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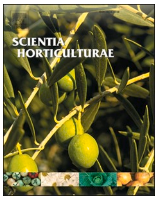

Research Paper

Tackling postharvest tomato losses in tropical climates using a passive cooling blanket

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ABSTRACT

In sub-Saharan Africa, >40 % of fruit and vegetables are lost between farm and consumer. Cooling produce after harvest is key to reducing these losses. Passive evaporative cooling offers a promising solution, particularly for smallholder farmers in low- and middle-income countries, but challenges related to cost, scalability and complexity limit its adoption. To address these challenges, we developed the charcoal cooling blanket (CCB), an affordable and scalable solution for storing fresh produce. In a pilot study in the Ugandan tomato supply chain, we tested the CCB against natural shade to improve tomato storage and transport. We also evaluated pre-harvest factors such as ripening stage and irrigation scheduling and post-harvest attributes such as weight, firmness, colour, soluble solids content (SSC) and acidity. CCB reduced the average ambient temperature by 1.5 °C, with a maximum reduction of up to 20 °C during the hottest periods. Relative humidity increased by 10 %, reducing tomato shrinkage. Storage in the CCB resulted in up to 10 % less weight loss, 20 % less firmness loss, slower colour change and a 4 % increase in the SSC/pH ratio compared to ambient conditions. Moderate water stress during cultivation combined with CCB storage reduced weight loss in green tomatoes by 17 %. Overall, CCB increased the quality index and shelf life of tomatoes by up to 60 %. The CCB has shown significant potential for reducing post-harvest losses, making it a viable option for preserving fresh produce and improving food security in low- and middle-income countries.

1. Introduction

The primary challenge confronting agricultural research is the imperative of ensuring the procurement of sufficient nourishment for a population projected to exceed 9.1 billion individuals by the year 2050 (El-Beltagi et al., 2023). Consequently, there is an imperative to achieve a 60 % increase in food production by 2050 to effectively address global food supply demands (Parfitt et al., 2010). It is evident that enhancing food production is not the sole solution to this problem. On a global scale, between 25 % and 50 % of fruits and vegetables are lost during the process from farming to consumption, a phenomenon termed post-harvest losses or Food Loss and Waste (FLW) (El-Beltagi et al., 2023). This loss is estimated to account for approximately one-third of the total food produced worldwide (Bancal and Ray, 2022). The reduction of food loss is of pivotal importance in the context of enhancing nutrition for a greater number of individuals on a global scale, with a particular emphasis on low- and middle-income countries (LMICs) where the gross national income (GNI) per capita is below $4516 (Bank W, 2025).

In the context of Sub-Saharan Africa's LMICs, the prevalence of food losses and waste is particularly pronounced, especially among small-holder farmers, with over 40 % occurring post-harvest (Bank W, 2025). This is a matter of particular concern, given that >70 % of the population in countries of this region, such as Uganda, are small-holder farmers (Sies and van Hintum, 2023). Consequently, this results in a considerable income loss for a significant proportion of the population, thereby exacerbating the cycle of poverty that is prevalent in these regions. Furthermore, a significant proportion of the impoverished

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Nomenclature

Symbols

E	energy [J·mol-1]
I	respiration-driven quality indicator [%]
η	cooling efficiency
k	rate constant [s^{-1}]
Q	food quality
R	universal gas constant [J·mol-1·K-1]
RH	relative humidity [%]
T	temperature [°C] or [K]
t	time

Subscripts

a	activation
avg	average
db	dry bulb
f	fruit
sc	supply chain
wb	wet bulb

Superscripts

n	reaction order

Abbreviations

CCB	charcoal cooling blanket
FAO	food and agriculture organization
FLW	food loss and waste
FSCs	food supply chains
GNI	gross national income
LMICs	low- and middle-income countries
MUARIK	Makerere university agricultural research institute Kabanyolo
RSL	remaining days of shelf life
SSC	soluble solids content

population depends on short Food Supply Chains (FSCs), which frequently lack adequate postharvest infrastructure and access to contemporary technologies such as packing houses and refrigeration facilities (Parfitt et al., 2010). In addition to being small-scale, the production of most fruits and vegetables in these regions involves varying degrees of participation in local markets (Jayne et al., 2006). In an effort to reduce postharvest losses within these systems, the primary focus of efforts is on improving training and technical capabilities. Such capabilities include postharvest handling and management, and the reduction of reliance on labor-intensive technologies. Despite the efforts made, there remains a significant shortage of cold storage facilities for fruits and vegetables, extending from farms to local markets within this region. It is evident that this constitutes a pivotal factor that has contributed to the substantial economic losses incurred.

Cold storage has been shown to significantly prolong the shelf life and quality of fresh produce by slowing down biochemical degradation reactions (Onwude et al., 2022). However, in many cases in Sub-Saharan Africa's LMICs, fruits and vegetables are stored only under natural shade after harvest and transported to the local market without cooling, leading to rapid wilting and decay. Consequently, farmers frequently sell their produce immediately after harvest at lower prices, without generating significant profit. Evaporative passive cooling technology has been identified as a potential solution to address these challenges. It has been demonstrated that the cooling of fresh produce by means of ambient airflow over a wetted porous medium has the capacity to enhance fruit quality and extend shelf life by a period of between two and six days (Defraeye et al., 2024). Despite the evident advantages of evaporative coolers, their deployment remains infrequent. The existing coolers, including clay-based and brick coolers, necessitate advanced construction expertise and significant initial capital expenditure, thus hindering their adaptability to meet the requirements of smallholders. This indicates that the extant evaporative cooling solutions are inaccessible to smallholder farmers. The rationale underpinning the recent development of a self-supporting, scalable and affordable passive cooling blanket is described in the present work. Preliminary findings indicate that this innovation is showing promising results in terms of cooling and extending the shelf life of fruits and vegetables (Defraeye et al., 2024). However, further testing and adaptation of this technology to real-world settings in dry and warm LMICs, where smallholder farmers and traders can access it, are necessary to quantify its true impact on reducing food loss.

In order to enhance the sustainability and efficiency of tomato production, deficit irrigation was also evaluated in order to assess its impact on storage behavior. Despite the evidence in the literature that irrigation schedules can impact the quality of tomatoes, including firmness, soluble solid content, vitamin C content, and titratable acidity (Rajesh et al., 2022), the precise impact of deficit irrigation and its interaction with harvest at different ripeness levels remains to be fully elucidated.

The objective of this study was to reduce post-harvest food loss within the local tomato supply chain in Uganda, from farm to market, by employing the charcoal cooling blanket (CCB) and investigating the impact of pre-harvest practices, such as harvest time and irrigation techniques, on the fruit quality parameters (weight, firmness, colour, SSC/pH ratio) of tomatoes stored with CCB.

2. Materials and methods

2.1. Laboratory experiment

A laboratory experiment was conducted in two climate chambers at Agroscope (Wädenswil, Switzerland) from April to July 2023. The purpose was to test the cooling performance of a small cooling blanket and to assess the impact of packaging on cooling performance and fruit quality before the main experiments in Uganda. The temperature in the chambers was set to 23 °C and the relative humidity (RH) was set to 60 %. Both were continuously monitored and adjusted.. These conditions were designed to simulate the average weather conditions typical of Uganda during the test period. Three different types of packaging were tested: A plastic crate (58.5 × 39 × 32.3 cm), a woven basket (35.5 × 39 cm) and a wooden crate (54 × 20 × 17 cm) (Figure S1). These types of packaging were chosen because wooden crates and woven baskets are commonly used by smallholder farmers in Uganda, whereas plastic crates are the standard recommendation for fruit and vegetables. Commercially grown tomatoes cv. Peretti, (Bettio Glarona, Wädenswil, Switzerland) were used for the storage experiments without further analyzing the ripeness or quality of the tomatoes. The tomatoes were stored using charcoal cooling blankets (CCBs) made of burlap and divided into compartments filled with dry wood charcoal of medium size (50 × 50 mm). Other materials can be used to fill the CCBs, such as rice husk or sawdust, although charcoal is the primary energy source for 65 per cent of urban households in Uganda (FAO, 2023). There are also increasing efforts by the Ugandan government to make charcoal more sustainable through selective harvesting and the production of charcoal from wood energy plantations. We placed three 3 × 0.4 m CCBs in one chamber and a larger 10 × 0.9 m CCB in the other. In the first case, a small blanket was wrapped around each plastic, woven and wooden container. In the second case, all three packages were placed inside the large CCB. A plastic box, a wooden box and a woven basket were also used to form the control group (Figure S1). To drive the evaporative cooling, water was poured onto the side of the blanket using a garden watering can. The amount of water (L) was equal to 1/3 of the weight of the charcoal contained in the blanket. The application of water to the blanket is called watering. During storage, the tomatoes must be kept dry to avoid the formation of mold on the surface. The presence of water droplets on the skin of the tomatoes, coupled with the high RH, promotes the proliferation of microorganisms.

2.2. Field experiments in Uganda

2.2.1. Study site

The study took place at Makerere University Agricultural Research Institute Kabanyolo (MUARIK), (0° 28′ 8.35297’’N, 32° 36′ 26.7768’’E), 20 km north of Kampala, Uganda. The experiment was carried out from August to November 2023. During this period, the average temperature recorded by the weather station (Agriscope, France) was 22.5 °C, with a minimum of 18.9 °C and a maximum of 28.3 °C. The experiment started at the beginning of the rainy season with short showers, but the rainfall increased towards the end. The experiment was repeated twice in a fenced shelter that was paved and protected from animal attacks and rainfall. The shelter provided a shaded environment except from 5pm to 6pm.

2.2.2. Storage of tomatoes at different ripening stages

2.2.2.1. Fruit selection. Tomatoes cv. Ansal were harvested on 31 August 2023 from a field in MUARIK (Kabanyolo, Uganda). For the experiments, tomatoes that had not sustained external damage, such as cracks or bruises, were meticulously selected. During the harvesting process, the tomatoes were meticulously detached from their petioles, which are the slender stalks that connect the fruits to the stem. The harvesting process was executed concurrently at three distinct stages of ripening: green, breaker, and red in accordance with the United States standards for the grading of fresh tomatoes (Garcia et al., 2019). Approximately 8 to 10 kg of tomatoes were collected at each ripening stage and weighed using an analogue scale (Avaweigh, Industrial Hanging Scale, China). Each experimental unit comprised a crate containing 2.5 kg of tomatoes.

2.2.2.2. Specifications of the passive cooling blanket. Three passive cooling blankets, crafted from burlap, were utilized in the experiment. The blankets were produced at Empa, St. Gallen, and subsequently dispatched to Uganda for distribution to local farmers. The dimensions of each blanket were 3.5 × 0.6 m, with a division into compartments of 150 mm. Each compartment was filled with charcoal broken into pieces with an average volume between 100–125 cm^3. Each blanket contained 10 kg of charcoal. The blanket was wrapped around a plastic crate (0.6 × 0.4 × 0.3 m) containing the harvested tomatoes. The plastic crate was selected for the field experiment on the basis that it demonstrated the optimum cooling performance and fruit quality in comparison to the wooden crate and woven basket, as had been established in laboratory experiments. Half of a clay brick was placed between the blanket and the crate on all four sides, thus creating a space measuring 7–8 cm between the CCB and the crate. The same method was used to elevate the crate from the ground. In order to enhance adhesion to the bricks, a rubber belt was affixed around the blanket. A cover composed of desiccated palm leaves was subsequently applied to the system, with the objective of ensuring hygrothermal insulation and preventing the rapid dissipation of cold and humid air from the cooler (Fig. 1). In order to maintain elevated levels of relative humidity and thereby enhance the cooling performance, the cooling blanket was subjected to watering, particularly in instances of significant reductions in relative humidity or increases in temperature. Water was dispensed using a standard watering can, with 3 liters allocated for each blanket, and this process was repeated three times per week.

2.2.2.3. Ambient storage experiment. The tomatoes were stored within three plastic crates, at an ambient temperature (T) and relative humidity (RH), without the use of a passive cooling blanket. The three crates were utilized as a benchmark, i.e. the quality of tomatoes following ambient storage was compared with that of tomatoes stored inside the cooling blankets.

2.2.2.4. Monitoring variation of temperature and relative humidity. Within each crate, a Bluetooth hygrothermal sensor (SHT4X SMART GADGET, Sensirion AG, Stäfa, Switzerland) was positioned without direct contact with the tomatoes to prevent water penetration (Figure S2a). The sensor measured the temperature and relative

Fig. 1. Three filled charcoal cooling blankets (CCB) wrapped around three plastic crates of tomatoes at different ripening stages (green, breaker, red) and kept inside the shelter showing the rubber strap tied around the CCB and the leaf cover on top of the blankets.

humidity of the environment near the tomato inside the passive cooler. Furthermore, IoT Wi-Fi hygrothermal sensors equipped with probes (UbiBot WS1 Pro, Hong Kong) were utilized to record the temperature and humidity inside and outside the blanket (Figure S2b). These sensors enabled the real-time monitoring of the temperature and humidity of the cooling system from any location. Temperature data loggers with probes (Tinytag Talk 2 - TK-4023, West Sussex, United Kingdom) were utilized to collect data on the core temperature of tomatoes. The probe was then inserted into the tomato and fixed in place using adhesive tape (Figure S2c). The same sensors were positioned in the shelter to record temperature and relative humidity as benchmarks. The accuracy of the sensors is reported in the supplementary material (Table S1). The temperature and relative humidity measured by the sensors were utilized to calculate the cooling efficiency (η) of the evaporative cooling system (Eq. (1)). Evaporative cooling attains its theoretical minimum temperature, designated as the wet-bulb temperature (T_{wb}), in which the process is at its most efficient. The temperature is principally influenced by the ambient temperature (dry-bulb temperature, T_{db}) and relative humidity. Consequently, an increase in humidity results in an increase in T_{wb}, which approaches T_{db}, thereby reducing the potential temperature decrease achievable through evaporation.

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

2.2.2.5. Experimental design. The experiment comprised six groups, with three different ripening stages (green, red, and breaker) being considered for both CCB and the benchmark, in natural shade. Each crate contained 5 kg of tomatoes at varying stages of ripening, depending on the treatment applied. Tomatoes at varying stages of ripening were isolated to prevent the influence of one stage on others due to the varying levels of ethylene production, which could interfere with the ripening process and obscure the effects of the chemical. The storage period lasted 14 days for each treatment, after which groups of tomatoes were removed from the crate and evaluated for various quality parameters. In order to ensure the reproducibility of the results, the storage and irrigation experiments were replicated twice.

2.2.3. Irrigation experiment

The cultivation of tomatoes cv. Ansal was undertaken in the Foodland field at MUARIK (0°27′56.0″N 32°36′47.1″E). Five distinct treatments were implemented in relation to the irrigation schedule of the tomatoes (Table 1) with the objective of investigating the impact of water deficit on postharvest quality parameters applying the cooling blanket. Treatment C1 and C2 were used as a control. The objective of the I_{MDY} and I_{ADY} treatment was to maximize yield. In this instance, irrigation was initiated at a soil water tension of 20 kPa. The objective of the I_{ADS} treatment was to optimize shelf life applying mild water deficit and irrigation was initiated at a soil water tension of 40 kPa.

The tomato seedlings were planted on 4 August 2023, and the harvest took place on 5 October, 12 October and 27 October 2023. The harvesting of tomatoes was undertaken at the green stage due to the impact of a fungal disease, specifically *Alternaria linariae*, which was rapidly deteriorating the tomatoes following a change in color. The tomatoes from the initial harvest were stored within the cooling blanket and subsequently analyzed to gather quality data. Three repetitions were conducted concurrently under the shelter. Storage for the three repetitions lasted 14 days; tomatoes belonging to different irrigation treatments were numbered and mixed within the crates.

Table 1
List and explanation of the five irrigation treatments in the field located at MUARIK. Treatments were randomly assigned to five plots and two replicates.

Irrigation system	Explanation
C_R	Control, rainfed
I_M	Control, manual irrigation by watering can, decision on common practice
I_{MDY}	Manual drip irrigation, Chameleon sensors, yield optimization
I_{ADY}	Automated drip irrigation, Watermark sensors, yield optimization
I_{ADS}	Automated drip irrigation, Watermark sensors, shelf-life optimization

2.2.4. Supply chain experiment: farm to fork

The tomatoes cv. Ansal were sourced from the same field as described above. Two plastic crates, each measuring 0.6 × 0.4 × 0.3 m, were utilized for the purpose of storing 25 kg of tomatoes in each. The tomatoes were harvested at the green stage and then stored for a period of two days under a shelter in the field prior to transportation. Sensirion sensors were affixed to the exterior and interior surfaces of each crate (Figure S3a). The internal temperature of two tomatoes per crate was measured using two Tiny Tag sensors (Figure S3b). In order to simulate the transport procedure of the tomatoes, two local motorcycles (boda) were utilized. Rubber bands were employed to secure the leaf cover on the blanket and the crates on the motorcycles. The measurement of wind speed was facilitated by an anemometer (Testo 405i, Hampshire, United Kingdom) attached to the CCB (Figure S3c). The motorcycles traversed a distance of 2 km from the farm to the market of Kabanyolo (0°28′14.4″N 32°36′22.3″E). The total duration of the transport was 20 min. Subsequently, two local tomato sellers collected both crates of tomatoes in the same market stall (Figure S3d). The tomatoes remained at the market for a period of five days. On a daily basis, the sensors and the wetness of the blanket were checked while in the market. Figure S4 provides a graphical overview of the local tomato supply chain from farm to market.

2.3. Food quality loss and shelf life modeling

The food quality loss (Q_{loss} %) was modelled with and without the charcoal cooling blanket (CCB) in the local tomato supply chain. The model was based on the first-order kinetic model of temperature-induced food quality degradation, as described in Eq. (2). The first-order rate-law model indicates an exponential decline in respiration-driven fruit quality over time (Onwude et al., 2022). This change in this tomato quality indicator or index is quantified by the respiration-driven quality indicator (*I* %).

$$-\frac{dI(t)}{dt} = k_{quality}(T_f)\cdot I(t)^n \tag{2}$$

In Eq. (3), $I(t)$ is the respiration-driven remaining fruit quality (%) at any time instant *t*, $k_{quality}(T_f)$ is the temperature-dependent rate constant (s^{-1}), *n* is the reaction order (=1 in this case). Here, T_f is the measured core fruit temperature (K) of the fruit from the farm to the market.

$$Q_{loss} = [I_0 - I(t)] \tag{3}$$

where I_0 is the initial quality after harvest, which is assumed to be 100 %.

In the present calibration, $I = 20$ % was designated as the threshold for the termination of shelf life for the tomato, with all model parameters being recalibrated accordingly. The temperature dependence of the rate constant $k_{quality}$ (T_f) was accounted for by the Arrhenius equation for reaction rates, as shown in Eq. (4).

$$k_{quality}(T_f) = k_{0,quality}\exp\left(-\frac{E_{a,quality}}{RT_f}\right) \tag{4}$$

where ($k_{0,quality}$, s^{-1}) is the pre-exponential factor, $E_{a,quality}$ is the activation energy ($J\cdot mol^{-1}$), *R* is the universal gas constant (8.314 $J\cdot mol^{-1}\cdot K^{-1}$).

To account for the dependence of shelf life on storage temperature, we assumed a Q_{10} factor between two and three (Eq. (5)).

$$Q_{10} = \frac{k_{quality,\ (T_f+10)}}{k_{quality,\ T_f}} \tag{5}$$

where $k_{\text{quality,(Tf+10)}}$ and $k_{\text{quality,Tf}}$ correspond to the rate constants at temperatures (T_f+10) and T_f K, respectively.

The remaining shelf-life days (RSL) of the tomato sold with and without CCB were predicted based on the same kinetic rate model, by storing the vegetable in the open market's average temperature air condition of 25 °C. In this section, the typical dynamic conditions encountered during retail were also considered. RSL was calculated until the remaining respiration-driven quality indicator (I) quality attained the threshold of acceptable quality (20 %) (Onwude et al., 2022).

2.4. Quality measurements

The quality of the stored tomato was measured on days 0, 4, 7, 10, and 14 with regard to green tomatoes. For breaker tomatoes, quality parameters were measured on days 0, 3, 6, 9, 12, and 14. With regard to the red tomatoes, quality parameters were measured on days 0, 2, 4, 6, 8, 10, 12, and 14. At each sampling point, the tomatoes were evaluated non-destructively in terms of weight, firmness, and color. Subsequently, the fruits were subjected to a destructive assessment, which included measuring the pH and soluble solids content (SSC). Although titratable acidity (TA) is the more common measurement in fruit quality analyses, the logistics of the experiment did not allow for measuring TA. Thus we aimed at approximating TA by measuring pH since studied show that pH and TA are typically well correlated (Anthon et al., 2011; Paulson and Stevens, 1974) and the human perception of sour taste as a quality parameter is well correlated to pH given a constant ratio of organic acids (Da Conceicao Neta et al., 2007).

2.4.1. Weight loss

The weight was measured using a digital precision scale with 0.01 g of resolution (EMB 500–2S, KERN, Switzerland). Subsequently, the fruit were weighed on different days according to their initial ripening stage (Eq. (6)). The weight reduction in the tomato samples was indicated as the accumulated percentage of weight lost from the original weight (Kabir et al., 2020).

$$Weight\ Loss\ (\ \%) = \frac{weight_{day\ 0} - weight_{day\ x}}{weight_{day\ 0}} \times 100 \tag{6}$$

With the initial weight ($\text{weight}_{\text{day0}}$) at the start of the experiment and the reduced weight depending on the time or day ($\text{weight}_{\text{dayx}}$), respectively.

2.4.2. Colour and firmness

The color of the fruit's skin was measured using a color reader (Colorpin Pro, NCS, Stockholm, Sweden) using the L*a*b* notation. The purpose of the calculation of the a*/b* value was to quantify the degree of redness during the process of ripening (Khairi et al., 2015). Tomato softening was monitored during the storage period using a digital penetrometer (FTA GS-25, Umweltanalytische Produkte GmbH, Ibbenbüren, Germany). The fruits was measured on one side first and the opposite side afterwards in a location that was as flat as possible.

2.4.3. pH & soluble solids content

The extraction of the juice from individual tomatoes was accomplished by means of a domestic blender (SN-780, Samsung, South Korea). Subsequently, a sieve was employed, and the liquid was decanted into plastic vials. A select number of drops were then subjected to analysis using a digital refractometer (PR-32a, Atago Co. Ltd., Tokyo, Japan). Measuring soluble solids content (SSC) in Brix degrees (° Brix). Subsequently, the residual juice was immersed in the pH meter probe (827 pH lab, Metrohm, Zofingen, Switzerland) to ascertain the pH.

2.5. Statistical analysis

All data analyses were carried out using Excel 2016 and ORIGIN 2022 (OriginLab, Northampton, Massachusetts, USA), while the statistical tests were performed using R (version 4.3.1) and RStudio (version 1.4.1106). In instances where substantial effects were identified through analysis of variance (ANOVA), the Tukey–Kramer honestly significant difference (HSD) test was employed to ascertain the disparities among means (Table 1). In instances where the assumptions underlying the ANOVA were not met, a non-parametric Kruskal-Wallis test was conducted, subsequently followed by Dunn's post hoc test with Bonferroni correction. This approach was employed to ascertain any significant differences between the groups. The significance level was set at $p = .05$ for all tests. The correlation plot was executed using the ORIGIN PRO 2022 software (OriginLab, Northampton, Massachusetts, USA). The dependent variables of this study were weight loss, firmness, color and SSC/acidity, while the independent variables were relative humidity, temperature, ripening stage and storage time. The correlation type was identified as Pearson, with significant levels set at 0.05, 0.01 and 0.001.

3. Results and discussion

3.1. Laboratory experiments

The first objective was to evaluate the cooling effectiveness of the cooling blankets. In the small blanket, a decrease in temperature (T) and an increase in relative humidity (RH) was observed when water was applied to the blankets. For the smaller blankets, an average temperature drop of 2 °C was recorded across different packaging methods (Fig. 2a). A decrease of 4 °C was evident after a five-day storage period of tomatoes in plastic and wooden crates that had been wrapped with a small blanket (Fig. 2a). However, the temperature within woven baskets remained relatively stable, with a decline of merely 2–3 °C, irrespective of the duration of storage. The trends regarding the increase in relative humidity demonstrate a marked rise in the small blankets on day 5 for the plastic crate and the woven basket, while a later rise is in rH evident for the wooden crate on day 6 (Fig. 2b). It is noteworthy that the small blanket required several days to reach a quasi-steady state condition, as evidenced by the relatively constant and high humidity levels. Consequently, it can be deduced that the utilization of the small blanket was a pragmatic approach, necessitating a low expenditure of resources (water, charcoal, burlap, etc.) and a low requirement for manpower, while yielding results that were analogous to previously published results (Wittkamp, 2023).

The plastic crate exhibited superior performance in all evaluated parameters when compared to wooden and woven containers. The wooden and woven containers, while facilitating the cooling process, exhibited heightened susceptibility to mold due to their material properties, which facilitated moisture absorption and promoted microbial proliferation. Fungal infestations have been demonstrated to modify the appearance of products by affecting their color and surface, thereby diminishing their aesthetic appeal. Moreover, the presence of these fungi constitutes a potential health hazard for both humans and animals in the vicinity of affected crates or produce (Borysiuk et al., 2022).

The findings demonstrated that the small cooling blanket wrapped around the plastic crate and the one wrapped around the wooden crate exhibited a cooling efficiency of 38 %, while the small cooling blanket wrapped around the woven basket showed a cooling efficiency of 28 %.

3.2. Impact of tomato ripening stage on CCB performance

In this study, we present the initial findings from the implementation of the charcoal cooling blanket (CCB) in Uganda, with the objective of assessing its effectiveness in enhancing the preservation of fresh produce under authentic climatic conditions. It is important to note that the thermal properties of tomatoes at different ripening stages are quite

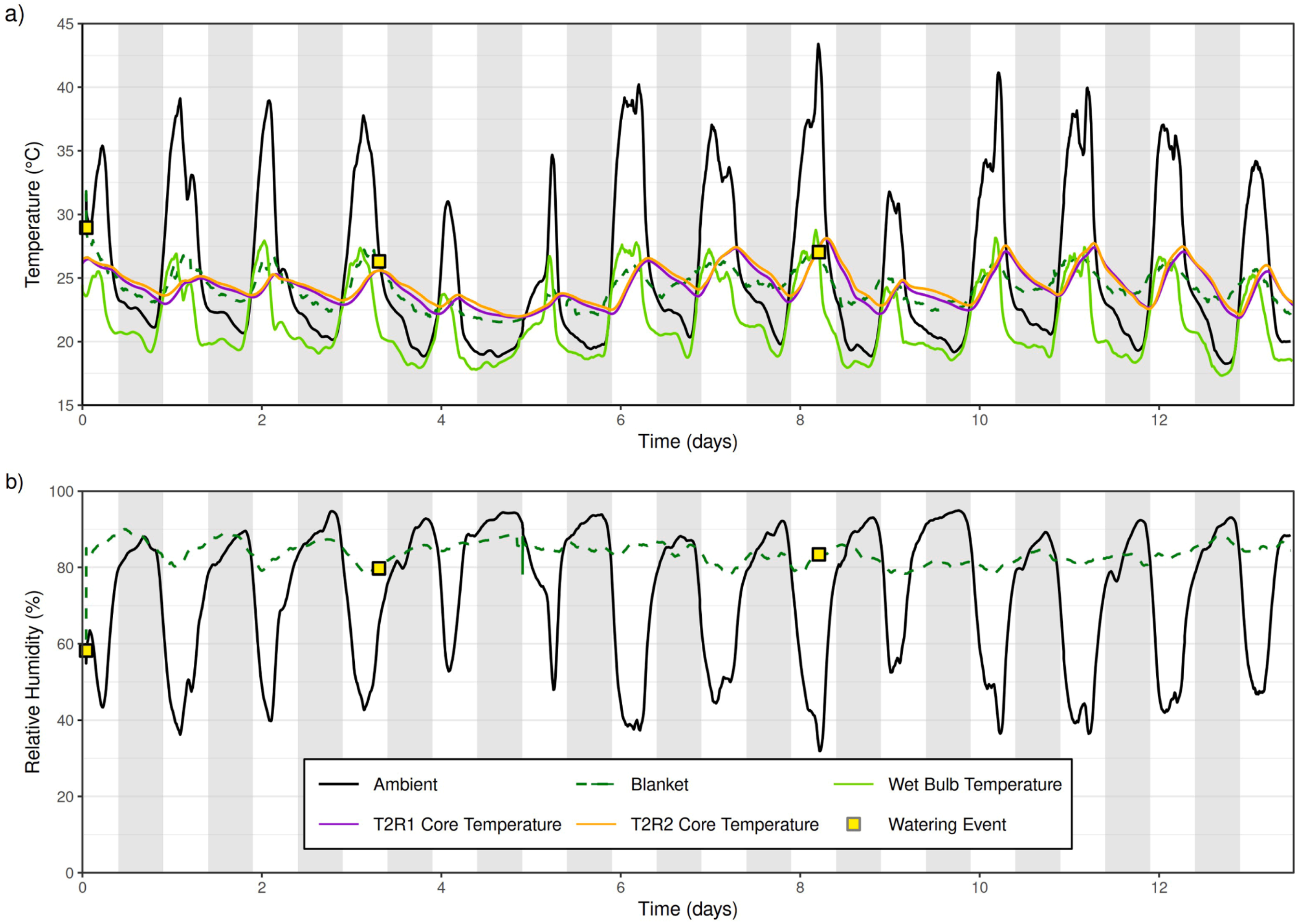

Fig. 2. Hygrothermal sensor data of tomato storage using the small cooling blankets (a, b) and the big cooling blankets (c, d) inside climatic chambers at Agroscope (Wädenswil, Switzerland). Plot (a, c) show the air temperature as a function of time. Plot (b, d) shows the relative humidity as a function of time. The average ambient temperature was 23 °C, the relative humidity 60 %.

consistent, and the heat generated by respiration (~0.425 kJ/h) is negligible. The mean ambient temperature (Tambient) was 24.5 °C, with a maximum of 38.3 °C and a minimum of 17.45 °C (Fig. 3a). The mean relative humidity within the shelter was 74 %, with a maximum of 97 % and a minimum of 34 % (Fig. 3b). For all three ripening stages, the average temperature (Tavg) recorded within the blankets was approximately 23 °C, reflecting a decrease of 1.5 °C compared to the average ambient temperature. However, temperature fluctuations reveal a noTable 13.5 °C decrease during the hottest part of the day. The nighttime ambient temperatures ranged from 18 to 20 °C, which is a few degrees cooler than the average temperature recorded within the blankets (Fig. 3a). It is evident that the cooling performance is most effective during daylight hours, particularly when the ambient temperature exceeds 35 °C. The oscillations in ambient temperature were found to be approximately 20 °C, whilst within the blankets, the oscillations were smaller, measuring between 1–3 °C for red tomatoes and 3–7 °C for breaker and green tomatoes (Fig. 3a).

It is imperative to acknowledge that the core temperature of the fresh produce is of greater significance than the ambient air temperature in preserving tomatoes. As illustrated in Fig. 3a, the three distinct ripening stages exhibited a uniform behavior, with an average core temperature of 23 °C. However, a discernible delay is observed in the response of the internal temperature, which can be attributed to the low thermal conductivity exhibited by tomatoes. The cooling efficiency of the blankets ranged from 68 % when storing green tomatoes and 71 % when storing breaker and red tomatoes. The present study found that the cooling efficiency during the day was superior to that of the laboratory experiment, owing to the higher daily temperature fluctuations.

The three blankets exhibited an average internal relative humidity (RHavg) ranging from 86–89.5 %. Within the confines of the blankets, daily fluctuations never exceeded 10 %, whereas in the surrounding environment, oscillations were much larger, reaching up to 55 %. The blanket containing red tomatoes demonstrated the least variability. Previously, an increase in transpiration has been observed during the ripening process (Fich et al., 2020; Paul and Srivastava, 2006). This phenomenon may provide a rationale for the higher relative humidity (RHavg) recorded in the blanket containing red tomatoes, despite the application of an equivalent amount of water.

Quality parameters were measured after 14 days of storage in order to ascertain the ripening stage at which CCB most effectively reduced quality loss. The results of the pH and SSC measurements are presented as a ratio, as this method encapsulates the balance between sweetness and acidity into a single, easily interpretable value. Irrespective of the degree of ripeness, fruits within the blanket exhibited a more uniform and predictable behavior. The weight of the green tomatoes within the blanket was reduced by 7 % of their initial weight, while the green tomatoes outside the blanket experienced a loss of 19 % of their initial weight (Fig. 4a). However, in the case of red and breaker tomatoes, the 1.5 °C temperature drop coupled with the humidity rise was not sufficient to significantly reduce the high rate of water transpiration from the fruit to the environment. The study revealed a significant loss of 20.6 % for breaker tomatoes within the blanket and 23 % for those outside the

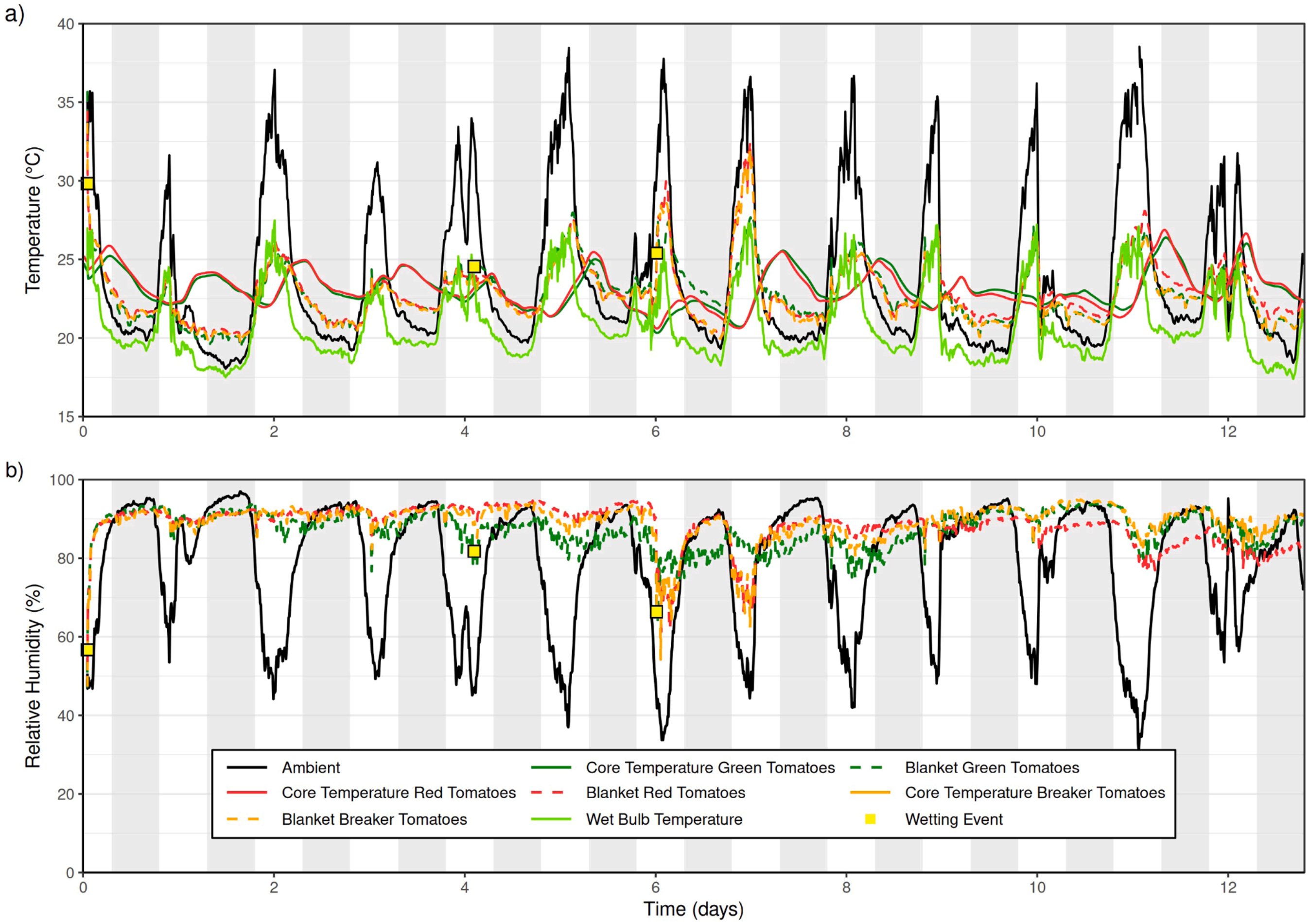

Fig. 3. Hygrothermal sensor data of three cooling blankets containing three different ripening stages (green, breaker and red) taking place inside the shelter at MUARIK (Kabanyolo, Uganda). Plot (a) shows the air temperature as a function of time. Plot (b) shows the relative humidity as a function of time. The average ambient temperature was 24.5 °C, the relative humidity 74 %.

blanket. The experiment revealed that tomatoes of the red variety exhibited a 28 % loss within the blanket and a 20.6 % loss outside the blanket.

During the process of ripening, it was observed that a sealing behavior of transcuticular pores occurred subsequent to the detachment of trichomes from the skin in certain tomato cultivars (Fich et al., 2020). This mechanism may potentially mitigate weight loss during postharvest storage, though its efficacy is strictly cultivar-dependent, and the manner in which its efficiency changes at different ripening stages remains to be elucidated. It is hypothesized that this sealing behavior may have exerted an influence on green tomatoes, though not on red or breaker tomatoes.

The application of the blanket resulted in a significant reduction in firmness loss when the red tomatoes were stored in the blanket (Fig. 4b). In comparison, the breaker tomatoes showed an insignificant reduction in firmness loss and the green tomatoes even showed a higher loss of firmness when stored inside the blanket (56 %). The ripening of tomatoes is characterized by the softening of the fruit, which is indicative of alterations in tissue structure. The exocarp and mesocarp of a mature tomato have been shown to play a significant role in determining the firmness of the fruit. As the maturation process continues, these components undergo substantial modifications, resulting in changes in the mechanical resistance of the tomato corresponding to its mature stage (Bui et al., 2010). Following a 15-day storage period, it is evident that green tomatoes exhibit a greater loss of firmness compared to red tomatoes as they undergo the entire ripening process. This process involves the softening of fruit cell walls and the modification of turgidity. The utilization of the blanket was found to impede this process, with the exception of the breaker and red tomatoes (Fig. 4c). It has been demonstrated that harvesting at the green ripening stage can prolong shelf-life, but concomitantly engender greater variability among the fruits (Tilahun et al., 2019).

The rate of color change, which was measured as an increase in redness, was found to be slower for green and breaker tomatoes stored within the blanket (Fig. 4c). In the case of green tomatoes, a 20 % increase in redness was documented, significantly different to only 6 % in those within the blanket. The red coloration is attributable to the breakdown of chlorophyll and the subsequent synthesis of lycopene and other carotenoids. This phenomenon occurs concomitantly with the transformation of chloroplasts into chromoplasts (Fraser et al., 1994). This finding is consistent with the hypothesis that the color of tomatoes is not significantly impacted by storage conditions, as evidenced by the observation that red tomatoes retained a higher ratio of a*/b* irrespective of their storage environment.

Significant differences for the SSC/pH ratio change were found only between red tomatoes (Fig. 4d). In all other cases, a decrease in the SSC/pH ratio was observed in comparison to the initial reading (day 0) but no differences where observed between storing tomatoes inside or outside the blanket. Green tomatoes characteristically exhibit a reduced soluble solid content (SSC) and elevated acidity (lower pH) in comparison to ripened tomatoes. The SSC/pH ratio of green tomatoes is typically in the range of 0.8 to 1.2, indicating an optimal level of acidity and sweetness. The onset of sugar accumulation in breaker tomatoes is accompanied by a concurrent decline in acidity, thereby restoring balance to the fruit.

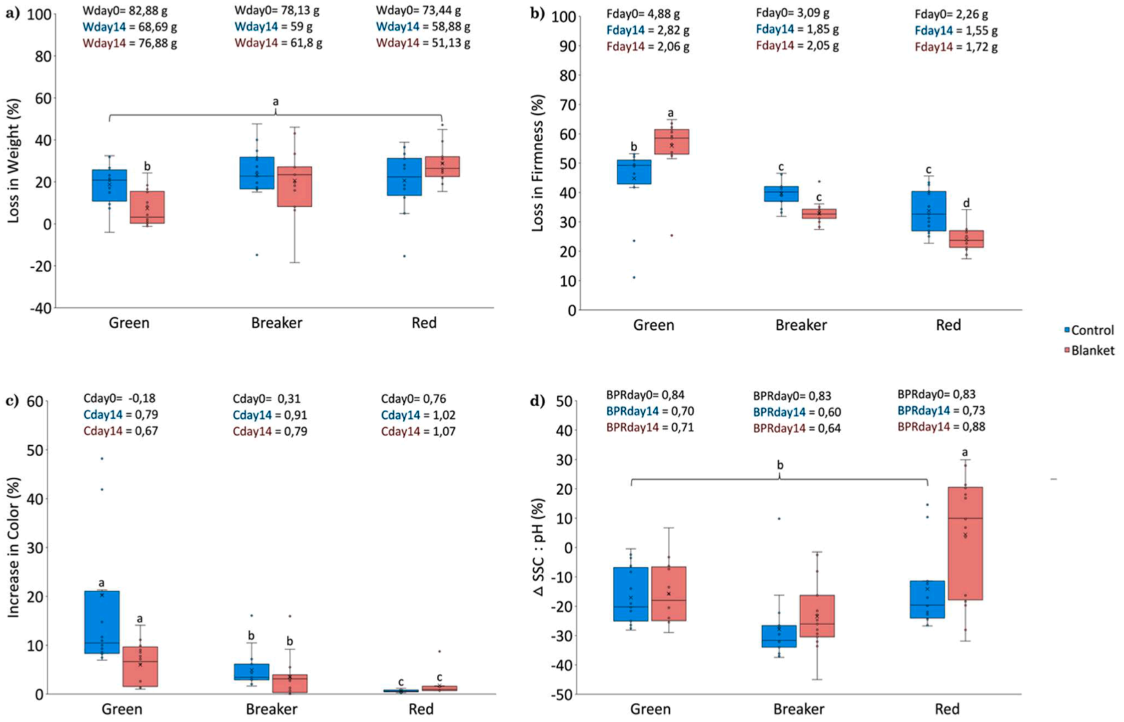

Fig. 4. Boxplot showing percentage change of a) weight, b) firmness, c) color and) Δ SSC/pH of tomatoes on the last day of storage (day 14). The boxes show values from single tomatoes. The “x” represents the averages as percentage. Writings on top of the boxes represents the averages of the real values on day0 (black) and day14 (red-blanket and blue-control) for weight and firmness and ripening stages. Different letters above the boxes within each maturity stage indicate statistically significant differences between treatments ($p > .05$).

The optimal SSC/pH ratio is considered to be in the range of 1.0 to 1.5. (Dzakovich et al., 2017).

In general, changes in the quality and quantity of fresh produce after harvest are irreversible. Nevertheless, these changes can be mitigated to a certain extent, within specific limits (Gundewadi et al., 2018). It has been demonstrated that a decrease in temperature and an increase in humidity can reduce the loss of moisture from tomatoes and mitigate the factors that cause decay during ripening, such as mold growth and bacterial infections. (Ambuko et al., 2017). Following detachment, there is an interruption to the water supply to the plant, which in turn results in a reduction in the weight of fresh produce as a consequence of respiration. This quality loss can be measured as firmness loss, shriveling, visual quality decline and the loss of nutritional value (Caleb et al., 2013). The reduction in product mass, particularly as a result of transpiration and respiration, additionally the marketable mass of fresh produce (Caleb et al., 2013).

3.3. Impact of water stress on performance of the CCB

Next, the impact of irrigation practices on the quality parameters of green tomatoes stored within the CCB was evaluated. During the course of this trial, the ambient temperature (Tambient) rose to extremely high levels, exceeding 40 °C (Fig. 5a). Notwithstanding this, the tomatoes exhibited an average temperature of 24 °C, 1 °C below the mean ambient temperature. However, during periods of peak daytime heat, a significant temperature difference of 20 °C was observed between the exterior and interior of the blanket (Fig. 5a). The employment of the CCB has been demonstrated to significantly mitigate temperature fluctuations, thereby reducing the heat stress that can compromise fruit quality and accelerate ripening. The relative humidity within the blanket was 83 %, representing a 10 % increase compared to ambient humidity levels (Fig. 5b). The cooling blankets were irrigated with 9 liters of water whenever the internal relative humidity fell below 90 %. Following the third watering event, the relative humidity did not exceed 90 %, likely attributable to the elevated temperature, which accelerated the process of transpiration. It can be hypothesized that the occurrence of an additional watering event would have been beneficial in order to maintain elevated levels of relative humidity. The core temperature of the tomatoes reflected the trend of the temperature of the air inside the blanket. The cooling efficiency of the system was found to be 87 % during the experiment. Furthermore, the process of cooling was found to be more efficient during nocturnal hours, owing to the elevated temperatures observed in comparison to the initial experiment.

The present study investigated the impact of three different irrigation techniques on the quality of tomatoes stored in CCB. In particular, two treatments were conducted using automated irrigation system sensors. The aim of the first treatment was to increase the yield, while the second treatment involved a water deficit variant in order to optimize the product’s shelf life. It is evident that water stress is the most hazardous environmental factor influencing the physicochemical, biochemical and biophysical characteristics of tomato crops (Alordzinu et al., 2022). The physiological responses of tomatoes have been observed to be influenced by two distinct factors: prolonged periods of water stress and stress occurring during the early stages of the reproductive phase (Quinet et al., 2019). In contrast, the presence of water stress towards the end of the growing season has been demonstrated to have a positive effect on the quality of tomato fruits by increasing the levels of total soluble solids, which are of crucial importance during the ripening stage (Yin et al., 2010).

The statistical analysis revealed a significant impact of CCB on the weight loss, firmness, color and SSC/pH ratio of tomatoes cultivated based on the irrigation treatment and the use of the blanket. A substantial disparity in weight reduction was identified in the utilization of the blanket across the I_{ADY}, C_R and I_M treatments (Fig. 6a). The application of the blanket was found to be effective in reducing moisture loss from the fruits in the case of I_{ADY} and C_R. Conversely, tomatoes exposed to the ambient temperature exhibited an increase in weight during the ripening process. Among the smart irrigation treatments, tomatoes

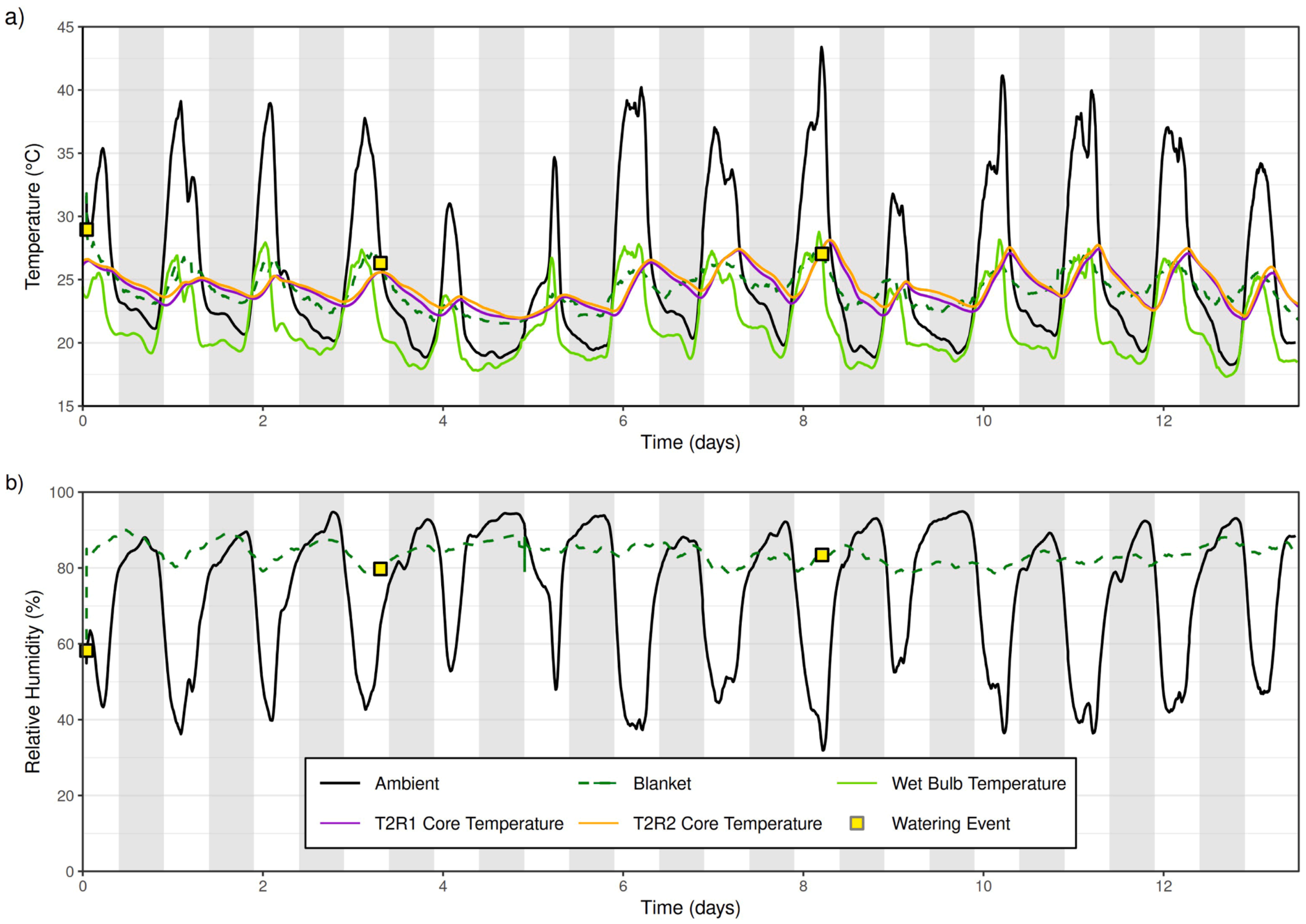

Fig. 5. Average hygrothermal sensor data of three repetitions of one blanket containing green tomatoes irrigated under five different treatments, at the shelter at MUARIK (Kabanyolo, Uganda). Plot (a) shows the average air temperature as a function of time. Plot (b) shows the average relative humidity as a function of time. The average ambient temperature was 25.35 °C, the relative humidity 74.34 %.

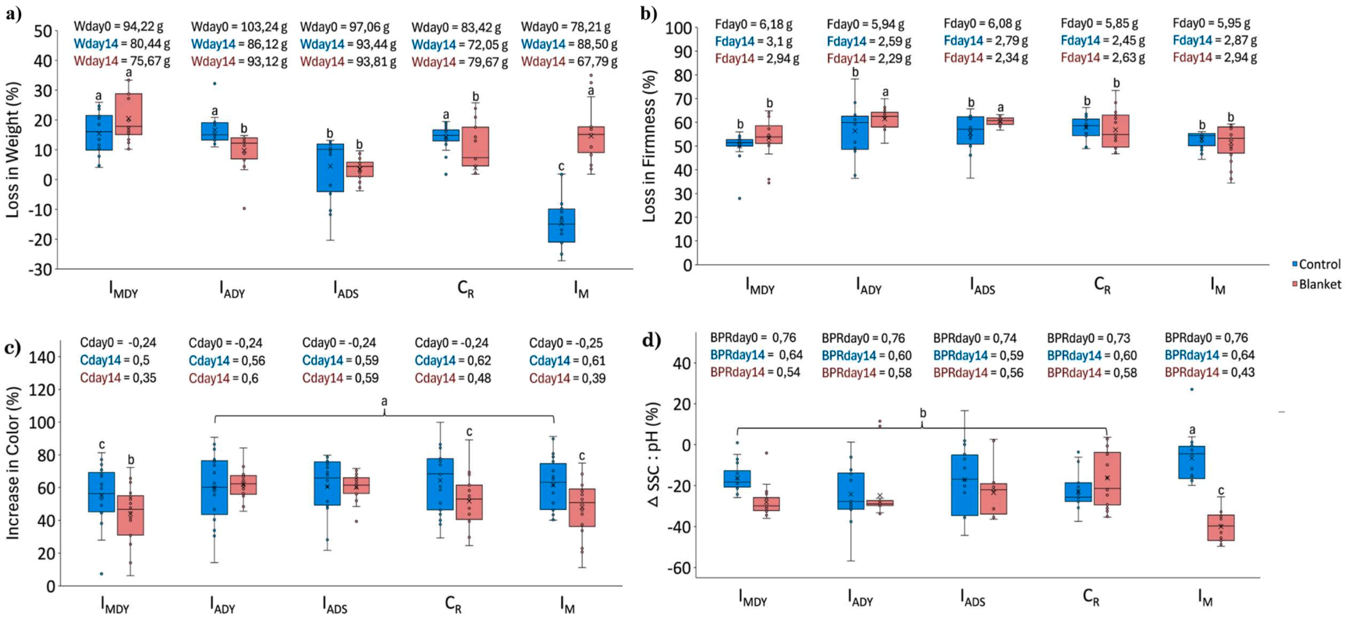

Fig. 6. Boxplot showing percentage change of a) weight b) firmness c) color and d) Δ SSC:pH of tomatoes on the last day of storage (day 14). The boxes show values from single tomatoes cultivated under five different irrigation systems (x-axis). Writings on top of the boxes represents the averages of the real values on day0 (black) and day14 (red-blanket and blue-control) for weight and firmness and ripening stages. Different letters above the boxes within each maturity stage indicate statistically significant differences between treatments ($p > .05$).

under the I_{ADS} regime exhibited a reduced loss in weight (3–4 %) in comparison to I_{ADY} (9–16 %) and I_{MDY} (15–20 %), which demonstrated the most substantial weight loss (Fig. 6a). Previously, a robust positive correlation had been identified between the initial water content and the rate of water loss in both pepper fruit and tomatoes (Bouzo and Gariglio, 2016). This might explain why tomatoes with a higher weight at harvest (I_{ADY}) lost more weight in comparison to tomatoes belonging to I_{ADS}.

Significant differences in firmness was identified between the samples with and without the cooling blanket for green tomatoes that had been irrigated following treatments I_{ADY} and I_{ADS} (Fig. 5b). In both cases, a discrepancy of 5 % is observed when the blanket is utilized. A lower firmness loss was measured in I_{MDY} and I_M.

In terms of color change, significant disparities were identified in the application of CCB for the treatments I_{MDY}, C_R and I_M (Fig. 6c). In all three cases, the tomatoes inside the blanket demonstrated a lower increase in redness compared to the tomatoes kept outside. The cooler conditions inside the blanket may have delayed the ripening process, which led to the color change appearing later than outside the blanket. With regard to the treatments I_{ADY} and I_{ADS}, a similar increase in redness was observed (approximately 60 %), irrespective of the utilization of the blanket (Fig. 6c).

The SSC/pH ratio always decreased, and a significant difference was found between treatment I_M and all the other treatments (Fig. 6d). Within treatment I_M a significant difference was found between blanket and control. Tomatoes belonging to I_M kept within the blanket recorded the biggest decrease in SSC/pH ratio equal to 40 % while when keeping the tomatoes outside the decrease in SSC/pH ratio equal to 6,5 % (Fig. 6d). Water deficit triggers the conversion of starch to sugar. During water stress, carbohydrate metabolism is disrupted, frequently resulting in the accumulation of sugars (Pulupol et al., 1996). However, the I_{ADS}, which was responsible for the significant water stress, exhibited a comparatively diminished decrease in SSC/pH in comparison to the other two irrigation systems (I_{MDY} and I_{ADY}).

Nevertheless, it is challenging to ascertain the true impact of the irrigation schedule due to the substantial precipitation and the emergence of fungal diseases. This combination resulted in a significant reduction in both yield and quality of the tomatoes. The state of the fruit at the time of harvest exerts a significant influence on its performance during postharvest storage. This encompasses factors such as the appropriate maturity stage, nutritional status, and resistance to specific storage pathogens (Khan and Ali, 2018).

3.4. *Passive cooling in transit to market*

The objective of the experiment was to demonstrate the use of a charcoal cooling blanket (CCB) in the tomato supply chain, from the farm to the local market in Kampala, Uganda. A substantial decline in temperature (Fig. 7a) was observed at approximately 9:15, attributable to substantial rainfall, resulting in a decline in the core temperatures of all tomatoes while they were stored at a shelter in proximity to the field. This temperature decrease was unrelated to the watering event, which only affected tomatoes placed inside the blanket (Fig. 7a). Following the manual application of water to the blanket, transportation commenced at 10:15, reaching the market by around 10:40. Evaporative cooling, facilitated by higher wind speeds, maintained the core temperatures of the tomatoes inside the blanket below 22 °C (Fig. 7a).

As illustrated in Fig. 7b, the tomatoes, which had been subjected to cooling during the transportation process, were characterized by a

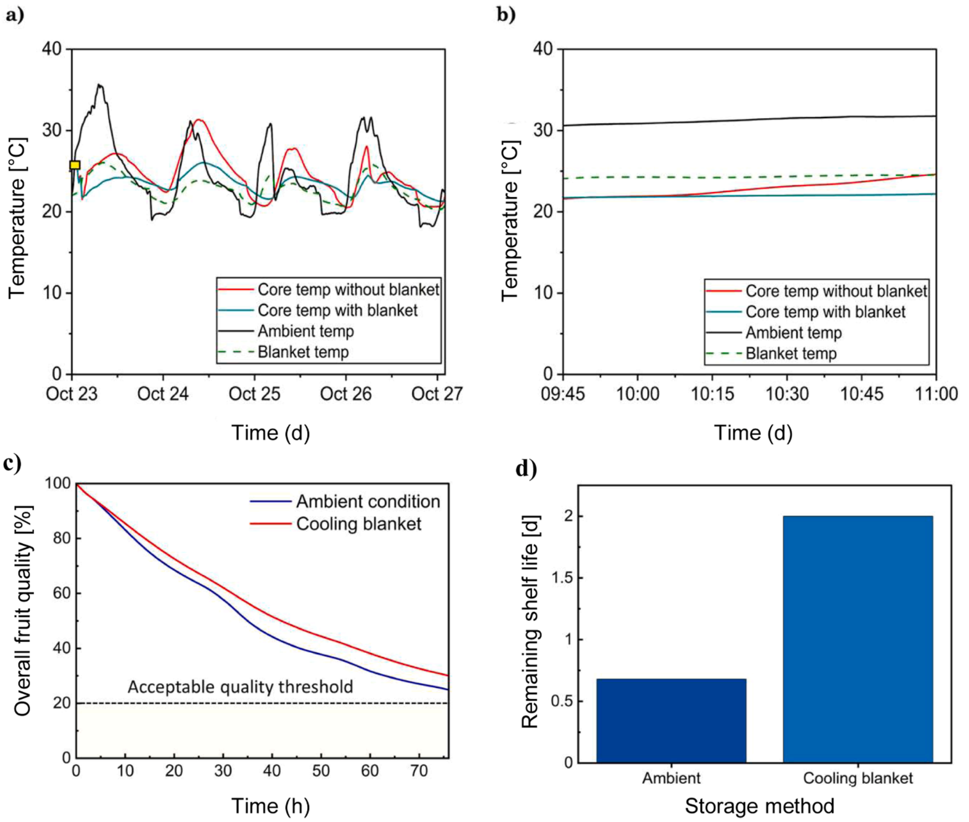

Fig. 7. Temperature sensors data showing ambient temperature, internal temperature of the blanket and the core temperature of four tomatoes, two stored inside the blanket and two stored without the blanket at the local market (a). The monitoring lasted 5 days and included transport plus storage at the local market. Temperature sensors data showing ambient temperature, internal temperature of the blanket and the core average temperature of two tomatoes stored inside the blanket and two stored within the control crate (b). The focus is only on the transport, which took place between 10:00–10:30 am. Evolution of the overall fruit quality along the supply chain, comparing the CCB (red line) and ambient storage (blue line) over a period of 3 days (c). Increase of remaining shelf-life days by a factor of 2 when using the CCB (d). (Flaticon & Openart, 2024).

diminished core temperature upon entry into the storage facility at the market. Specifically, tomatoes transported and stored inside a crate without CCB exhibited an average core temperature of 24.45 °C, which was higher than the core temperature of tomatoes stored within the blanket (Fig. 7b). On the second day of the storage period, a maximum temperature difference of 10 °C was recorded between the core temperature of tomatoes stored inside the blanket and those stored at ambient temperature.

The transportation of fruits and vegetables is a process that demands meticulous attention. Frequently, the utilization of refrigerated transport and the employment of suitable packaging are imperative to ensure that these produce reach their destination in optimal condition (Mohan et al., 2023). However, such infrastructure is often unavailable or unaffordable for smallholder farmers and traders in Uganda. Inadequate transportation infrastructure has the potential to result in damage to food items, which can in turn lead to issues such as bruising and other injuries (Al-Dairi et al., 2022). Furthermore, factors such as time and distance can exacerbate postharvest losses in fresh produce during transportation. It is evident that these factors have the capacity to accelerate both enzymatic and metabolic processes, thus resulting in heightened losses at market level (Cherono and Seyoum Workneh, 2018). The present experiment indicates that the implementation of a cold supply chain for fresh produce using a charcoal cooling blanket is a feasible prospect. In addition, evaporative cooling blankets, which can be readily produced by small-scale farmers and traders, hold considerable potential as an additional transport cooling method even on motorbikes, a common mode of transport in Uganda.

A significant challenge within the tomato supply chain is ensuring its shelf life remains intact at the market level. In order to ensure optimal preservation of the fruit, it is recommended that ripe tomatoes be stored at temperatures ranging from 10 to 15 °C, with the relative humidity maintained at levels between 80 and 90 % during the postharvest stage (Arun, 2017). In the present study, on-site visual inspections revealed discrepancies by the third day of storage. Tomatoes that had been stored inside the blanket remained fresh and of acceptable quality for sale and consumption. In contrast, tomatoes that had been stored in crates without CCB had deteriorated due to shriveling or cracking to such an extent that they were unsellable and ultimately discarded. Furthermore, tomatoes stored within the cooling blanket were sold after an average of five days, providing an additional two days of revenue compared to those stored without the blanket. The market vendor who had stored tomatoes in the crate without CCB lost approximately 25 tomatoes, equivalent to roughly 2.5 kg. Conversely, the vendor utilizing the CCB incurred a loss of merely two tomatoes. In order to demonstrate the implications of this phenomenon from a financial perspective, the mean price of tomatoes per kilogram was estimated at 0.59 USD. In Uganda, the price of tomatoes exhibits significant fluctuations between 0.054 USD and 1.12 USD per kilogram. This variability is attributable to the cyclical fluctuations in tomato production, which peaks during the wet seasons and experiences a decline during the dry season (Ddamulira et al., 2021). The vendor who did not utilize the blanket incurred a loss of 1.5 USD, which is 12 times the loss of the vendor who did utilize the blanket.

In order to provide further support for the impact of CCB on the reduction of food loss and the increase in shelf life at the market, a model of the entire local tomato supply chain was created, from farm to market, with and without CCB. The data collected during the experiment were entered into a kinetic rate model based on Eq. (1)–4. The quality of the tomatoes was found to have improved by approximately 10 % after three days of storage at a lower temperature (Fig. 7c). This finding indicates that the utilization of the blanket, by reducing the average temperature of the product by 1 °C from the farm to the market, resulted in an extended shelf life of 2 days (Fig. 7d). Kinetic models, such as the one employed here, facilitate the quantification and prediction of the behaviour of nutritional and sensory qualities of fresh products based on system temperature (Onwude et al., 2020). The model accurately reflected the real-life scenario and provided coherent information. The placement of the blanket under dry conditions characterized by a moderate wind speed (5 m/s) during the period of maximum temperature (12–1 pm) has the potential to yield a greater reduction in food wastage over an extended period of time when the CCB is employed.

3.5. Pre- and postharvest factors affecting tomato quality inside the CCB

A correlation map (Fig. 8) was constructed in order to examine the relationship between pre-harvest factors, such as ripening stage, and postharvest factors, including storage time, temperature, and humidity, with quality parameters such as firmness, weight, color, pH, and SSC. The strongest positive correlation was found between the ripening stage and the change in color (Fig. 8). As the tomato fruit ripens, it undergoes a transformation in color, shifting from green to red. This change is attributable to the concurrent degradation of chlorophyll and the synthesis of carotenoids (Carrillo-López and Yahia, 2014). The higher concentration of carotenoids, specifically lycopene, in the exocarp is responsible for the red coloration of tomatoes during the ripening process. The color exhibited a positive correlation with the storage relative humidity and a negative correlation with storage temperature (Fig. 8). It has been established that the increase in lycopene content, which is responsible for the redness of ripe tomatoes, occurs more slowly in tomatoes stored at lower temperatures compared to those stored at room temperature (Khairi et al., 2015). This observation indicates a negative correlation between temperature and the rate of lycopene accumulation.

The ripening stage exhibited a robust negative correlation with firmness, as illustrated in Fig. 8. As tomatoes ripen, their firmness decreases due to the softening of the fruit, a process involving the breakdown of cell wall components such as hemicellulosic and pectic polysaccharides (Saladié et al., 2007). A lower negative correlation was found between firmness and relative humidity, and a strong positive correlation between firmness and storage temperature (Fig. 8). The softening of tomato flesh has been linked to heightened expression levels of various enzymes responsible for degrading cell walls. These enzymes include polysaccharide hydrolases, transglycosylases, lyases, and other proteins involved in loosening the cell wall (Saladié et al., 2007). An increase in storage temperature has been shown to increase reaction kinetics of these enzymes, thus explaining the negative correlation between storage temperature and firmness.

Furthermore, a strong positive correlation was observed between weight loss and storage time, while a moderate negative correlation was identified between weight loss and ripening stage (Fig. 8). This phenomenon has been attributed to the enhanced weight loss observed in green tomatoes, attributable to elevated dehydration rates, particularly within the pericarp tissues, in conjunction with dehydration occurring during the ripening process (Moneruzzaman et al., 2008). Conversely, weight loss exhibited a positive correlation with storage relative humidity and temperature (Fig. 8). The strong positive correlation between increasing relative humidity and decreasing weight loss can be explained by a reduced water loss from the fruit to the environment. It has been demonstrated that elevated storage temperatures are a contributing factor. Conversely, elevated storage temperatures are hypothesized to enhance weight reduction; however, this assertion remains unconfirmed by the correlation map.

The SSC/acidity ratio demonstrated a substantial negative correlation with relative humidity and ripening stage (Fig. 8). In some cases, the quality of the stored tomatoes had been adversely affected by a fungal attack in the field. The activity of certain microorganisms has been demonstrated to convert sugar into small alcohols and acids (Tabikha et al., 2010). Elevated levels of relative humidity may promote the activity of microorganisms, thereby contributing to the occurrence of acids tomatoes. However, it is anticipated that the progression towards ripening and during the course of prolonged storage would result in the production of tomatoes with a more pronounced sweetness. In the preliminary phases of development, the immature tomato fruit

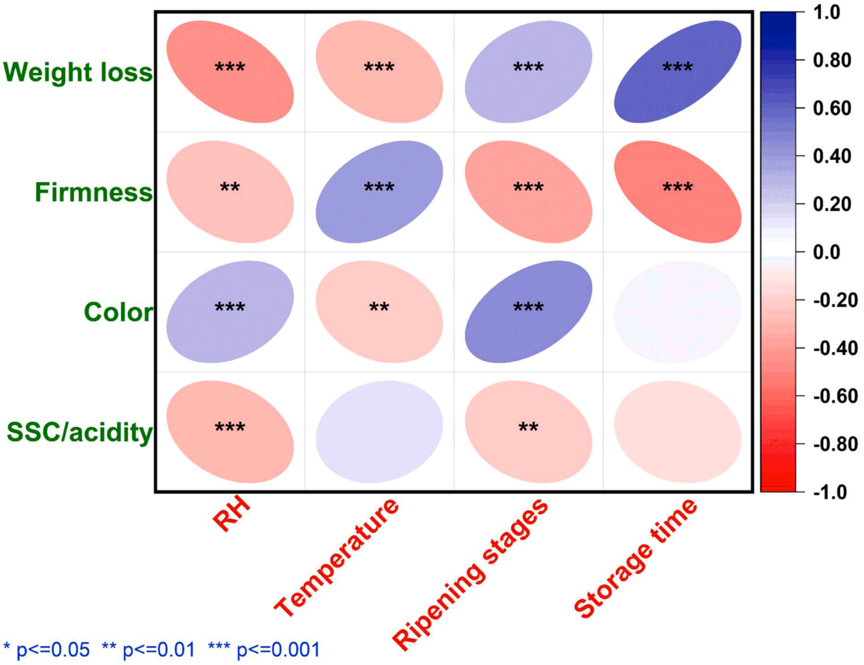

Fig. 8. Correlation matrix plot showing relationships between variables: weight loss (%), firmness (g), color (-) and SSC/acidity ratio. The shapes of the ellipses are opposite for positive (blue) or negative (red) correlations. The more intense the color and the thinner the ellipse, the stronger the correlation. Asterics indicate the significance of the correlation.

temporarily accumulates starch, which subsequently undergoes conversion into soluble sugars during subsequent stages of growth (Robinson et al., 1988).

In conclusion, the correlations obtained provide a comprehensive understanding of the relationships between pre- and postharvest factors and tomato quality parameters. It is evident from these findings that the inside the charcoal cooling blanket (CCB) must be controlled in order to preserve the weight and firmness of the tomatoes. In a similar manner, effective regulation of the relative humidity and the adept management of the ripening stages are of paramount importance in ensuring the maintenance of minimal weight loss, optimal firmness, color, soluble solids content, and the soluble solids content/acidity ratio during the postharvest storage phase. Furthermore, the correlation map emphasizes the importance of the duration of tomato storage using CCB to mitigate weight loss, firmness reduction, and pH increase.

4. Conclusions and future research

The objective of this study was to evaluate the effectiveness of the charcoal cooling blanket (CCB) in reducing postharvest losses within the local tomato supply chain in Uganda, with a particular focus on smallholder farmers who do not have access to packinghouses and refrigeration facilities. Furthermore, an investigation was conducted into the impact of pre-harvest factors, including ripening stage and irrigation schedule, on tomato quality when stored using CCB, with a comparison made against ambient storage conditions. The following key findings are derived from the analysis:

- The CCB was found to have a significant impact on the temperature within the blanket, with a recorded reduction of up to 1.5 °C. This reduction in temperature led to a subsequent decrease in core tomato temperatures, thereby decelerating the progression of firmness, weight, and color changes.
- During the maximum daytime temperature, the CCB exhibited a decline in storage temperature of up to 20 °C, while concurrently sustaining a storage relative humidity (RH) level of approximately 85 %. Within the CCB, plastic crates were identified as the optimal packaging solution for tomatoes. This was due to their ability to significantly reduce mold incidence when compared with wooden or woven baskets, while also preserving cooling efficiency.
- Following a quality assessment conducted after a period of 10 days of storage, in comparison with tomatoes stored under ambient conditions, those stored within the CCB exhibited a reduction in weight loss (5–10 % in green and breaker tomatoes) and firmness loss (15–20 % in breaker and red tomatoes). Furthermore, the reddening of the tomatoes was found to be delayed in green and breaker tomatoes, and a 2–3 % increase in pH was observed, resulting in tomatoes of a lower acidity level across all ripening stages.
- The use of the CCB during transport on a motorbike and at the market was found to be an effective solution, leading to a significant increase in the shelf life of tomatoes. This enhancement, estimated to extend the shelf life by two days, is anticipated to result in a substantial increase in sales revenue, estimated at 1.5 USD per vendor.
- The implementation of the CCB throughout the farm-to-fork process has been demonstrated to result in a 10 % reduction in tomato quality losses following a period of three days of storage at the market.
- The present study sought to ascertain the relationship between pre- and postharvest factors within experimental contexts. The findings indicated that elevated relative humidity during storage can result in a reduction in weight loss, while concomitantly maintaining the firmness of the tomatoes and slowing down sugar accumulation. Storage temperature has been demonstrated to have the most significant impact on weight loss and firmness. The ripening stage and storage time exhibited analogous effects; an increase in storage time and progression in the ripening process of the fruit resulted in elevated levels of weight loss and diminished firmness, consequently leading to softer fruits.

The charcoal cooling blanket is a straightforward solution, with a simple assembly process and observable results within a few days. Nonetheless, there is scope for enhancement to be made to the system. The pilot study conducted in Uganda yielded several insights for future research, the details of which are outlined below:

- The blanket described here was composed of burlap, a material not commonly found in Ugandan farming communities. Farmers proposed the utilization of sisal, a material that is both readily available and durable, commonly employed for the transportation of coffee beans. Producing an operational CCB would need four sisal bags ~20′000UGX, 10 kg of charcoal ~8′000UGX, Needle and thread ~8′000 UGX one plastic crate ~50′000UGX, one rubber band ~1′000UGX and a leaf cover ~10′000UGX resulting in a Price of 100′000UGX or $28. The rubber band and plastic crate should hold indefinitely while all the other material can be reused until degradation and used as charcoal/firewood afterwards.
- The implementation of standardized CCB watering practices for local populations has been demonstrated to be a beneficial measure but can be inaccurate. In this experiment, the CCB performance was lower when RH fell below 90 %. The ideal watering timepoints were identified using humidity sensors in this study but sensor reliance is problematic due to theft or malfunction. The development of a real-time digital twin of the supply chain, from harvest to consumer, has the potential to identify critical times blanket watering events.
- The present study concentrated on the impact of the CCB on tomato quality. However, it is hypothesized that the CCB could also benefit other major perishable crops such as avocadoes, mangoes, passion fruits, eggplants, and green peppers.

The CCB was developed and deployed in Uganda, but there are also opportunities for its expansion to other sub-Saharan countries. For instance, regions characterized by arid climates and a necessity for social, environmental and economic enhancement. Information pertaining to the locations in which CCB would exert the most significant influence with regard to climate can be accessed digitally (FAO 2023). The versatility of the charcoal cooling blanket allows for adoption across the entire supply chain, thus ensuring accessibility for those who may not have the financial means to procure expensive cooling systems. It is imperative to acknowledge the significance of adaptability in facilitating widespread adoption and mitigating postharvest losses within the fresh produce supply chain in low- and middle-income countries (LMICs).

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

During the preparation of this work, the authors used DeepL Write in order to refine grammar and syntax. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Sofia Felicioni: Writing – original draft, Methodology, Investigation, Conceptualization. **Andreas Bühlmann:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Thijs Defraeye:** Writing – review & editing, Conceptualization. **Philippe Hess:** Writing – review & editing, Investigation. **Joshua Wanyama:** Writing – review & editing, Supervision, Investigation. **Isa Kabenge:** Writing – review & editing, Supervision, Investigation. **Joel Ikabat:** Writing – review & editing, Investigation. **Daniel Onwude:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Andreas Buehlmann reports financial support was provided by H2020 Food Security Sustainable Agriculture and Forestry Marine Maritime and Inland Water Research and the Bioeconomy under the grant FOODLAND — FOOD and Local, Agricultural, and Nutritional Diversity, Grant Nr. 862802. Daniel Onwude reports financial support was provided by Rodenberry Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scienta.2025.114313.

Data availability

Data available under https://doi.org/10.5281/zenodo.15856413.

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