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

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Abstract

Evaporative cooling is a high-potential technology to help preserve fresh produce after harvest. This passive cooling solution is especially interesting for marginal and smallholder farmers in remote, off-grid areas. However, evaporative coolers are still rarely deployed. We currently lack simple, small-scale evaporative cooling systems that are affordable for marginal and smallholder farmers. As a solution, we present, design, and test an alternative evaporative cooler – a charcoal cooling blanket. The blanket can be made in any size from locally-sourced materials such as charcoal and burlap, or other biodegradable textiles. The blanket's cost scales down quasilinearly with the length of the blanket. The blanket has several compartments to hold the charcoal and is semi-self-supporting. When building a cold storage room or retrofitting sheds to cooling rooms, the blanket acts as a structural component. The blanket is useable throughout the supply chain. Examples are temporary on-farm storage, cooling during transport by truck, or cooling at the local markets. Single-family households can deploy this cooler in rural, peri-urban, or urban areas for last-mile cooling. In our lab experiments, the blanket cooled the air and the fruit temperature by 5 °C below ambient in a moderately humid environment. This temperature was only 2-3°C above the wet-bulb temperature. The humidity inside our 56L cooler was 85-95%. In field experiments, a 600L blanket cooler achieved a temperature reduction of 2-3°C below the outside air temperature. The lower temperature and higher humidity inside the evaporative blanket cooler reduce thermal food degradation and wilting. The materials to construct the blanket have a carbon footprint of 15 kg CO_2-eq/m^2. The environmental impact of operating a charcoal-blanket storage room of a twenty-foot equivalent unit (33 m^3) is 200 times lower than that of a similar-sized commercial refrigeration unit for a 14 days storage period. We also present a business solution leveraging digitalization to accelerate the adaption of this technology. The charcoal blanket lowers the expertise to construct and operate evaporative coolers. It additionally reduces the cost of microscale cooling facilities. With these blankets, we therefore aim to catalyze the deployment of evaporative coolers.

Keywords

charcoal; textile; refrigeration; fruit and vegetables; cold storage; sustainable; passive cooling

1 Introduction

In 2020, about 768 million people were undernourished globally (FAO et al., 2021). Next to hunger, malnutrition leads to stunting, wasting, and over-weight with 22%, 6.7%, and 5.7% of the children under five years (FAO et al., 2021). To help solve these problems, we need to better preserve nutritious food, such as fruits and vegetables. We also need to ensure that more people have access to them. Unfortunately, the losses of fresh fruit and vegetables are among the highest compared to other foods (FAO, 2019; Gustavsson et al., 2011). Saving more of the fruits and vegetables that we produce will help fight micronutrient deficiency and hunger, and decrease the need to produce more food. A large part of these fruits (~ 30%) and vegetables (~ 15%) are currently produced by smallholder or marginal farmers, which have farms under 2 hectares (Ricciardi et al., 2018). Food losses are exceptionally high with smallholder farmers (Ricciardi et al., 2018). One reason is the lack of cold storage facilities. Fruits and vegetables are therefore often stored only under natural shade. Here, high exterior temperature and low humidity induce accelerated aging and wilting.

Several initiatives currently promote the access of smallholder farmers or farmer groups to cooling facilities (ACES, 2022; BASE, 2022a, 2022b; CleanCoolingCollaborative, 2022). Examples are small-scale, solar-power-driven cooling units. Nevertheless, remote off-grid areas and farmers with limited financial resources remain underserved. Innovative business models address this issue for some farmers. For those excluded, passive cooling solutions are an alternative (Elansari et al., 2019). Many solutions are based on the principle of evaporative cooling (Kitinoja, 2013; Teutsch and Kitinoja, 2018). Evaporative cooling is considered one of the top 22 investable innovations that can transform food systems in emerging markets (GKI, 2017; Verploegen, 2021a). These low-risk, high-gain solutions could be implemented with little training and low capital costs.

Several types of evaporative cooling systems are known and developed nowadays. We give an overview of evaporative coolers in Figure 1, and we discuss the results in section 3.1. These coolers typically lower the air temperature in the cooler by 3-10 ºC and increase the relative humidity inside to 70 -100%. Thermally-driven food degradation is slowed down, and moisture loss is reduced, increasing shelf life. However, the widespread deployment of evaporative coolers is still lacking, despite their clear benefits. A study showed that in Kenya, less than 1% of the farmers used charcoal or sand-and-brick coolers (Kanali et al., 2017). Research and scientific publications on evaporative coolers, particularly for postharvest storage of fruits and vegetables, are also limited compared to other postharvest technologies, such as active cooling solutions (Figure 1).

Several bottlenecks hinder their deployment and use in rural areas, mainly in developing countries (Verploegen, 2021b). First, evaporative coolers require some expertise to construct. The proper education and training are often not available to smallholders to build and operate these systems. The reason is that they often live in very remote areas. More so, there are just so many smallholder farmers, so it is a daunting and tedious task to reach and educate them all. Second, such evaporative coolers also require suitable materials, such as wood, brick, metal meshes, or piping, which often cannot all be sourced locally. Apart from being challenging to construct for a non-specialist, the initial capital cost is too high for smallholder or marginal farmers. In the end, the main problem of evaporative coolers for smallholder farmers is one of scale. These coolers are too small, and too many farmers need access to expertise, training, and sufficient capital to build and operate evaporative coolers. Reported successful evaporative coolers are large and operated by farmer cooperatives (Figure 2) (D-LAB, 2021a, 2021b). This scale problem leaves a lot of rural, peri-urban, and urban marginal or smallholder farmers underserved in terms of passive postharvest cooling solutions.

We take a step in democratizing evaporative coolers to marginal and smallholder farmers. We present an alternative concept to charcoal coolers, namely a charcoal blanket. Compared to existing systems, it is designed to be a simple cooler. One can make the blanket in any size and from locally-sourced materials. The cost correlates quasilinearly with the length or height of the blanket. This scalability makes it more accessible and affordable for smallholder or marginal farmers. The blanket is designed to be used in different supply chain stages. After presenting the charcoal blanket concept, we characterize the charcoal material, including its microstructure and wetting kinetics, since these are critical determinants for its performance. Then, we evaluate the blanket's performance by lab experiments and field experiments. We also assess the environmental impact of producing and operating a charcoal blanket. Finally, we present a business solution leveraging digitalization to accelerate the adoption of this technology. The extensive description of materials and methods are included directly in the supplementary material to keep the paper condensed.

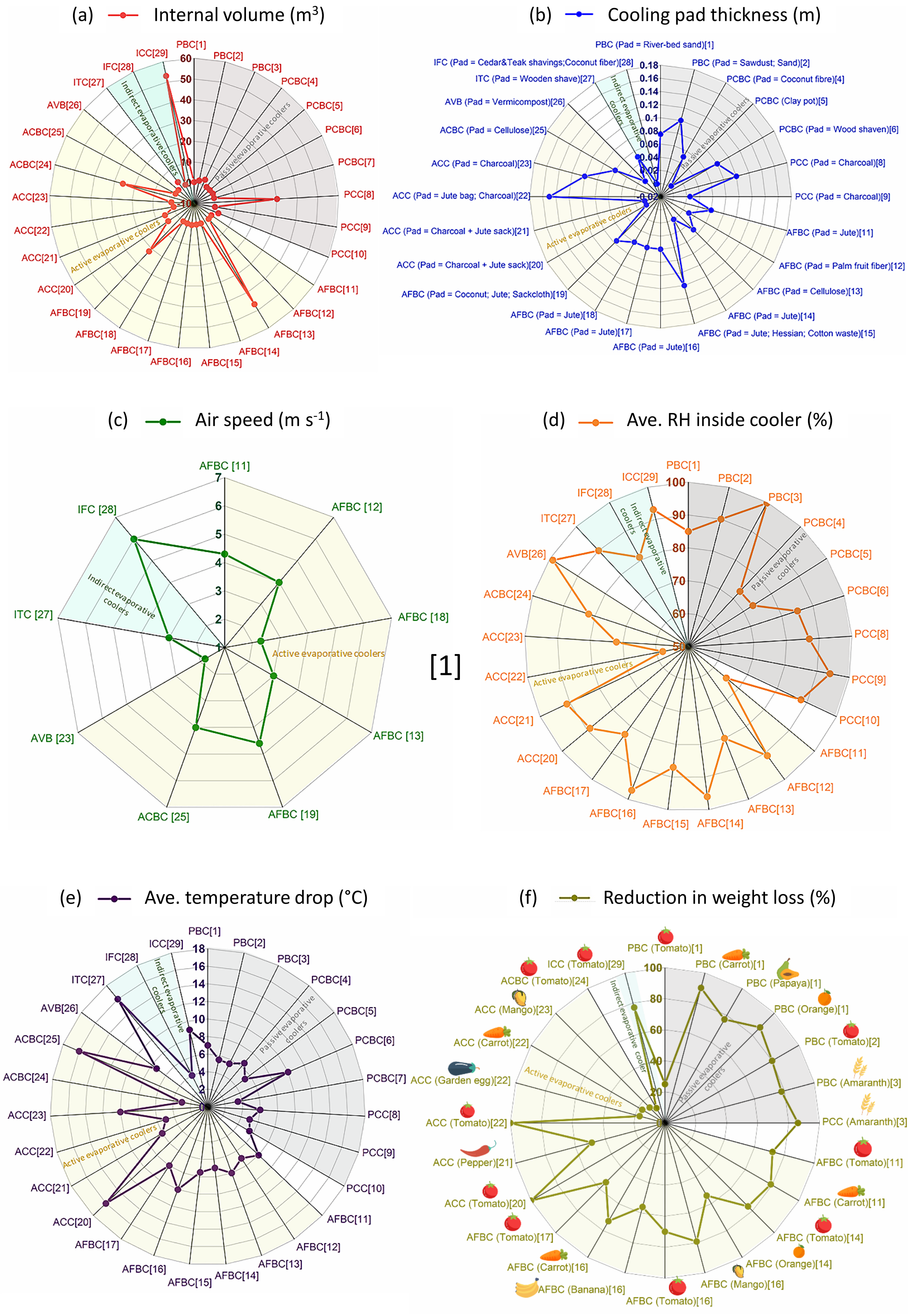
(a) Internal volume (m³)
PBC[1]
PBC[2]
PBC[3]
PCBC[4]
PCBC[5]
PCBC[6]
PCBC[7]
PCC[8]
PCC[9]
PCC[10]
AFBC[11]
AFBC[12]
AFBC[13]
AFBC[14]
AFBC[15]
AFBC[16]
AFBC[17]
AFBC[18]
AFBC[19]
ACC[20]
ACC[21]
ACC[22]
ACC[23]
ACBC[24]
ACBC[25]
AVB[26]
ITC[27]
IFC[28]
ICC[29]
60
50
40
30
20
10
Passive evaporative coolers
Active evaporative coolers
Indirect evaporative coolers
(b) Cooling pad thickness (m)
PBC (Pad = River-bed sand)[1]
PBC (Pad = Sawdust; Sand)[2]
PCBC (Pad = Coconut fibre)[4]
PCBC (Clay pot)[5]
PCBC (Pad = Wood shaven)[6]
PCC (Pad = Charcoal)[8]
PCC (Pad = Charcoal)[9]
AFBC (Pad = Jute)[11]
AFBC (Pad = Palm fruit fiber)[12]
AFBC (Pad = Cellulose)[13]
AFBC (Pad = Jute)[14]
AFBC (Pad = Jute; Hessian; Cotton waste)[15]
AFBC (Pad = Jute)[16]
AFBC (Pad = Jute)[17]
AFBC (Pad = Jute)[18]
AFBC (Pad = Coconut; Jute; Sackcloth)[19]
ACC (Pad = Charcoal + Jute sack)[20]
ACC (Pad = Charcoal + Jute sack)[21]
ACC (Pad = Jute bag; Charcoal)[22]
ACC (Pad = Charcoal)[23]
ACBC (Pad = Cellulose)[25]
AVB (Pad = Vermicompost)[26]
ITC (Pad = Wooden shave)[27]
IFC (Pad = Cedar&Teak shavings;Coconut fiber)[28]
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
-0.02
Passive evaporative coolers
Active evaporative coolers
Indirect evaporative coolers
(c) Air speed (m s⁻¹)
AFBC [11]
AFBC [12]
AFBC [18]
AFBC [13]
AFBC [19]
ACBC [25]
AVB [23]
ITC [27]
IFC [28]
7
6
5
4
3
2
1
Indirect evaporative coolers
Active evaporative coolers
[1]
(d) Ave. RH inside cooler (%)
PBC[1]
PBC[2]
PBC[3]
PCBC[4]
PCBC[5]
PCBC[6]
PCC[8]
PCC[9]
PCC[10]
AFBC[11]
AFBC[12]
AFBC[13]
AFBC[14]
AFBC[15]
AFBC[16]
AFBC[17]
ACC[20]
ACC[21]
ACC[22]
ACC[23]
ACBC[24]
AVB[26]
ITC[27]
IFC[28]
ICC[29]
100
90
80
70
60
50
Passive evaporative coolers
Active evaporative coolers
Indirect evaporative coolers
(e) Ave. temperature drop (°C)
PBC[1]
PBC[2]
PBC[3]
PCBC[4]
PCBC[5]
PCBC[6]
PCBC[7]
PCC[8]
PCC[9]
PCC[10]
AFBC[11]
AFBC[12]
AFBC[13]
AFBC[14]
AFBC[15]
AFBC[16]
AFBC[17]
ACC[20]
ACC[21]
ACC[22]
ACC[23]
ACBC[24]
ACBC[25]
AVB[26]
ITC[27]
IFC[28]
ICC[29]
18
16
14
12
10
8
6
4
2
0
Passive evaporative coolers
Active evaporative coolers
Indirect evaporative coolers
(f) Reduction in weight loss (%)
PBC (Tomato)[1]
PBC (Carrot)[1]
PBC (Papaya)[1]
PBC (Orange)[1]
PBC (Tomato)[2]
PBC (Amaranth)[3]
PCC (Amaranth)[3]
AFBC (Tomato)[11]
AFBC (Carrot)[11]
AFBC (Tomato)[14]
AFBC (Orange)[14]
AFBC (Mango)[16]
AFBC (Tomato)[16]
AFBC (Banana)[16]
AFBC (Carrot)[16]
AFBC (Tomato)[17]
ACC (Tomato)[20]
ACC (Pepper)[21]
ACC (Tomato)[22]
ACC (Garden egg)[22]
ACC (Carrot)[22]
ACC (Mango)[23]
ACBC (Tomato)[24]
ICC (Tomato)[29]
100
80
60
40
20
Passive evaporative coolers
Active evaporative coolers
Indirect evaporative cooler

Figure 1. Selected literature results of direct passive ("grey" shaded area), direct active ("yellow" shaded area), and indirect evaporative coolers ("green" shaded area) for fruits and vegetables. We show (a) internal volume of the different coolers, (b) cooling pad/wall thickness, (c) airspeed for active and indirect cooling, (d) average relative humidity inside the coolers, (e) average temperature reduction in the cooler, (f) reduction in food weight loss compared to storage at ambient conditions. References: (Dadhich et al., 2008[1]; Vanndy et al., 2008[2]; Ambuko et al., 2017[3,10]; Anyanwu, 2004[4]; Mittal et al., 2006[5]; Chinenye, 2011[6]; Patel et al., 2021[7]; Shitanda et al., 2011[8]; Manuwa and Odey, 2012[9]; Mogaji and Fapetu, 2011[11]; Chinenye et al., 2013[12]; Raza et al., 2021[13]; Adekanye et al., 2019[14]; Olosunde et al., 2009[15], 2016[16]; Zakari et al., 2016[17]; Mogaji et al., 2013[18]; Alam et al., 2017[19]; Getinet et al., 2008[20]; Samira et al., 2013[21]; Ogbuagu et al., 2016[22]; Korir et al., 2017[23]; Nkolisa et al., 2018[24]; Poku et al., 2017[25]; Abaranji et al., 2021[26]; Jain, 2007[27]; Deoraj et al., 2015[28]; Sibanda and Workneh, 2019[29]). Abbreviations: PBC = Passive brick cooler, PCBC = Passive clay-based cooler, PCC = Passive charcoal cooler, AFBC =Active fiber-based cooler, ACC = Active charcoal cooler, ACBC = Active cellulose-based cooler, AVB = Active vermicompost cooler, ITC = Indirect two-staged cooler, IFC = Indirect fiber-based cooler, ICC = Indirect charcoal cooler, Ave. = Average, and RH = Relative humidity. (For interpretation of the references to color in this figure, the reader is referred to the Web version of this article).

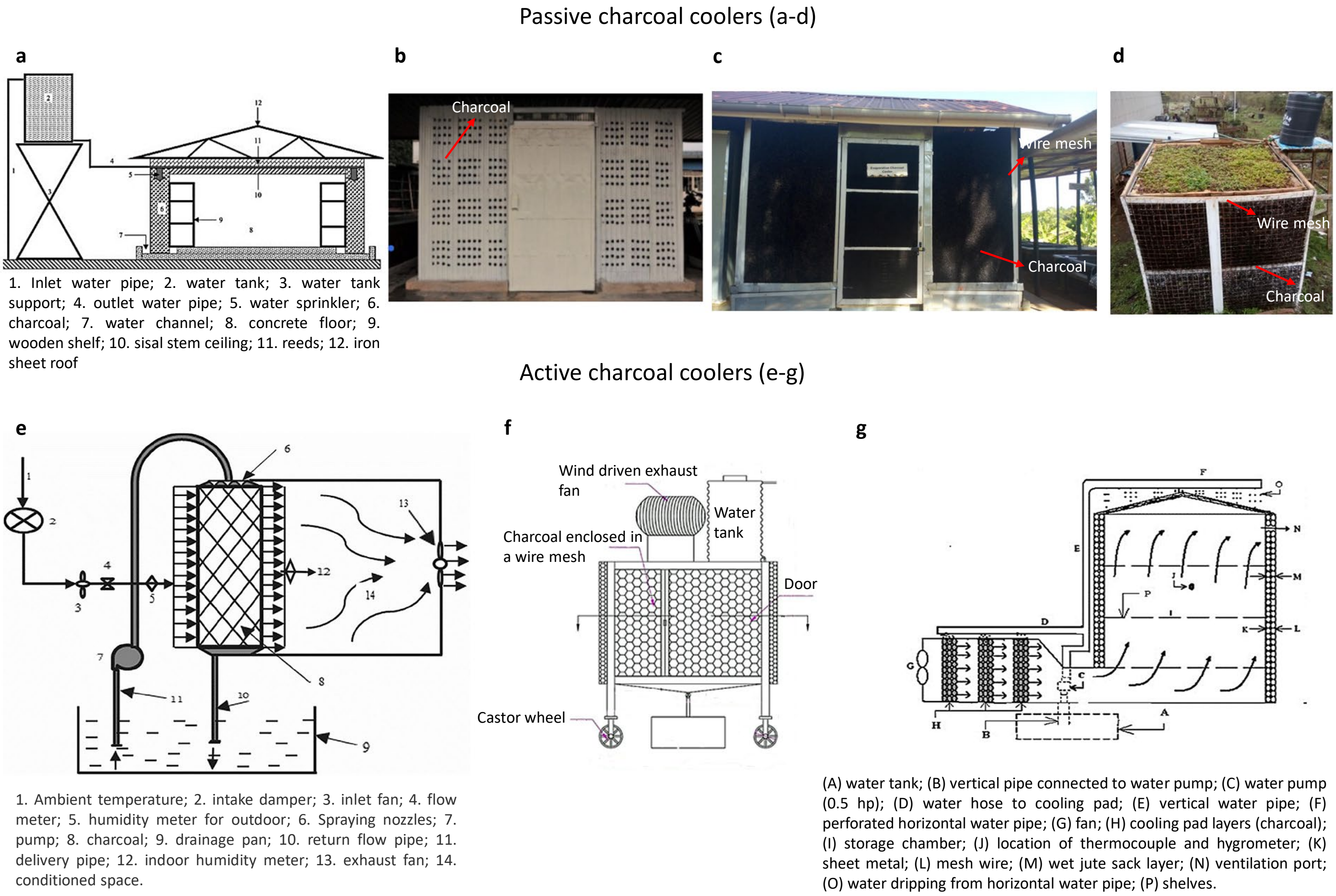

Figure 2. Evaporative charcoal coolers: (a-d) Passive charcoal coolers (Ambuko, 2020[b]; Frey et al., 2019[c]; Ronoh et al., 2018[d]; Shitanda et al., 2011[a]); (e-f) Active charcoal coolers (Getinet et al., 2008[g]; Ndukwu et al., 2017[e]; Wayua et al., 2012[f]).

2 Concept: The charcoal blanket

2.1 State of the art on evaporative coolers

The findings of the research reported in Figure 1 are discussed. The types of coolers include direct evaporative coolers, both passive and active ones, and indirect evaporative coolers. Indirect evaporative coolers only cool the air without increasing the humidity of the air. Active coolers apply forced airflow generation. From the literature reviewed, the commonly used evaporative coolers for postharvest food storage are the active (~ 50%) and passive (~30%) direct coolers, whereas the remaining 20% are indirect coolers. Direct passive evaporative coolers are used by smallholder farmers in developing countries and are the focus of this study. Examples of passive evaporative coolers are the zeer pot, clay-based coolers, sand and brick coolers, khus-mat coolers, and charcoal coolers (Elansari et al., 2019; Teutsch and Kitinoja, 2018).

Passive coolers have an internal volume typically between 0.01 – 10 m^3. They store liquid water in a porous material, namely a cooling pad or wall. This material is chosen to hold a considerable amount of water and provide a large specific surface area for evaporation, such as charcoal. Such material characterization of charcoal are given in section 3.1. The cooling pad is typically between 0.01 – 0.1 m thick. Upon evaporation of this water into the environment, the required latent heat of vaporization is extracted from the material and the surrounding air. Thereby, the air and food products are cooled down by typically 3-10 °C. This temperature depression slows down thermally-driven deterioration processes in the foods. The relative humidity in the cooler is elevated up to 70 -100%, consequently reducing moisture loss from the products. Such evaporative coolers work best in dry and warm regions, for example, Sub-Saharan Africa. Passive coolers have been used to preserve coriander leaves, fenugreek leaves, spinach, tomato, green onion, carrot, radish, peas, papaya, sapota, orange, plum, and grapes (Dadhich et al., 2008). The remaining days of shelf life for different fruits and vegetables could be increased by 2-6 days using an evaporative cooling system, as indicated by previous studies. Passive coolers also reduced the weight loss of tomato, carrots, papaya, orange, and amaranth during storage by up to ~90% compared to ambient storage conditions (Dadhich et al., 2008; Ambuko et al., 2017). Since no additional energy is required for cooling, these systems are attractive for remote areas that have access to water. Evaporative coolers are more sustainable than active cooling solutions.

2.2 What is a charcoal blanket?

A charcoal blanket is a textile-based, air-permeable, hydrophilic blanket. Burlap, for example, is a material with suitable properties. A concept drawing of such a blanket is shown in Figure 3. A flowchart of how the charcoal cooling blanket is constructed and used by a farmer is shown in Figure 4. This blanket is sewed together to subdivide it into compartments with a certain width. Subsequently, these compartments are filled with charcoal pieces of an appropriate caliber. The caliber reflects the size distribution of the charcoal pieces. The charcoal blanket is thereby a composite system. The compartment's cross-section is elliptical or circular. The compartment's thickness (D_{co} [m]) should be in the order of 10 – 15 cm. Then, these compartments are large enough to be filled with charcoal pieces and of similar thickness as typical evaporative coolers ((Ronoh et al., 2020; Shitanda et al., 2011), Figure 1b).

The filled charcoal blanket works as any charcoal cooler. Charcoal is periodically or continuously wetted. By liquid water evaporation, latent heat is extracted from the surrounding air, the charcoal, and the food inside the cooler, which induces cooling. In addition, a more humid environment is created around the food, reducing moisture loss. Periodic wetting is done by spraying or pouring water over the charcoal blanket. Continuous wetting requires complementing the blanket with a piping system, similar to other evaporative coolers.

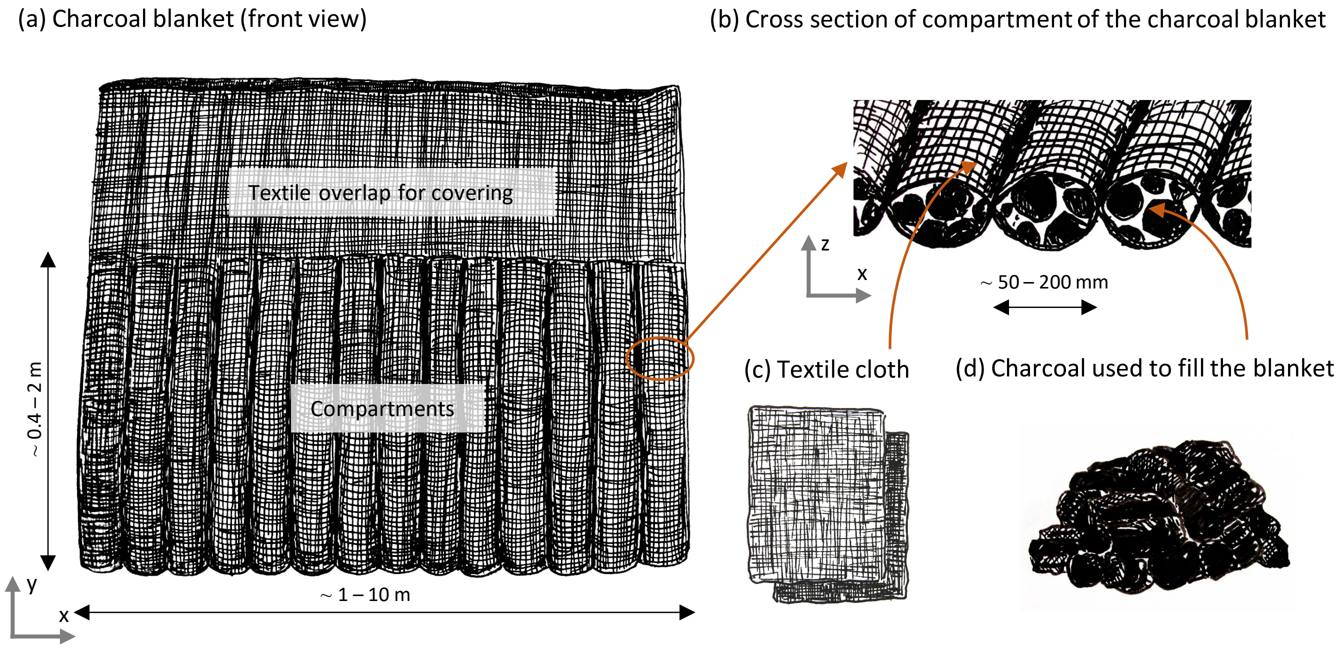

Figure 3. Concept of the (a) charcoal blanket with the characteristic dimensions and (b) the compartments, and (c-d) the materials. The z-axis is perpendicular to the x-y plane.

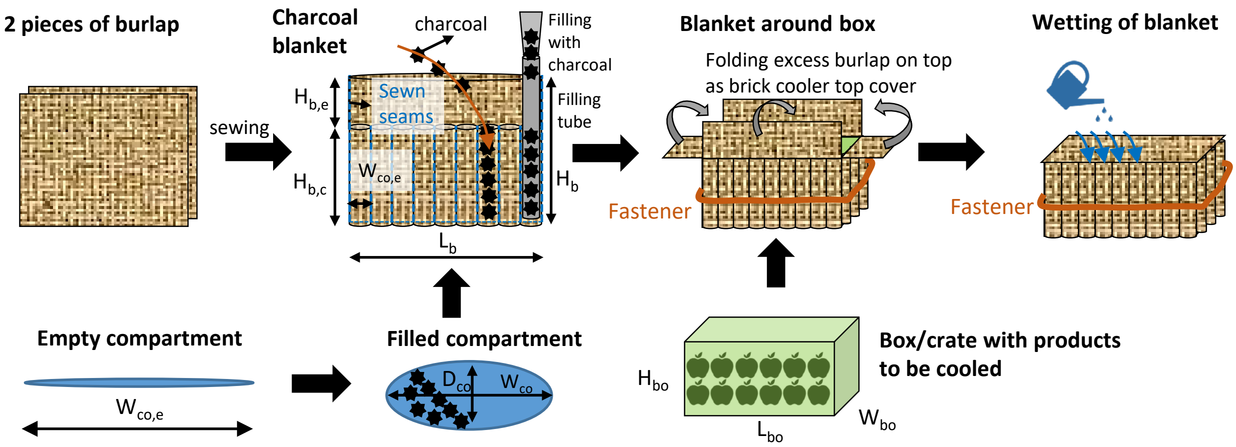

Figure 4. The schematic flowchart and technical drawings on how to construct a charcoal blanket and use it. The drawings are detailed for the case where the blanket is wrapped around a box of fruit. $H_{b,e}$ = height of unsewn part of the blanket [m], $H_{b,c}$ = height of the blanket compartments filled 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].

There are several key design parameters to engineer a charcoal blanket:

- The size of the compartments that are filled with charcoal ($W_{co,e}$ when empty and W_{co} when filled with charcoal [m] ~ 50-200 mm, (Figure 3b)). This size determines the wall thickness of the blanket ($D_b = D_{co}$, [m]). In turn, this thickness defines the mechanical properties of the composite system and the bending and buckling stability.
- The caliber of the charcoal that is filled in the compartments (D_{cc} [m]) and its size distribution. The caliber determines how dense the compartments can be loaded and how much water the blanket can absorb in the end. Smaller pieces will lead to a heavier blanket, which absorbs more water in a shorter period.
- The air permeability, strength, and hydrophilicity of the used textile material.

- The length (L_b [m]) and height ($H_{b,c}$ [m]) of the blanket.
- The configuration in which the blanket is used (Figure 5). With indirect flow-through cooling, the air flows through the blanket that is wrapped around products (Figure 5a). In a similar configuration, the blanket is also made into a cool room where several crates of fruit are placed (Figure 5b). As air passes through the blanket, it is cooled. This cold air then cools down the products inside the cooler, similar to a cooling pad. With contact cooling or direct cooling, the blanket is placed on a top-ventilated box of products (Figure 5c).

Several characteristics of the composite system can be calculated from these design parameters. The area density or surface density (ρ_A [kg m^{-2}]) is the weight per square meter of the filled blanket. This area density is defined in a dry and wetted state ($\rho_{A,dry}$, $\rho_{A,wet}$). This weight-related parameter is essential for handling smaller blankets. For larger blankets, it determines the blanket's ability for partial self-support. The water holding capacity (WHC) of the blanket or the area-based moisture content ($w_{A,PM} = \rho_{A,wet} - \rho_{A,dry}$ [kg m^{-2}]) is an indicator of the cooling capacity (section 4). The air permeability of the blanket (k_a [s]) or, inversely, the pressure resistance of the composite system indicates how well air can pass through the blanket walls. This resistance is determined by the textile material, the charcoal caliber, and size distribution. A low air permeability will force air to flow around and not within or through the charcoal blanket, which will reduce the evaporation rate of the blanket.

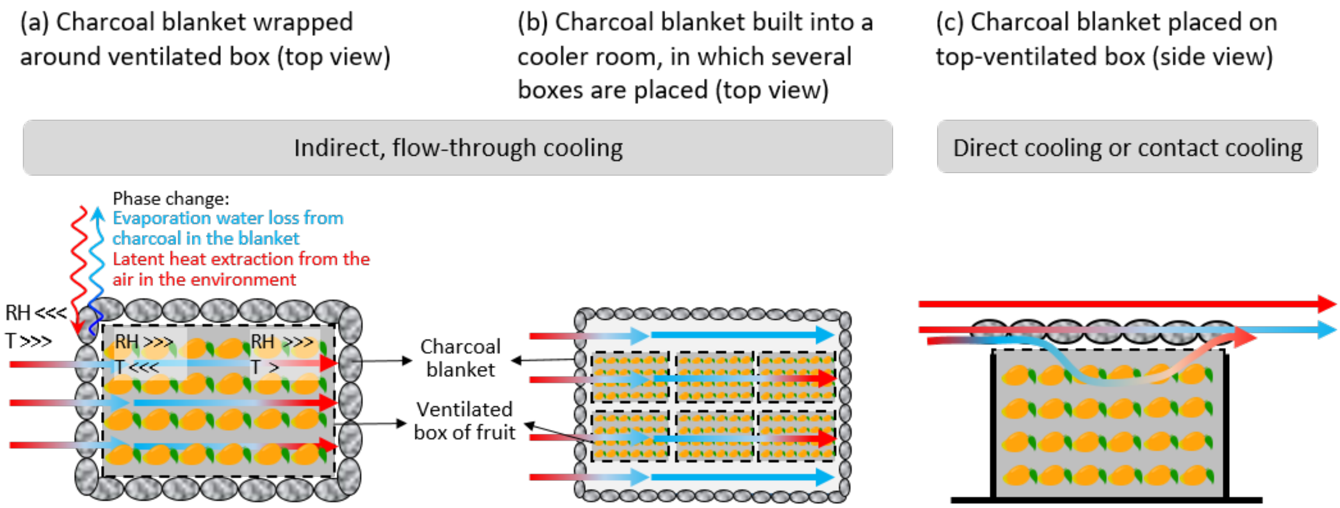

Figure 5. Different configurations in which the charcoal blanket can be used: (a) Wrapped around a ventilated crate of fruit, (b) As walls of a cool room, in which several crates of fruit are placed; (c) Placed on top of a top-ventilated box. The airflow is also indicated with arrows, where red implies a high temperature and blue a lower temperature due to evaporative cooling. The symbols >>> and <<< indicate that the temperature (T) or relative humidity (RH) are relatively high or low, respectively.

Possible concepts where the charcoal blanket can keep fresh food cooler and under more humid conditions are depicted in Figure 6. These examples are listed in order of downstream use in the supply chain.

- Intermediate cooling of crates by a blanket at the farm between harvest and precooling or postharvest storage by placing blankets over or wrapping them around the crates (Figure 6a1). This cooling method complements the popular intermediate storage under natural shade. Similarly, the blanket is useable for temporary cooling before transport.
- Intermediate cooling at local markets, whereas blankets are placed over crates of fresh produce (Figure 6a2).
- Postharvest storage in a rectangular or round charcoal cooler silo. These silos can be walk-in, so with a door opening, or made so one can directly reach in by having a lower height (Figure 6b).
- Postharvest storage in a permanent or makeshift shed by using the blanket as a replacement wall (Figure 6c). One or more walls are replaced. The semi-self-supporting blanket is placed by attaching it to vertical posts. The blanket can also be hung from the ceiling. Based on the predominant/prevailing wind direction, we connect this charcoal blanket to the windward wall. As such, only one or two walls need to be replaced. Additional blankets can be hung within these sheds to provide additional cooling power.

- Cooling of the cargo on a truck (Figure 6d). We need to provide shaded conditions for the blanket if possible. Some shelter from excessive airflow during driving is essential to ensure the blanket does not quickly deplete its absorbed water.
- Postharvest storage for urban gardening communities. Charcoal blankets can be easily tailored and scaled to the specific size of the urban farms. Since gardens are often on rooftops, sufficient wind speed for the charcoal cooler is usually guaranteed. Several previous configurations can be deployed on these roofs (Figure 6a, b, c). If there is a prevailing wind direction, the blanket should be placed preferably on the windward side of the construction.

A similar design concept was already put forward (Frerich, 2012). To our knowledge, this concept was not yet built, tested, or deployed in the field. The materials used in this concept design are not detailed. The material also seems impermeable for airflow and is made from synthetic polymers. Another compartmentalized blanket concept has been implemented in postharvest technology for ethylene absorption (Deltatrak, 2021). These blankets are (0.51 x 0.63 m) filled with activated aluminum beads impregnated with potassium permanganate. They are hung inside sizeable cold storage rooms or refrigerated containers.

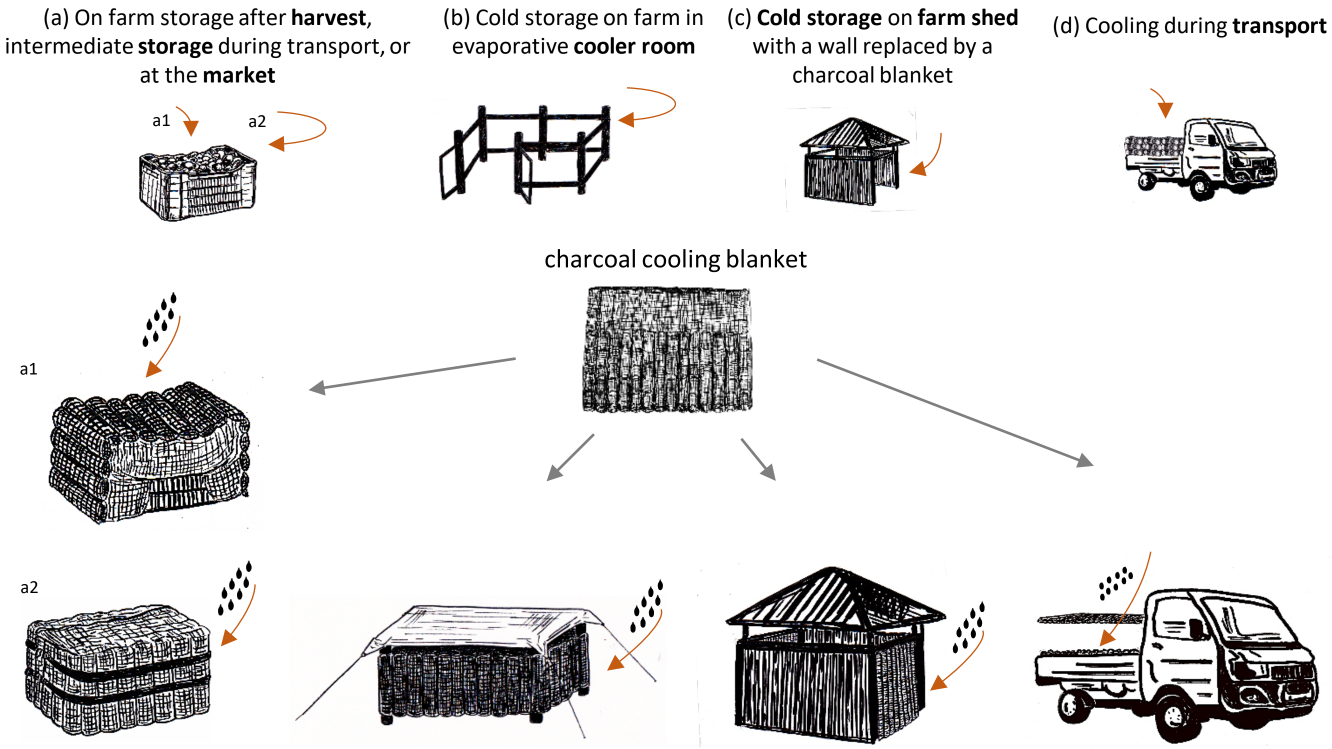

Figure 6. Concept illustrations on how and where the charcoal blanket can be applied in different steps of the supply chain, including (a-b) temporary or intermediate storage at the farm or market, (c) longer-term storage in silos or permanent and makeshift sheds as a replacement wall and (d) during transport.

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

A detailed SWOT analysis is given in the supplementary material. The most important points are highlighted below.

Strengths

Concerning its usability, the charcoal blanket is simple and easy to use. Once this evaporative cooling blanket is constructed by sewing, it 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), Figure 2). Our 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 often a current bottleneck inhibiting the widespread use of charcoal coolers for postharvest storage

(Verploegen, 2021b). The charcoal blanket is also a light and mobile structure. A dry charcoal blanket of 100 mm thick weighs below 10-30 kg m^{-2}. The blanket also does not require an additional energy source for cooling compared to active cooling facilities, including solar-powered ones.

Concerning the materials, they can be sourced locally. Charcoal can be produced almost everywhere in the world. The textile material for the blanket, such as burlap fabric or even cotton, is produced in several countries. The materials are recyclable and reusable. Charcoal can also be used for heating or cooking after the cooler reaches its end of life.

Concerning its design, the compartmentalized blanket provides mechanical stability in bending and buckling. The compartmentalization provides a bending resistance in the longitudinal direction (x-axis, Figure 3). As such, a self-supporting system can be easily created by just adding a few poles into a silo-like structure. The blanket, however, is flexible in the y-direction (Figure 3). 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.

The system is easily scalable, without additional constraints to the required expertise or materials needed. Its scalability makes it attractive for individual rural, peri-urban, or urban farmers, both marginal and smallholder farmers or larger farmer cooperatives. Single households can even use such a charcoal cooler in remote areas. The costs of the blanket scale down quasilinear with the length or height of the blanket, even down to the smallest sizes. Thereby, coolers are affordable to smallholder farmers and can be easily homemade. This evaporative cooler thereby democratizes cooling to all farmers.

Weaknesses

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. Evaporative cooling is only relevant for cooling fresh foods in dry and warm environments. This technology is thereby not suitable for storing all crops in optimal conditions. Furthermore, the cooling temperature and the cooling capacity are not constant and strongly dependent on the external hygrothermal weather conditions.

For the charcoal blanket, in particular, its main weakness is the textile material. Burlap, for example, is 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).

Opportunities

First, the simplicity and scalability of the system make that we can reach smallholder 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. Second, such small-scale evaporative cooling systems are attractive for urban farmers but are not yet frequently used in these communities.

Threats

Charcoal coolers are still not deployed in a local setting. One reason is that the system is still not sufficiently user-friendly or underperforms. As a result, the farmers often do not see the cooler's added value for saving food, and they cease to use it. To mitigate this threat, extensive testing in different regions and for different target groups (rural, peri-urban, and urban farmers) is essential, as other research groups did in the past (D-LAB, 2021a, 2021b). That way, we can identify in which part of the supply chain the charcoal blanket has the most significant potential for adaptation and the highest impact for preserving food.

3 Results

3.1 Material characterization of charcoal

The properties of the filler material used for holding water in the charcoal blanket cooler strongly determine its performance. We use charcoal or char wood, so the lump form of charcoal, but not briquettes. Note that many of these properties are very specific, depending on the origin of the used charcoal and its size. The material properties are indicated in Table 1. We give the typical ranges reported in the literature, showing large spreads. We also included our experimentally-determined properties. Experimental details are given in the supplementary material.

The charcoal used for these experiments was commercially purchased. It had a caliber of 20-80 mm. At least 80% of the charcoal pieces fell within this range. The charcoal was made of beech, alder, birch, and oak wood. It had a fixed carbon amount of 83% and a maximal amount of ash of 4%. It had a maximal initial moisture content of 8% and had a heating potential of 30 000 kJ/kg.

Table 1. Material properties of charcoal used in this study, and comparison with literature sources.

Parameter	Symbol	Value from experiments	Value from literature and reference
Charcoal			
Density material	$\rho_{PM,eq}$ [kg m_{PM}^{-3}]	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)
Solid material matrix content	w_s [kg m_{PM}^{-3}] $w_s = \rho_{PM,eq} - w_{PM,eq}$	w_s = 442 kg m^{-3}	-
Moisture content at equilibrium Dry base moisture content at equilibrium	$w_{PM,eq}$ [kg m_{PM}^{-3}] X_{eq} [kg kg_{PM}^{-1}]	w_{PM} = 25 kg m^{-3} X_{eq} = 5.7% +/- 0.25	3-10% (Energypedia, 2021), 5-10% (FAO, 1983)
Saturated moisture content	$w_{PM,sat}$ [kg m_{PM}^{-3}]	654 +/- 65 kg m^{-3} (after 32 days)	-
Open internal porosity at the microscale	ϕ_0	65% +/- 6%	25%-70% (Mathieson et al., 2015)
Caliber / size	D_{cc}	20 - 80 mm (80% of the pieces fall within this range)	10-60 mm (FAO, 1983)
Thermal conductivity	λ_{cc} [W $K^{-1}m^{-1}$]	-	0.07 (Eltom and Sayigh, 1994), 0.084 (Ronoh et al., 2020), 0.030 (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 effusivity or thermal inertia	I_{cc} [J m^{-2} K^{-1} $s^{-1/2}$]	-	119 J m^{-2} K^{-1} $s^{-1/2}$ (based on data of (Dos Santos et al., 2020))
Charcoal bulk			
Bulk porosity of charcoal	$\phi_{0,bulk}$	61% +/- 1%	-
Bulk density of charcoal	$\rho_{PM,bulk}$ [kg m_{bulk}^{-3}]	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)
Saturated bulk moisture content	$w_{PM,sat,bulk}$ [kg m_{PM}^{-3}]	168 kg m^{-3}	-

Apart from these material properties, also other water-transport characteristics can be determined.

- The pore structure and porosity can be determined via scanning electron microscopy or 3D X-ray imaging. Examples of the microstructure of wood charcoal are given in Figure 7 (Watanabe, 2018).
- The pore size distribution can be determined using mercury porosimetry, amongst others. An example is shown in Figure 8 (Pastor-Villegas et al., 2006).
- A sorption experiment can determine the sorption isotherm. Here the equilibrium moisture content at different humidity levels is quantified. This experiment quantifies if the material is hygroscopic or not. Experiments on torrefied wood illustrate that pyrolysis of wood reduces the hygroscopicity of the material (Kymäläinen et al., 2015). Torrefied wood is an intermediate between raw wood and charcoal as it is processed at 200-300 °C. Pyrolyzed wood still contains a non-negligible amount of adsorbed moisture, about 3% at a RH of 50%.

- The wetting kinetics map how fast charcoal is wetted after contact with liquid water. An example of the wetting kinetics of charcoal is given in Figure 9 from our wetting experiment. Experimental details are given in the supplementary material. These wetting curves are dependent to some extent on the piece's caliber.

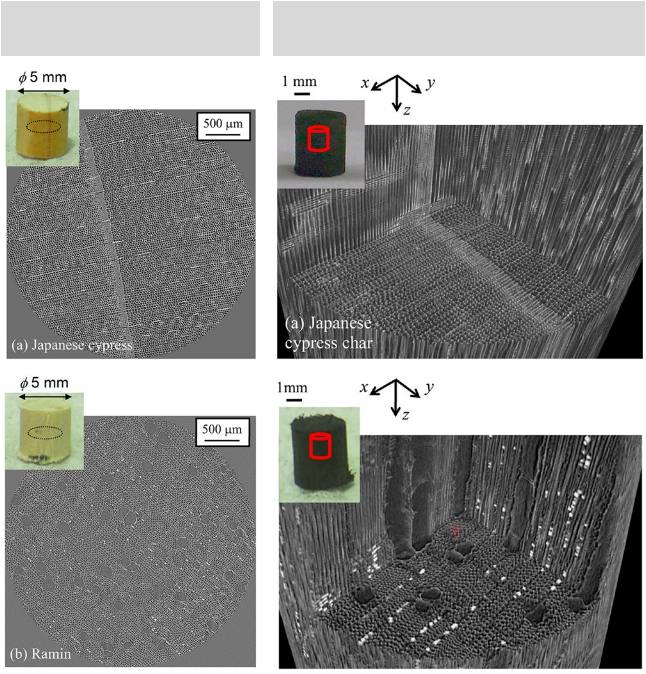

Figure 7. 2D X-ray CT images of raw Japanese cypress and Ramin wood (left). 3D X-ray computed tomography images of charcoal made out of Japanese cypress and Ramin wood (right) (Watanabe, 2018).

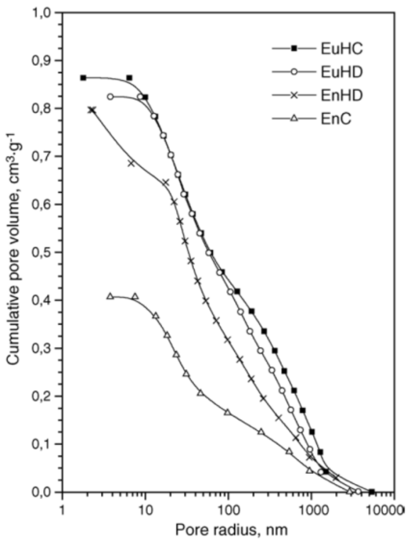

Figure 8. Pore size distribution of different wood charcoal made from oak (EnHD, EnC) and eucalyptus wood (EuHC, EuHD), as determined from mercury porosimetry (Pastor-Villegas et al., 2006).

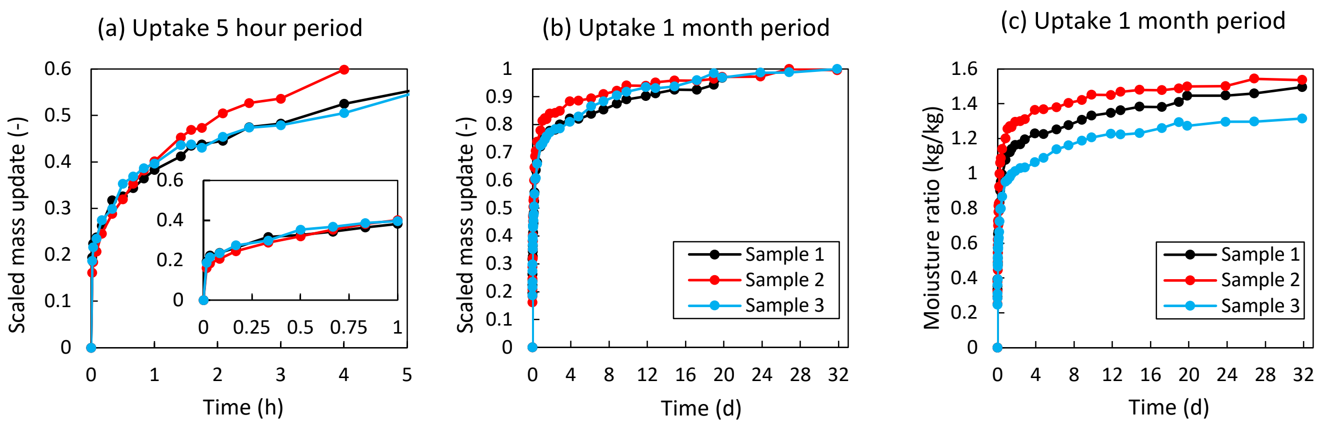

Figure 9. Moisture uptake in three charcoal samples as a function of time, scaled with the final moisture uptake after one month (a-b) and scaled with the initial mass of the sample (c). Three different time windows are depicted (a-c).

From the material properties of charcoal, we can conclude the following:

- Charcoal has a very fine pore structure, where 50% of the pores are below about 60 nm for the charcoal considered in Figure 8.
- The open porosity of charcoal is very high. The values reported in Table 1 are measured from water saturation. In addition to that, an additional amount of pores is closed.
- Charcoal is hygroscopic as it contains a considerable amount of adsorbed water in ambient conditions (e.g., 5.6% in this study). The small pore sizes also suggest hygroscopic behavior.
- Charcoal wets very fast, where about 20-30% of the saturated moisture content is taken up in the first minutes (Figure 9a). This fast wetting also implies that charcoal takes up about 1/3 of its initial weight in water at this time. Afterward, charcoal takes up water for several days before being saturated. The wetting kinetics will depend mainly on the size of the charcoal pieces. Thereby the obtained curves are very case-specific (Figure 9).
- When saturated ($\rho_{PM,sat}$), charcoal holds more water (w_{PM} = 650 kg m_{PM}^{-3}) as its initial dry weight (w_s = 450 kg m_{PM}^{-3}). The density of saturated charcoal is about 1050 kg m^{-3}, similar to that of water. Dry charcoal floats in water, but saturated charcoal and the charcoal blanket likely sinks. In practice, such a high saturation level will not be reached for the charcoal blanket since wetting for extended periods is required.
- Dry charcoal has a low thermal inertia (or thermal effusivity). It is over ten times smaller than water. This inertia implies that the blanket responds fast to temperature changes, so the charcoal blanket cools down quickly and heats up rather rapidly. However, the absorbed water inside the charcoal will add thermal inertia, which will slow down temperature response.
- Charcoal has a low bulk density. As such, the charcoal blanket will also be relatively light. For our experiments (section 4.3), a charcoal blanket (1 m^2) had a dry weight of 5.6 kg for a compartment size of 0.12 m and a resulting thickness of 0.075 m. As such, the surface or area density was only 5.6 kg m^2.

3.2 Structural stability

The compartments in the charcoal blanket possess specific structural stability to bend in the x or z-direction (Figure 3). The reason is the substantial moment of inertia of the elliptical compartment in the x-z plane. Also, the composite structure of the blanket provides a specific stiffness. The stiffness comes from the charcoal material itself, the filling that creates tension within the burlap, and the sharp-edged charcoal pieces that interlock. The compartmentalized charcoal blanket, composed out of different columns of charcoal pieces, can be made self-supporting, mainly when adding a few poles, such as in a silo (Figure 6). The primary failure mode will occur due to self-buckling under the weight of the walls.

The resistance to buckling under self-weight was estimated theoretically in the supplementary material. We found that a two-meter-high self-supporting structure can be created with the charcoal blanket that does not buckle under self-weight. This is the case if the E-modulus of the charcoal-filled compartments exceeds 9.6 MPa or 0.0096 GPa.

This E-modulus of 9.6 MPa is very low and in the range of rubbers or polymer foams. As such, self-supporting silos can be easily created. This finding was also confirmed in part in the field and lab experiments, where self-supporting blankets of 0.4 m were made (section 4.3 - 4.4).

3.3 How well does the charcoal blanket cool in lab experiments?

To investigate the performance of the charcoal cooling blanket in a climatic chamber, we performed a cooling experiment. We cooled a ventilated box filled with 5 kg of apples, stored at controlled conditions (23°C, 40% RH). The experimental setup is detailed in the materials and methods section in the supplementary material. The results of the experiments are shown in Figure 10. Note that there is no air space between the box and the blanket in this experiment. All air needs to pass through the box, increasing the airflow resistance. Other designs of cool rooms (e.g., section 4.4) leave some space between the boxes and the charcoal cooler walls.

Concerning cooling, we observed that the air temperature inside the cooler and the temperature of the fruit inside markedly dropped by evaporative cooling. The blanket successfully cooled down the air and the fruit with about 5 °C below ambient in this moderately humid environment. In more dry and warm environmental conditions, this temperature drop will be even higher. We reached an air temperature in this 56 L cooler close to the wet-bulb temperature but two to three degrees above this theoretical limit for convective evaporation. The air temperature measured by the sensor placed a bit above the fruit was typically lower.

Concerning the humidity in the cooler, we find that it was markedly higher than in the climatic chamber. This humidity was within the ideal range (85-95%) to store several fresh produce.

Concerning the airflow impact, we see that without any forced convective airflow, a significant drop in temperature can be achieved already. This finding implies that the charcoal cooler works already under low airflow conditions. The efficiency of the evaporative cooler we obtained was about 60%. The efficiency is defined as the ratio of the temperature difference between the ambient air (23°C) and the temperature in the cooler (~17.5-18°C) over the temperature difference between the ambient air and the wet-bulb temperature of the ambient air (~14.9°C). This efficiency at this temperature drop is in line with previous charcoal cooling experiments (Ronoh et al., 2020). With additional **airflow**, the temperature reduced slightly more (Figure 10). However, the water in the cooler depleted faster at higher airflow rates. Once the water in the charcoal cooler was depleted, the temperature rose quickly, with a simultaneous drop in relative humidity. Too high airflow rates can thereby have a detrimental effect. With airflow, the air temperature distribution in the cooler became more uniform. The sensed air temperature values all became closer to one another, indicating better mixing.

We see the watering events appearing in the air temperature. The reason is that the added water was at 23 ºC. Since the cooler is at a lower temperature, we see a slight temperature rise. The available water will rarely be at the same temperature or colder than the air in the charcoal cooler in most practical settings. Otherwise, this water could be used directly for cooling the foods. In most cases, the water temperature is higher than the evaporative cooler. Therefore, it is strongly advised not to overwater any charcoal cooler, which makes the charcoal equilibrate fast to the water temperature. If then the water temperature is much higher than the environment inside the cooler, the charcoal material needs to be cooled down by evaporative cooling, which takes time.

This experiment shows the necessity for monitoring hygrothermal conditions to evaluate the performance of an evaporative cooler. Without sensing inside and outside the cooler, we do not know if the cooler is performing well and if the water is already depleted, among others.

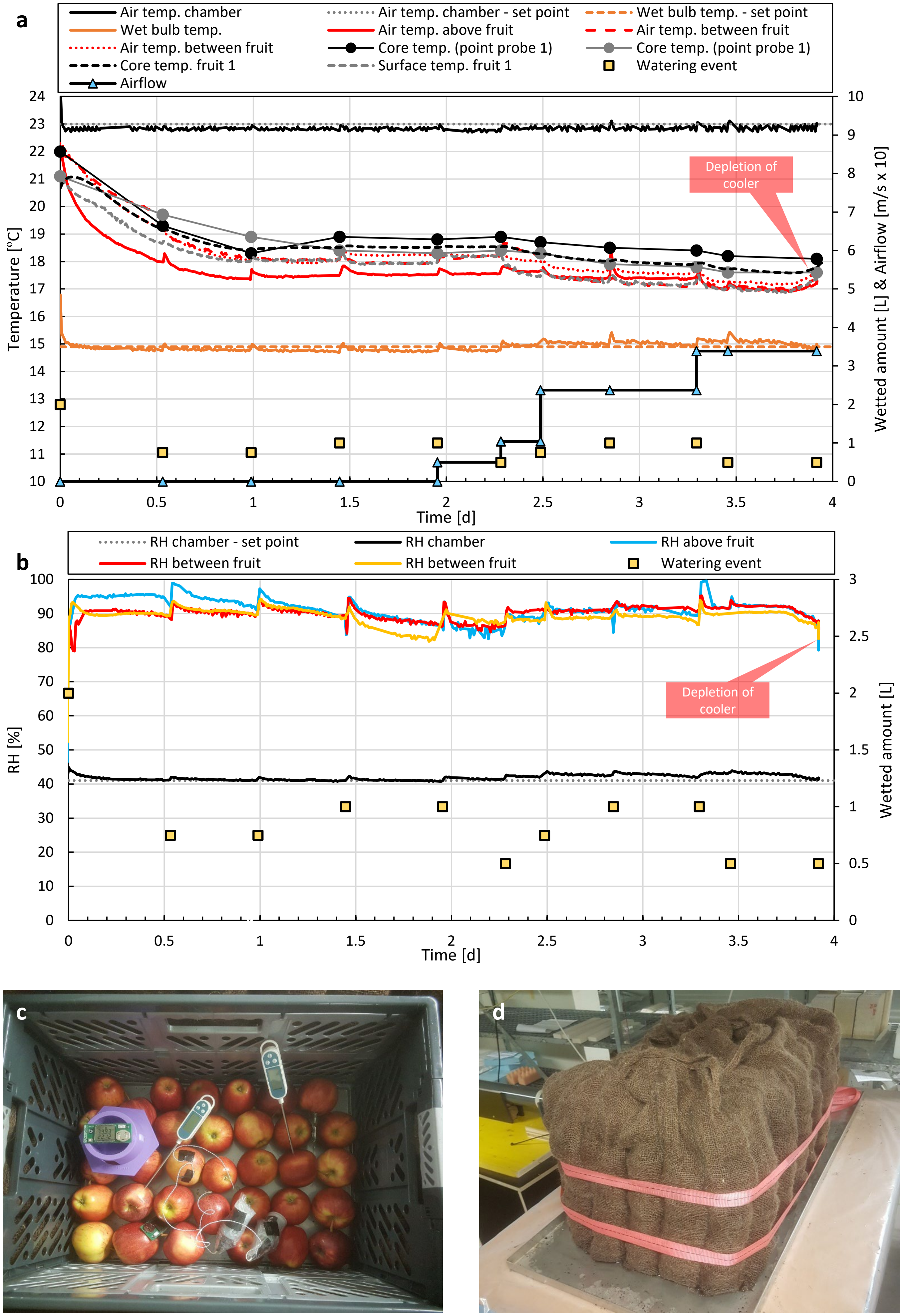
a
Air temp. chamber
Air temp. chamber - set point
Wet bulb temp. - set point
Wet bulb temp.
Air temp. above fruit
Air temp. between fruit
Air temp. between fruit
Core temp. (point probe 1)
Core temp. (point probe 1)
Core temp. fruit 1
Surface temp. fruit 1
Watering event
Airflow
Depletion of cooler
Temperature [°C]
Wetted amount [L] & Airflow [m/s x 10]
Time [d]
b
RH chamber - set point
RH chamber
RH above fruit
RH between fruit
RH between fruit
Watering event
Depletion of cooler
RH [%]
Wetted amount [L]
Time [d]
c
d

Figure 10. Laboratory-scale charcoal cooler: (a) Plot of air temperature above and in between the fruit as well as in the climatic chamber, fruit temperature, wet bulb temperature, airspeed, and watering events as a function of time; (b) Plot of relative humidity, and watering events as a function of time; (c) Top-view of the laboratory-scale setup of the crate of fruit that was cooled with the charcoal blanket; (d) Charcoal blanket wrapped around the crate of fruit.

3.4 How well does the charcoal blanket cool in field experiments?

In a field experiment, we upscaled the charcoal cooling blanket to a medium-sized cooler (1 x 1.5 x 0.4 m so 0.6 m^3 or 600 L). This cooler can cool about 8-12 crates of fruit, that were used in the lab experiments. The cooler was not entirely filled with fruit. One reason is that this experiment aimed primarily to identify the cooling potential of the charcoal blanket in field conditions. We did not aim to quantify how long it would take to cool down an entire batch of fruit in the cooler, which could take several days. Secondly, evaporative coolers are often not filled fully with warm fruit at once. Additional boxes are placed periodically within the cooler, between the already cold fruit, depending on the harvest. So in practice, also no precooling of large quantities is required. A 56 L crate with 5 kg apples was stored in our experiment before the initial watering. The air temperature inside the cooler was measured continuously (Figure 11). A detailed description of the experimental setup is given in the supplementary material). The cooler was tested in early autumn in Europe under relatively cold temperatures and high humidities (September, St. Gallen, Switzerland). These prevalent weather conditions were not optimal for achieving the highest temperature reduction in the evaporative cooler. The results are shown in Figure 11 for the second and third day of cooling. The first day was used to start up the cooling procedure.

During the day, the temperature inside the cooler was a few degrees below the outside temperature (Figure 11a-b). Furthermore, it can be observed that the relative humidity inside the cooler was mainly maintained over 90% (Figure 11c-d). The cooling efficiency was the highest around noon, so between 2-4 h after the first watering event (Figure 11f). However, this efficiency decreased towards the end of the day, where the external conditions also got cooler and more humid. In conclusion, we see that the prevalent weather conditions highly influence the conditions inside the cooler. For warmer and dryer climates, the temperature depression that is achieved with the evaporative cooler will be larger.

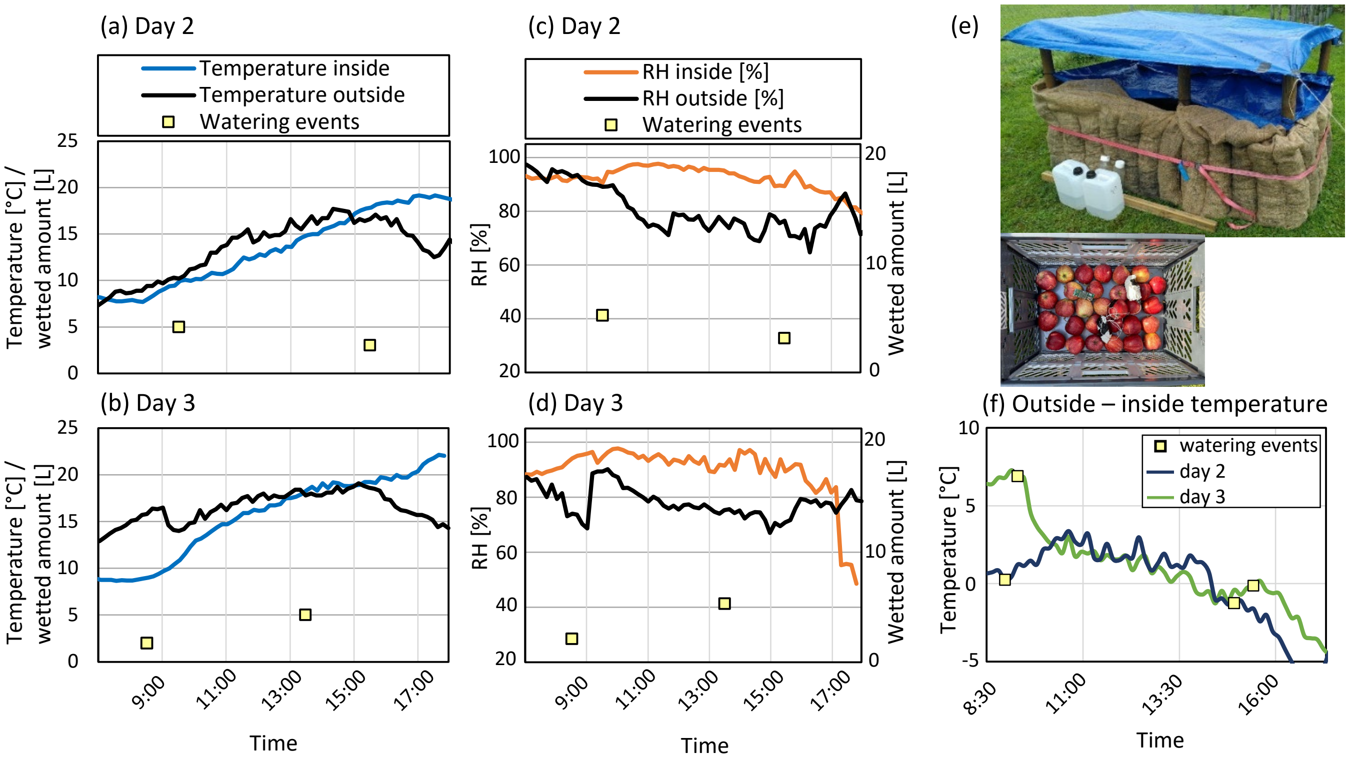

Figure 11. Field-scale charcoal cooler: (a-b) Monitored air temperature (inside and outside the cooler) and amount of water used for wetting the blanket as a function of time; (c-d) Relative humidity (inside and outside) and wetted amount of water; (e) Experimental setup; (f) Difference of cooler outside and inside air temperature.

3.5 What is the environmental impact of a charcoal blanket?

We determined the climate-change-related impact of the charcoal blanket and its components. We quantify this impact in kilograms of CO_2-equivalents per square meter of the charcoal blanket. We also calculated the total impact of operating a cooling room built with the charcoal blanket (33 m^3). We compared it to a commercial refrigerated cold storage unit (33 m^3), equivalent to a 20-foot container. Smallholder farmers often use such micro-scale cold storage facilities in remote regions (Alammar et al., 2020; Ambuko et al., 2018; Freecold, 2022). We compare coolers with a similar size as they have the same capacity to store fruit. The environmental impact assessment is detailed in the supplementary material.

The materials used in the charcoal cooling blanket have a lower environmental impact than those used in the commercial cooler. A charcoal blanket of 120 mm thickness has an environmental impact of 15 kg CO_2-eq/m^2, which is ~30% lower than the environmental impact of a 120 mm thick polyurethane (PUR) foam for a commercial refrigeration unit. The environmental impact of constructing a charcoal blanket cooler room (as in Figure 6c), equivalent to a 20-foot container (33 m^3), is about 3 times lower than building a commercial refrigerated unit of the same size. The charcoal blanket cooler room is more "simple" and less complex to construct than a commercial refrigerated unit. It is just made of a combination of charcoal, jute, and wooden supports. Compared to a commercial refrigerated unit, it does not need mechanical intervention in its construction. Furthermore, when storing fruit for two weeks, the environmental impact of cooling down 1 ton of fruits in the charcoal blanket cooler room and keeping it cool is 200 times lower than that of the commercial refrigerated unit.

In summary, the charcoal blanket is more environmentally-friendly in construction and operation compared to a small refrigerated cold store. Note, however, that an active refrigerated cold store cools down food faster and will maintain the food at rather constant temperature and humidity levels. With the charcoal cooler, the air temperature inside the cooler will be dependent on the environmental conditions and will vary throughout the day. As such, active coolers will likely preserve food better and induce less food loss. We did not consider the environmental impact of food loss in our calculation so far.

3.6 What does it take to ship a full charcoal blanket cooler room?

A key advantage of the charcoal blanket is its limited size and weight when the blanket is not filled with charcoal. This trait makes the unfilled blanket easy to transport. In that way, these blankets – so actually entire charcoal cooling rooms – can be quickly produced centrally or nationally. Once assembled, this lightest component of the charcoal blanket can be shipped. Afterward, it is filled on-site with charcoal sourced locally by the users. As an example, a rectangular charcoal cooling room (2 x 1 x 0.8 m) with a capacity of 1.6 m^3 will only require a charcoal blanket (180 g m^{-2}) with a weight of about 2 to 2.5 kg. Delivery drones can even carry such packages to remote areas (Jung and Kim, 2021).

4 What is a viable business solution for deployment and scalability?

Digitalization and innovative business models can be leveraged to facilitate the adoption of this evaporative cooling technology. The reduction in food loss for the smallholder farmers, enabled by the charcoal cooler, translates into an increase in income. Therefore, this solution provides an added value to these farmers, which can be monetized with a sustainable business model to enable the scale-up of its adoption and thereby its impact. For example, farmers can pay a small fixed or pay-per-use service fee over an extended period when using larger evaporative coolers. The fee can always be set to be lower than the income gains generated from the reduction in food loss.

With digitalization, remote guidance can also be provided for the users to assemble the charcoal blanket cooler room. In addition, connecting IoT-enabled sensors provides services such as shelf-life prediction and notifications to ensure proper maintenance and operation, such as periodic watering. Sensors and data analysis also make it possible to monitor the cooling process and cooler's effectiveness and provide feedback for improving its design. The user interface to these digital services can be a mobile application. Some features offered by such a solution could include:

1. Collecting user inputs that describe the requirements based on which the feasibility of the charcoal blanket cooler room is assessed. Examples of inputs include the type and volume of the crop to be stored, the available area to build the cooler, local weather conditions, and availability of water and charcoal. A tailored design is then computed for the user, who receives information on the estimated increase in shelf life and reduction in food loss.
2. Enabling users to edit the suggested design of the cooler room (such as size), and to select or unselect additional features such as sensors for temperature and humidity monitoring.
3. Providing a list of materials required.
4. Enabling users to order all or part of the materials and collect payment. Pay-per-use or monthly fees instead of upfront payments can be enabled. Appropriate repayment incentive mechanisms will need to be designed to enable this functionality.
5. Providing tracking of the shipment.
6. Providing step-by-step instructions on how to assemble the cooler room, including sensor set-up, preferably with videos.
7. Providing instructions and notifications for the cold room operation, such as watering requirements.
8. Acting as a digital inventory for an overview of the crops stored in the room.
9. Reading hygrothermal sensor data and providing estimated shelf life of the fresh produce in the room.
10. Feeding data to the cloud to monitor the deployment of the technology worldwide, and to monitor shelf life gains. These data enable us to assess the overall performance of the cooling blankets.

5 Outlook

The concept of a charcoal-blanket evaporative cooler was put forward in this study. We give an outlook on which aspects should be considered as the following steps to deploy this concept further.

Concerning the design of the blanket, optimization is advised. We need a parametric study on the impact of the cooler's thickness and the charcoal pieces' size on the cooling performance. Smaller pieces obtained from crushing larger pieces will have a much higher surface area for water absorption. They will, however, induce a higher pressure resistance for the airflow to flow through the cooler. As a result, a tradeoff likely exists between reducing the airflow through the cooler and increasing the evaporative capacity.

Concerning operating the cooler, additional features can be implemented. Piping with a dripping pipe could avoid manual watering and likely enable a more stable cooler operation. In addition, continuous watering will also reduce the water loss we observed during periodic watering in the field experiments. Also, pumps for water supply have been installed in evaporative coolers (Figure 2). Installation of a fan can increase the evaporation rate and thus the cooling efficiency. Such fans have already been installed in several evaporative coolers to promote airflow and optimize their evaporative performance (Mogaji et al., 2013; Ogbuagu et al., 2016; Korir et al., 2017; Getinet, Seyoum, & Woldetsadik, 2008; Samira et al., 2013). However, these additional materials will increase the carbon footprint of the charcoal blanket cooler.

Concerning the materials that are used for the blanket, alternatives are possible. Polypropylene is a major competitor of burlap and is superior in terms of durability. It is, however, not biodegradable. More biodegradable materials might also serve as alternatives, such as PLA (polylactic acid). Alternatives to charcoal could be any type of evaporative cooling material (Doğramacı and Aydın, 2020). Important here is that the structure remains permeable for airflow through the blanket. Minimal ventilation is essential to ensure a sufficiently high evaporation rate. The use of other charcoal-based materials, such as charcoal briquettes or activated carbon, is less suitable due to availability and higher cost.

Concerning operating the evaporative charcoal cooler, we are stressing the need to monitor the hygrothermal conditions inside the cooler. These conditions are the air temperature and the relative humidity in the air. These data are essential to evaluate the performance of an evaporative cooler, especially given that day-night cycling is taking place. Moreover, since the cooler is exposed to different conditions each day, the amount of water it needs for cooling and the cooling efficiency differ. Robust sensors for measuring hygrothermal conditions are cheap nowadays and can be bought under 20 USD. Nevertheless, very few evaporative coolers are equipped with such sensors to our knowledge. Apart from monitoring the cooler's performance, such data also gives the operators a better sense of how the cooler is working. A considerable danger exists when the cooler is not optimally working. Underperformance can induce a loss of trust by the farmers operating it if the coolers do not preserve the food well. Even though the concept of evaporative cooling is proven, malfunctioning coolers can thus slow down their deployment.

Furthermore, monitoring the fresh food temperature is also advised. The reason is that there is a significant delay of the food temperature changes, compared to the air temperature inside the cooler, due to the thermal inertia of the food. Many temperature variations are inherently present during evaporative cooling, e.g., day-night cycling. Thereby, the air temperature will not represent the food pulp temperature. Pulp temperature monitoring thus provides complementary data. As an alternative, the hygrothermal sensor data of the air could be combined with physics-based modeling to build a digital twin of the food in the cooler (Defraeye et al., 2019; Shoji et al., 2022). These twins can translate the air temperature sensor data into pulp temperature using a virtual sensor. The digital twins can also calculate the remaining shelf life.

Concerning the design of cold storage rooms with a blanket, we should make sure that we do not waste the cold air. In the cold room configuration, a part of the air that is cooled by the evaporative cooling walls does not come in direct contact with the fruit before leaving the cold room. This is the case if the cold room is not filled. Also, one could install the blanket on only a few walls since the primary cooling comes from the blanket's windward, upstream part. The leeward, downstream part of the blanket will not affect the air temperature significantly. If wind directions often change, it is advised to have a blanket on all sides.

We could build on our concept of the compartmentalized evaporative cooler to develop **similar concepts**. Such ideas could rely on the same principle that light compartments (1) are filled on-site with a locally-sourced material; (2) have a self-supporting role and keep the structure upright; and (3) provide some thermal inertia to dampen out fluctuations in air temperature. One idea is an alternative system to a commonly-known brick cooler. In brick coolers, two brick walls are used to hold a layer of sand in between. The sand is wetted, then evaporates, and cools the cooler. The brick mainly provides a structure to keep the sand together, similar to a Zeer pot. As an alternative, bags made out of burlap could be filled with sand. These bags can be stacked on top of one another to make up the walls of a 'sandbag' cooler (Figure 12). No bricks are needed as the sandbags take up the structural function. The design is similar to a sandbag bunker used to mitigate floods. An advantage is that sandbags need to be transported and filled locally with sand. This design could be much more sustainable and cheaper than a brick cooler, as bricks have a higher environmental impact and are more costly to produce. This is also a very modular and scalable system, so it can be made in any size. However, this concept would need to be tested and benchmarked to a brick cooler.

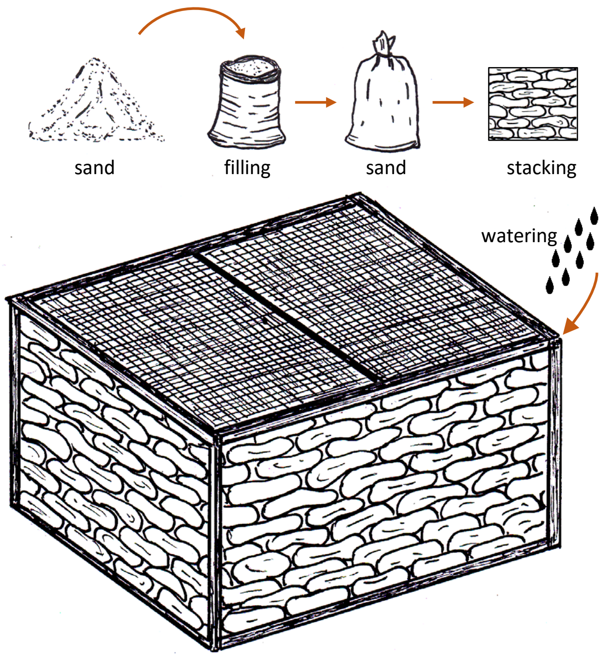

Figure 12. Sandbag cooler concept and the construction steps.

6 Conclusions

We proposed and tested a new concept of an evaporative cooler, namely a charcoal blanket. This concept aims to catalyze the currently lagging deployment of sustainable evaporative coolers for smallholder and marginal farmers or single-family households. Our proposed cooler lowers the expertise to construct and operate it and reduces the cost for small-scale cooling facilities. Our SWOT analysis showed that a key strength is a flexibility in size and materials. The blanket can be made in any size, from locally-sourced materials, namely charcoal and a biodegradable textile, such as burlap. Since the blanket's cost scales down quasilinear with the length or height, it becomes affordable for many individual farmers or single-family households in rural, peri-urban or urban areas. Compartmentalization of the blanket makes the blanket semi-self-supporting. Thereby, it reduces the need for additional supporting structures. The blanket can be the key structural component for building a cold storage room. Apart from longer-term cold storage, the blanket is deployable for intermediate on-farm storage, cooling during transport by truck, or cooling at the local markets.

Our lab and field experiments proved that the blanket successfully cools down the air and the fruit close to the wet-bulb temperature, thus slowing down food decay. The air and the fruit temperature could be cooled by 5 °C below ambient in a moderately humid environment. We reached a temperature in a 56 L cooler that was close to the wet-bulb temperature, namely below 2-3°C. At the same time, the blanket increased the humidity in the cooler to 85-95%, inhibiting wilting. We found that users should especially take care not to overwater the charcoal cooler. Since the water used is often warmer than the cooler walls, excessive watering will 'thermally reset' the cooler to a higher temperature. The charcoal cooling blanket materials have a low environmental impact, namely 3 times lower than constructing a commercial cold storage room of similar size. The carbon footprint of the blanket is 15 kg CO_2-eq/m^2. When storing fruit for two weeks, the environmental impact of operating a charcoal cooling blanket is 200 times lower than a commercial refrigeration unit.

The concept is now ready to be implemented in a full-scale pilot. In contrast to our field experiments in Europe, it would be advised to test the cooler in a drier and warmer climate. However, further optimization is required to reduce the threshold for dissemination in remote and underserved farmer communities. An essential component of the deployment of evaporative coolers is to monitor the hygrothermal conditions inside the cooler. The reason is that the performance of evaporative coolers is strongly dependent on the daily-varying environmental conditions. Guaranteeing a good performance in food quality preservation is only possible when we know the hygrothermal conditions to which the fresh food is subjected.

Nevertheless, very few evaporative coolers are equipped with such sensors to our knowledge, especially in smaller units. Apart from monitoring the cooler's performance, such data also gives the operators a better sense of how the cooler is working. Closely monitoring to guarantee an optimal performance is essential for the farmers to trust the added value evaporative coolers bring. In the next step, translating these sensor data into actionable metrics, such as the remaining shelf life of the food, removes the need for these stakeholders to have sufficient expertise to interpret the data.

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AUTHOR CONTRIBUTIONS

T.D. conceptualized the study and acquired funding; T.D. did the project administration; T.D. performed the investigation, developed the methodology; T.D., S.S., C.S executed the experiments with key input from D.O.; D.O. critically reviewed past literature and performed carbon footprint analysis together with E.C.; T.M. developed the business model innovation and digitalization concept for deployment and scalability; T.D. wrote the original draft of the paper; T.D., S.S. and K.U. did the visualization; D.O., S.S., K.S., E.C., T.M., K.U. and CS performed critical review and editing.

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