (0.59 × 0.40 × 0.24 m, 57 l) or three for CL, respectively, and fixed with a tension belt. A lid made from a woven bast mat (Fig. 2e) was placed on top of the blanket to seal the system. A thin layer of plastic sheeting was attached to the underside of the lid as an additional vapour barrier to prevent the formation of mold and further keep the humidity in the blanket high. Detailed information on how to construct the cooling blanket is included in the supplementary material (S1). Unless otherwise specified, the following always assumes the configuration an airflow cooler. The cooling blankets were constructed under a roof, providing shade at all times.

The same is true for all evaporative coolers; water needs to be added regularly to maintain the cooling effect of evaporation. This was done by pouring water onto the individual compartments (Fig. 2c). The amount of water required depends on the evaporation rate, which in turn depends on the ambient conditions, especially the relative humidity. During the experiments, water was added until the padding material felt wet and was no longer absorbing (about 5 l for the small blankets every 1–2 days and 12 l for the large blanket, Table 1, as the experiments were conducted during the rainy season, which prolonged the blanket's moisture retention. Under different climatic conditions, rewetting frequency or evaporative performance may vary, but this does not alter the structural design of the PCB. Note that once the blanket is fully saturated with water, no more water should be added. Once saturation is reached, the evaporative cooling effect does not further increase. Adding additional water to the system, at least if it is not chilled water, would have the opposite effect, as the additional quantity would also have to cool down (see S1, Wetting, for additional information).

Per experimental run, 35 kg of tomatoes (cv. *Terminator F1* and *Ansal*) were obtained from a farm in Njukiri, Embu, Kenya. They were commercially harvested on the first day of the experiment at *breaker* to *turning* color, which corresponds to the usual harvest stage of tomatoes (United States Department of Agriculture, 1991). Tomatoes showing any defects (bruises, cracks, other damage) or being riper were excluded. The fruit were randomly divided into the five treatment groups (per crate 4.5 kg ± 5 % tomatoes; filled to 15 % of capacity). One crate each was put inside CS, SS, the charcoal cooler, and under shade as a control group, while three crates were put inside the blanket CL. The tomatoes were stored in the cooler for five days. The experiment was replicated once. The cooling systems were not filled to 100 % capacity to minimize post-experiment food waste and make efficient use of available resources. Partial loading provided sufficient data to evaluate system performance, with results scalable to full-capacity scenarios.

In order to investigate the suitability of storing other commodities, another experiment was performed with African kale (*Sukuma wiki)*, snap peas, and zucchinis (each 10 kg). Moreover, this experiment explored the cooling performance of an alternative application of the blanket by placing PCB SS over the box instead of being wrapped around it (for direct cooling, Fig. 3). The crops were obtained from the farm of the University of Embu (kale) and the local market in Embu (peas, zucchini) harvested on the first day of the experiment. They were randomly divided into four groups (CL was not used), whereas each group contained the same ratio of the different crop commodities. Each crate contained 7.5 kg ± 5 % vegetables (filled to 50 % of capacity). The filled crates were put inside the cooling systems and under permanent shade, respectively, and stored for five days. The experiment was replicated in the following week.

Metrics to analyze the cooling performance

The cooling performance of the PCBs was assessed based on the following key metrics: (1) interior air temperature, (2) interior relative humidity, (3) fruit core temperature, and (4) overall cooling efficiency (%). Multiple sensors were used to measure the hygrothermal conditions of the cooling systems during the experiments. The sensors were placed in the following locations:

- In the center of each crate, between the fruit (air temperature and relative humidity), Fig. 2b
- A core probe thermometer was inserted in one tomato per treatment at a penetration depth of 20 mm (fruit core temperature), Fig. 2b. The value was recorded on the days of the quality measurements at around 11.00
- A weather station close to the cooling blankets to record the wind speed at the same height as the cooling blankets
- A hygrothermal sensor next to the weather station for logging the ambient temperature and relative humidity

The specifications of the sensors are detailed in supplementary material (S3).

Metrics to analyze the fruit quality

For each commodity and treatment group, 20 randomly picked fruit of similar size and ripeness stage were analyzed at the same time in the morning on days 0, 2, 4, and 5 (for kale every day due to the high perishability) to assess quality deterioration (kale and peas) and post-harvest ripening (for climacteric tomatoes) during storage. For the tomatoes, weight, firmness, and color were measured non-destructively to enable repeated measurements of the same fruit during the experiment. For kale weight and color were measured, for zucchini and peas, only weight. Moreover, they were visually inspected for evidence of deterioration, such as fungal growth, dehydration, rot, and discoloration, using the rating scale by Kader and Cantwell (Kader & Cantwell, 2005), Table 2.

1. Weight measurement

The weight loss of the fruit (Eq. (3)) was determined using the KERN EMS 6K0.1 (Switzerland) precision scale (accuracy 0.1 g).

$$weight\ loss\ [\%] = \left(1 - \frac{m_t}{m_{init}}\right) \times 100\% \tag{3}$$

With the initial weight (m_{init}) at the start of the experiment and the changed weight mt during progressed storage.

2. Color measurement

Surface color values were measured using the Colorpin Pro (NCS, Sweden). On each tomato, readings at two predefined points on the circumference of the fruit (sun and shade sides) were conducted, and the average was recorded. For the kale leaves, the measurements were taken within two diagonally lying quadrants, the first measurement one-third from the midrib, the second one-third from the leaf edge. For the tomatoes, the redness values were determined as a*/b* ratio. For kale, hue angles were calculated as $\tan^{-1}(b^*/a^*)$ (Camelo & Gómez, 2004; Gutiérrez-Rodríguez et al., 2012).

3. Firmness measurement

In conformity with Schouten et al. (Schouten et al., 2007), the firmness of the tomatoes was measured non-destructively using a hand-held fruit pressure tester (Type FT 327, QA Supplies, USA) with a cylindrical stainless-steel plunger (11 mm). Two measurements were performed per fruit at opposite spots, midway between the stem and blossom end. Firmness was determined as the force [kg] necessary to compress the tomato 1 mm at a uniform speed (no penetration). Readings were recorded to the nearest 0.1 kg.

Table 2
Rating scale for fruit quality assessment by Kader and Cantwell (2005).

Rating	Description
1	extremely poor quality (not usable)
3	poor quality (serious deterioration, limit of usability)
5	fair quality (deterioration evident, but not serious, limit of saleability)
7	very good quality (minor symptoms of deterioration, not objectionable)
9	excellent quality (essentially no symptoms of deterioration)

Methodology for the interviews with target users

Structured individual interviews were conducted with farmers and fruit vendors in the County of Embu, Kenya. The design of the questionnaires was based on the previous interviews on evaporative cooling of MIT's D-Lab (Verploegen et al., 2018; Verploegen et al., 2019). The interviews examined the types of crops produced, respectively sold, existing storage methods for fresh produce, the need for improved storage technology, the availability and cost of materials used for the passive cooling blanket, as well as the willingness to adopt the concept. Thirty respondents were randomly selected near Karurumo and Embu (20 farmers, 10 vendors). KoboToolbox was used as a data collection tool. Details of the survey methodology are discussed in the supplementary material S5.

Cost calculation for the use of the blanket

To quantify the economic benefit of using the cooling blanket, the payback period was calculated for farmers and fruit and vegetable vendors. It represents the period needed to recover from the investment (Eq. (4)) (Tilahun, 2010). Assumptions for the cost calculation were made based on the results of the field experiments and testimonials of the fruit vendors.

$$Simple\ payback\ (in\ years) = \frac{cost\ of\ investment}{annual\ cash\ inflow} \tag{4}$$

Data analysis and statistics

For the monitored cooling performance, the sensor data was plotted, and the aforementioned metrics between the treatment groups (mean values and standard deviation) were compared. Measured weight, firmness, and color values were averaged for each treatment per day and analyzed with a repeated-measures ANOVA (F-test) for differences between the treatments. A Tukey HSD was conducted as a post hoc test. All data analyses were performed using ORIGIN 2022 while the statistical tests were performed with IBM SPSS Statistics (version 29).

Results and discussion

How well did the blanket perform in cooling down and preserving vegetables?

Hygrothermal analysis of air and fruit cooling

To assess the cooling performance of the different systems, the sensor data is plotted in Fig. 4, showing (a) the ambient, wet-bulb, and interior temperature of the air and the fruit core temperature and (b) the humidity of the cooling blanket (CS), the charcoal cooler, and the control group in the shade for the first experiment for 5 days. For reasons of clarity, the data on the other two PCBs (SS and CL) and the data on the second experiment are included in the supplementary material (S4).

At first glance, it is already noticeable that the PCB and charcoal cooler performed very similarly. This indicates that the passive cooling blanket could serve as a viable alternative to the large charcoal cooler room. Taking the sensor data of all experiments into account (not only the data displayed in Fig. 4), the air temperature of the PCB CS was, on average 18.7 °C, and the charcoal cooler was slightly lower (18.4 °C). This corresponds to a temperature reduction of 3–5 °C. These values are in the same order of magnitude as those Defraeye et al. achieved with the PCB in laboratory experiments (reduction of 5 °C) (Defraeye et al., 2024). Furthermore, both coolers successfully reduced peak

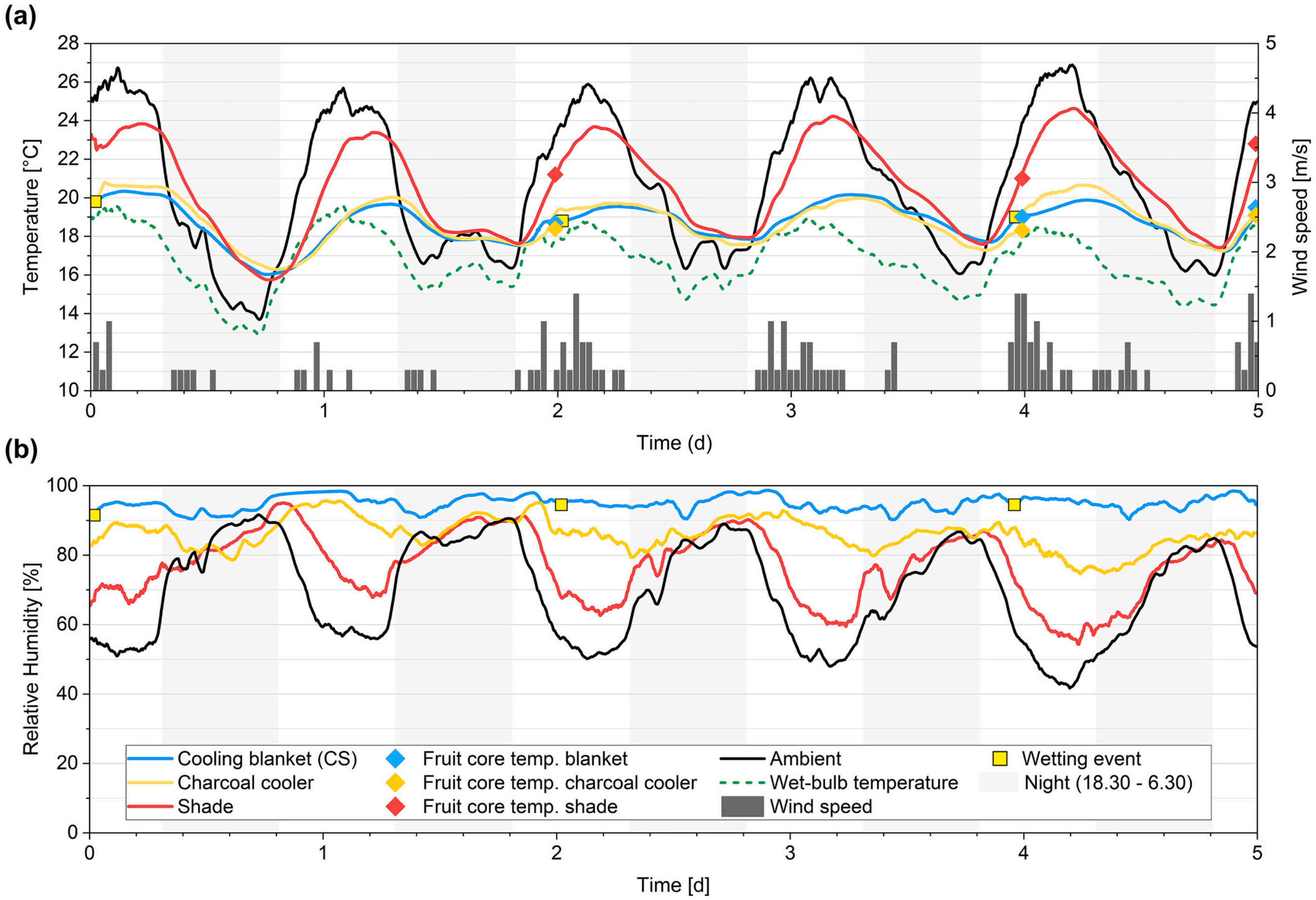

Fig. 4. Hygrothermal sensor data of the first field experiment (storage of tomatoes): a) Plot of air temperatures as a function of time; b) plot of relative humidity as a function of time. The legend applies to both diagrams. The average ambient temperature was 21 °C, the relative humidity 69 %, and the average wind speed was 0.19 m/s.

temperatures by up to 10 °C. However, it is not the air temperature that is decisive for preserving vegetable quality, but that of the product itself. Due to the low thermal conductivity of fruit, the temperature will respond with a time lag, and the produce will often experience less fluctuation than the surrounding air. At the individual measurement times, the fruit core temperatures always coincided with the air

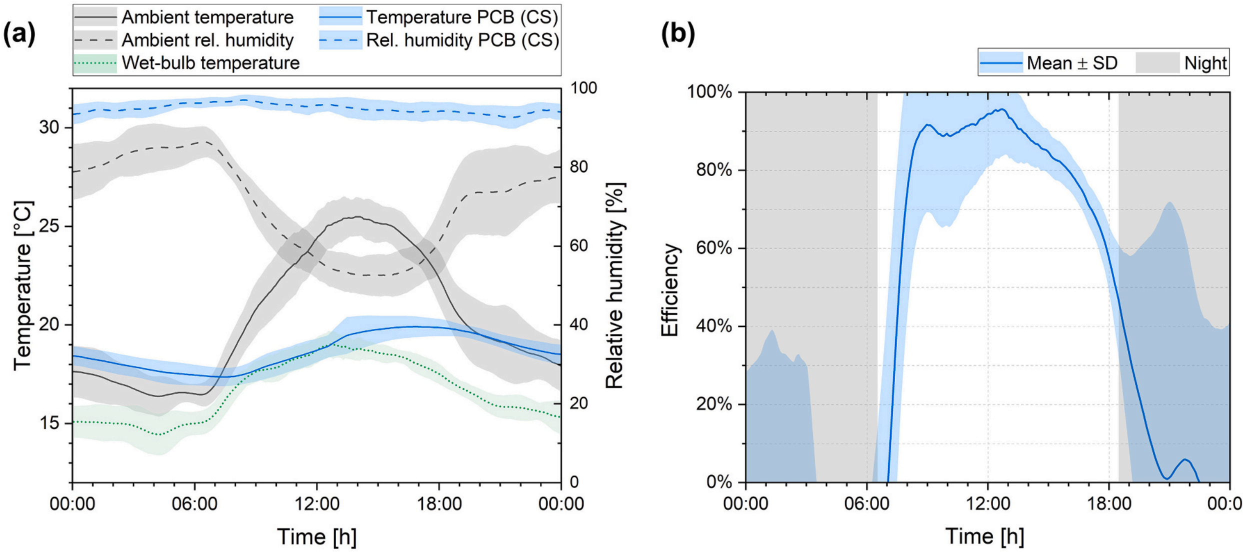

Fig. 5. a) Hygrothermal fingerprint of the small charcoal cooling blanket (PCB CS) for July in Karurumo (Kenya), based on the empirical data from the experiments. Depicted are the averaged values of 10 days with the standard deviation (SD) as a band. The average ambient conditions were 20 °C and 72 % RH. b) Cooling efficiency of the cooling blanket based on the experimental data.

temperatures inside the system (±0.5 °C), since the cooling process is rather slow and the fruit cools relatively uniformly and follows the air temperature fluctuations. Therefore, the air temperature already provides a good reference point as a proxy for fruit temperature due to the slow fluctuations in the cooler.

Regarding relative humidity, the PCB maintained an average of 95.0 % (SD ± 2.4), the charcoal cooler with 91.0 % (SD ± 3.3), so 4 % less. High relative humidity prevents water loss (desiccation and dehydration) of fresh produce. For the stored vegetables, the optimum relative humidity ranged between 90 and 98 % (Suslow & Cantwell, 2023; C. of A. S. Oregon State University, 2023; The Engineering ToolBox, 2023). Therefore, the cooling blanket, in particular, provided very good hygric conditions to preserve the vegetable quality, which is discussed in detail in below. Also, in this regard, the blanket could serve as a viable alternative to the large charcoal cooler room.

Since temperature and humidity exhibited oscillatory behavior on a daily basis, the data can be displayed in aggregated form for 24 h (mean values ± SD). In this way, a distinctive hygrothermal *fingerprint* of the cooling blanket for that particular time of year at that location is generated (Fig. 5a). This allows fast identification of parameters like the time of the largest temperature reduction (12.00–16.00) or the maximum temperature fluctuation of the PCB. Such fingerprints depict the average hygrothermal performance of the blanket. Thus, they allow a fast visual comparison of evaporative coolers deployed at different locations or times of the year.

The efficiency of the cooling blanket (CS) is displayed in the same manner in Fig. 5b. It becomes apparent that the efficiency during the day was on average 70 %, which is in accordance with previous research about evaporative coolers (Wayua et al., 2012; Rong et al., 2017; Lal Basediya et al., 2013; Ronoh et al., 2020). Towards the end of the day, the efficiency decreased quickly, and the systems did not provide any cooling effect at night. The nighttime air temperature even drops below the temperature in the PCB. This can be explained because the response of the interior air temperature was too slow to reach the ambient temperature (or lower). This delayed adjustment of the systems is favorable during the day because it helps to maintain the cool temperature from the night and reduces the daily fluctuations significantly. While the ambient temperature in Karurumo fluctuated by up to 17 °C throughout a given day, the temperature inside the cooling blanket varied by 2–4 °C. It is beneficial to preserve fresh produce if the temperature inside the cooler remains constant and does not fluctuate greatly daily, even if the average temperature drop is not significant (Verploegen et al., 2019). This can also prevent condensation problems from occurring. Apart from a reduced fluctuation, the temperature in the cooler must remain as low as possible throughout the day, so over prolonged times, as the high-temperature damage is a cumulative effect. Short peaks in temperature do not necessarily have a detrimental effect, but prolonged exposure to higher temperatures is detrimental to food quality.

Comparing the different sizes of the blankets, it was observed that the small and large charcoal blanket performed similarly ($\theta_{CL,mean}$ = 18.8 °C, $\varphi_{CL,\ mean}$ = 94 %). This suggests that the system can be easily scaled up and down without reducing the efficiency. A graphical representation of the results can be found in the supplementary material (S4). In the second field experiment, SS was tested as a direct cooler, where the crate is more exposed. It was found that the interior conditions adjusted much faster to the environment than for the standard (airflow) configuration of the PCB (Fig. 3). The interior temperature for this setup was similar to the control group in the shade (max. 1 °C lower). However, the interior humidity remained at about 90 % most of the time; therefore, it was higher than in the control group.

Considering the impact of the different padding materials, the interior temperature of the blanket filled with sawdust was, on average, about 1 °C higher ($\theta_{SS,\ mean}$ = 19.5 °C, $\varphi_{SS,\ mean}$ = 96 %) than charcoal (refer to Supplementary Material S4). One reason for this performance is that sawdust is denser and can restrict airflow through the blanket walls compared to charcoal. This could slow the evaporation process, hence the cooling effect, taking the temperature further away from the theoretical limit (wet bulb temperature). However, SS still provided a significant improvement compared to the control group. Moreover, the material brings further advantages: i) it is a sustainable material that is a by-product of woodworking and can be obtained for free; ii) due to the lower area density and smaller particle size, the blanket is light and flexible, which makes it very user-friendly. This is a major benefit, especially where fruit vendors are the primary users. iii) Preliminary laboratory experiments revealed that with external airflow (e.g., fan-driven), the system can maintain high humidity for longer than charcoal, likely as it can absorb and store more water. Depending on the region where the blanket is deployed, the availability of materials used for the cooling pad might vary. A large and growing body of literature has investigated alternative pad materials, particularly as a sustainable replacement for charcoal, such as coconut coir or rice husk (Singh & Yadav, 2012; Kapilan et al., 2023), which are also suitable as alternative materials for the cooling blanket.

During the experiments, the wind speed was on average 0.17 m/s (SD = 0.29), which is low for that location, as derived from the wind rose in S4. No impact of the wind (speed) on the cooling performance could be observed. This implies that the blanket is already effective for low airflow rates, confirming the results of Defraeye et al. (Defraeye et al., 2024). Higher airflow rates might promote evaporation and reach a temperature closer to the wet bulb temperature.

Due to the significant differences in storage capacity between the blanket and the charcoal cooler, the latter was operated at a lower fruit loading capacity (<1 %) than the cooling blankets (15 %) which ensured practical feasibility and minimized food waste during the experiment. The cooling performance differs if more fruit is stored inside because more mass needs to be cooled down, and more heat energy is stored, respectively, generated by respiration. Therefore, it can be expected that the efficiency of the charcoal cooler would be lower if it were operated at a higher capacity, at least for the first day. The thermal time constant of the system is strongly dependent on the amount of fruit that is stored inside. The cooling systems were not filled to their maximum because the primary objective was to determine the potential to cool down the interior air. It is beyond the scope of this study to examine how long it takes to cool down a whole batch of fruit. Moreover, in practice, evaporative coolers and even cold storage rooms with active cooling are usually not filled completely at once (Defraeye et al., 2024).

Lastly, it is worth mentioning that the achieved cooling effect by evaporation must always be interpreted in relation to the environmental conditions, as they drastically affect its potential. The experiments were conducted in season with low evaporative cooling potential but when the foods of interest were harvested. Thus, the temperature drop will be even higher for hot and dry conditions (so between Nov–March). However, we should remember that using evaporative cooling for farmers is only relevant during harvesting time. Otherwise, there is no need for improved storage.

Fruit quality evaluation

In the postharvest fruit supply chain, the quality of individual units is primarily assessed by their appearance (Schouten et al., 2007). For most fruit and vegetables, the key quality attributes related to appearance are color, firmness, absence of defects, and shriveling due to water loss (Tilahun, 2010; Suslow & Cantwell, 2023; C. of A. S. Oregon State University, 2023). For the selected commodities, loss of weight, firmness, and color change were measured non-destructively to analyze the effectiveness of the PCB in preserving fruit quality.

Shelf life. To assess the overall gain in shelf life when stored in the cooling blanket, a rating scale was used to evaluate the quality of the fresh produce visually. The results are summarized in Fig. 7. For all fruit, the PCB (CS) slowed down the quality degradation compared to storage in the shade. For instance, in the first two days, the saleable quantity of kale was 45 % higher when stored in the cooling blanket (Fig. 7 only displays mean values). PCB CS and CC performed very similarly, only for kale, the difference was greater. This is likely attributed to the higher relative humidity inside the blanket, which is favorable for the storage of most leafy vegetables. Looking at the cooling blanket as a direct cooler (SS), it becomes clear that this configuration did not perform as well as the standard airflow setup due to the more open design which can maintain the temperature less effectively. Nonetheless, the vegetable deterioration was still decelerated compared to storage under shade. Therefore, this configuration is still interesting for intermediate, short-term cooling, or even while transporting, as it is very quickly assembled.

Tomatoes were solely evaluated at the end of the experiment for any visual defects. After five days of storage, the postharvest losses of tomatoes stored in one of the evaporative coolers ranged from 2 to 4 % and were 26–28 % lower compared to storage in the shade. With lower losses, more tomatoes will reach the market in a saleable condition, thereby maximizing potential revenue for farmers or traders.

Weight loss. Weight loss results in reduced freshness, evidenced by shriveling, wilting, and loss of firmness and crispness (Ambuko et al., 2017). Fig. 8 shows the weight loss of all crops when stored for up to five days. For kale, zucchini, and peas, the statistical difference between the groups was significant ($F(3,76) = 21.927$, $p < .001$; $F(3,71) = 22.719$, $p < .001$; $F(3,76) = 78.53$, $p < .001$) and the weight loss in the shade was significantly higher than for PCB CS and the charcoal cooler (see Fig. 6). This means that the impact of PCB on how much weight is lost depends on the type of fresh produce being stored. Also, vegetables lost more weight when they were kept in the shade than when they were kept in the PCB CS or the charcoal cooler. Regarding tomatoes, weight loss was also highest in the shade. However, the intergroup difference was not statistically significant. In the case of kale and peas, it should be considered that already a small absolute weight loss makes a major difference in relative terms due to the low individual weight of the vegetables. In addition, the saleability of these products is also most sensitive to weight loss.

When examining the different cooling blankets, it can be observed that the blanket filled with sawdust (SS) performed comparably well in the tomato storage trial which confirms that sawdust and charcoal have comparable physical properties and are both suitable for the evaporative cooler. Like for the overall shelf life also regarding weight loss, the alternative configuration (direct cooling) for the experiment with zucchini, peas, and kale was notably less effective in preserving the vegetables. Nevertheless, the observed weight loss was still lower than when stored in the shade (on average 20 % less). Furthermore, the weight loss attributed to the storage in CC was, on average, 3 % higher than for PCB CS. Again, this difference is likely due to the higher humidity in the blanket, which plays a significant role in reducing weight loss.

Overall, the cooling blanket (CS) reduced the average weight loss for all produce by 50–60 % compared to storage under shade a result of the constant high relative humidity. The difference was most pronounced for kale and zucchini. Since fruits and vegetables are typically sold by weight, the use of PCBs can result in up to 60 % more profit for farmers or traders by minimizing weight loss during storage. Essentially, this highlights how using PCBs not only helps reduce postharvest losses but also directly impacts profitability for small-scale stakeholders within the local horticultural value chain.

Color change. During the ripening and senescence process, many fruits and vegetables undergo color changes. Typically, the green color of

Fig. 6. African kale, zucchini and peas stored for 5 days under shade (a–c) and in the small charcoal cooling blanket (d–f) for the second field experiment. Storage in the cooling blanket slowed down weight loss and general quality deterioration.

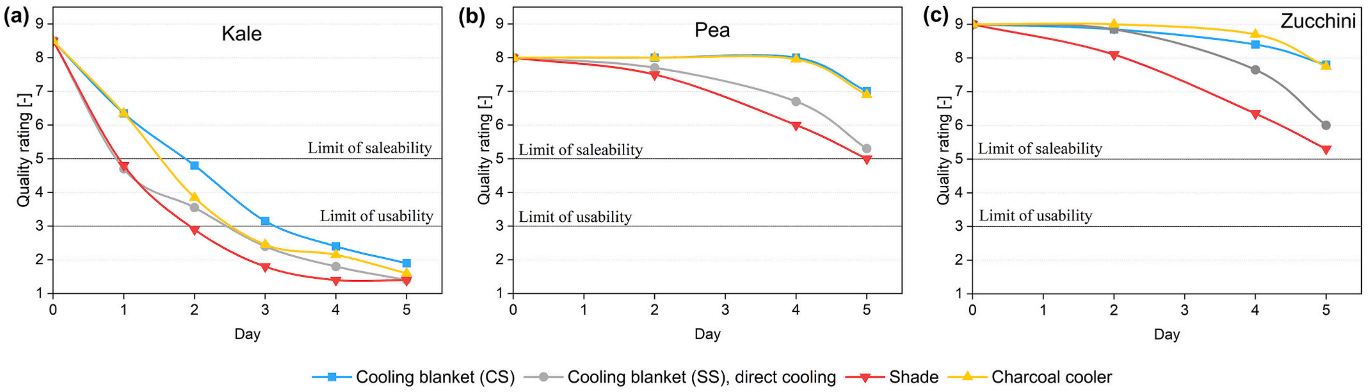

Fig. 7. Overall quality reduction including limit of saleability and usability based on the rating scale from Kader and Cantwell (2005), Table 2, for a) Kale, b) Peas, and c) Zucchini. Displayed are the means of the samples.

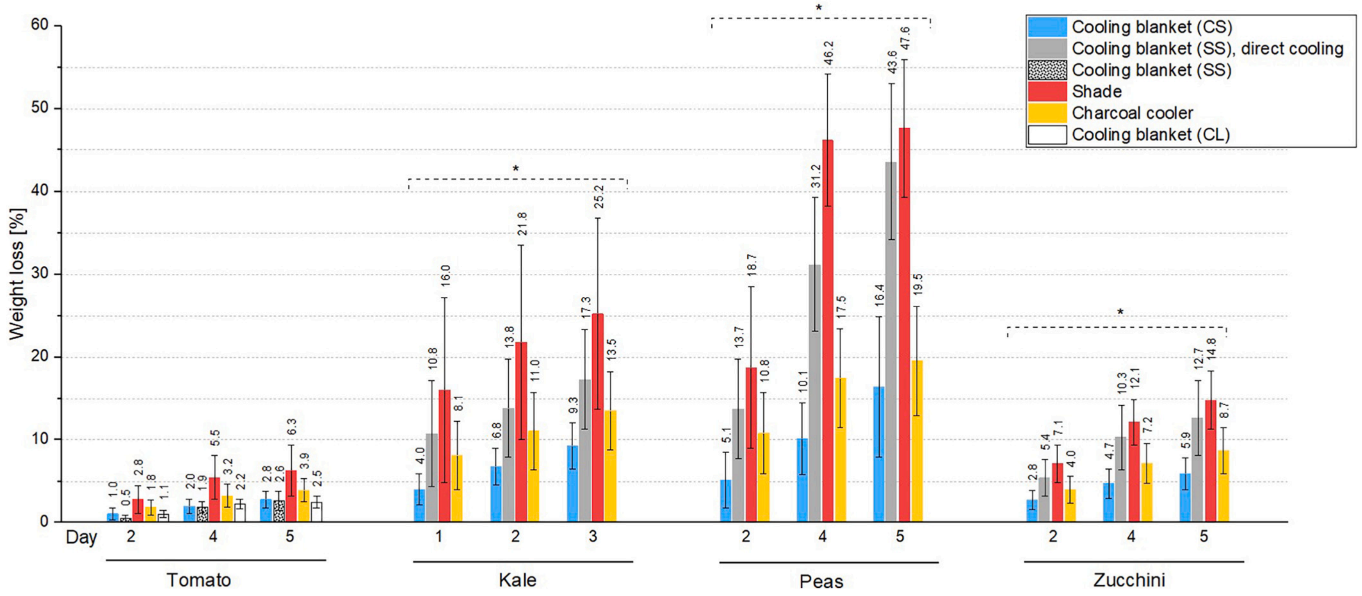

Fig. 8. Weight loss [%] for storage up to 5 days in the small charcoal blanket CS, the charcoal cooler, the small sawdust blanket SS (as airflow cooler or direct cooler), the large charcoal cooler CL, and in the shade compared to the start of the experiment (day 0) of four crops. Values are presented as means ± SD. The statistical intergroup difference is marked (* = $p < .05$).

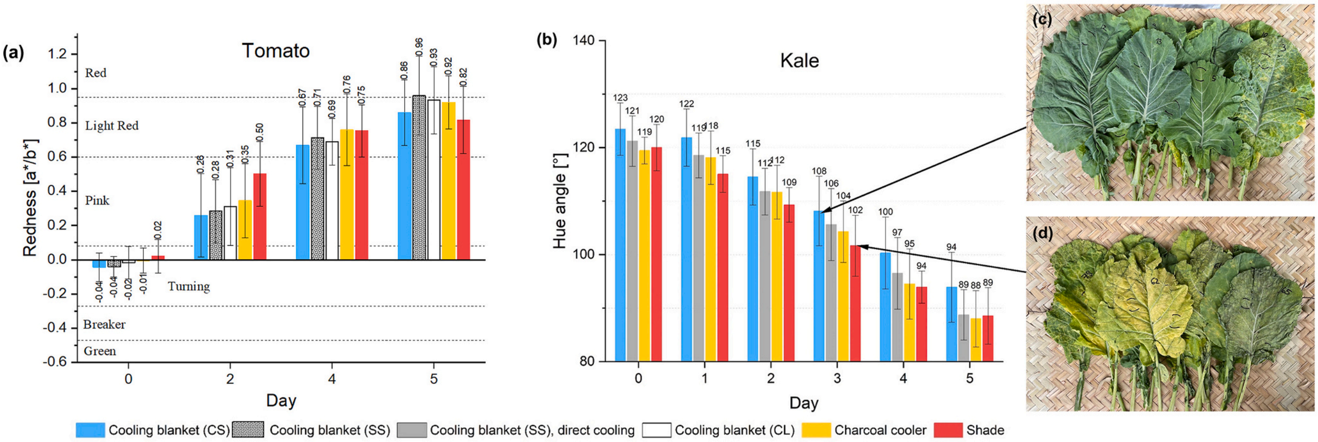

Fig. 9. a) Redness of tomatoes and b) Hue angle of kale leaves when stored for 5 days in different systems: CS = small charcoal blanket; CL = large charcoal blanket; SS = small sawdust blanket. Values are presented as means ± SD. Color classification of tomatoes derived from Batu (2004). Kale leaves after three days of storage in c) the cooling blanket (CS) and d) an open crate under shade. The average ambient conditions during the experiment were 21.0 °C and 66.8 % relative humidity.

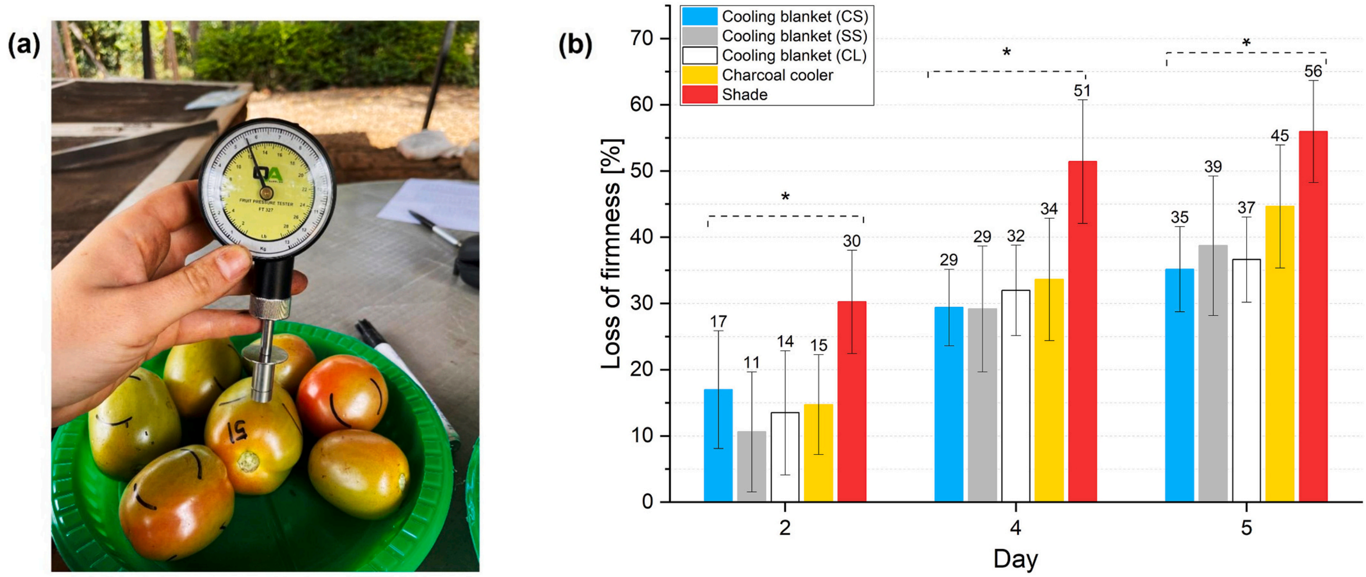

Fig. 10. a) Photo of the analog firmness tester. b) Loss of firmness of tomatoes when stored for 5 days in different systems: CS = small charcoal blanket; SS = small sawdust blanket; CL = large charcoal blanket. Values are presented as means ± SD. The statistical intergroup difference is marked (* = $p < .05$).

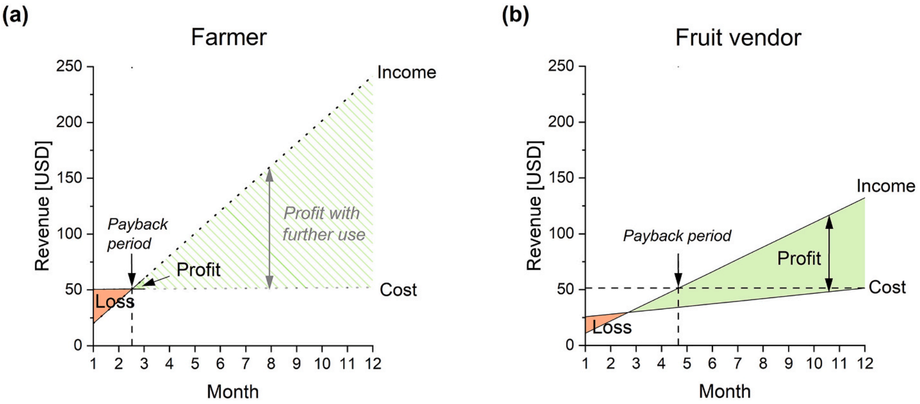

Fig. 11. Graphical representation of additional income and costs when using the cooling blanket as a function of time for a) farmers and b) fruit vendors, as well as the payback period.

unripe fruit becomes lighter due to the breakdown of chlorophyll and underlying yellow and red pigments are revealed (or synthesized, such as carotenoids in tomatoes). Fig. 9 shows the color change of tomato and kale during storage. The color change in tomatoes is due to ripening, while in kale it indicates decay. For both crops color change is a strong indicator of shelf-life (Farneti, 2014; Cantwell et al., 2012).

Fig. 9a–b implies for both commodities that the storage in an evaporative cooler did not noticeably decelerate the color transformation greatly, and the intergroup differences were not statistically significant. Fig. 9c–d kale leaves after three days of storage in the PCB and under shade, illustrating how a difference of ~6° in hue angle is perceived visually. From the pictures, it is visible that not only the color change plays a crucial role, but also that the PCB preserved the overall quality of the leaves better as they are less brittle and wrinkled.

Color change during storage is related to many pre- and postharvest factors, such as temperature, light, abiotic stress, or mineral nutrients and ripeness after harvest (Farneti, 2014). The achieved temperatures inside the cooling systems were always above the optimal temperatures of the stored fruit. Thus, it seems reasonable that no significant improvement regarding color change was reached with evaporative cooling. This means that the color change is not that sensitive to the significant reduction in temperature change. This finding shows that PCBs could potentially help farmers and traders sell fresher and visually appealing vegetables to consumers, enhancing customer satisfaction and loyalty.

Firmness. For tomatoes, loss in firmness was measured as an additional quality attribute (Fig. 10). Softening during storage and distribution is a major problem as the tomatoes become more susceptible to physical damage and it also reduces the marketability (Batu, 2004).

The difference between the treatment groups was statistically significant ($F(4,95) = 6.76, p < .001$), and storage in an evaporative cooler reduced firmness loss greatly compared to storage under shade (Fig. 10 b). After two days, the tomatoes in the control group lost 13 % more firmness and even 21 % more after five days. Hence, CS reduced the firmness loss after five days by 35 % compared to the control group. The other blankets (SS and CL) and the CC performed slightly worse but still provided a significant improvement in the reduction of the firmness loss (24–28 %) which is consistent with the results of weight loss from the tomatoes in the different blankets. At this point, it should be noted that a manual, analog fruit pressure tester was used (Fig. 10a), resulting in inevitably lower measurement accuracy compared to digital penetrometers. In general, storing vegetables after harvest using the passive cooling blanket helps to reduce the loss of firmness. For example, tomatoes can be stored successfully for at least five days in the PCB, while still having a marketable firmness compared to storage in the shade.

Why are evaporative coolers not more commonly used, and how is the willingness to adopt the cooling blanket?

All of the interviewed farmers and vendors grew and sold various vegetables that are suitable to be stored inside the cooling blanket (more information on which fruits and vegetables can be stored in an evaporative cooler is included in the Supplementary Material, S5). Interestingly, one third of the respondents stated that they would want to use a (different) storage method but at the same time the percentage of those who would test and adopt the cooling blanket was very high at 97 %. This discrepancy indicates that the farmers and fruit vendors have worked out a way that functions well for them. Still, they also realize the great potential benefits of a cost-effective storage method. The reasons for not using a storage device, such as the high manufacturing/acquisition costs, do not apply to the cooling blanket, which explains the entirely positive resonance. But, more awareness and training on PCB needs to be done in these areas for it to have the intended impact.

The potential advantages of using a system like the passive cooling blanket differ slightly for farmers and vendors. For the former, it may primarily increase the flexibility of the harvesting time and prolong the marketability of the produce, which in turn would lead to a competitive advantage over other farmers. On the other hand, vendors are facing higher food losses. Hence, with the cooling blanket, they could be reduced due to the extended shelf life of the fresh produce, which will also result in an economic advantage. Compared to other evaporative coolers, the cooling blanket provides the properties the vendors would need, such as the required storage volume (contrary to clay pot coolers, (Mogannam et al., 2022)), the mobility of the system, and low cost to purchase and operate (different from charcoal coolers). Possible bottlenecks for adopting the system are mainly the acquisition of burlap and the insufficient storage capacity for medium-sized farmers. Further research would be interesting to investigate how widespread burlap is in other target countries of evaporative coolers and to test alternative, locally available fabrics.

Economic evaluation of using the cooling blanket

Assuming a farmer would use a large cooling blanket filled with sawdust and three crates capacity (=90 kg tomatoes), the annual costs to purchase and operate the cooling system accumulate to USD 51 in the first year (Fig. 11a). For the cost calculation, an exchange rate of 1 KES = 0.007 USD was used. Compared to the traditional charcoal cooler, the investment costs of the PCB are 6–12 times lower (based on the testimonies of local farmers). The financial advantage is attributed to the minimal expenditure on both materials and operational expenses.

We assumed that the blanket is only used within three months of low demand for tomatoes in Karurumo (May to August), and this would allow the farmer to sell 20 % more of the harvested batch that otherwise would spoil before being sold. In addition, all tomatoes can be sold for an additional USD 0.07 per kg on average as the farmer can dictate the terms of sale and price more. If per month, the cooling system is entirely filled twice (=180 kg per month), the cost-benefit calculates to USD 60, with tomatoes valued during that season at USD 0.21 per kg [3 months* (0.2*180 kg*0.21$/kg +180 kg *0.07$/kg)]. The detailed cost analysis can be found in the supplementary material (S6). This corresponds to a payback period of 0.85 years for the first year using Eq. (4). However, the number is misleading when related to a whole year (which would imply 10.2 months), as the actual period of use is only three months. If related to three months, the payback period coincides with the intersection of the total cost and income curve, as shown in Fig. 11a (payback calculated to 2.6 months). The steep income curve in Fig. 11a indicates that the potential profit would be much higher if the farmer used the blanket for a longer period, which is likely if a variety of crops is grown.

For the fruit vendors, it is assumed that they use a small cooling blanket filled with sawdust and with the capacity of one crate (=30 kg of tomatoes). The annual costs to purchase and operate the cooling system would accumulate to USD 51 in the first year as well (Fig. 11b). As the material increases quasilinear with the blanket's size, the material costs are lower than for the farmer. However, the estimated labor costs are higher as the vendor needs to assemble the system daily (accounting for 53 % of the total annual costs). Hence, costs increase more over time than for the farmer, whose variable costs derive only from the water consumption to operate the cooling system. Although, the flat cost curve in Fig. 11a illustrates that it contributes little to the total cost.

Furthermore, it is assumed that the cooling blanket would help reduce the amount of spoiled tomatoes by 5 % daily (which is a low estimation considering the reduction in PHL over 5 days during the experiments was 26–28 % for tomatoes). Consequently, the retailer could sell an additional 1.5 kg of tomatoes per day, resulting in an added annual income of USD 134, using an average price of tomatoes of USD 0.32 per kg [1.5 kg * 0.32 $/kg * 280 d]. Subsequently, the payback period is calculated to be 0.4 years for a storage space of 0.06 m^3 for tomatoes, meaning the cost of the investment is recovered after five months. Thereby, it becomes evident from Fig. 11b that the vendor can expect to reap the financial benefits within three months.

Conclusions

We investigated the potential of the passive cooling blanket (PCB) to preserve vegetables and, ultimately, improve postharvest storage in a real-world setting. We did this by deploying two different-sized cooling blankets using sawdust and charcoal as natural padding materials to store climacteric tomatoes and non-climacteric kale, zucchini, and peas in Kenya. The cooling blanket could significantly extend the shelf life of various fruits and vegetables, and reduce postharvest losses by up to 45 %. The largest impact of PCB was observed for highly perishable vegetables. The key findings of our study are as follows:

- The blanket successfully reduced air and fruit temperature by up to 10 °C compared to ambient conditions and at the same time maintained a constant relative humidity of around 95 %. The cooling blanket (both the small and the large one) performed very similarly to an established stationary charcoal cooler.
- The average cooling efficiency of the PCB was 70 % during daytime operation.
- The cooling blanket significantly extended the shelf life of fruits and vegetables, and postharvest losses were reduced by up to 45 %, depending on the product. Especially for highly perishable vegetables, which should optimally be stored at relative humidity levels of 95–98 % (such as kale), a substantial improvement in shelf life and overall quality was observed compared to ambient storage.
- Regarding the individual quality attributes, the difference between storage in PCB and shade was most pronounced for firmness and weight loss.
- With PCB, weight loss was lowered by 50–60 % compared to shade storage, especially for kale and zucchini. In addition, firmness loss in tomatoes was reduced by 35 %, and saleable quality was significantly preserved, particularly in leafy vegetables like kale.
- One key feature of the blanket is its scalability. No significant difference in cooling performance of both blanket sizes and the large charcoal cooling room was observed (although with different loading capacity), which advocates the suitability for up- and downscaling of the PCB.
- The blanket provides the benefit that any padding material can be used. Even though charcoal as a padding material achieved overall lower temperatures, sawdust has also emerged as a suitable material choice, mainly due to the ease of use of the blanket and the sustainability aspects. In general, the materials required for the blanket

are natural and can be obtained locally. This makes the system environmentally friendly and cost-effective.

- To be adopted by the intended user, the technology's benefits must outweigh the investment costs and cost of additional labor. In this respect, the blanket has substantial value. The payback period calculation has shown that for both main stakeholders, smallholder farmers and fruit vendors (traders), a profit can already be recorded after three months (at moderate use). Traditional charcoal coolers, by contrast, require an initial investment that is 6 to 12 times higher. Given the significantly lower cost of the passive cooling blanket, combined with its short payback period of approximately three months under moderate use, the technology presents a more accessible and economically attractive option for smallholder farmers and traders. This affordability strongly contributes to a higher willingness to adopt the system compared to conventional charcoal cooling solutions.

From a practical and managerial perspective, the PCB offers a highly adaptable and scalable storage solution that fits the needs of smallholder farmers and market vendors. It requires minimal capital, uses natural and locally available materials, and demonstrated profitability. In contrast, traditional charcoal coolers are harder to scale. The socio-economic impact of the PCB is substantial. By extending shelf life and reducing weight loss, the system enables farmers to reach more distant markets where demand is higher. This leads to expanded business opportunities and increased market competitiveness, ultimately improving both revenue potential and food security. Farmers and vendors showed a 97 % willingness to adopt the PCB, highlighting its relevance, affordability, and acceptance in local contexts. Despite all these positive practical benefits of PCB, this study also acknowledges several limitations:

- Cooling performance may vary with seasonal and regional climate conditions even though this study was conducted during a season with relatively low evaporative cooling potential.
- The fruit loading capacity differed between systems, which may have influenced the comparative efficiency of the charcoal cooler.
- The study did not evaluate long-term durability or maintenance of the blanket under real usage conditions.

Future studies should therefore explore the cooling performance of several fruits and vegetables under high-temperature, low-humidity conditions (e.g., Nov–March in Kenya or other countries in Africa with different climatic conditions). The material durability and design optimization for frequent transport and field use should also be a focus of future study. The potential for solar or hybrid energy integration to power fan to further enhance airflow and blanket effectiveness should be explored. Broader economic modeling and life-cycle assessments to inform scaling and policy integration in local low-resource setting should also be a future focus. Finally, more campaigns, awareness, and training should be conducted for farmers and traders to highlight the benefits of storing their produce using PCB.

Overall, the passive cooling blanket demonstrates strong technical suitability, economic viability, and social acceptability for enhancing postharvest vegetable storage. With further refinement and outreach, it could play a vital role in improving horticultural value chains, reducing food waste, and increasing resilience and income for small-scale producers in the Global South.

CRediT authorship contribution statement

Theresa Wittkamp: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation. **Thijs Defraeye:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **Rebecca Yegon:** Writing – review & editing, Supervision, Methodology. **Daniel Onwude:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2025.101787.

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