

Evaluating passive evaporative cooling blanket for improved postharvest storage of fruit and vegetables in low- and middle-income countries

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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 m³ and 0.18 m³ 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 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 equally well or was 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 interesting 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.

Keywords: evaporative cooling, postharvest technology, cold storage, fresh produce

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1 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 more than 70% of the rural population in 2023 [1], [2]. However, in Sub-Saharan countries, postharvest losses are generally high – especially for fruit and vegetables, which are estimated at 30–50%. The main reasons for those significant losses are the lack of efficient and affordable storage solutions and improper handling practices [3]. Postharvest loss results in a decrease in farmer's income and reduced access to nutritious food [4]. 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 have negative externalities on society [5].

Proper storage conditions are crucial to preserve the quality of fresh produce after harvesting. For most fruits and vegetables, this means a cold and sufficiently humid environment to decelerate fruit deterioration, as temperature and humidity are the main drivers for degradation. Lower temperatures help to slow down the rate of spoilage and ripening processes. High relative humidity prevents moisture loss [6], [7]. Several initiatives currently promote the access of smallholder farmers or farmer groups to cooling facilities in developing countries [8], [9], [10], [11]. Yet, most cold storage techniques depend on electricity, which is not available, affordable, or stable in many rural parts of the country. Consequently, access to affordable and efficient postharvest storage solutions is often restricted, and farmers living in off-grid areas or with limited financial resources remain underserved [12].

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 [13]. It is considered one of the top 22 investable innovations that can transform food systems in emerging markets [14]. Several different designs of passive evaporative coolers exist, for instance, charcoal coolers, brick cooling chambers, or clay pot coolers [15], [16], [17]. 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% [18]. 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. For high ambient humidity ($\phi > 70\%$), the potential temperature depression is less pronounced since the maximal achievable evaporation rate is lower [19].

A considerable amount 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 [20]. Since passive evaporative coolers do not require any energy source, these systems are 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 [12]. Despite their huge potential, evaporative coolers are rarely deployed. For instance, a study in Kenya revealed that less than 1% of the farmers currently use charcoal or sand-and-brick evaporative coolers [21]. Major factors limiting the adoption are high capital costs, inappropriate storage capacity, and missing availability of the required materials, as well as the lack of awareness, expertise, and trust [18].

To address these drawbacks, Defraeye et al. recently developed a novel design for an evaporative cooler: the passive cooling blanket (PCB) [18]. 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. 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. 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 [22]. The most promising regions in the world to deploy passive cooling and the months in which the highest cooling effect can be achieved are depicted also in an open-source online map [23].

As a step towards further adaptation of the PCB in these countries, this study aimed to quantify the effectiveness of the PCB in maintaining postharvest quality and reducing losses of stored fruit and vegetables in Kenya. The cooling blanket was benchmarked against the common storage practice, namely under permanent shade in ambient conditions and a locally established large charcoal cooling chamber [15]. Moreover, the performance of different PCB padding materials was evaluated, namely charcoal and sawdust, as heat and mass transfer medium for the cooling of fruit. In the next step, a survey was conducted among smallholder farmers and local fruit vendors to develop a deeper understanding of the current need for improved postharvest storage methods and to obtain initial feedback on the concept of the PCB. Lastly, the profitability of using the blanket amongst different stakeholders was quantified. Overall, this study provides a critical basis to further advance the knowledge of the passive cooling blanket required to successfully promote the technology and, ultimately, improve postharvest storage in developing countries.

2 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 (capacity of 0.06 m³ and 0.18 m³) to preserve horticultural products was analyzed (Fig. 1). Storage under permanent shade and in a local stationary charcoal cooler of 40 m³ (CC, Fig. 1) served as benchmarks. The latter was built in 2020 by the University of Nairobi in collaboration with MIT's D-Lab [15]. The PCB was piloted in two different sizes (capacity of 0.06 and 0.18 m³), applications (airflow cooling, direct cooling), and with two padding materials (charcoal, sawdust). 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.



Figure 1: Overview 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.

2.1 Study area

Karurumo, Kenya is located at 1,439 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 [24]. The major crops of the county are tea, coffee, dairy, cassava, and horticultural crops such as tomato [25], [26], [27], [28]. 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 [29], [30], [31]. This strategic approach ensures that varieties 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.

2.2 Design and construction of the blanket

Three cooling blankets (two small ones with $L_b = 3$ m and $W_{co,e} = 0.12$ m, and one large blanket, $L_b = 5.25$ m $W_{co,e} = 0.15$ m) were made from burlap (180 g/m²) according to Figure 2a. For all blankets, the height of the compartments was 0.4 m (H_b). The first small PCB (referred to as CS, "Charcoal Small") and the large blanket (CL) were filled with charcoal. The second small cooling blanket (SS) was filled with sawdust from the sawmill residues. After filling, the length was reduced to 2.3 m (CS, SS) and 4.2 m for CL, respectively, due to the compartmentalization. The 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). Table 1 summarizes the main characteristics of the cooling systems used in the experiments.

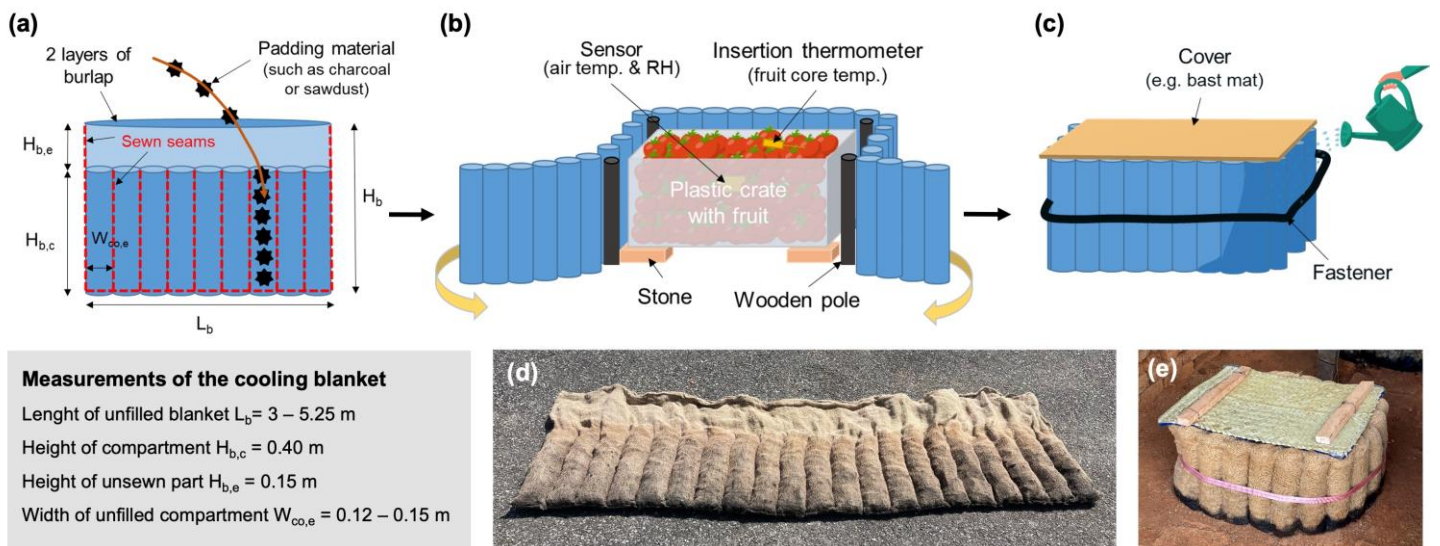


Figure 2: (a) Technical drawing of the cooling blanket. Each compartment is filled with padding material up to $H_{b,c}$; (b) Construction of the blanket exemplar for one crate with supportive structures; (c) Assembled blanket covered with a lid and watered for usage; (d) Cooling blanket filled with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

Table 1: Characteristics of the different cooling systems tested in the experiments. 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
Dimensions [m]	0.6 x 0.4 x 0.3	0.6 x 0.4 x 0.3	1.3 x 0.6 x 0.3	4.0 x 4.0 x 2.5
Storage capacity [m ³]	0.06	0.06	0.18	40
Storage capacity [MT]	0.03	0.03	0.10	2
Storage capacity [standard crates]	1	1	3	72
Water volume per wetting [l]	5	5	12	Automatic (volume unknown)

2.3 Field experiments

In the first field experiment, the aim was to compare the performance of the PCB in different sizes as well as that 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 x 0.40 x 0.24m, 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 vapor 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 as airflow cooler. The cooling blankets were constructed under a roof construction, 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). Note that adding too much water is not advised. The reason is that water is often at ambient temperature which implies that the charcoal would be loaded with a lot of “warm” water which needs to be cooled away again.

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 [32]. 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 \pm 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.

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 \pm 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.

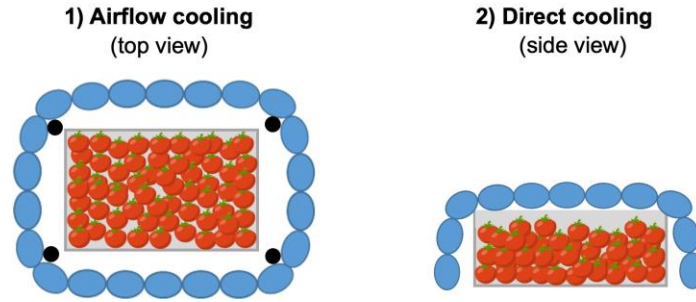


Figure 3: Operating configurations of the passive cooling blanket (in blue). For airflow cooling wooden poles (black circles) are used to obtain a gap between the blanket and the crate. Illustration not to scale.

2.3.1 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), Figure 2b
- A core probe thermometer was inserted in one tomato per treatment at a penetration depth of 20 mm (fruit core temperature), Figure 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).

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 [33]. 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 [23]. Following, the efficiency (η) of an evaporative cooling system is calculated as defined in Equation 1. T_1 is the air temperature reached inside the cooling system [34], [35].

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

2.3.2 Metrics to analyze the fruit quality

For each commodity and treatment group, 20 randomly picked fruit of similar size and ripeness stage were analyzed 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 postharvest 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 [36], Table 2.

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)

Weight measurement

The weight loss of the fruit (Eq. 2) was determined using the KERN EMS 6K0.1 (Switzerland) precision scale (accuracy 0.1 g).

$$\text{weight loss [\%]} = \left(1 - \frac{m_t}{m_{init}}\right) \times 100\% \quad (2)$$

With the initial weight (m_{iti}) at the start of the experiment and the reduced weight depending on the time or day (m_i), respectively.

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 $\tan^{-1}(b^*/a^*)$ [37], [38].

Firmness measurement

In conformity with Schouten et al. [39], 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.

2.4 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 [4], [19]. 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.

2.5 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. 3) [40]. Assumptions for the cost calculation were made based on the results of the field experiments and testimonials of the fruit vendors.

$$\text{Simple payback (in years)} = \frac{\text{cost of investment}}{\text{annual cash inflow}} \quad (3)$$

2.6 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).

3 RESULTS and DISCUSSION

3.1 How well did the blanket perform to cool down and preserve vegetables?

3.1.1 Hygrothermal analysis of air and fruit cooling

To assess the cooling performance of the different systems, the sensor data is plotted in Figure 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).

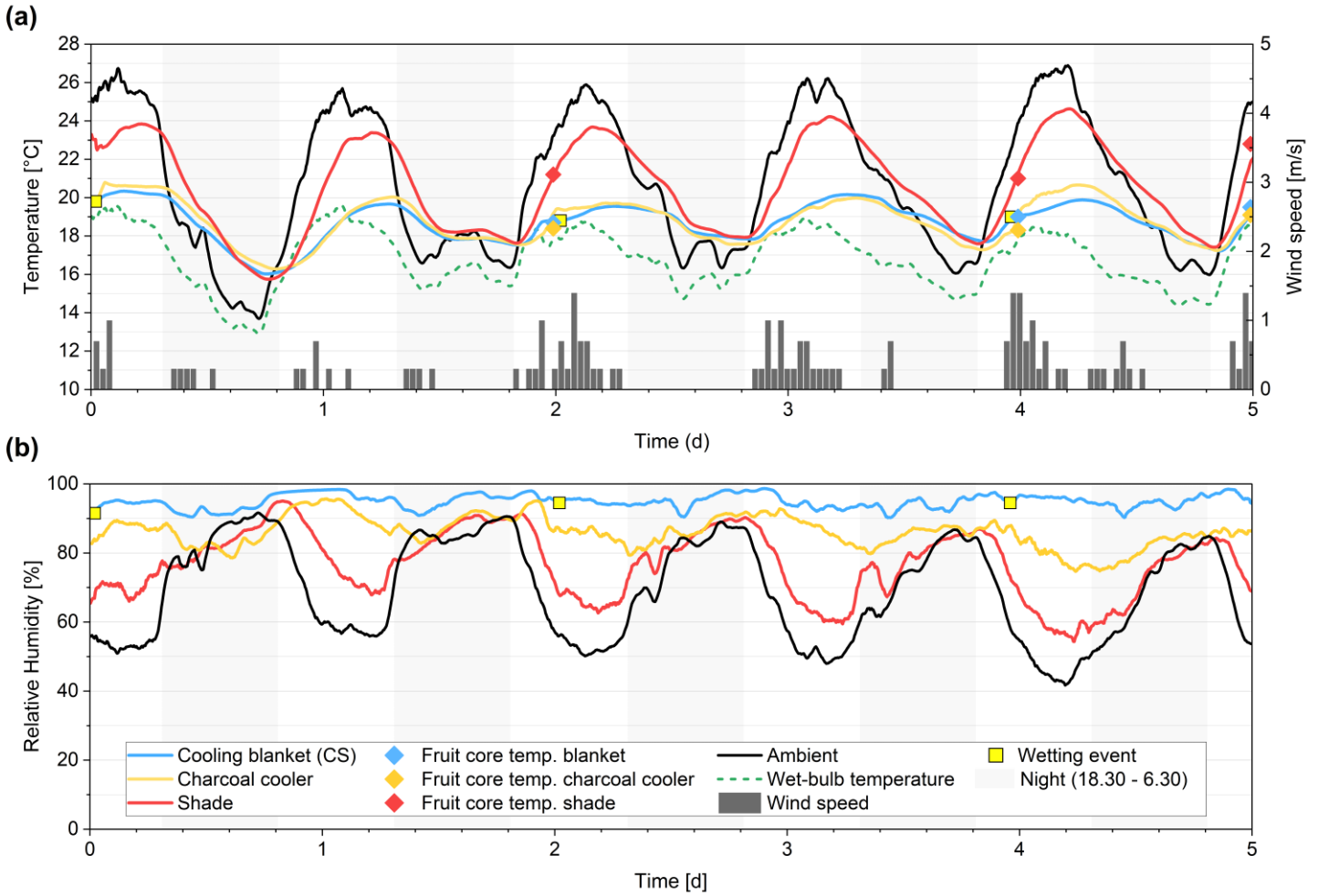


Figure 4: Hygrothermal sensor data of the first field experiment (storage of tomatoes): a) Plot of air temperatures as a function of time; b) plot of relative humidity as a function of time. The legend applies to both diagrams. The average ambient temperature was 21°C, the relative humidity 69%, and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

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 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) [18]. Furthermore, both coolers successfully reduced peak 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 temperatures inside the system ($\pm 0.5^\circ\text{C}$), 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 90–98% [41], [42],

[43]. Therefore, the cooling blanket, in particular, provided very good hygric conditions to preserve the vegetable quality, which is discussed in detail in section 3.1.2. 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 hours (mean values \pm 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 Figure 5b. It becomes apparent that the efficiency during the day was on average 70%, which is in accordance with previous research about evaporative coolers [27], [44], [45], [46]. 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 [19]. 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.

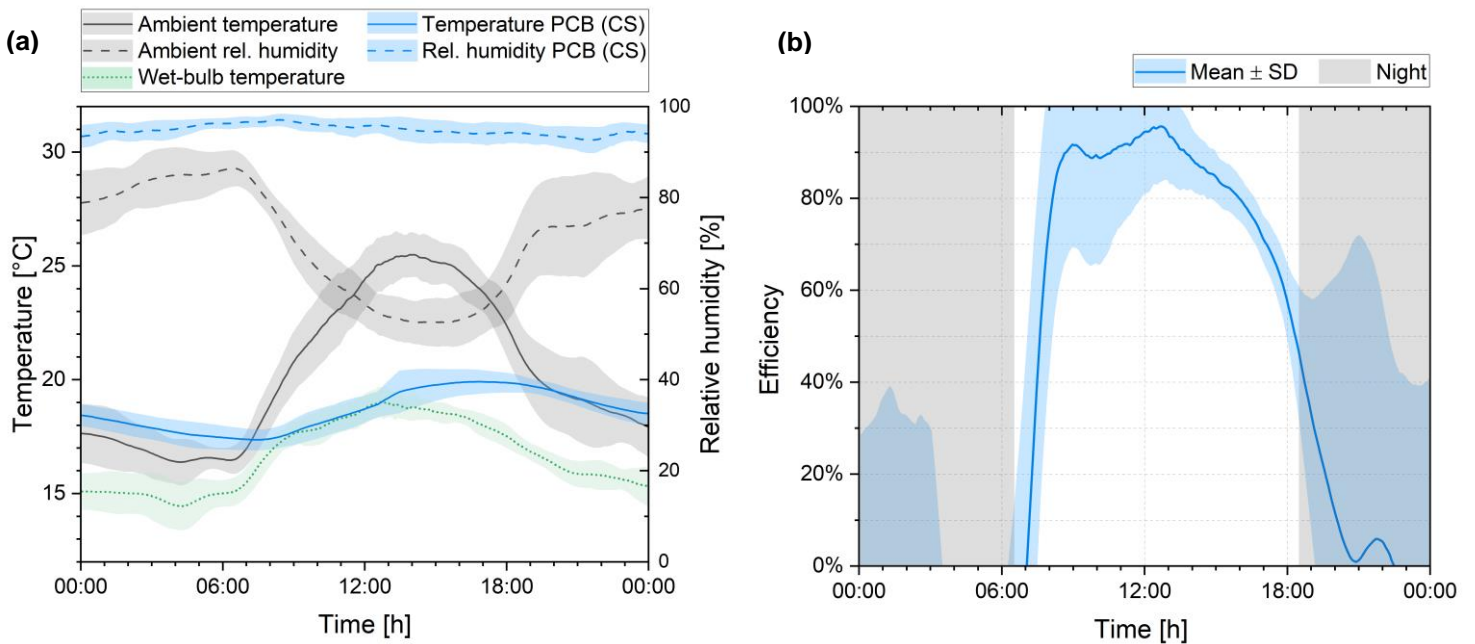


Figure 5: a) Hygrothermal fingerprint of the small charcoal cooling blanket (PCB CS) for July in Karurumo (Kenya), based on the empirical data from the experiments. Depicted are the averaged values of 10 days with the standard deviation (SD) as a band. The average ambient conditions were 20°C and 72%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

Comparing the different sizes of the blankets, it was observed that the small and large charcoal blanket performed similarly ($\theta_{CL,mean} = 18.8^\circ\text{C}$, $\phi_{CL,mean} = 94\%$). 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 one degree higher ($\theta_{SS, \text{mean}} = 19.5^\circ\text{C}$, $\phi_{SS, \text{mean}} = 96\%$) 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 [47], [48]. Those are equally suitable for the cooling blanket since the physics of the evaporative cooling process do not differ for the different evaporative cooler designs.

During the experiments, the wind speed was on average 0.17 m/s (SD = 0.29), which is low for that location, as can be 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. [18]. Higher airflow rates might promote evaporation and reach a temperature closer to the wet bulb temperature.

At this point, it should also be noted that the charcoal cooler was operated at a lower fruit loading capacity (< 1%) than the cooling blankets (15%). 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 [18].

Lastly, it is worth remembering 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.

3.1.2 Fruit quality evaluation

In the postharvest fruit supply chain, the quality of individual units is primarily assessed by their appearance [39]. For most fruit and vegetables, the key quality attributes related to appearance are color, firmness, absence of defects, and shriveling due to water loss [40]–[42]. 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 summarised in Figure 6. 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 (Figure 6 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 performed not as well as the standard airflow setup. 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 2–4% 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.

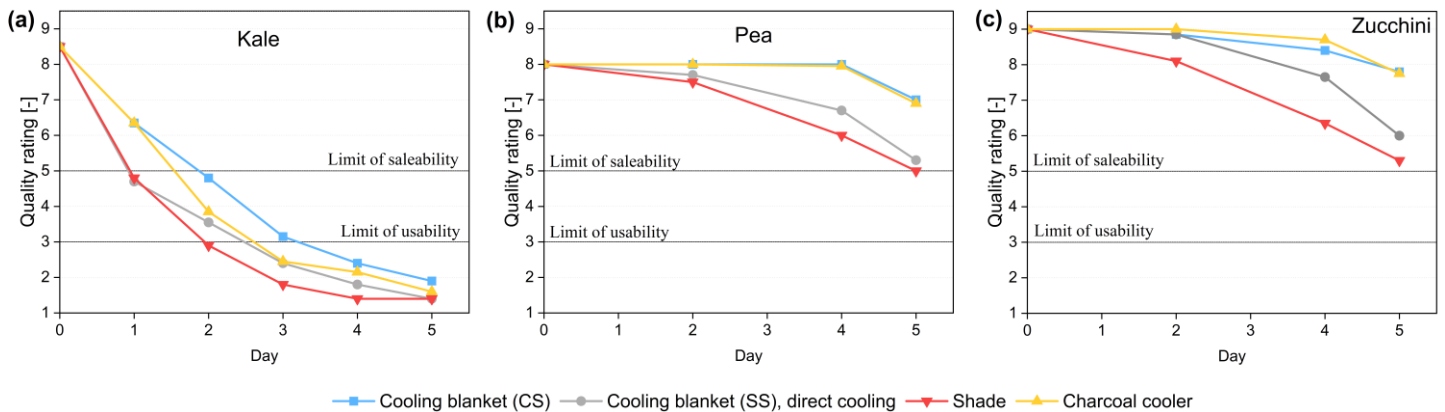


Figure 6: Overall quality reduction including limit of saleability and usability based on the rating scale from Kader and Cantwell (2005), Table 2, for a) Kale, b) Peas, and c) Zucchini. Displayed are the means of the samples.

Weight loss

Weight loss results in reduced freshness, evidenced by shriveling, wilting, and loss of firmness and crispness [49].

Figure 7 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. 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. 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. 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.

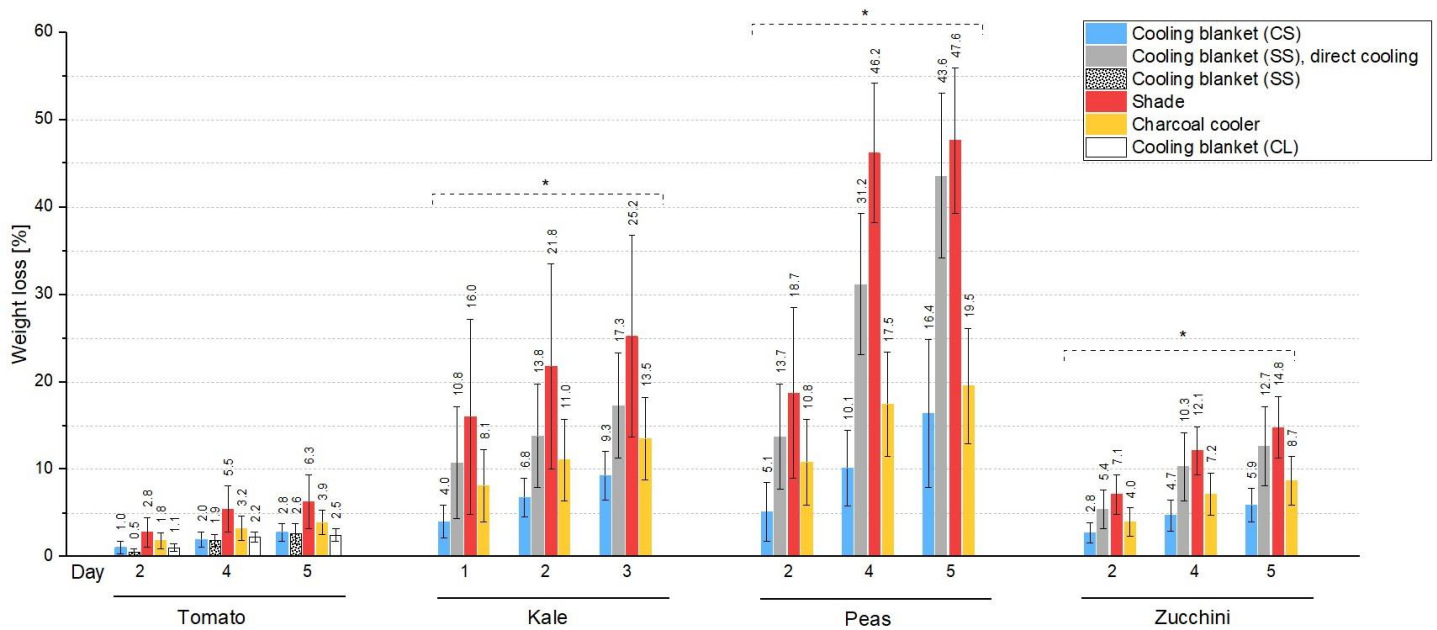


Figure 7: Weight loss [%] for storage up to 5 days in the small charcoal blanket CS, the charcoal cooler, the small sawdust blanket SS (as airflow cooler or direct cooler), the large charcoal cooler CL, and in the shade compared to the start of the experiment (day 0) of four crops. Values are presented as means \pm SD. The statistical intergroup difference is marked (* = $p < .05$).

Color change

During the ripening and senescence process, many fruits and vegetables undergo color changes. Typically, the green color of 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). Figure 8 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 [50], [51].

Figures 8a-b imply 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. Figure 8c-d kale leaves after three days of storage in the PCB and under shade, illustrating how a difference of $\sim 6^\circ$ 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 [50]. 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.

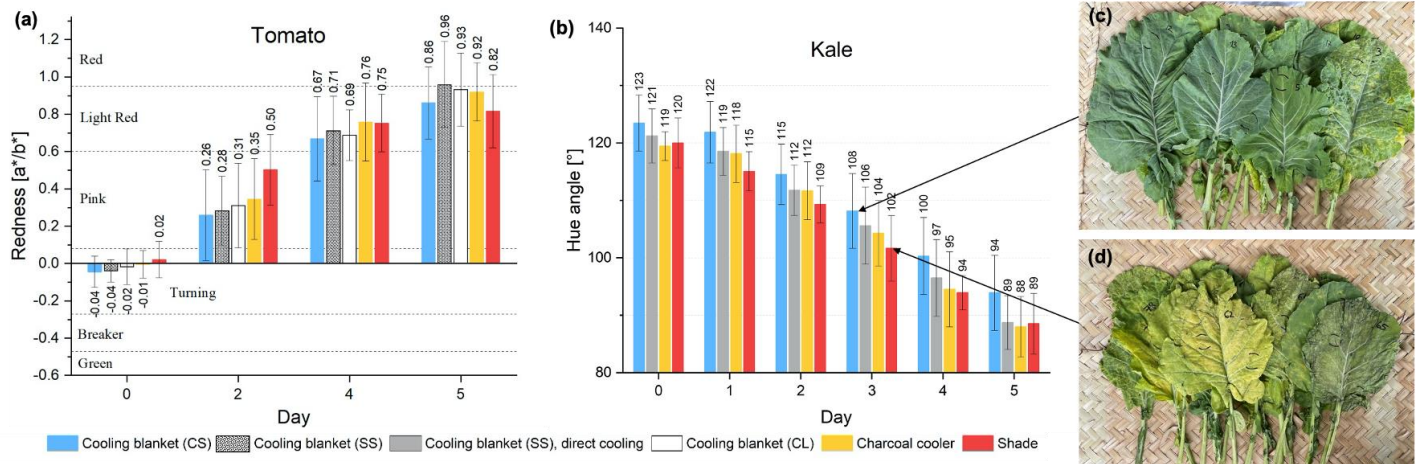


Figure 8: a) Redness of tomatoes and b) Hue angle of kale leaves when stored for 5 days in different systems: CS= small charcoal blanket; CL = large charcoal blanket; SS = small sawdust blanket. Values are presented as means \pm SD. Color classification of tomatoes derived from Batu (2004). Kale leaves 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.

Firmness

For tomatoes, loss in firmness was measured as an additional quality attribute (Figure 9). Softening during storage and distribution is a major problem as the tomatoes become more susceptible to physical damage and it also reduces the marketability [52].

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 (Figure 9). 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) performed slightly worse but still provided a significant improvement in the reduction of the firmness loss (24–28%). At this point, it should be noted that a manual, analog fruit pressure tester was used, resulting in inevitably lower measurement accuracy compared to digital penetrometers. In general, storing vegetables after harvest using the passive cooling blanket helped to reduce 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.

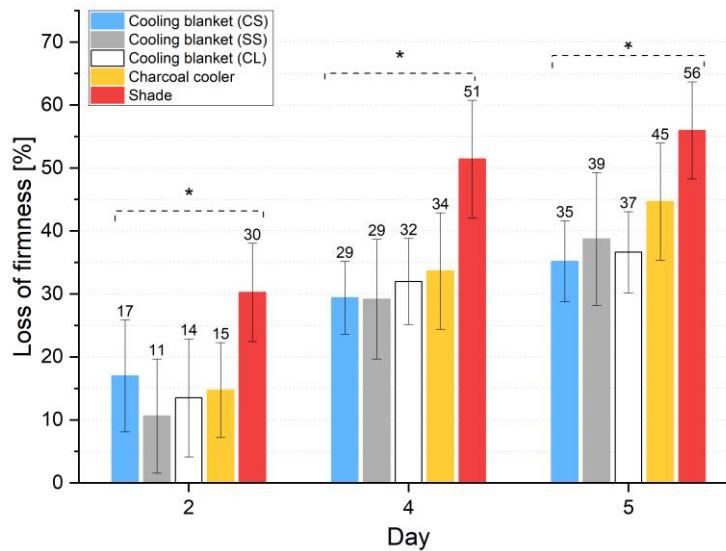


Figure 9: Loss of firmness of tomatoes when stored for 5 days in different systems: CS = small charcoal blanket; SS = small sawdust blanket; CL = large charcoal blanket. Values are presented as means \pm SD. The statistical intergroup difference is marked (* = $p < .05$).

3.2 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, [16]), 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.

3.1 What is the economic benefit 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 (Figure 10a). 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 \cdot (0.2 \cdot 180 kg \cdot 0.21\$/kg + 180 kg \cdot 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 Equation 3. 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 Figure 10a (payback calculates to 2.6 months). The steep income curve in Figure 10a 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.

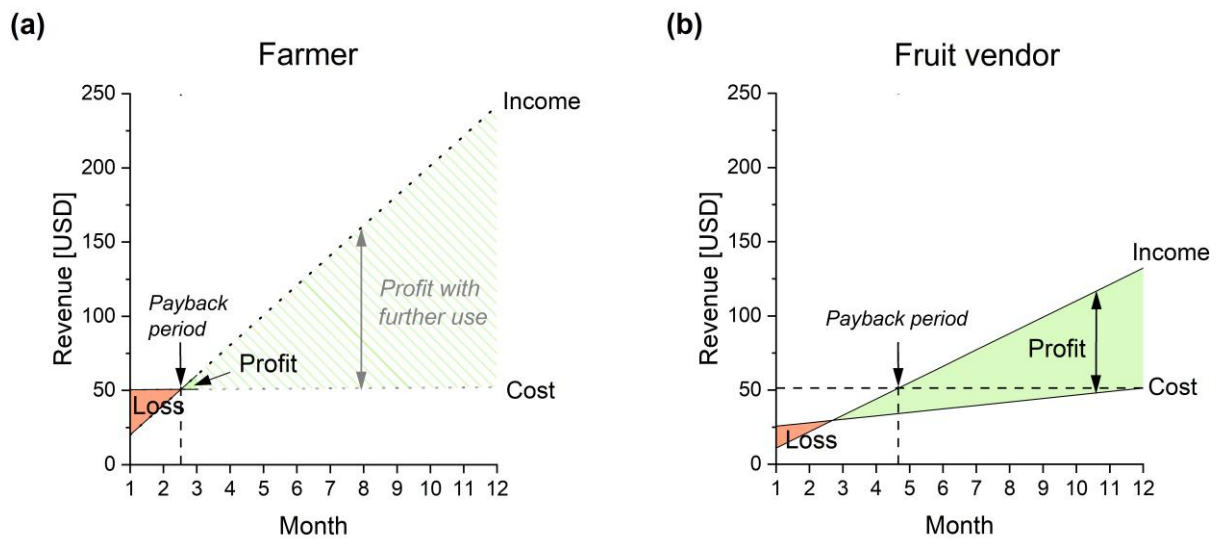


Figure 10: Graphical representation of additional income and costs when using the cooling blanket as a function of time for a) farmers and b) fruit vendors, as well as the payback period.

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 tomatoes). The annual costs to purchase and operate the cooling system would accumulate to USD 51 in the first year as well (Figure 10b). 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 Figure 10a 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 \cdot 0.32 \$/kg \cdot 280 d]. Subsequently, the payback period is calculated to be 0.4 years for a storage space of 0.06 m³ for tomatoes, meaning the cost of the investment is recovered after five months. Thereby, it becomes evident from Figure 10b that the vendor can expect to reap the financial benefits within three months.

4 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 fruit 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 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 could significantly extend the shelf life of fruit 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 an evaporative cooler and shade was most pronounced for firmness and weight loss.
- 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, which advocates the suitability for up- and downscaling of the PCB.
- The blanket provides the benefit that any padding material can be utilized. 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 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 – a profit can already be recorded after three months (at moderate use). In contrast, the investment costs of the traditional charcoal cooler are 6 to 12 times higher. Due to the low investment costs, the willingness to deploy the system is therefore higher than with the traditional charcoal cooler.
- With reduced losses and improved quality using PCB, farmers and traders may have the opportunity to access broader markets. They can potentially supply to distant markets where demand is higher, leading to expanded business opportunities and increased market competitiveness.

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AUTHOR CONTRIBUTIONS

T.W., T.D. and D.O. conceptualized the study and did the project administration, D.O. acquired funding; T.W. performed the investigation, developed the methodology, performed the experiments with key input

from D.O., R.Y. and T.D; T.W. wrote the original draft of the paper and did the visualization with key input from D.O.; T.D., D.O. and R.Y. performed critical review and editing.

REFERENCES

- [1] Central Bank of Kenya, “Report on the Agriculture Sector Survey,” Nairobi, May 2023. Accessed: Sep. 08, 2023. [Online]. Available: https://www.centralbank.go.ke/uploads/market_perception_surveys/588251064_Agriculture%20Survey%20May%202023.pdf
- [2] “Kenya at a glance - The agriculture sector in Kenya,” FAO. Accessed: Sep. 10, 2023. [Online]. Available: [https://www.fao.org/kenya/fao-in-kenya/kenya-at-a-glance/en/#:~:text=Currently%2046%20per%20cent%20of,\(chronically%20malnourished\)%20in%20Kenya.](https://www.fao.org/kenya/fao-in-kenya/kenya-at-a-glance/en/#:~:text=Currently%2046%20per%20cent%20of,(chronically%20malnourished)%20in%20Kenya.)
- [3] E. Makule, N. Dimoso, and S. A. Tassou, “Precooling and Cold Storage Methods for Fruits and Vegetables in Sub-Saharan Africa—A Review,” *Horticulturae*, vol. 8, no. 9. MDPI, Sep. 01, 2022. doi: 10.3390/horticulturae8090776.
- [4] E. Verploegen, O. Sanogo, and T. Chagomoka, “Evaporative Cooling Technologies for Improved Fruit & Vegetable Storage in Mali,” 2018.
- [5] J. Aulakh, A. Regmi, J. R. Fulton, and C. E. Alexander, “Estimating post-harvest food losses: Developing a consistent global estimation framework,” 2013.
- [6] B. M. McGregor, *Tropical products transport handbook*, no. 668. US Department of Agriculture, Office of Transportation, 1989.
- [7] D. Onwude *et al.*, “Physics-driven digital twins to quantify the impact of pre- and postharvest variability on the end quality evolution of orange fruit,” *Resour Conserv Recycl*, vol. 186, p. 106585, 2022, doi: <https://doi.org/10.1016/j.resconrec.2022.106585>.
- [8] P. L. Singh, P. C. Jena, S. K. Giri, B. S. Gholap, and O. S. Kushwah, “Solar-powered cold storage system for horticultural crops,” in *Energy and Environment: Select Proceedings of ICWEES-2016*, Springer, 2018, pp. 125–131.
- [9] M. Sadi, A. Arabkoohsar, and A. K. Joshi, “Techno-economic optimization and improvement of combined solar-powered cooling system for storage of agricultural products,” *Sustainable Energy Technologies and Assessments*, vol. 45, p. 101057, 2021.
- [10] O. M. Odeyemi and N. C. Ikegwuonu, “Solar-Powered Cold Storage: ColdHubs in Nigeria,” in *Cold Chain Management for the Fresh Produce Industry in the Developing World*, CRC Press, 2021, pp. 175–182.
- [11] H. Takeshima, F. Yamauchi, D. Bawa, S. O. Kamaldeen, H. O. Edeh, and M. A. Hernandez, *Solar-powered cold-storages and sustainable food system transformation: evidence from horticulture markets interventions in northeast Nigeria*, vol. 2047. Intl Food Policy Res Inst, 2021.
- [12] E. Verploegen, M. Sharma, R. Ekka, and G. Gill, “Low-Cost Cooling Technology to Reduce Postharvest Losses in Horticulture Sectors of Rwanda and Burkina Faso,” in *Cold Chain Management for the Fresh Produce Industry in the Developing World*, CRC Press, 2021, pp. 183–210. doi: 10.1201/9781003056607-17.
- [13] S. K. Roy and D. S. Khardi, “Zero energy cool chamber,” *India Agricultural Research Institute: New Delhi, India. Research Bulletin*, no. 43, pp. 23–30, 1985.
- [14] GKI, “Innovating the future of food systems - A global scan for the innovations needed to transform food systems in emerging markets by 2035,” 2017.
- [15] E. Verploegen and C. Padalino, “Evaporative cooler construction with University of Nairobi.” Accessed: Jul. 04, 2023. [Online]. Available: <https://d-lab.mit.edu/news-blog/blog/evaporative-cooler-construction-university-nairobi>

- [16] L. Mogannam, F. Cissé, K. S. Cissé, K. E. Ognakossan, and E. Verploegen, “Clay Pot Cooler Training in Mali: Outcomes and Impacts,” 2022.
- [17] “Evaporative cooling technologies for fruit and vegetable preservation in Kenya,” Abdul Latif Jameel Water & Food Systems Lab, MIT. Accessed: Sep. 10, 2023. [Online]. Available: <https://jwafs.mit.edu/projects/2019/evaporative-cooling-technologies-fruit-and-vegetable-preservation-kenya>
- [18] T. Defraeye *et al.*, “The charcoal cooling blanket: A scalable, simple, self-supporting evaporative cooling device for preserving fresh foods,” *Preprint on engrxiv.org*, 2022, doi: 10.31224/2221.
- [19] E. Verploegen, R. Ekka, and G. Gill, “Evaporative Cooling for Improved Vegetable Storage in Rwanda & Burkina Faso,” 2019.
- [20] S. M. Dadhich, H. Dadhich, and R. C. Verma, “Comparative study on storage of fruits and vegetables in evaporative cool chamber and in ambient,” *International Journal of Food Engineering*, vol. 4, no. 1, 2008, doi: 10.2202/1556-3758.1147.
- [21] C. Kanali *et al.*, “Energy efficient rural food processing utilising renewable energy to improve rural livelihoods in Kenya,” *RE4Food Project Report. Kenya: Jomo Kenyatta University of Agriculture and Technology (JKUAT)*, 2017.
- [22] T. Defraeye, K. Shoji, S. Schudel, D. Onwude, and C. Shrivastava, “Passive evaporative coolers for postharvest storage of fruit and vegetables: Where to best deploy them and how well do they perform,” *Frontiers in Food Science and Technology*, vol. 3, p. 1100181, Apr. 2023, doi: 10.3389/FRFST.2023.1100181.
- [23] Simulating Biological Systems Group, “Evaporative Cooling Potential,” Empa. Accessed: Sep. 03, 2023. [Online]. Available: https://empasimbiosys.github.io/evapo_cooling_map/index.html
- [24] R. Jaetzold, H. Schmidt, B. Hornetz, and C. Shisanya, “Farm Management Handbook of Kenya Vol. II,” 1982.
- [25] J. O. Ouma, F. M. Murithi, W. Mwangi, H. Verkuijl, M. Gethi, and H. De Groote, “Adoption of maize seed and fertilizer technologies in Embu district, Kenya,” 2002.
- [26] S. K. Geoffrey, N. K. Hillary, K. M. Antony, M. Mariam, and M. C. Mary, “Challenges and Strategies to Improve Tomato Competitiveness along the Tomato Value Chain in Kenya,” *International Journal of Business and Management*, vol. 9, no. 9, Aug. 2014, doi: 10.5539/ijbm.v9n9p205.
- [27] F. O. Wayua, M. W. Okoth, and J. Wangoh, “Design and performance assessment of a low cost evaporative cooler for storage of camel milk in arid pastoral areas of kenya,” *International Journal of Food Engineering*, vol. 8, no. 1, 2012, doi: 10.1515/1556-3758.2323.
- [28] E. Mujuka, J. Mburu, A. Ogutu, and J. Ambuko, “Returns to investment in postharvest loss reduction technologies among mango farmers in Embu County, Kenya,” 2019, doi: 10.1002/fes3.195.
- [29] J. Arim *et al.*, “Smallholder Horticulture Empowerment & Promotion Project for Local and Up-Scaling - Kale Production,” 2019. Accessed: Feb. 12, 2024. [Online]. Available: https://www.jica.go.jp/Resource/project/english/kenya/015/materials/c8h0vm0000f7o8cj-att/materials_24.pdf
- [30] Willis. N. Ochilo *et al.*, “Characteristics and production constraints of smallholder tomato production in Kenya,” *Sci Afr*, vol. 2, p. e00014, 2019, doi: <https://doi.org/10.1016/j.sciaf.2018.e00014>.
- [31] C. and Z. L. and K. E. Stöber Silke and Moraza, “Low-Tech Irrigation Strategies for Smallholder Vegetable Farmers in Kenya,” in *Rainwater-Smart Agriculture in Arid and Semi-Arid Areas: Fostering the Use of Rainwater for Food Security, Poverty Alleviation, Landscape Restoration and Climate Resilience*, J. Leal Filho Walter and de Trinchiera Gomez, Ed., Cham: Springer International Publishing, 2018, pp. 215–233. doi: 10.1007/978-3-319-66239-8_12.
- [32] United States Department of Agriculture, “United States Standards for Grades of Fresh Tomatoes,” 1991.

- [33] J. T. LeRoy and T. H. Kuehn, *ASHRAE Fundamentals Handbook*. ASHRAE, 2001.
- [34] P. A. Dođramacı and D. Aydın, “Comparative experimental investigation of novel organic materials for direct evaporative cooling applications in hot-dry climate,” *Journal of Building Engineering*, vol. 30, p. 101240, 2020, doi: <https://doi.org/10.1016/j.jobbe.2020.101240>.
- [35] W. A. Olosunde, J. C. Igbeka, and T. O. Olurin, “Performance Evaluation of Absorbent Materials in Evaporative Cooling System for the Storage of Fruits and Vegetables,” vol. 5, no. 3, 2009, doi: [doi:10.2202/1556-3758.1376](https://doi.org/10.2202/1556-3758.1376).
- [36] A. Kader and M. Cantwell, “Produce quality rating scales and color charts.” Postharvest Technology Research and Information Center University of California, Davis, 2005.
- [37] A. F. L. Camelo and P. A. Gómez, “Comparison of color indexes for tomato ripening,” *Hortic Bras*, vol. 22, pp. 534–537, 2004.
- [38] E. Gutiérrez-Rodríguez, J. H. Lieth, J. A. Jernstedt, and T. V Suslow, “Prediction of Spinach Quality Based on Pre-and Postharvest Conditions,” 2012.
- [39] R. E. Schouten, T. P. M. Huijben, L. M. M. Tijskens, and O. van Kooten, “Modelling the acceptance period of truss tomato batches,” *Postharvest Biol Technol*, vol. 45, no. 3, pp. 307–316, 2007, doi: [10.1016/j.postharvbio.2007.03.012](https://doi.org/10.1016/j.postharvbio.2007.03.012).
- [40] S. W. Tilahun, “Feasibility and economic evaluation of low-cost evaporative cooling system in fruit and vegetables storage,” 2010.
- [41] T. V. Suslow and M. Cantwell, “Tomato: Recommendations for Maintaining Postharvest Quality,” Department of Plant Sciences, University of California, Davis. Accessed: Jun. 17, 2023. [Online]. Available: https://postharvest.ucdavis.edu/Commodity_Resources/Fact_Sheets/Datastores/Vegetables_English/?uid=36&ds=799
- [42] C. of A. S. Oregon State University, “Squash, Zucchini and Summer.” Accessed: Aug. 21, 2023. [Online]. Available: <https://horticulture.oregonstate.edu/oregon-vegetables/squash-zucchini-and-summer>
- [43] The Engineering ToolBox, “Fruits and Vegetables - Optimal Storage Conditions Optimal temperature and humidity conditions for common fruits and vegetables.” Accessed: Aug. 26, 2023. [Online]. Available: https://www.engineeringtoolbox.com/fruits-vegetables-storage-conditions-d_710.html
- [44] L. Rong, P. Pedersen, T. L. Jensen, S. Morsing, and G. Zhang, “Dynamic performance of an evaporative cooling pad investigated in a wind tunnel for application in hot and arid climate,” *Biosyst Eng*, vol. 156, pp. 173–182, Apr. 2017, doi: [10.1016/j.biosystemseng.2017.02.003](https://doi.org/10.1016/j.biosystemseng.2017.02.003).
- [45] A. Lal Basediya, D. V. K. Samuel, and V. Beera, “Evaporative cooling system for storage of fruits and vegetables - A review,” *J Food Sci Technol*, vol. 50, no. 3, pp. 429–442, Jun. 2013, doi: [10.1007/s13197-011-0311-6](https://doi.org/10.1007/s13197-011-0311-6).
- [46] E. K. Ronoh, C. L. Kanali, and S. N. Ndirangu, “Effectiveness of an evaporative charcoal cooler for the postharvest preservation of tomatoes and kales,” *Research in Agricultural Engineering*, vol. 66, no. 2, pp. 66–71, 2020, doi: [10.17221/52/2019-RAE](https://doi.org/10.17221/52/2019-RAE).
- [47] Y. Singh and Y. K. Yadav, “Evaporative cooling chambers using alternative materials,” *gril Mechanization in Asia, Africa and Latin America*, vol. 43, no. 2, pp. 75–78, 2012.
- [48] N. Kapilan, A. M. Isloor, and S. Karinka, “A comprehensive review on evaporative cooling systems,” *Results in Engineering*, vol. 18. Elsevier B.V., Jun. 01, 2023. doi: [10.1016/j.rineng.2023.101059](https://doi.org/10.1016/j.rineng.2023.101059).
- [49] J. Ambuko, F. Wanjiru, G. N. Chemining’wa, W. O. Owino, and E. Mwachoni, “Preservation of Postharvest Quality of Leafy Amaranth (*Amaranthus* spp.) Vegetables Using Evaporative Cooling,” *J Food Qual*, vol. 2017, 2017, doi: [10.1155/2017/5303156](https://doi.org/10.1155/2017/5303156).

- [50] B. Farneti, “Tomato quality:from the field to the consumer. Interactions between genotype, cultivation and postharvest conditions,” 2014.
- [51] M. Cantwell, G. Hong, A. Fibriyanti, J. Ara, and K. Albornoz, “Postharvest handling considerations for kale as intact and fresh-cut product,” *Respiration*, vol. 25, no. 30, p. 35, 2012.
- [52] A. Batu, “Determination of acceptable firmness and colour values of tomatoes,” *J Food Eng*, vol. 61, no. 3, pp. 471–475, Feb. 2004, doi: 10.1016/S0260-8774(03)00141-9.
- [53] D-Lab MIT, “Evaporative Cooling Decision Making Tool.” Accessed: Sep. 04, 2023. [Online]. Available: <https://d-lab.mit.edu/resources/publications/evaporative-cooling-decision-making-tool>
- [54] D. Onwude *et al.*, “Bottlenecks in Nigeria’s fresh food supply chain: What is the way forward?,” *Trends Food Sci Technol*, vol. 137, pp. 55–62, Jul. 2023, doi: 10.1016/j.tifs.2023.04.022.

SUPPLEMENTARY MATERIAL

Evaluating passive evaporative cooling blanket for improved postharvest storage of fruit and vegetables in low- and middle-income countries

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Nomenclature

Symbols

H	height [m]
L	length [m]
l	liter
RH	relative humidity [%]
SD	standard deviation of sample
T	temperature [°C]
W	width [m]

Greek symbols

η	evaporative cooling efficiency [%]
θ	temperature [°C]
φ	rel. humidity [%]

Subscripts

b	blanket
co	compartment
db	dry-bulb
e	empty
init	initial
t	time
wb	wet-bulb

Abbreviations

CC	charcoal cooler
CL	large charcoal blanket
CS	small charcoal blanket
EC	evaporative cooler/evaporative cooling
EPS	expanded polystyrene
PCB	passive cooling blanket
PHL	postharvest loss(es)
SS	small sawdust blanket

S1 Additional information for the construction and use of the cooling blanket

Construction

The cooling blanket is made of two layers of an air-permeable fabric (such as burlap) sewed into equal-sized compartments of a certain width ($W_{co,e}$). A padding material is then filled into these compartments. This material should be capable of absorbing a high amount of water (water holding capacity) and have a large specific surface area. Examples of suitable materials are charcoal or sawdust.

The compartment width is one design parameter that must be chosen when manufacturing the blanket. According to Defraeye et al., the compartment width (W_{co}) should be in a range of 50–200 mm when filled with charcoal. Large compartments not only facilitate the filling process but also increase the thickness of the blanket. The thickness, in turn, determines the mechanical properties of the blanket (mainly the buckling and bending stability) and affects the amount of water that is absorbed per surface area [1]. The latter is also dependent on the charcoal caliber and distribution. Smaller pieces increase the bulk density (and area density) and, thus, the total weight of the blanket. In addition, the surface area enlarges, which also increases the water absorption capacity and speed. In total both the thickness and the charcoal caliber influence the pressure resistance (how easily air can pass through the blanket). All of which have an impact

on the cooling capacity. It is, therefore, crucial to identify the optimal dimensions for both. The size of the blanket (L_b and H_b) can be adjusted according to the required storage volume.

In general, for reasons of user-friendliness, it is advised to use a compartment size of around 12 cm for a small blanket (for one crate). A larger width is favorable for a large blanket ($L_b > 5$ m) to ease the filling process.

To mount the cooling blanket, there are two options: 1) the blanket is wrapped directly around the crate to be stored, 2) in a rectangle slightly larger than the box(es), wooden poles are driven into the ground, around which the blanket is wrapped tightly and fixed. The first variant has the advantage that the whole system can be installed independently of the sub-floor, is mobile and can be erected very quickly. The second variant, on the other hand, is very convenient when the cooling system is to be used for longer, as the boxes can be easily inserted and removed. In addition, the variant is preferable when storing several boxes and adjusting the distance between the blanket and the boxes is possible. This in turn, has two advantages, 1) it facilitates the movement of air inside, increasing the cooling effect and 2) excess water from the wetting event will not come into contact with the fruit. The limitation of the second variant is that the location must allow the wooden bars to be inserted into the ground. Additional information on how to construct the cooling blanket can be found in the supplementary material of Defraeye et al. (2022).

To lift the crates slightly off the ground, a flat stone was placed under each corner of all crates (to improve air circulation and protect them from excess water). All systems were fixed with a tension belt.

To ensure the cool and moist air remains inside, a lid (e.g. a woven bast mat or made from "gunia") is placed on top of the blanket to seal the system. It is also advisable to attach a layer of plastic sheeting to the underside of the lid. This creates a barrier between the lid material and the moist air inside, preventing mold formation.

Location

For the best cooling performance, the blanket must be installed in the shade (for instance, under a large roof construction). In addition, the cooling effect is enhanced at locations with high wind speeds.

If the wet bulb temperature is taken into account, the cooling effect is greatest in dry and hot regions. The technology also works in other climate zones, but the difference between dry-bulb and wet-bulb temperatures is less pronounced (= the temperature reduction).

Wetting

To maintain the cooling effect, water must be replenished regularly. The frequency and volume depend heavily on the prevailing relative humidity, the ambient temperature, the wind speed and the design of the ceiling. It is therefore difficult to generalize. If no sensor is used to control the hygrothermal conditions inside the blanket, from time to time, the lid of the system may be lifted to check if the fruit feels cool to the touch and the blanket looks damp. If this is not the case, water must be added again.

One risk that always exists with evaporative coolers is that the humidity in the system is permanently too high (if there is too much watering or if the ambient humidity rises significantly at certain times of the day (often the case at night). Here, it can help to remove the cover of the system completely at night to allow a better exchange of air and reduce interior humidity. If the humidity is very high over a longer period, the risk of mold forming in the blanket or on the surface of the fruit increases. To avoid this, it is important to ensure that no water from watering accumulates in the crate itself (see *Construction above*).

During wetting, not all the water is completely absorbed by the blanket and a certain amount drips onto the floor and is therefore lost. A tray can be placed under the system to collect the water to avoid this.

Contamination prevention

Preliminary tests have shown that termites can be attracted to the natural materials of the blanket (wooden poles and burlap). If termites are common in the designated location, the areas of the blanket that are in contact with the ground and the wooden poles (if used) should be treated preventively, e.g., with engine oil.

S2 Suitability of fruits and vegetables for storage in an evaporative cooler

The temperature in an evaporative cooler is typically 3-10°C below ambient conditions, and the relative humidity is 70-100%. This means that crops that are best stored in dry/moderate humidity are not suitable for evaporative cooling, for instance, onions, potatoes, or cereals/millet. Otherwise, the high humidity would induce rot and mold growth [2]. Secondly, one should know the optimal storage temperature as an evaporative cooler could reach lower temperatures depending on the environmental conditions. In this case, the product should not be stored in an evaporative cooler either. However, this will rarely occur, and the optimum temperature is relatively low for most fruits and vegetables.

A crucial aspect that must always be considered when various crops are to be stored together in one cooler is ethylene production and sensitivity. Ethylene is a plant growth regulator that stimulates the ripening process of ethylene-sensitive fruits, leafy greens and vegetables. In particular, ethylene accelerates biochemical reactions, resulting in faster senescence processes and overall fruit deterioration during postharvest storage [3]. Therefore, to maximize postharvest life, ethylene-sensitive commodities (e.g., tomatoes or bananas) must not be stored together with crops that produce high ethylene.

S3 Sensors

Table 1: Sensor types used in the laboratory and field experiments and their characteristics. RH stands for relative humidity.

Sensor Type	Sensed driver	Accuracy	Range
UbiBot WS1 Pro	Air temperature	$\pm 0.3^\circ\text{C}$	-20 to 60°C
	Relative humidity	$\pm 3\%$ RH	10–90% RH
Sensirion SHT4x Smart Gadget	Air temperature	$\pm 0.2^\circ\text{C}$	-40 to 125°C
	Relative humidity	$\pm 1.8\%$ RH	0–100% RH
Core Probe Thermometer	Fruit pulp temperature	$\pm 0.5^\circ\text{C}$	- 10 to 100°C
	Water temperature		
TFA Dostmann Testo 405i Thermal anemometer	Air speed	± 0.1 m/s + 5% m.v.	0–2 m/s
		± 0.3 m/s + 5% m.v.	2–15 m/s
Weather station PCE-FWS 20 N	Air temperature	$\pm 0.2^\circ\text{C}$	-40 to 60°C
	Relative humidity	$\pm 4\%$ RH, $\pm 6\%$ RH	20–80% RH; other ranges
	Wind speed	± 1 m/s	0–5 m/s
Volcraft HS-50	Mass of blanket	± 20 g	0–50 kg
	Mass of fruits		

FT 327 Penetrometer	Firmness of tomato	± 0.1 kg	0.5–3 kg
QA Supplies			
Kern Scale EMS 6K0.1	Mass of single fruit	± 0.1 g	0–6000 g

S4 Supplementary material of the field experiments

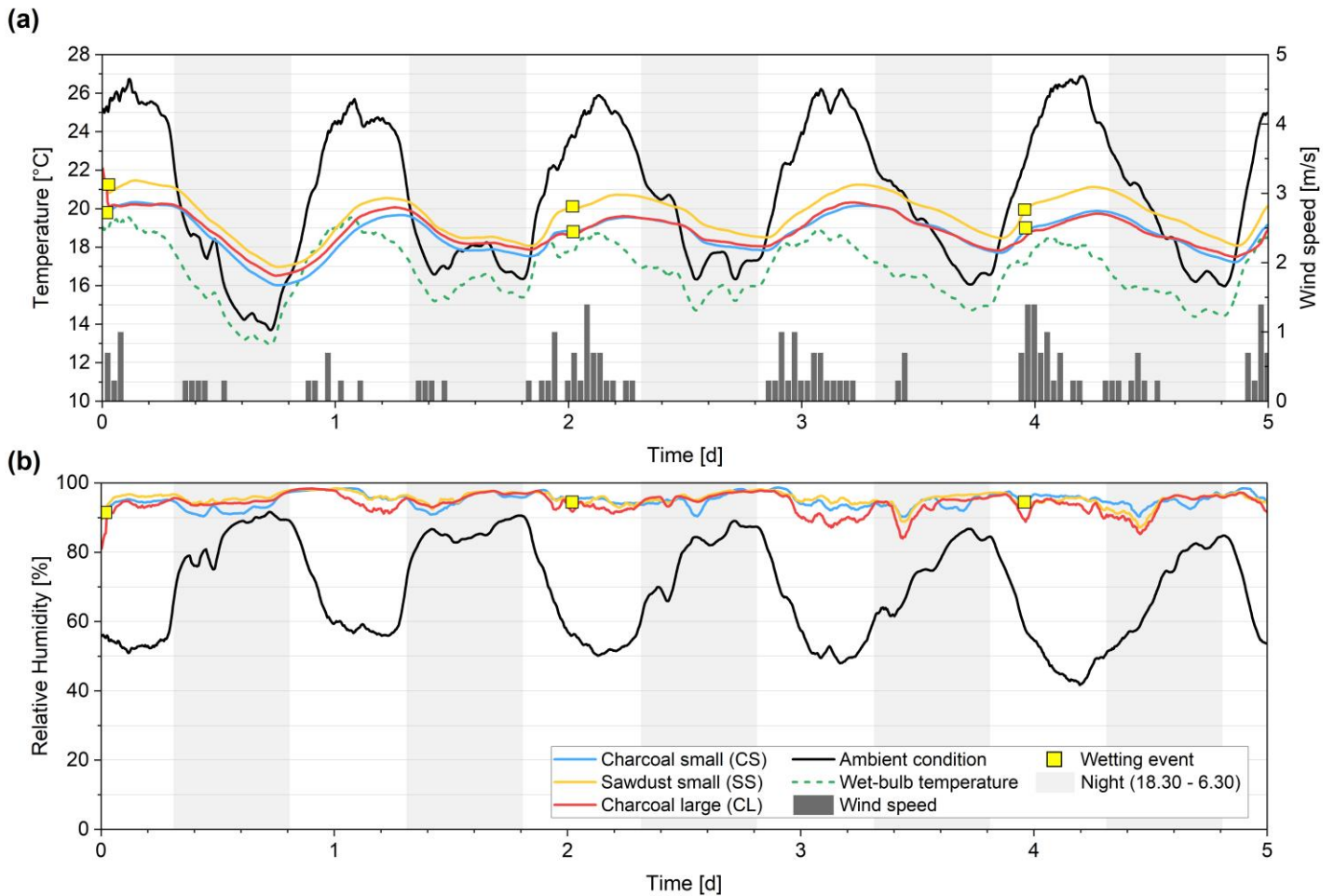


Figure 1: Hygrothermal sensor data of the first field experiment (storage of tomatoes) for the small charcoal blanket CS, the small sawdust blanket SS and the large charcoal blanket CL. a) Plot of air temperatures as a function of time; b) plot of relative humidity as a function of time. The legend applies to both diagrams.

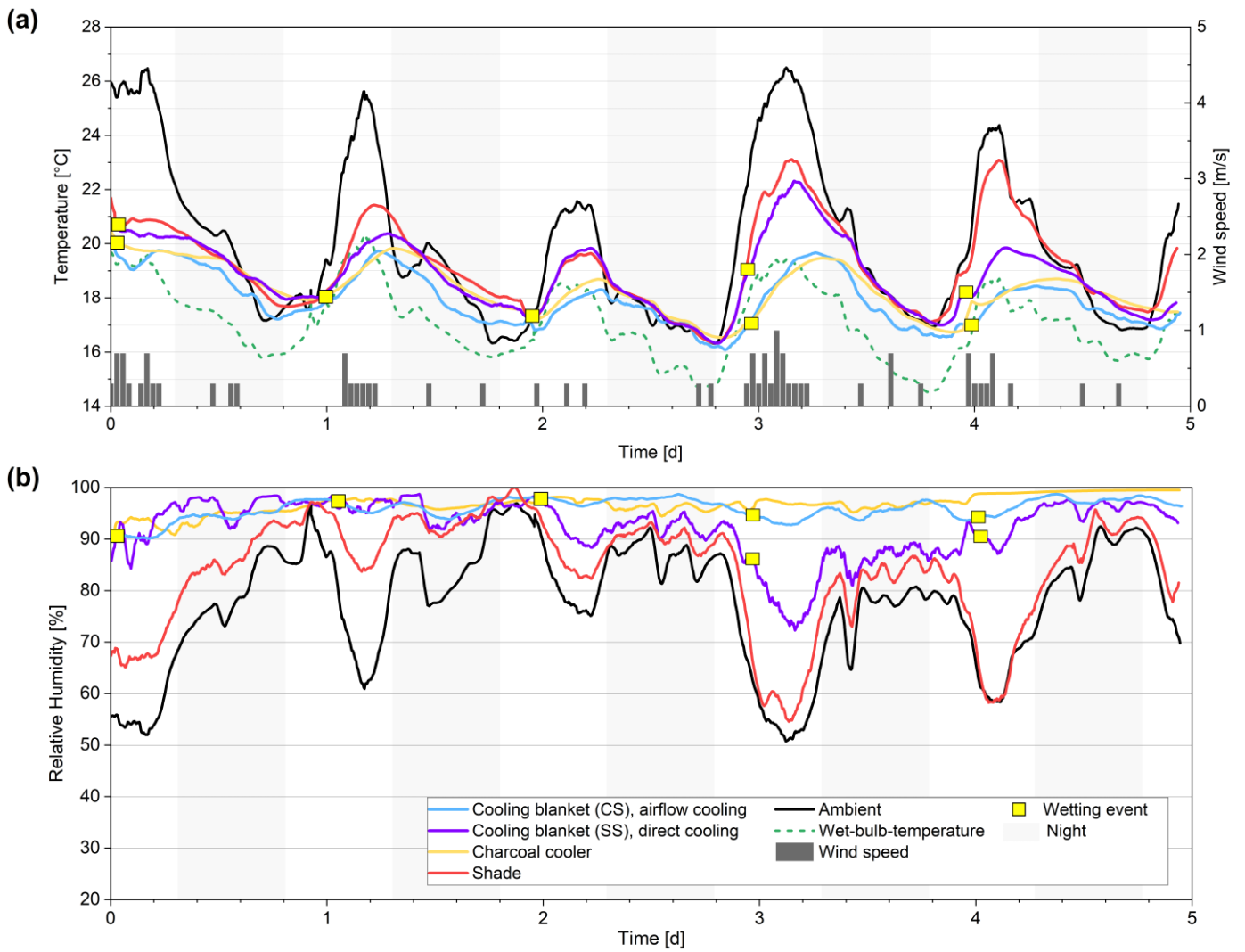


Figure 2: Hygrothermal sensor data of the second field experiment (storage of kale, peas, zucchini) for the small charcoal blanket CS, the small sawdust blanket SS as direct cooler, the charcoal cooler and storage in the shade. a) Plot of air temperatures as a function of time; b) plot of relative humidity as a function of time. The legend applies to both diagrams.

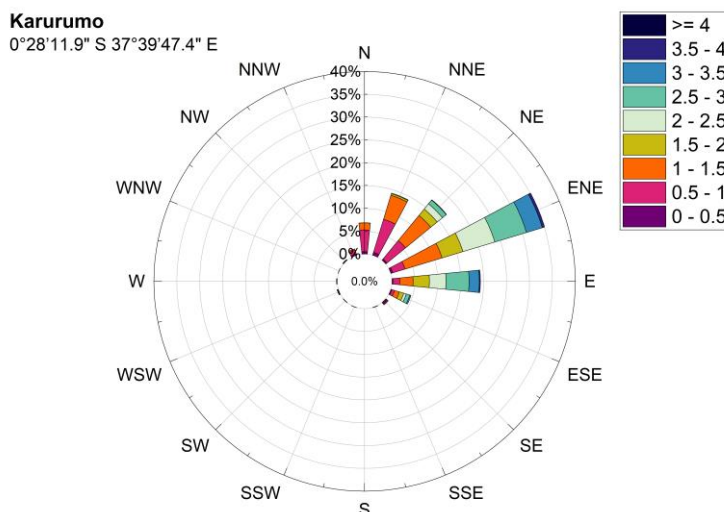


Figure 3: Wind rose for Karurumo, Kenya, based on hourly data from 2021, obtained from the Nasa Power database.

S5 Supplementary material on the interviews

Participants were recruited through a purposive sampling approach, targeting individuals directly involved in farming and fruit vending activities. The recruitment process involved outreach through local agricultural extension officers, who provided contact information for potential participants. To ensure inclusivity, we also engaged community leaders to help identify and encourage participation from a diverse group of farmers and vendors, including those from different age groups and gender backgrounds. Participation was voluntary, and informed consent was obtained from all participants before the interviews were conducted.

The interviews were conducted over a three-week period between June and July 2023. This timing was chosen because it coincided with the post-harvest season, a critical period when storage issues are most prevalent for both farmers and vendors. The specific dates for the interviews were coordinated with participants to avoid any conflict with their farming or vending activities, thereby ensuring maximum participation.

The study was conducted following ethical guidelines to ensure the protection of participants' rights and the integrity of the research process. Before the commencement of interviews, participants were informed about the purpose of the study, the nature of the data being collected, and how their information would be used. The administered questionnaire (see section S5.1) also contains information for the participants prior to the interview. Confidentiality was strictly maintained, with personal identifiers removed from the data set to ensure anonymity. The study protocol was reviewed and approved by Empa and University of Embu, ensuring that the research adhered to the highest ethical standards.

Farmers

The farmers reported selling total volumes ranging from 30 to 2,000 kg per week, depending on the size of the farm and the diversity of the products. The most common crops are summarized in Table 2. The price at which they are sold varies greatly depending on the market demand. Farmers aim to grow crops in such a way that they can harvest in the lean season, which requires a high degree of forecasting and greatly depends on the (non-predictable) weather conditions.

80% of the respondents did not use a storage method; the remaining 20% stored the crops under permanent shade if not sold directly (Fig. 4). They try to align their harvesting time with customer orders and, thus, avoid periods when they would have to store fresh produce. Consequently, the actual food losses on the farmers' side are low, and they reported to sell, on average, 96% ($\pm 3\%$) of the harvested crops. Moreover, the mentioned losses are mainly due to plant diseases. Nevertheless, with an appropriate storage method,

farmers would have the flexibility to store their produce longer and, in turn, sell at a higher price as the market is less saturated.

35% of the participants said they would prefer having a storage method, of which 88% specified the charcoal cooler. Overall, a considerable 70% have already heard of evaporative coolers, mainly charcoal coolers. The respondents see the main advantages in their longevity and the potential to prolong the shelf life of harvested products. In addition, they would be less expensive than cooling facilities. However, none of the farmers used one due to the high manufacturing cost ("USD 300-700") or because they knew too little about it. 40% also stated that their harvest volume was too low to use a charcoal cooler.

All of the farmers liked the cooling blanket concept and were willing to test the system, mainly because of its scalability and simplicity. However, some mentioned that the maximum capacity of the blanket would need to be higher for their demand. Still, they saw the benefit of running a small pilot project to discover the potential of the system and evaporative cooling in general for themselves and then investing in a larger-scaled charcoal cooler. An interesting finding was, however, that the fabric (burlap) used for the blankets is less common than it was a few years ago. Most farmers stated that they did not know where to get it and how to sew the blanket. Nevertheless, they would readily buy the blanket from a tailor.

Table 2: Percentage of crops grown or sold by the interviewed farmers and vendors. The asterisk marks the products which are not suitable for storage in an evaporative cooler.

Crop	Farmers [%]	Vendors [%]
Tomato	85	70
Maize*	75	-
Leafy vegetables (cabbage, kale, spinach, etc.)	70	60
Banana	65	30
Mango	50	10
Avocado	35	40
Onion, garlic, ginger*	30	40

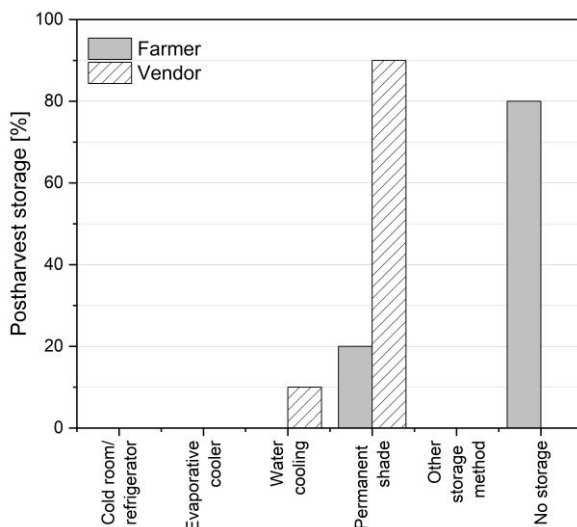


Figure 1: Postharvest storage methods practiced by vendors and farmers [%]. No storage method means the crops are sold on the same days as harvested (only applicable for farmers).

Fruit and vegetable vendors

All vendors interviewed in the town of Embu and Karurumo sold a variety of fruits and vegetables, which are included in Table 4. They purchase between 2 and 150 kg of a given fruit per day and sell about a third each day. Most vegetables must be sold within 3 to 4 days, after which the quality is too poor. The sellers reported losing between 3 and 33% of their fresh produce, depending greatly on the commodity. All of the vendors store their fresh produce in ambient conditions under the shade of the market stalls. One-third mentioned they would prefer a cold room or refrigerator for storage but could not afford it. The remaining respondents were unaware of other suitable options to preserve vegetables, and 60% had never heard about evaporative coolers.

Thereby, 90% of the vendors showed great interest in testing the cooling blanket. However, they acknowledged the same concerns as the farmers that burlap was difficult to obtain and that they could not sew it themselves. Access to water would, however, not be a problem for the majority (70%). Moreover, the capacity of the blanket corresponds well with the needs of the vendors, who would want to store about 100-150 kg or ten crates respectively. They would need a mobile system that can be set up and taken down quickly, which matches the characteristics of the cooling blanket. Some also mentioned using the cooling blanket to store their vegetables at home.

Questionnaire

The questionnaires were adopted from Verploegen et al. [4], [5] and modified. The interviews were conducted using KoboToolbox as a data collection tool.

5.1 Questionnaire: Potential Users of Cooling Blanket – Farmers

A. INTRODUCTION

As part of a research project at the University of Embu on the evaporative cooling of fruits and vegetables after

harvesting, we would like to ask you a few questions to get a better understanding of the current situation and the

farmer's needs. The results of this study will be available in publications summarizing the findings of this study.

Your name will not appear in any data that is made publicly available.

Do you consent to this survey?

Yes No

1. Your name:_____
2. Sub-county:_____
3. Village:_____
4. GPS:_____

B. GENERAL HOUSEHOLD ASSESSMENT

1. Gender: Male Female
2. How old are you?_____
3. What is your position in the household?_____

4. How many people live in your household?_____
5. What is the primary source of livelihood or income in your household?_____
6. Do you or others in your household have any other jobs or roles in the community?_____
7. Do you belong to any organizations or community groups? _____
If yes, what type of group?_____
8. Do you or anyone in your household produce or farm any food products? _____
What types of crops are grown?_____

C. PRODUCTION AND PURCHASE OF AGRICULTURAL PRODUCTS

1. Do you or anyone in your family grow fruits or vegetables? Yes [] No []

If yes:

	Vegetable/fruit type			
Are the crops grown, consumed or sold?				
Where do you sell the crops?				
When are the peak seasons when it's difficult to sell them?				
How much do you sell these crops for?				
How do you transport the products for sale?				
kg sold per week				
kg of vegetables spoilage (postharvest losses)				
How much of the harvested fruits and veg. are normally sold?				
Are the fruits sold on the same day as harvested?				
Storage method (material, price)				
Do you store the F&V (e.g., which you couldn't sell)				

D. VEGETABLES AND STORAGE

1. For the foods mentioned, what storage methods do you use for each?

Type of food	What type of storage do you use?	With this method, how long do you typically store this food?	With this method, how long until this food spoils?	What are the reasons for spoilage?

2. In more detail about the stated storage methods...

Specified storage method above	Does this form of storage use electricity?	How much food can store with this method?	What are the benefits of this method?	What are the weaknesses of this method?	How much does this storage method cost you? (purchase/operation)

3. Are there any other methods of storing foods that you would prefer to use? Yes [] No []

If yes:

- a. Which storage method(s) would you prefer? _____
- b. Why do you prefer this storage method? _____
- c. Why are you not using this method? _____
- d. How much will this storage method cost you (purchase and/or operation)? _____

E. Evaporative cooling technology

- a. Have you heard about evaporative coolers (e.g., ZEBC, Pot-in-pot cooler/Clay pot cooler, Brick cooler, Charcoal cooler)? [] Yes [] No [] Not sure

We are testing a DIY cooling system ("Cooling Blanket") made from jute/sisal, charcoal, and dried palm/banana leaves (show images).

- b. Would you say it's easy and affordable to get jute and charcoal here? _____
- c. Do you know how to sew? [] Yes [] No
- d. Do you have access to water that can be used for vegetable cooling on a daily basis? [] Yes [] No
- e. The vegetables are stored inside a standard *plastic crate* and then put inside the cooling system. Is a crate expensive to acquire here? [] Yes [] No [] Not sure
- f. Would you test and adopt such a "DIY"- cooling system? [] Yes [] No [] Not sure

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Thank you for taking part in the survey!

5.2 Questionnaire: Potential Users of Cooling Blanket – Fruit Vendors

A. INTRODUCTION

As part of a research project at the University of Embu on the evaporative cooling of fruits and vegetables after

harvesting, we would like to ask you a few questions to get a better understanding of the current situation and the

farmer's needs. The results of this study will be available in publications summarizing the findings of this study.

Your name will not appear in any data that is made publicly available.

Do you consent to this survey?

Yes No

1. Your name:_____
2. Sub-county:_____
3. Village:_____
4. GPS:_____

B. PRODUCTION AND PURCHASE OF AGRICULTURAL PRODUCTS

1. Do you or anyone in your family sell fruits or vegetables? Yes No

If yes:

	Vegetable/fruit type			
Where do you buy the crops?				
How often do you go to this place/buy fresh F&V?				
How far is this place?				
How do you transport the products?				
How much do you purchase the fruits for? Are there seasonal or other variations?				
How much do you sell the fruits for? Are there seasonal or other variations?				
How many kg do you sell per day?				

Do you have any issues with spoilage? If yes, how many kg of spoilage?				
How do you store the F&V?				
How many days after purchasing can you still sell the F&V?				
What do you do with the fruits you have not sold at the end of the day?				

C. VEGETABLES AND STORAGE

1. For the foods mentioned, what storage methods do you use for each and how long do you typically store this food?

2. In more detail about the stated storage methods...

Specified storage method above	Does this form of storage use electricity?	How much food can store with this method?	What are the benefits of this method?	What are the weaknesses of this method?	How much does this storage method cost you? (purchase/operation)

3. Are there any other methods of storing foods that you would prefer to use? Yes [] No []

If yes:

- Which storage method(s) would you prefer? _____
- Why do you prefer this storage method? _____
- Why are you not using this method? _____
- How much will this storage method cost you (purchase and/or operation)? _____
- Which capacity of the storage device would be necessary to meet your demand? _____

D. Evaporative cooling technology

- a. Have you heard about evaporative coolers (e.g., ZEBC, Pot-in-pot cooler/Clay pot cooler, Brick cooler, Charcoal cooler)? Yes No Not sure

We are testing a DIY cooling system ("Cooling Blanket") made from jute/sisal, charcoal, and dried palm/banana leaves (show images).

- b. Would you say it's easy and affordable to get jute and charcoal here? _____
- c. Do you know how to sew? Yes No
- d. Do you have access to water that can be used for vegetable cooling on a daily basis? Yes No
- e. The vegetables are stored inside a standard *plastic crate* and then put inside the cooling system. Is a crate expensive to acquire here? Yes No Not sure
- f. Would you test and adopt such a "DIY"- cooling system? Yes No Not sure

Thank you for taking part in the survey!

S6 Supplementary material of the cost analysis

Table 3: Annual cost statement for a farmer using a large cooling blanket ($L_b = 5.25$ m) filled with sawdust as padding material. It is assumed that the blanket remains assembled during usage. Since some materials can be reused in subsequent years, the costs decrease after the first year. If charcoal is used, additional costs of KES 1012 (USD 7) for 30 kg charcoal incur which results in total costs of KES 8473 (USD 59) for the first year. (Exchange rate: 1 KES = 0.007 USD).

Cost	Qty	1. year		2. year		Remark
		KES	USD	KES	USD	
Fixed costs						
<i>Material</i>						
Sawdust [kg]	15	0	0	0	0	
mat	2	600	4.2	-	-	
crate	3	3600	25.2	-	-	
blanket incl. manufacturing	1	2100	14.7	2100	14.7	
Watering can	1	550	3.85	-	-	
<i>Labour</i>						
Filling of blanket [h]	3	261	1.8	261	1.8	Average minimum wage (2023): 15120 KES/month, hence 87 Ksh/h (for 40 hours week) [6]
Assembly [h]	1	87	0.6	87	0.6	
Variable costs (annual*)						
Water [L]	4380	263	1.84	262.8	1.84	Water consumption: 12 L/d water price: 60 Ksh/m ³ [7]
Total cost (annual)		7461	52	2711	19	

*Annual usage was calculated based on 280 working days (6 days per week minus 10% due to illness or other absences)

Table 3: Annual cost statement for a fruit vendor using a small cooling blanket ($L_b = 3$ m) filled with sawdust as padding material. It is assumed that the blanket needs to be (di-)assembled during usage. If charcoal is used, additional costs of KES 338 (USD 4) for 10 kg charcoal incur which results in total costs of KES 7682 (USD 54) for the first year. (Exchange rate of 1 KES = 0.007 USD).

Cost	Qty	1. year		2. year		Remark
		KES	USD	KES	USD	
Fixed costs						
<i>Material</i>						
Sawdust [kg]	5	0	0	0	0	
mat	1	300	2.1	-	-	
crate	1	1200	8.4	-	-	

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blanket incl. manufacturing	1	1200	8.4	1200	8.4	
Watering can	1	550	3.85	-	-	
<i>Labour</i>						
Filling of blanket [h]	1	87	10.6	87	10.6	<i>Average minimum wage (2023): 15120 KES/month, hence 87 Ksh/h (for 40 hours week) [6]</i>
Variable costs (annual*)						
Assembly [h]	44.8	3898	27.28	3898	27.28	<i>10 min per day</i>
Water [h]	1825	110	0.77	110	0.77	<i>Water consumption: 5 L/d water price: 60 Ksh/m³ [7]</i>
Total cost (annual)		7344	51	5294	37	

**Annual usage was calculated based on 280 working days (6 days per week minus 10% due to illness or other absences)*

OUTLOOK

Looking ahead, the next steps required to improve the accessibility of evaporative coolers include building partnerships with farmers, cooperatives, universities, and organizations to increase awareness, training, financial accessibility and adoption. Workshops and training must be organized with the local community, and comprehensive operating instructions should be available online and in different (local) languages. Further, efforts must be made to increase the availability and supply of the materials. These instructions can also be extended to how to manufacture or repair these blankets by the farmers. We foresee that this is one of the largest hurdles that would need financial support since the cost of the blanket as such is not so high and can even be homemade. Awareness raising and training are, however, very time-intensive.

In addition, it would be of interest for future research to advance knowledge about different applications of the blanket along the supply chain, for example, during transport from the farm to the local market. It should be mentioned that the prospective user must evaluate the individual suitability for evaporative cooling before deployment. This includes the operating conditions, namely, whether the local climate is favorable for the technology, whether a suitable location for constructing the cooling system is available, and whether the cooler is effective in the harvest season. If necessary, precautions must be taken (e.g., insect protection). Some tools and diagrams have been created by scientists to simplify this step and to replace the conventional and tedious method of extracting relevant information from psychrometric charts. For instance, the Decision-Making Tool created by MIT's D-Lab can be used to quickly assess the suitability of a location [53]. Additionally, stakeholders can openly access an online global map illustrating the temperature reduction attributed to evaporative cooling for four distinct months [23].

Nonetheless, the optimal performance can only be guaranteed if the hygrothermal conditions inside the cooler are monitored with the help of sensors. In this way, the operation can be tailored to the ever-changing weather conditions, and it is clear when the water has to be replenished. One approach to help interpret such sensor data is to provide the stakeholders with service tools – like a mobile app - for translating this data into easy-to-use information. For instance, feeding the real-time sensor data into digital fruit models ("digital fruit twin") can provide actionable metrics, such as the remaining shelf life [54].

This study demonstrates the potential of the passive cooling blanket to improve postharvest storage in low- and middle-income countries like Kenya. However, the major challenge remains to increase dissemination among those needing such technology. The evidence provided in this paper is the initial step toward establishing trust in the technology and raising awareness about its benefits. Promoting postharvest storage methods is crucial to reducing the vast postharvest losses, increasing access to nutritious food and improving the farmer's income. On a broader scale, these efforts also contribute to the sustainable use of

scarce resources and the reduction of greenhouse gas emissions arising from food waste. Innovations such as the evaporative cooler have the potential to play a pivotal role in achieving the Sustainable Development Goals. The combination of cold temperatures and elevated humidity makes this storage method interesting for preserving several fruits or vegetables, whereas active cooling systems often do not actively humidify.

REFERENCES

- 1] T. Defraeye *et al.*, “The charcoal cooling blanket: A scalable, simple, self-supporting evaporative cooling device for preserving fresh foods,” *Preprint on engrxiv.org*, 2022, doi: 10.31224/2221.
- 2] T. V. Suslow and M. Cantwell, “Tomato: Recommendations for Maintaining Postharvest Quality,” Department of Plant Sciences, University of California, Davis. Accessed: Jun. 17, 2023. [Online]. Available: https://postharvest.ucdavis.edu/Commodity_Resources/Fact_Sheets/Datastores/Vegetables_English/?uid=36&ds=799
- 3] G. Cocetta and A. Natalini, “Ethylene: Management and breeding for postharvest quality in vegetable crops. A review,” *Frontiers in Plant Science*, vol. 13. Frontiers Media S.A., Nov. 14, 2022. doi: 10.3389/fpls.2022.968315.
- 4] E. Verploegen, R. Ekka, and G. Gill, “Evaporative Cooling for Improved Vegetable Storage in Rwanda & Burkina Faso,” 2019.
- 5] E. Verploegen, O. Sanogo, and T. Chagomoka, “Evaporative Cooling Technologies for Improved Fruit & Vegetable Storage in Mali,” 2018.
- 6] Kenya National Bureau of Statistics, “Kenya Minimum Wages,” 2023. Accessed: Aug. 23, 2023. [Online]. Available: <https://tradingeconomics.com/kenya/minimum-wages>
- 7] WASREB, “Gazetted Tariffs Embu,” Water Services Regulatory Board. Accessed: Aug. 23, 2023. [Online]. Available: https://wasreb.go.ke/wasrebsystems/tariffs/tariff_webdisplay.php?wsp=29