SUPPLEMENTARY MATERIAL to:

The charcoal cooling blanket: A scalable, simple, self-supporting evaporative cooling device for preserving fresh foods

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1 What are its strengths, weaknesses, opportunities, and threats (SWOT)?

1.1 Strengths

USEABILITY

The charcoal blanket is **plug-and-play**. Once this evaporative cooling blanket is constructed by sewing, it only needs to be filled with charcoal, placed at the target location and wetted with water. **No other expertise** or materials are required to build and use it. The charcoal blanket requires fewer materials and tools than typical self-made charcoal coolers with wire meshes (Appropedia, 2021). This cooler satisfies the stringent need for charcoal coolers that are easier to self-construct, require less training, and are simple to use. These missing traits are a current bottleneck inhibiting the widespread use of charcoal coolers for postharvest storage (Verploegen, 2021). Detailed instructions on manufacturing it are given below (section 3).

The charcoal blanket is a **light structure**. Charcoal has a density of 200-600 kg m^{-3}. The macro-porosity between the charcoal pieces is about 50-60%, but highly depending on the caliber and piece size distribution. As such, the bulk density of charcoal pieces is low (~ 100-300 kg m^{-3}). Consequently, a (dry) charcoal blanket of 100 mm thick weighs below 10-30 kg m^{-2}. This weight is about 20 times less than the weight of a brick wall.

The charcoal blanket is **mobile**. Each blanket or an ensemble of blankets can be reused wherever necessary, unlike the current static-built charcoal cooler rooms. Blankets can be used for longer-term cold storage before transport and intermediate cooling between the different stops in the supply chain. This mobility also induces flexibility in farm planning. Moving a brick cooler or a charcoal cooler room is more challenging when repurposing land.

The charcoal blanket is a **zero-energy system**. Compared to solar-powered, active cooling facilities, the blanket does not require an additional energy source for cooling or cooling control. Maintenance of the unit is not required.

MATERIALS

The **materials can be sourced locally**. Charcoal can be produced almost everywhere in the world. The textile material for the blanket, such as burlap fabric, is produced in several developing countries. For a long time, burlap has been used for storing and transporting horticultural products. This textile backbone of the charcoal cooler is very light and has a small volume compared to wood or brick materials. It can also be prefabricated centrally within a country or province and then easily distributed country-wide at a low cost. These charcoal coolers become bulky and less easy to transport only after filling with charcoal on-site.

The **textile material holds charcoal instead of a metal wire mesh**. As such, much smaller pieces of charcoal can be held by the charcoal blanket. Thereby, the surface area for evaporation increases, and the blanket's cooling capacity. Some metal wire meshes can rust, which poses food hygiene problems.

The materials are **recyclable and reusable**. Textiles such as burlap are biodegradable, which, however, makes them less durable. Alternative fabrics should be locally sourceable, knittable into compartments, cheap, permeable for air, and preferably hydrophilic. An example would be cotton. Charcoal can be burned and therefore used for heating or cooking after the cooler reaches its end of life. No plastic is used but instead biodegradable materials, which avoids the need for collection or recycling.

Charcoal and burlap are **non-toxic materials**, so they do not raise a safety concern when used in direct contact with dry food products (EFSA, 2012). There are types of burlap that are treated specially for contact with foods.

DESIGN

The compartmentalized blanket, by design, provides **mechanical stability** in terms of bending and buckling. The blanket is very flexible in the transverse direction (around the y-axis, Figure 3 in (Defraeye et al., 2022)). Due to the compartmentalization, it has structural stability in the longitudinal direction (around the x-axis, Figure 3 in (Defraeye et al., 2022a)). This filling creates tension within the burlap, which induces bending stiffness around the x-axis. The sharp-edged charcoal pieces also interlock, increasing the bending stability even more than when these compartments would be filled with spherical pieces (or briquettes). These adjacent compartments strengthen the bending resistance. As such, a **self-supporting system** can be easily created by just adding a few poles and shaping it into a silo-like structure.

The blanket, however, has highly anisotropic mechanical properties. It is thereby **flexible** in the y-direction (Figure 3 in (Defraeye et al., 2022)). As such, it can be wrapped around or over a box or pallet of fruit, for example. The anisotropic mechanical behavior is a crucial advantage of the blanket. On the one hand, the blanket serves as a semi self-supporting wall. On the other hand, these walls are shapeable in any ground plan due to their transverse flexibility (around the y-axis).

The system is **easily scalable**, without additional constraints to the required expertise or materials needed. It is useable for individual rural, peri-urban, or urban farmers, both by marginal and smallholder farmers or larger farmer cooperatives. Single households can even use such a charcoal cooler in remote areas. For urban rooftop farmers, tailoring the cooler's size to their farm is a significant added value. The system is versatile as it can be manufactured in any size and applied in almost every step of the postharvest supply chain (Figure 6 in (Defraeye et al., 2022)).

The scalability makes the **costs scale quasilinear** with the length or height of the blanket, even down to the smallest sizes. As an example, we scale down the cooler (Figure 4 in (Defraeye et al., 2022)) by reducing its length (L_b). In that case, halving the length halves the material cost for the charcoal and burlap. When both the length and height ($H_{b,c}$) are halved, the price reduces by a factor of 4. Note that when we also change the compartment size (W_{co}), the costs scale non-linearly. Thereby, coolers are affordable to small-scale farmers. This evaporative cooler democratizes cooling to marginal farmers without being a farmer cooperative member. Compared to other fixed installed evaporative charcoal coolers, the initial capital cost is typically lower. The reason is that fewer materials are needed, and it can be easily homemade (section 3).

1.2 Weaknesses

Weaknesses of evaporative coolers

The charcoal blanket cooler has similar weaknesses as any evaporative charcoal cooler.

- The minimal cooling temperature is limited by a **theoretical limit**, namely the wet-bulb temperature. This hard limit makes the technology only relevant for relatively dry and warm environments and less effective in humid regions.
- Evaporative cooling is **not suitable for all crops**, but only for those that should be stored at high humidity and temperatures well above 0 °C (e.g., 10-14 °C). Examples of such crops include tomato, banana, carrot, mango, papaya, orange, and bell pepper (Figure 1f in (Defraeye et al., 2022)). Guidelines on which crops evaporative coolers are suitable for are reported (MITD-Lab, 2021). A list of optimal storage conditions of relevant fruit and vegetables is provided in section 5.
- A minimal **airflow** by wind or mechanical ventilation is required for optimal functioning. In regions with low wind speeds in the free field, optimal charcoal cooler locations would be rooftops or balconies, for example, in urban gardens.
- The cooling temperature and the cooling capacity are **not constant** and strongly dependent on the external hygrothermal conditions. The current weather and the day-night cycling thereby strongly affect cooler performance.
- **Water availability** on-site is essential for evaporative cooling. The water supply should be sustained so that the cooler does not deplete. Periodic wetting (e.g., a few times per day) can induce a good performance (Shitanda et al., 2011).

Weaknesses of the charcoal blanket

An evaporative blanket's thermal capacity is lower than a standard evaporative charcoal storage room. Such rooms are often made of brick walls as well. As such, almost no heat is stored in the blanket. Thereby, the blanket is more sensitive to fluctuations in external environmental conditions. On the other hand, the blanket has a faster response time than other charcoal cooling units. This reaction time is beneficial when used for intermediate storage. Thermal capacity could be added to dampen fluctuations by installing thermal storage elements inside the cooler, such as water containers or stone material. After these are cooled down, they help keep a low temperature inside the cooler.

Textile materials such as burlap are biodegradable and water-sensitive. Charcoal blankets are less durable than evaporative coolers constructed with wood and a metal wire mesh. Nevertheless, commercially-available burlap textiles or burlap-based geotextiles for outdoor use have a lifetime of 1-3 years during external use (Ghosh et al., 2019;

Wu et al., 2020). The durability is further reduced due to the tension in the fibers and sustained wetness. Textiles based on other natural fibers have an even longer life. Even if the fabric degrades after a few years, the charcoal can just be reused and filled into a new blanket.

The current design of the charcoal blanket does not include a system for continuous wetting. An additional piping system can be included to do so. These additional materials will increase the charcoal blanket's complexity, cost, and carbon footprint.

A charcoal blanket can be easily placed over a ventilated box of fruit or a pallet. However, the water leaking from the blanket can render the fruit dirty with charcoal residue. The food should be shielded with plastic foil if this is an issue. This shielding reduces the cooling rate as ventilation within the boxes is inhibited. The blanket should be wrapped vertically around the box to avoid such soiling (Figure 6a2 in (Defraeye et al., 2022)).

1.3 Opportunities

The charcoal cooling blanket has unique opportunities. First, the simplicity and scalability of the system make that we can reach small-scale and marginal farmers and small-scale peri-urban farmers. Due to their small size and financial situation, they often have no access to active cooling solutions. Classical homemade evaporative coolers can be built (Appropedia, 2021). They require additional expertise and materials (Figure 2 in (Defraeye et al., 2022)), which only become financially viable at a specific scale. Second, these small-scale evaporative cooling systems are attractive for urban farmers but are currently rarely used. On urban rooftops, often, airspeeds are sufficiently high, and local humidity is often low enough for efficient evaporative cooling.

1.4 Threats

A fundamental threat of the charcoal blanket, and all charcoal coolers for that matter, is that they are still not deployed in a local setting. A reason is that the system is still not sufficiently user-friendly or underperforms. As a result, the farmers likely do not always see the added value for saving food, and they cease to use it. We plan to explore its use in different regions globally and for different target groups (rural, peri-urban and urban farmers) soon to mitigate this threat. In addition, we plan to test the blanket with different stakeholders in the food supply chain, as other research groups did in the past (D-LAB, 2021a, 2021b). That way, we identify in which part of the supply chain the charcoal blanket has the most considerable potential for adaptation and the highest impact.

Another threat is that the durability of the textile used in the charcoal blanket, for example, burlap, limits the long-term use of the charcoal cooler (Ghosh et al., 2019). Also, microbiological growth could pose a problem. More durable and microbiologically-inert materials, such as polypropylene or other geosynthetic textiles or membranes, could be used to mitigate this threat (Koerner et al., 2017). Such meshes are now a large competitor of burlap for food packaging (jute bags), geotextiles, or solar screens. However, this material is not biodegradable and is a potential source for (micro)plastic pollution (Karbalaei et al., 2018).

2 Materials and methods

2.1 Charcoal material characterization

The details on the material properties of the charcoal blanket are given in Table 1. The weight of the charcoal pieces was measured with a balance (Voltcraft PS-200, 0-200 g ± 0.01 g). For the wetting experiment, three samples of charcoal were taken, with each sample containing a set of 3 charcoal pieces. Each dry sample weighed between 50-60 grams. These samples were placed in a container of water, where they were fully submerged. The samples were periodically removed from the water container and weighed for up to 32 days.

Table 1. Material properties of charcoal and a description of how they are determined.

Parameter	Symbol	Description	Value charcoal from experiment s	Value from literature and reference	Experimental details
Material					
Density material	$\rho_{PM,eq} = w_s + \underbrace{w_{l,eq} + w_{v,eq}}_{w_{PM,eq}} + \cancel{w_a}$ [kg m_{PM}^{-3}]	Density of the porous material (charcoal) under equilibrium conditions of the ambient environment (50%, 23ºC). The weight of air (w_a) is negligible here.	467 ± 25 kg m^{-3}	200-600 kg m^{-3} (Energypedia, 2021) 300-430 kg m^{-3} (Pastor-Villegas et al., 2006) 345 kg m^{-3} (Dos Santos et al., 2020)	The density was determined by measuring the weight of charcoal pieces at equilibrium at ambient conditions (50%, 23ºC). Afterward, the volume of these pieces was measured volumetrically by submersion in water (see below). The mass of the pieces divided by the volume renders the density. In the experiment, ten repetitions were performed.
Volume	V_{PM} [m^3]	Bulk volume of a charcoal piece, including the internal pore space	Variable, dependent on the piece	Variable, dependent on the piece	The volume of a charcoal piece was determined by submerging the piece in a graduated cylinder. The difference in volume (liter) before and after submersion is the volume of the piece. Since charcoal rapidly absorbs water during the first minutes in its interior pore structure, the charcoal pieces were first submerged in water 30 minutes before measuring the volume. That way, the bulk volume of the piece is obtained (charcoal material and inner pore volume). The inner pore structure is included in this volume. These experiments were performed for every piece where the volume was required.
Solid material matrix content	w_s [kg m_{PM}^{-3}] $w_s = \rho_{PM,eq} - w_{l,eq} - w_{v,eq} + \cancel{w_a}$ $w_s = \rho_{PM} - w_{PM}$	Density dry-base	w_s = 442 kg m^{-3}	-	The solid matrix content was measured by drying a piece for over 12 hours at 80 ºC in a drying oven. The drying process was stopped if the weight of the piece did not change anymore over time. Based on this dry weight and the volume of the piece, the solid matrix content was determined. In the experiment, five repetitions were performed.
Moisture content at equilibrium under ambient conditions	$w_{PM,eq} = \rho_{PM,eq} - w_s$ $w_{PM,eq} = w_{l,eq} + w_{v,eq}$	Moisture content of the charcoal under equilibrium conditions of the ambient environment (50%, 23ºC).	w_{PM} = 25 kg m^{-3}	-	The moisture content at equilibrium is measured by determining the weight of a piece at these conditions. Afterward, the pieces were dried for over 12 hours at 80 ºC in a drying oven. The drying process was stopped if the weight of the piece did not change anymore over time. The dry weight was then measured. The difference between these weights enabled a determination of the moisture content at equilibrium using the volume of the piece. In the experiment, five repetitions were performed.
Dry-base moisture content at equilibrium under ambient conditions	$X_{eq} = \frac{w_{PM,eq}}{w_s}$ $X_{eq} = \frac{\rho_{PM,eq} - w_s}{w_s} = \frac{\rho_{PM,eq}}{w_s} - 1$	Dry-base moisture content of the charcoal under equilibrium conditions of the ambient environment (50%, 23ºC).	X = 5.7 ± 0.25 %	3-10% (Energypedia, 2021) 5-10% (FAO, 1983)	
Saturated moisture content	$w_{PM,sat}$ [kg m_{PM}^{-3}] $w_{PM,sat} = w_{l,sat} + w_{v,sat} = \rho_{PM,sat} - w_s$ $\approx \rho_{PM,sat} - \rho_{PM,eq}$	Moisture content when the piece is fully saturated with water	654 ± 66 kg m^{-3} (after 32 days, three samples)	-	The piece is submerged in water for a prolonged time until the weight does not change anymore over time. Based on the saturated weight and corresponding saturated density, the saturated moisture content can be calculated. The initial weight of a piece was

					measured, so the material's equilibrium density was determined. The initial moisture content at equilibrium ($w_{PM,eq}$), which is low, is not included in the saturated moisture content. From the water uptake experiment, it is clear that the uptake process is very lengthy until full saturation, as displayed in the data. In the experiment, three repetitions were performed.
Open microscale porosity of the material	$\phi_0 = \frac{V_p}{V_{PM}} = \frac{\frac{m_l}{V_{PM}}}{\frac{m_l}{V_p}} = \frac{w_{PM,sat}}{\rho_l}$	Internal open porosity of charcoal, so pores that are accessible by water	65 ± 6% (after 32 days, three samples)	25-70% (Mathieson et al., 2015)	The open porosity was directly derived from the saturated moisture content and the density of liquid water (1000 kg m^{-3}).
Caliber / size of pieces	D_{cc}	Equivalent diameter or sieve size	20 - 80 mm (80% of the pieces fall within this range)	10-60 mm (FAO, 1983)	It is determined by the manufacturer.
Thermal conductivity	λ_{cc} [W $K^{-1} m^{-1}$]	-	-	0.07 W K^{-1} m^{-1} (at 30ºC) (Eltom and Sayigh, 1994) 0.084 W K^{-1} m^{-1} (Ronoh et al., 2020) 0.030 W K^{-1} m^{-1} (Dos Santos et al., 2020)	-
Specific heat capacity	$c_{p,cc}$ [J kg^{-1} K^{-1}]	-	-	1000 J kg^{-1} K^{-1} (Toolbox, 2021) 1017 J kg^{-1} K^{-1} (Dos Santos et al., 2020)	
Thermal diffusivity	α_{cc} [m^2 s^{-1}]	$\alpha_{cc} = \frac{\lambda_{cc}}{c_{p,cc}\rho_{cc}}$	-	6.32 x 10^{-8} m^2 s^{-1}	This parameter was derived based on the data of (Dos Santos et al., 2020))
Thermal effusivity or thermal inertia	I_{cc} [J m^{-2} K^{-1} $s^{-1/2}$]	$I = \sqrt{\rho_{cc} c_{p,cc} \lambda_{cc}}$	-	119 J m^{-2} K^{-1} $s^{-1/2}$	This parameter was derived based on the data of (Dos Santos et al., 2020))
Charcoal blanket or bulk charcoal					
Bulk porosity of charcoal	$\phi_{0,bulk}$ $\phi_{0,bulk} = \frac{V_{voids}}{V_{bulk}} = \frac{V_{bulk} - V_{PM}}{V_{bulk}}$	The amount of macroscale air pores between the individual charcoal pieces	61 ± 1%		The bulk porosity was measured by filling a container (0.775 L) with charcoal pieces. Then the container was filled with water. After equilibrium, when the charcoal did not absorb water anymore, the water in the container was refilled until it was filled again. Then the volume of water in the container was measured by gravimetrically determining the amount of water inside. The ratio of the volume of water to the volume of the container yields the porosity of the macroscopic pores in between the pieces. Note that this bulk porosity is dependent on the stacking density and the size of the container. In this study, the size of the compartments of the charcoal blanket will determine the bulk porosity. In the experiment, ten repetitions were performed.
Bulk density charcoal	$\rho_{PM,bulk}$ [kg m_{bulk}^{-3}] $\rho_{PM,bulk} = \rho_{PM}\left(1 - \phi_{0,bulk}\right)$	The bulk density of charcoal pieces, so for a volume including the charcoal pieces and the air voids in between	184 kg m^{-3}	180-220 kg m^{-3} (Energypedia, 2021) 200-330 kg m^{-3} (FAO, 1983) 155 kg m^{-3}(Dos Santos et al., 2020)	The bulk density was derived directly from the bulk porosity and the density of the charcoal pieces.

	$\rho_{PM,bulk} = \rho_{air} + \rho_{charcoal}$ $\rho_{PM,bulk} \approx \rho_{charcoal,bulk} = \frac{m_{PM}}{V_{bulk}}$ $= \frac{m_{PM}}{\frac{V_{PM}}{1-\phi_{0,bulk}}} = \rho_{PM}\left(1-\phi_{0,bulk}\right)$				
Saturated bulk moisture content	$w_{PM,sat,bulk}$ [kg m_{bulk}^{-3}] $w_{PM,sat,bulk} = w_{PM,sat}\left(1-\phi_{0,bulk}\right)$	Moisture content when fully saturated with water for a prolonged time	168 kg m^{-3}	-	The bulk saturated moisture content density was derived directly from the bulk porosity and the saturated moisture content.

2.2 Textile material

For the textile used to make the blanket, burlap fabric (or hessian) was chosen. Burlap is a woven fabric made from the jute plant's bast (skin/stem) fibers. Burlap can also be made from leaf fibers from sisal in combination with other fibers such as flax, ramie, hemp, and kenaf. Burlap fabric based on jute fibers was chosen as it (1) has a high porosity so also air permeability; (2) has sufficient strength to hold the charcoal in the compartments due to its high tensile strength; (3) is a biodegradable material and thereby possibly more environmentally sustainable than other synthetic materials; (4) can be produced in several parts of the world and is the second most produced and used natural fiber, next to cotton; (5) is affordable as it is argued to be the cheapest vegetable fiber procured from the bast of plants. Other textiles with similar properties can also be used, such as coconut-fiber-based textiles or cotton. The burlap used was single-knitted with an area density of 180 g m^{-2}. Additional advantageous properties of jute are that it is rather UV-resistant. On the flip side, the strength of the jute decreases when it becomes wet. At too high humidity, it can also be affected microbiological organisms.

2.3 Structural stability of the blanket: a simple buckling analysis

<u>Buckling under self-weight</u>

The structural stability of a compartmentalized charcoal blanket wall implies a specific resistance to self-buckling under the weight of the walls. Other failure modes are less likely to occur. Examples are compression failure of charcoal or breakage of burlap due to excessive tensile stress in the jute fibers. We analyze buckling analytically to identify which parameters play a role. We assumed a single compartment of the blanket. In reality, such an idealized buckling will not occur due to the inherent 3D construction of a charcoal blanket cooler since it has many connected compartments. The multiple intermediate attachment points to poles in a silo (Figure 6b in (Defraeye et al., 2022)), for example, also enhance the buckling stability. Therefore, the analysis below is rather qualitative and conservative. The buckling height will likely be more considerable in reality.

Buckling under the blanket's self-weight is dependent on the composite material (Young's modulus E [MPa]), the cross-section of the blanket so the compartment (A_{co}, [m^2]), the related second moment of area I [m^4], and the length of the column (L [m]). The buckling criterion under self-weight will determine the maximal height of the blanket $H_{b,max}$ [m] that can be achieved without buckling. This height is given for a free-standing column by (Cox and McCarthy, 1998):

$$H_{b,\max} = \left(\frac{9\left(1.866\right)^2}{4} \frac{EI}{\rho_{bulk} g A_{co}} \right)^{1/3} \quad (1)$$

Here g is the acceleration due to gravity [m s^{-2}], and $\rho_{b,bulk}$ is the bulk density of the blanket [kg m^{-3}]. The blanket's bulk density and especially the E modulus [Pa] are difficult to determine and highly dependent on the macroporosity. These mechanical properties of the porous charcoal filling are highly variable and difficult to control. Therefore, even with this simplified equation, the exact buckling length of a charcoal blanket is challenging to determine. Nevertheless, with this analytical equation, we can clarify how the size of the compartments affects the buckling length under self-load. For a circular compartment with radius R_{co}, the second moment of area equals $\pi/4\ R_{co}^4$. The critical height becomes:

$$H_{b,\max} = \left(7.8373 \frac{E\left(\frac{\pi}{4} R_{co}^4\right)}{\rho_{bulk} g \left(\pi R_{co}^2\right)} \right)^{1/3} \sim \left(R_{co}^2\right)^{1/3} \sim R_{co}^{\ 2/3} \tag{2}$$

As such, the critical buckling height increases with the size and radius of the compartment, but not linearly. Doubling the diameter of the compartment will only increase the buckling height with a factor of 1.58. We can also use this equation to determine the minimal E modulus that a free-standing compartment should have to not self-buckle for a certain height. Suppose we assume a 2 m high cooler silo (Figure 6b in (Defraeye et al., 2022)) with a circular blanket compartment of 100 mm in diameter and a bulk density of 300 kg m^{-3} (Table 1). In that case, we get a minimal E modulus by solving the following equation:

$$E = \frac{4\rho_{bulk} g H_{b,\max}^{\ 3}}{7.8373 R_{co}^2} \tag{3}$$

This E-modulus of 9.6 MPa or 0.01GPa is very low and in the range of rubbers or polymer foams. As we expect the charcoal-filled compartment's E modulus to be higher, this implies that a two-meter-high self-supporting structure can be created with the charcoal blanket that does not buckle under self-weight.

Increasing buckling height

The critical buckling height can be increased by (1) pinning the top of the wall with a sliding contact, (2) pinning points in between with a fixed or sliding contact; (3) instead of a cooling room made out of straight blanket walls, we can opt for a more self-stable structure such as a silo. Here pinning can be easily achieved by strapping around an additional support structure to increase buckling resistance (Figure 6a2 in (Defraeye et al., 2022)). In addition, we can also increase the thickness of the walls by increasing the compartment size or by having a two-layer thick wall. For a silo, the latter is easy to implement by just wrapping an additional blanket layer around the silo.

2.4 Lab experiments on a charcoal cooling blanket

Experiments were performed in a climatic chamber to evaluate the steady-state performance of the charcoal blanket. The climatic chamber was kept at 23 °C and 40% RH. A blanket was constructed with a compartment size of 0.12 m, a height of 0.4 m, and a length of 2 m (when filled with charcoal). The length of the unfilled blanket was 2.5 m (L_b), and the length of the filled blanket was about 2 m. The dry weight of the blanket, when filled with charcoal, was 5.64 kg. As such, the area density of this filled blanket was about 7 kg m^{-2}. The blanket was wrapped around a ventilated plastic crate of 0.54 x 0.37 x 0.28 $m^{3,}$ so 0.0560 m^3 or 56 L. Inside the plastic crate, 5 kg of apples were stored. The crate was sealed from the top with a plastic lid. In that way, high humidity and low temperature are maintained inside the cooler since air can only enter and exit the crate via the charcoal blanket. The fruit core and surface temperature were monitored, and the air temperature and relative humidity.

The blanket was wetted by pouring water from the top onto the individual compartments. The water temperature was also 23 °C. The amount of water poured onto the blanket was measured and varied between 0.5 L and 2 L per watering cycle. Water was added until it started to drip out from the bottom of the blanket. The air flows through the blanket and the crate. Evaporation cools the air surrounding the fruit and thereby also the fruit. We explored the impact of air circulation. A rotating table-top fan was placed at a distance (more than 1 meter) and set at different airspeeds after reaching a steady state. The specifications of the sensors are detailed in Table 2. The sensors were installed in the following locations.

- The air temperature and humidity at three locations around and above the fruit.
- The air temperature and humidity in the climatic chamber
- An airspeed sensor was used to measure the airspeed near the charcoal blanket.
- The temperature inside the fruit core (2 sensors measured by manual reading at discrete points in time and one sensor for continuous measurements).
- The surface temperature of the fruit.

Apart from watering by pouring water on the blanket, we also tested another water strategy: submersion/soaking the blanket in water. With submersion, the entire surface area of the charcoal is used directly for water absorption. Significant water absorption occurs within the first few minutes. We noticed that such submersion quickly resets the temperature of the entire blanket from the cool temperature it had, due to evaporative cooling, to that of the water it is submerged in. Short immersion is a very efficient technique to load the charcoal with water. Nevertheless, a significant amount of heat is added to the system via the absorbed water and heat transfer from the water to the charcoal material, with high heat transfer coefficients. Therefore, unless the water temperature is lower than that of the environment, submersion of the blanket is not advised. Spraying or pouring water on the blanket is often more advantageous.

Table 2. Sensor types and their characteristics.

Sensor type	Sensed driver	Accuracy	Range
Sensirion SHT31 Smart Gadget	Air temperature Relative humidity	± 0.3°C ± 2%	-10°C to 60°C 0-100% RH
TinyTag Talk 2	Fruit core temperature & fruit surface temperature	± 0.05°C	-40°C to 125°C
TFA core probe thermometer	Fruit core temperature	± 1°C	-50°C to 300°C
Testo 405i Thermal anemometer	Air speed	± 0.1 m/s + 5 % of m.v. ± 0.3 m/s + 5 % of m.v	0 to 2 m/s 2 to 15 m/s
Voltcraft HS-50	Mass charcoal blanket	± 20 g	0-50 kg

2.5 Field experiments

The charcoal cooling blanket was tested in a field experiment at external conditions on a green area next to Empa's campus in St. Gallen, Switzerland (47°24'48.3"N 9°20'33.1"E). For this, the same blanket's dimension and material properties were used as in the lab experiment, except that the length was extended to a 7 m (L_b, unfilled). After filling, this led to a length of about 5 m. The compartment size was 0.2 m ($W_{co,e}$, before filling). The dry weight of the blanket, when filled with charcoal, was 55 kg. As such, the area density of this filled blanket was about 23 kg m^{-2}. The blanket was wrapped around a structure (1 x 1.5 m) of six wooden poles, which were additionally fixed with nailed wood beams (Figure 1). The blanket was fixed on the poles with nails and tensioning ropes. The circumference of the charcoal cooler, when filled, was thereby 5 m. The total volume of the cooler was thereby 600 L (0.6 m^3, 1 x 1.5 x 0.4 m).

In a foldable ventilated plastic crate (0.54 x 0.37 x 0.28 m), 5 kg of apples together with hygrothermal sensors were stored inside the cooler to monitor its cooling behavior. The crate was placed on a second folded crate to reduce the direct thermal influence of the ground conditions, and another folded box was used as a lid. Subsequently, the cooler was closed with a plastic tarp. In that way, high humidity and low temperature are maintained inside the cooler since air can only enter and exit the cooler via the charcoal blanket. A second tarp was attached to protect the cooler from external weather conditions like direct solar radiation. Different materials than plastic can be used, such as jute or cotton, to reduce the carbon footprint of this cooler in future designs. This second tarp was placed 0.25 m above the first tarp to allow airflow between both tarps.

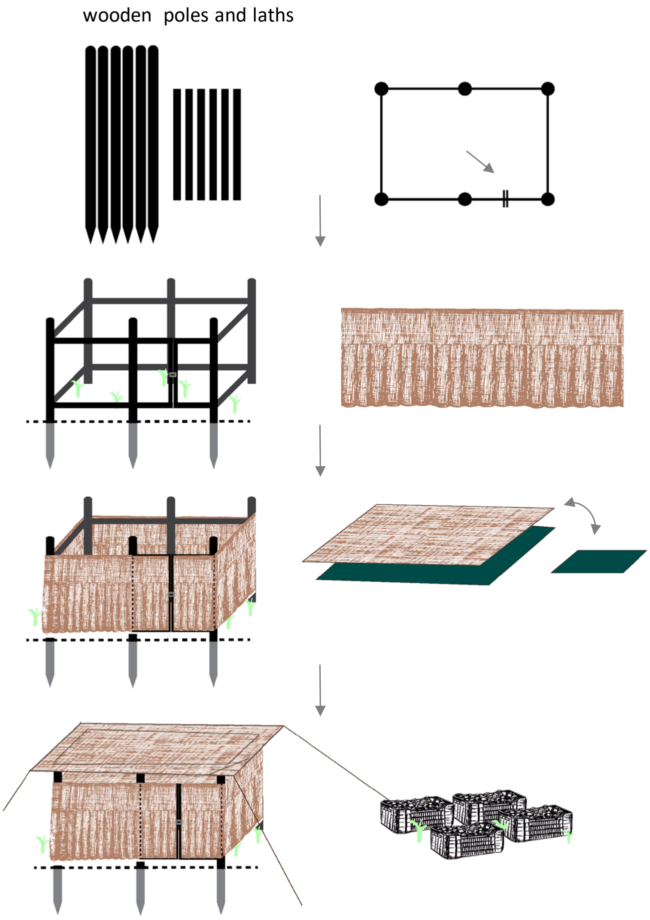

Figure 1. Illustration of the construction of the upscaled 600L charcoal cooler that was built and tested during the described field experiment.

The monitoring was performed over three days (21.-24.09.2021). The watering step was conducted every morning (between 8:00-9:00) and after about six hours. Depending on the weather and evaporation rate, 2 to 5 L were used to wet the blanket. Before watering, the water was initially filled in canisters and conditioned to the outside temperature.

The following sensors were installed (for specifications, see Table 2): fruit core and surface temperature (TinyTag Talk 2), and air temperature and humidity inside the cooler (Sensirion SHT31 Smart Gadget). The weather data, such as air -, ground -, dew point, and psychrometric wet bulb temperature, were collected from a nearby weather station through IDAWEB (MeteoSchweiz). In Figure 2, the monitored temperature and humidity data are shown for the period of the experiment.

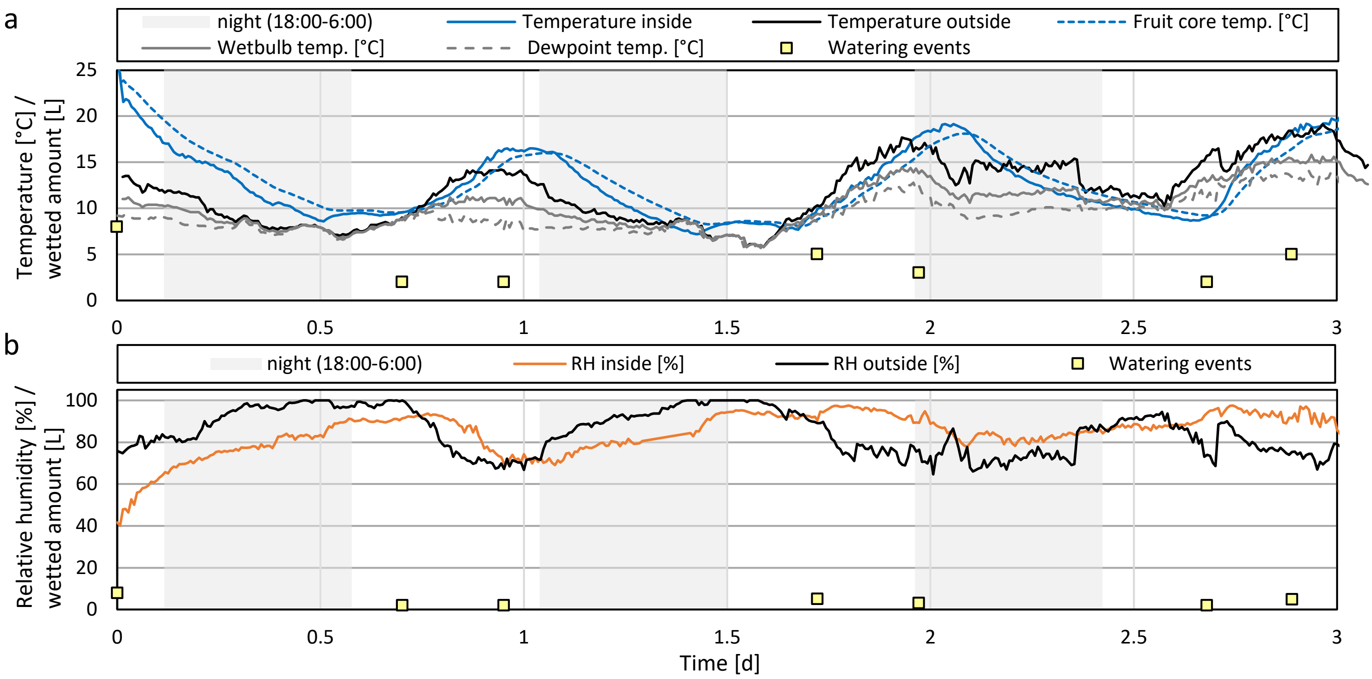

Figure 2. The (a) temperature inside and outside of the cooler, (b) relative humidity inside and outside of the cooler, and the wetted amount of water recorded for three days of the field experiment.

2.6 Environmental impact of a charcoal blanket versus an active refrigeration unit

Life cycle assessment (LCA) is a standardized system-thinking approach used to measure the environmental impacts of a specific product (or service) along its entire life cycle (ISO, 2006). This methodology involves four basic iterative steps, namely (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation of results. In this study, we use the global warming potential (GWP, kg CO_2-eq) as an indicator to measure the environmental impact of greenhouse gas emissions (IPCC, 2013). Below, we give more details on the carbon footprint of the different charcoal blanket components, a charcoal blanket cooler with a size of a 20-foot shipping container (~33 m³), and a commercial refrigerated unit of a similar size, based on literature data (Cascini et al., 2016).

2.6.1 Goal and scope definition

The study's goal is to determine the climate-related impact of constructing and operating a charcoal blanket cooler compared to a commercial refrigeration unit.

Functional unit. The functional unit expresses and identifies the operational unit of the analysis. The functional unit chosen in this study is a 33 m³ size system with a life span of 10 years. It cools down 15 tons of mango by 6 °C (from the initial fruit temperature of 25 °C to 19 °C). So the operational units are: (1) a 33 m³ size charcoal blanket cooler, and (2) a 33 m³ size commercial refrigeration system using R-404A refrigerant.

System boundaries. The life cycle system boundaries for this study include (1) the construction phase and (2) the use phase. The life cycle assessment of the end-of-life phase and the transportation of systems components from the production site to the installation location is beyond the scope of this analysis. Note that the use phase for the charcoal cooler is mainly represented by the quantity of water needed for cooling. The charcoal cooler cools down fruits without consuming any form of electricity or fuel.

Data collection. The life cycle inventory analysis (LCI) for the charcoal cooler was conducted using the information from our experimental studies (see sections 2.4-2.5) and information from the original equipment manufacturer, linearly scaled up to the size described by the functional unit. For the LCI of a commercial refrigeration unit, we extracted data from a study on a 5.12 m³ walk-in commercial refrigeration unit (Cascini et al., 2016). We scaled it up to the size of a 20-foot refrigerated container (33 m³). The Ecoinvent v.3.6 background database was used (ecoInvent, 2009).

Assumptions. We performed the analysis based on simplified assumptions, including the following:

- The lifespan of the charcoal blanket cooler and the commercial refrigeration unit is ten years. Note that the burlap (for the charcoal blanket) is assumed to have a lifespan of 3 years; therefore, more burlap material will be needed to reach the ten-year lifespan. The reduced burlap lifespan was factored in when calculating the environmental impact of constructing a charcoal cooler.
- The refrigerant leakage rate of 10% for the ten-year lifespan is assumed (Cascini et al., 2016).
- The systems are constructed in a European OECD country.

2.6.2 Life cycle inventory and emissions

The life cycle inventory for a charcoal blanket of 0.06 m^3 size is presented in Table 3. This charcoal blanket is capable of cooling a crate of fruit. Table 4 shows the life cycle inventory for constructing a 33 m^3 size charcoal blanket cooler, while that of a 33 m^3 size commercial refrigeration unit is presented in Table 5. The main parameters/values used to model the life cycle inventory for operating a charcoal cooler and a commercial refrigeration unit for 14 days are shown in Table 6. The carbon footprint values of each material are reported in the same tables.

Table 3. Life cycle inventory and emissions for constructing a 0.06 m^3 size charcoal blanket.

Material type	Size (kg)	Corresponding inventory in EcoInvent database v. 3.6	Carbon footprint (kg CO_2-eq / m^2)
Charcoal	6.87	Charcoal//[GLO]	14.14
Burlap	0.18	Textile, jute//[GLO]	0.42
Sewing thread	0.03	Fibre, polyester//[GLO]	0.13
Sewing needle	0.001	Steel, chromium steel 18/8//[GLO]	0.00
Total	**7.081**		**14.69**

Table 4. Life cycle inventory and emissions for constructing a 33 m^3 charcoal blanket cooler.

Material type	Size (kg)	Corresponding inventory in EcoInvent database v. 3.6	Carbon footprint (kg CO_2-eq/unit system)
Charcoal	1806.00	Charcoal//[GLO]	3716.848
Burlap	66.00	Textile, jute//[GLO]	152.722
Sewing thread	4.95	Fibre, polyester//[GLO]	20.850
Sewing needle	0.001	Steel, chromium steel 18/8//[GLO]	0.005
Nails	0.20	Steel, chromium steel 18/8//[GLO]	0.896
Wooden poles	128.00	Cleft timber, measured as dry mass//[RoW]	5.180
Tarpauline	33.00	Polyethylene, linear low density, granulate//[GLO]	74.554
Total	**2038**		**3971**

Table 5. Life cycle inventory and emissions for constructing a 33 m^3 commercial refrigeration unit (extracted from Cascini et al. (2016)).

Material type	Size (kg)	Corresponding inventory in EcoInvent database v.3.6	Carbon footprint (kg CO_2-eq)
Stainless steel	1876	Steel, chromium steel 18/8//[GLO]; Sheet rolling, chromium steel//[GLO]	9562.86
Polyurethane (PUR)	23.52	Polyurethane, rigid foam//[RoW]	157.51
Hermetic reciprocating compressor	17.00	Steel, chromium steel 18/8//[GLO]; Sheet rolling, chromium steel//[GLO]	86.66
Compressor frame	1.90	Aluminium, wrought alloy//[GLO]; Sheet rolling, aluminium//[GLO]	26.06
Copper-aluminium wire	1.93	Wire drawing, copper//[GLO]	1.22
Finned evaporator	8.80	Steel, chromium steel 18/8//[GLO]; Sheet rolling, chromium steel//[GLO]	44.86
Micro-channel condenser	2.00	Aluminium, wrought alloy//[GLO]; Sheet rolling, aluminium//[GLO]	27.43
Condenser frame	2.50	Aluminium, wrought alloy//[GLO]; Sheet rolling, aluminium//[GLO]	34.28
Evaporator fans	4.60	Fan, for power supply unit, desktop computer//[GLO]	71.31
Evaporator frame	12.10	Aluminium, wrought alloy//[GLO]; Sheet rolling, aluminium//[GLO]	165.96
Electric motors	12.00	Cast iron//[GLO]	21.86
Electronic control unit	0.80	Electronics, for control units//[GLO]; Aluminium, cast alloy//[GLO	33.97
Copper piping	9.10	Selective coat, copper sheet, black chrome//[GLO]	22.26

Valves	0.78	Brass//[RoW]	3.43
Support frame	179.18	Aluminium, wrought alloy//[GLO]; Section bar extrusion, aluminium//[GLO]	2508.67
Welding and soldering	3.80	Flux, for wave soldering//[GLO]	10.74
Total	**2156**		**12779**

Table 6. Main parameters/values used in the life cycle inventory for cooling mango fruits for 14 days using a charcoal cooler (left) and a commercial refrigeration unit (right).

Cooling	**Parameter**	**Unit**	**Charcoal cooler**	**Corresponding inventory in EcoInvent database v.3.6**	**Refrigeration unit**	**Corresponding inventory in EcoInvent database v.3.6**
	Weight of mango fruits per 22ft unit system	kg	15193.00	-	15193.00	-
	Weight of a unit system	kg	3099.85	-	2156.01	-
	Initial fruit temperature	°C	25.00	-	25.00	-
	Final fruit temperature	°C	19.00	-	19.00	-
	Electricity/ energy consumed per 1 kg of fruit	kWh/kg fruit	0.00	-	0.02	Electricity, medium voltage//[CH]
	Amount of water/refrigerant used per 1kg of fruit	kg/kg fruit	0.01	Tap water//[GLO]	0.00	Refrigerant R134a//[GLO]
Maintaining cooling	Power consumed to maintain refrigeration for a unit system	kW	0.00	-	5.42	-
	Amount of water required	kg	165.00	-	0.00	-
	Electricity consumed per 1 kg fruit	kWh/kg fruit	0.00	-	0.11	Electricity, medium voltage//[CH]
	Amount of water/refrigerant refilled (10% annual leakage for R404A refrigerant) per 1kg of fruit	kg/kg fruit	0.00013	Tap water//[GLO]	0.00	Refrigerant R134a//[GLO]

2.6.3 Life cycle impact assessment and interpretation of results

We determined the climate change-related impact of a charcoal blanket and that of constructing and operating a charcoal cooler compared to that of a commercial refrigeration unit, as shown in Table 7. It is clear from these data that: (1) the environmental impact of **constructing** a charcoal cooler room is much lower (~3 times) than that of a commercial refrigeration system; (2) the environmental impact of **operating** a charcoal cooler is over 200 times lower than that of a commercial refrigeration system. Although charcoal is considered an unsustainable fossil resource and leads to massive deforestation, its use in the charcoal cooler is acceptable. It only needs to be produced once, after which it can be used for many years.

Table 7. Carbon footprint impact of constructing and operating a charcoal cooler (left) compared with a commercial refrigeration unit (right)

Material/product	**Description**	**Carbon footprint of construction/material**	**Carbon footprint of operating a charcoal cooler and a refrigeration unit (kg CO_2-eq/tonne fruit)**	**Reference/calculation**
Charcoal	Environmental impact of 1kg of charcoal	2.06 kg CO_2-eq/kg of charcoal		EcoInvent v.3.6
Burlap	Environmental impact of 1kg of burlap	2.31 kg CO_2-eq/kg of burlap		EcoInvent v.3.6
Food loss	Environmental impact of 1 kg of mango fruit lost.	0.11 kg CO_2-eq/kg		EcoInvent v.3.6
Charcoal blanket (burlap + charcoal)	($1m^2$) – of 120 mm thickness, weight per m^2 of 7kg.	15 kg CO_2-eq/m^2		Calculated based on values from Table 3
Polyurethane (PUR) foam for commercial refrigeration unit	120 mm thickness PUR insulator (0.025kg/m^2)	20 kg CO_2-eq/m^2		Calculated based on values from Table 5
Charcoal cooler – the size of 20ft refrigerated container	A charcoal cooler of 33 m^3 internal volume	3971 kg CO_2-eq/unit storage room	0.00878	Calculated based on values from Table 4 and Table 6
Commercial refrigeration 20ft-size unit	A walk-in commercial cold storage unit of 33 m^3 internal volume	12782 kg CO_2-eq/unit storage room	1.8	Calculated from (Cascini et al., 2016) and upscaled as seen from values in Table 5, Table 6

3 How to construct a charcoal blanket

We give a step-by-step guide on making a charcoal blanket yourself, as illustrated in Figure 3.

1. Decide on the circumference and height of the cooling chamber (L_{cc}, H_{cc}); thus, the approximate blanket size you need (L_b, $H_{b,c}$). Since filling with charcoal reduces the actual length of the blanket ($L_{cc} < L_b$), you typically need to make that the length of the blanket is about 20%-30% longer than the final circumference of your cooling room depending on the width of the compartements (e.g., $L_{cc} = 1.3 \times L_b$ if $W_{co,e} = 200$ mm).
2. Decide on the thickness of the filled blanket so the size of the compartments you would like to have (D_{co}). Typical thicknesses of existing charcoal coolers are 50-200 mm.
3. Determine the width of the compartment ($W_{co,e}$) you would need to sow to obtain your required compartment thickness (D_{co}). Assuming you end up with circular compartments, this width is calculated as $W_{co,e} = \pi\ D_{co}/2$.
4. Choose the overlap length of the textile ($H_{b,e}$). This choice is arbitrary, but some overlap often helps cover the top of the cooler if you see this as beneficial.
5. Cut two pieces of burlap to the correct size ($L_b \times H_b$)
6. Sew these pieces together according to the plan with the compartments (Figure 3), leaving the compartments open on the top.
7. Fill the compartments with charcoal. There is an elegant way to avoid charcoal pieces getting stuck in the burlap on their way down, which makes the filling process rather tedious. Insert a plastic pipe with a diameter that is slightly smaller than the diameter of the cooler (D_{co}) in a compartment, all the way down to the bottom. Then poor or put charcoal pieces in the pipe. Afterward, retract the pipe, after which the charcoal pieces stay behind.
8. Close the blanket by sowing from the top or leave it open for a vertical charcoal cooler.

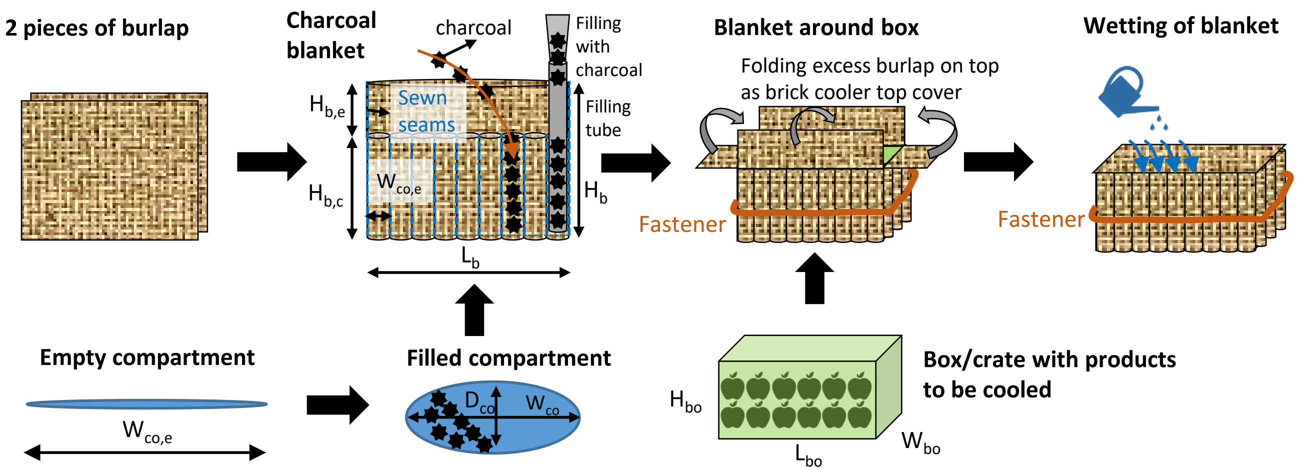

Figure 3. The schematic flowchart and technical drawings on how to construct a charcoal blanket and use it. The drawings are detailed for the case where the blanket is wrapped around a box of fruit. $H_{b,e}$ = height of unsewn part of the blanket [m], $H_{b,c}$ = height of the blanket compartments filled with charcoal [m], H_b = total height of the blanket [m], L_b = length of the unfilled blanket [m], $W_{co,e}$ = size of the empty compartment [m], W_{co} = size of the compartment when filled with charcoal [m], D_{co} = wall thickness of the blanket [m], H_{bo} = height of box with products to be cooled [m], L_{bo} = length of box with products to be cooled [m], and W_{bo} = width of box with products to be cooled [m].

Once you have the blanket, you can construct a charcoal cooler room. An example of how to do so is shown in Figure 1.

- Determine the size of the cold storage facility you want to build and design your blanket accordingly. Typical storage sizes are 0.2 - 30 m^3.
- Put poles (wood or metal) in the ground. If required, fix the poles from the top to improve stability.

- Fill the charcoal blanket with charcoal. The amount of charcoal largely depends on the compartment size and the size of the charcoal pieces that are locally sourced. It is therefore difficult to estimate a priori how much charcoal is needed.
- Wrap the filled charcoal blanket around the poles to make an enclosed room.
- Fix the blanket to the poles with rope or zip ties. One could also wrap a rope or belt around the entire structure.
- Put a spacer between the charcoal blanket and the ground (e.g., bricks or wooden spacer). This spacer avoids the burlap being in direct contact with the ground. The spacer reduces the degradation of the burlap at the bottom of the blanket.
- Put a cover or roof on the charcoal cooler to avoid moist and cold air from the inside to directly leave the cooler. Without a cover, the cold air is not viable anymore for cooling as it escapes from the top.
- Provide a shading structure at a certain distance (> 0.2 m) above the cooler to avoid excessive heat from the sun penetrating the cooler. This structure can be shade netting, for example. Burlap can be used as a shade net.
- If available, piping can be installed on the cooler for automatic watering.

4 Facts & figures on materials used

4.1.1 Jute and burlap

Jute is the fiber used to produce burlap (or hessian) textile (TIS, 2021; Wikipedia, 2021a, 2021b). Jute is sourced from the flowering plants *Corchorus capsularis* and *Corchorus olitorius*. These plants have a length of about 1.5-3 m and a diameter of 2-3 cm. From these plants, jute fiber is collected from the bast, so is a bast fiber. Jute is an affordable natural fiber. Its name means 'hair strand'. Next to cotton, it is the most produced and widely used plant fiber. It is the most popular stalk fiber, next to hemp and flax. Jute originally came from the Mediterranean area but is now mainly cultivated in India and Bangladesh. In 2019, 1 709 000 and 1 600 000 tons were produced in India and Bangladesh, respectively (FAO, 2021).

As a material, jute is mainly composed of cellulose and lignin, and the lignin content is high compared to other fibers (approximately 12-26%). The fiber is UV-resistant and has antistatic properties. It is a strong natural fiber with high tensile strength (393-800 MPa) and a relatively low Young's modulus (10-30 MPa) (Wu et al., 2020). These properties make it is useable for high-performance technical textiles. Jute has low extensibility, namely an elongation at break of 1-2%. The properties of the fiber make that jute bags can be stacked firmly. These bags do not shift, which is an advantage for maritime transport. Bags made out of burlap textiles, based on jute transport, primarily agricultural products, including coffee, cocoa, cereals, or spices.

Jute is sensitive to moisture absorption and is highly hygroscopic (TIS, 2021). Jute significantly loses strength when exposed to moisture, especially for prolonged periods. Jute also is sensitive to microbial attacks in humid environments. Nevertheless, jute is still a durable material. When used outdoors, jute decays in 2 to 3 vegetation periods. Since it is made out of natural fibers, it is naturally decomposable and is considered carbon dioxide neutral.

4.1.2 Charcoal

Charcoal is produced by heating wood to temperatures of above about 300-500 °C, which is called a pyrolysis process (Dias Junior et al., 2020; Tintner et al., 2018). This heating is done at low oxygen contents and removes water and other volatile compounds. As a result, water is removed from the wood without completely burning up the wood. The charcoal is thereby a light, black, carbon-based material. Charcoal can be used for heating and cooking purposes. The advantage of charcoal for these purposes is that it burns without smoke and with hardly any flame, compared to regular wood. Charcoal also produces higher temperatures. It is also much cheaper to transport and handle as the water is removed. Non-industrialized charcoal production often is one of the causes of deforestation due to the absence of a sustainable replanting policy. Therefore the material is under pressure for its low environmental sustainability.

5 List of horticultural products and their storage conditions

We list here key fruits and vegetables and their optimal storage conditions. These conditions are essential to evaluate for which crops evaporative cooling can be used to store them in the optimal range. This selection was made based on the most produced fruits and vegetables. This data was sourced from (Cantwell, 2001).

Table 8. List of specific horticultural products and their storage conditions.

Product		Optimal storage temperature [°C]	Optimal humidity [%]	Ethylene production	Ethylene sensitivity	Storage life	Comments
Apple	Not chilling sensitive	-1.1 - 0	90-95	VH	H	3-6 months	CA viable
Avocado	cv. Fuerte, Hass	3 - 7	85-90	H	H	2-4 weeks	CA viable
Banana		13-15	90-95	M	H	1-4 weeks	CA viable
Broccoli		0	95-100	VL	H	10-14 days	CA viable
Cabbage	Common, early crop	0	98-100	VL	H	3-6 weeks	-
	Common, late crop	0	95-100	VL	H	5-6 months	CA viable
Carrots		0	98-100	VL	H	3-6 months	No CA benefit
Cassava		0-5	85-90	VL	L	1-2 months	No CA benefit
Citrus, Lemon		10-13	85-90	-	-	1-6 months	CA viable
Citrus, Orange	CA, dry areas	3-9	85-90	VL	M	3-8 weeks	CA viable
Citrus, Mandarin		4-7	90-95	VL	M	2-4 weeks	-
Cucumber		10-12	85-90	L	H	10-14 days	CA viable
Eggplant		10-12	90-95	L	M	1-2 weeks	CA viable
Grape		-0.5 - 0	90-95	VL	L	1-6 months	CA viable
Mango		13	85-90	M	M	2-3 weeks	CA viable
Melon	Canteloupe	2-5	95	H	M	2-3 weeks	CA viable
Papaya		7-13	85-90	M	M	1-3 weeks	CA viable
Peach		-0.5 – 0	90-95	M	M	2-4 weeks	CA viable
Pear	European	-1.5 to -0.5	90-95	H	H	2-7 months	CA viable
Bell pepper		7-10	95-98	L	L	2-3 weeks	CA viable
Pineapple		7-13	85-90	L	L	2-4 weeks	CA Viable
Plantain		13-15	90-95	L	H	1-5 weeks	-
Potato	Early crop	10-15	90-95	VL	M	10-14 days	No CA benefit
	Late crop	4-8	95-98	VL	M	5-10 months	No CA benefit
Strawberry		0	90-95	L	L	7-10 days	CA viable
Tomato	Mature green	10-13	90-95	VL	H	2-5 weeks	CA viable
	Firm ripe	8-10	85-90	H	L	1-3 weeks	CA viable

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