EVALUATION

EVAPORATIVE COOLING TECHNOLOGIES FOR IMPROVED VEGETABLE STORAGE IN MALI

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Full Report
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MIT D-Lab works with people around the world to develop and advance collaborative approaches and practical solutions to global poverty challenges. The program's mission is pursued through interdisciplinary courses, research in collaboration with global partners, technology development, and community initiatives — all of which emphasize experiential learning, community-led development, and scalability. This research was made possible in part through support from Malcom B. Strandberg.

D-Lab led the research design, development of the sensors and the survey instruments, data analysis, and preparation of the report and other outputs.

World Vegetable Center

The World Vegetable Center, an international nonprofit research and development institute, is committed to alleviating poverty and malnutrition in the developing world through the increased production and consumption of nutritious and health-promoting vegetables. The World Vegetable Center helps farmers increase vegetable harvests, raise incomes in poor rural and urban households, create jobs, and provide healthier, more nutritious diets for families and communities.

The World Vegetable Center led the fieldwork, including the procurement and assembly of the evaporative cooling devices, selection of study participants, and data collection. The World Vegetable Center also contributed to the research design, data analysis, and preparation of the report.

MIT | CITE Comprehensive Initiative on Technology Evaluation

The Comprehensive Initiative on Technology Evaluation (CITE) at MIT is a program dedicated to developing methods for technology evaluation in global development. CITE is led by an interdisciplinary team, and draws upon diverse expertise to evaluate technologies and develop an understanding of what makes them successful in emerging markets. The methodologies developed by CITE were used as a foundation for the research design of this project.

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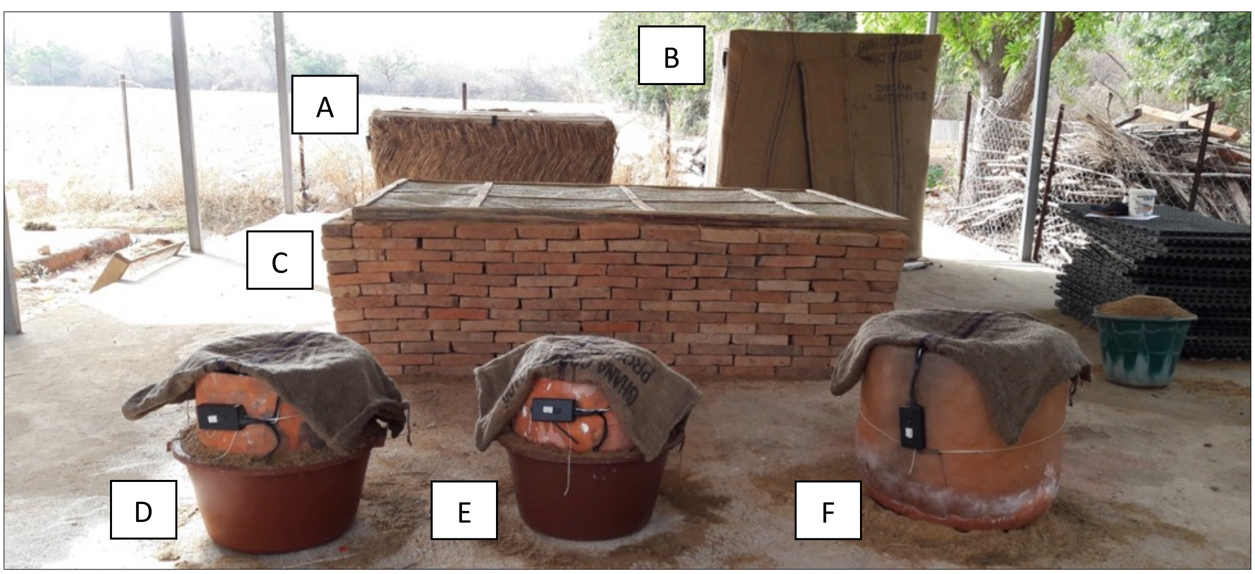
Executive Summary

Mali's horticulture sector plays a vital role in supporting the country's human nutrition and health, income generation for farmers, and poverty alleviation. A lack of affordable and effective post-harvest vegetable storage solutions often leads to vegetable spoilage, loss of income, reduced access to nutritious foods, and significant amounts of time spent traveling to purchase vegetables, particularly in rural communities. In Mali – and many other developing regions – these challenges are found where farming is the predominant source of income and food for populations who lack access to affordable methods for cooling and storage of vegetables and leafy greens.

The objective of this research study is to investigate the potential for non-electric evaporative cooling devices to address post-harvest vegetable storage challenges in rural Mali. The two classes of devices evaluated in this study are commonly known as "evaporative cooling chambers" (ECCs), which are generally used by horticulture cooperatives, and "clay pot coolers," which are generally used in households. These devices rely on the evaporation of water to create a cooling effect, and their performance is significantly affected by the ambient temperature and humidity of the environment in which they operate.

In this study, we used a combination of electronic sensors and structured user interviews to gather information about users' needs for improved post-harvest vegetable storage, current methods of post-harvest vegetable storage, and the performance of the evaporative cooling devices.



Above is an image of the three ECCs and three clay pot cooler devices included in this study: A) straw ECC, B) sack ECC, C) brick ECC, D) cylinder pot-in-dish, E) round pot-in-dish, and F) pot-in-pot.

Results

The results of this study indicate that low-cost evaporative cooling devices, such as clay pot coolers and ECCs, have the potential to benefit both off-grid populations with limited access to electricity and on-grid populations with high electricity and/or equipment costs for refrigerators. Evaporative cooling can improve vegetable storage shelf life by providing:

- A stable storage environment with low temperature and high humidity, which reduces water loss and spoilage in most vegetables
- Protection from animals and insects that contaminate and eat the vegetables

The improved storage environment can have positive impacts including reduced post-harvest losses, less time spent traveling to the market, increased availability of vegetables for consumption and monetary savings. These devices can also have farther-reaching impacts, particularly for women who could benefit economically from producing and selling clay pots.

Our comparison of three types of ECCs demonstrates that ECCs made of brick are superior to ECCs made of straw or burlap sacks. Brick ECCs provide a more stable low temperature and high humidity environment, are easier to refill with water, and provide protection from animals and insects. Due to these considerations, straw and sack ECCs are not recommended.

When comparing clay pot coolers, devices with the pot-in-pot configuration provided a greater temperature decrease than clay pot coolers with the pot-in-dish configuration. Both types of devices performed similarly on other metrics such as interior humidity, ease of watering, and protection from animals and insects. Ninety percent of those interviewed reported that they were no longer using any of their previous storage methods after receiving the clay pot coolers, indicating that the 50 liter capacity of the clay pot coolers used in this study is sufficient to meet the vegetable storage needs of most households. These results indicate that there are relatively loose design constraints for constructing a clay pot cooler that provides a basic level of performance, even if not optimized, creating an opportunity for locally available materials to be repurposed to create an effective clay pot cooler for vegetable cooling and storage.

Summary of key characteristics for each evaporative cooling device

Evaporative cooling device	Average temperature decrease*	Interior humidity range*	Minimum watering frequency	Protection from animals and insects	Storage volume	Cost
ECC (straw)	5.4 °C	30-50%	1-3 times per day	No	250-4000 L	$50 - $250
ECC (sack)	2.6 °C	10-30%	1-3 times per day	No	250-4000 L	$50 - $250
ECC (brick)	5.8 °C	80-100%	once per 1-7 days	Yes	500-5000 L	$70 - $350
Round pot-in-dish	5.1 °C	80-100%	once per day	Yes	10-150 L	$6 - $35
Cylinder pot-in-dish	4.7 °C	80-100%	once per day	Yes	10-150 L	$6 - $35
Pot-in-pot	6.7 °C	80-100%	once per day	Yes	10-100 L	$10 - $50

*For the data provided, the ambient relative humidity was less than 40% and the average daily ambient temperature was between 29 °C and 37 °C.

Recommendations

The most important first step for prospective users, producers, or promoters of ECCs and clay pot coolers is to consider the suitability of evaporative cooling devices for the specific context of interest by answering the question: *Does the technology have the potential to effectively meet the needs of the intended users?*

The following factors should be assessed to determine the suitability of evaporative cooling devices for a specific context:

- **Operating conditions:** Specific conditions are required for evaporative cooling devices to effectively operate: low humidity, high temperature, access to water, and a shady, well-ventilated location.
- **Need:** The storage conditions provided by evaporative cooling devices must meet the user's needs, and the need for improved vegetable storage must occur during times of the year when evaporative cooling devices can operate effectively.
- **Value:** The cost of the ECC or clay pot cooler must be affordable and justified by the benefits that will be realized due to the improved storage provided.

If evaporative cooling devices are deemed suitable for a given context, the key factors for increasing their use are awareness, availability, quality, and affordability in the specific region. If the devices can meet a community or region's vegetable cooling and storage needs, the following steps should be taken to increase their dissemination:

- Identify end users who could benefit from evaporative cooling technologies
- Raise awareness of the technology's benefits among prospective end users
- Increase availability of appropriately designed clay pots; organized production and distribution can increase availability, quality, and affordability

We have created an interactive "*Evaporative Cooling Decision Making Tool*" and an "*Evaporative Cooling Best Practices Guide*" to support the determination of ECCs and clay pot cooler suitability and the devices' proper construction and use. The intended audience for these resources includes government agencies, nongovernmental organizations, civil society organizations, and businesses that could produce, distribute, and/or promote ECCs or clay pot coolers.

These resources are available at: http://d-lab.mit.edu/resources/projects/evaporative-cooling

Introduction

In 2017, the MIT D-Lab Off-Grid Energy group, in partnership with the World Vegetable Center and the Comprehensive Initiative on Technology Evaluation (CITE), conducted an evaluation of low-cost technologies designed to improve the storage of vegetables through evaporative cooling. Most techniques for cooling and storing vegetables rely on electricity – which is lacking or unaffordable in most rural areas in Mali – limiting access to effective and affordable post-harvest storage options. Effective, affordable cooling and storage technologies have the potential to prevent food loss, increase access to fresh vegetables, and create opportunities for additional income generation in off-grid areas and where electricity is intermittent or prohibitively expensive. Because the evaporative cooling devices that are the subject of this study function without the use of electricity, they are well suited for regions without electricity access, or where electricity dependent cooling and storage technologies are not affordable.

The objective of this study is to evaluate a set of non-electric cooling and storage technologies – evaporative cooling chambers (ECCs) and clay pot coolers – for their suitability to meet the post-harvest storage needs of vegetable producers and consumers in rural Mali. The challenges faced by the horticulture sector in Mali are prevalent in many other developing regions where farming is the predominant source of income and food for populations who lack access to affordable electricity for proper cooling and storage of vegetables and leafy greens.

The Challenge

In Mali, the role horticulture sector is playing an increasingly critical role in human nutrition and income generation for farmers (Matsumoto-Izadifar, 2008). As malnutrition and poverty are prevalent in rural Mali (World Health Organization, 2018), minimizing vegetable spoilage following harvest is critical for improving health and livelihoods.

Vegetables are living, breathing parts of plants and contain 65% to 95% water (Gorny, 2001). Once vegetables are harvested, their nutrients and water reserves begin to decline, contributing to deterioration and rot. Deterioration of a vegetable starts from the moment it is harvested and lasts until it reaches the table of the consumer. Post-harvest losses – including mechanical damage, physiological, and biological deterioration – are affected by the handling, transportation, storage, and processing of the vegetables (Kumar, Basavaraja, & Mahajanshetti, 2006; Kader, 2005; Emana, et al., 2017). Storage conditions throughout the supply chain play an important role in preventing post-harvest losses for vegetables and leafy greens. While the optimal storage conditions vary for different vegetables and food products, many vegetables are best stored in a cool and humid environment (McGregor, 1989).

Deteriorating vegetables in need of improved storage: eggplants and tomatoes stored in a hanging metal dish (left), cabbages, eggplants, and peppers, and lettuce stored on a wet cloth (right).

While evaporative cooling post-harvest storage technologies have the potential to address these challenges, there are no systematic studies that look at product performance under real world usage conditions along with user behavior and feedback. This lack of information is a hindrance for increasing the dissemination of evaporative cooling technologies in regions where they may be able to provide improved post-harvest vegetable storage. This study looks to address this gap by providing:

- Quantitative information about the performance of evaporative cooling and storage devices, namely the temperature and humidity inside the devices as a function of ambient temperature and humidity, and the frequency of watering.
- Information on user behavior and perception of evaporative cooling devices for post-harvest vegetable storage
- Guidance on determining the suitability of evaporative cooling technology for a given context
- Recommendations for increasing the dissemination of evaporative cooling technologies in appropriate contexts

Audience for this Report

Increased availability of suitable cooling and storage technologies would allow vegetable producers, distributors, and consumers to improve vegetable shelf life, leading to reduced food loss, increased access to nutritious foods, and financial savings. The results of this evaluation will allow various stakeholders to determine if evaporative cooling technologies are a viable option for improving post-harvest vegetable shelf life based on a set of key considerations. These considerations include; availability and cost of materials to construct an evaporative cooling device; seasonal weather variations (temperature and humidity), access to water, the need for improved post-harvest storage, and vegetable post-harvest storage requirements.

The information presented in this report is of value to any organization or individual that may be interested in distributing and/or promoting these technologies to vegetable producers, distributors, and consumers who are looking for improved vegetable storage solutions. Examples include non-governmental organizations (NGOs) and government agencies that promote horticultural best practices or social enterprises and local businesses that may have an interest in producing and marketing vegetable storage technologies.

Left: Farmers in need of improved vegetable storage in Bankass, Mopti, Mali; Top right: World Vegetable Center staff discussing best practices with farmers in Finkolo, Sikasso, Mali; Bottom right: clay pots for sale on the roadside in Sikasso, Mali.

The results and discussion of this report are structured in the following way:

- The **Sensor Results** section of this report provides information on the interior storage conditions (temperature and humidity) that were achieved during field-testing of various types of ECCs and clay pot coolers as a function of ambient weather conditions and watering frequency.
- The **Interview Results** section provides insights into the user perception of the vegetable storage devices and the impact of the ECCs and clay pot coolers on the shelf life of common vegetables.
- The **Construction and Cost** section gives an overview of how to construct ECCs and clay pot coolers and associated costs.
- The **Conclusions and Recommendations** section provides an overview of the findings, the comparative advantages of each type of evaporative cooling device, their suitability based on various contextual factors, and a set of recommendations for disseminating these technologies in regions where they can provide benefits.

When using this report, it is important to consider the specific context, as each of the evaporative cooling technologies evaluated are not suitable for all contexts. Furthermore, local weather, access to water, and vegetable storage needs can have seasonal fluctuations, and evaporative cooling and storage technologies only provide significant benefits to users during times of the year when there is hot and dry weather; access to water; and need for improved post-harvest vegetable storage.

To support the dissemination of these technologies, we created the following resources for prospective users, producers, and promoters of evaporative cooling devices:

- **Evaporative Cooling Decision Making Tool:** An interactive Microsoft Excel-based decision making tool to help determine if evaporative cooling devices are suitable for a specific context, and to guide the calculation of potential financial savings: http://d-lab.mit.edu/resources/projects/Evaporative-Cooling-Decision-Making-Tool

- **Evaporative Cooling Best Practices Guide:** Key considerations for suitability and best practices for construction and usage of evaporative cooling devices: http://d-lab.mit.edu/resources/projects/Evaporative-Cooling-Best-Practices-Guide

Overview of the Technologies Evaluated

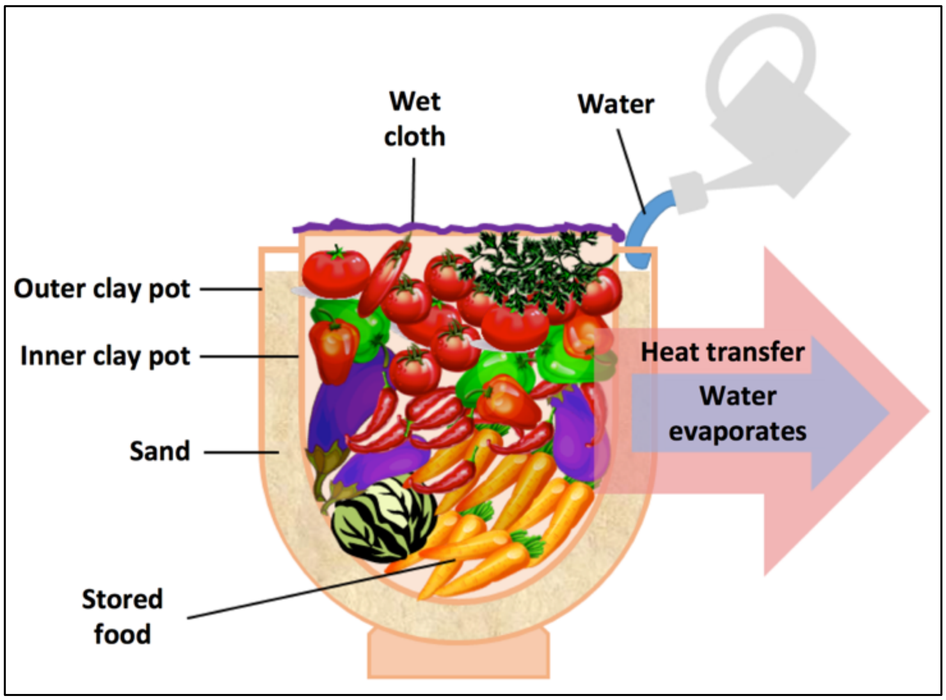
Two classes of non-electric cooling and storage technologies were evaluated in this study:

- Evaporative cooling chambers (ECCs) – also known as "zero energy cool chambers (ZECCs)"
- Clay pot coolers – also known as "Zeer pots"

Both of these technologies are currently being used in Mali, but have not gained widespread adoption, due in part to a lack of understanding of the contexts when they are suitable.

How evaporative cooling works

The ECC and clay pot cooler devices in this study function on the principle of direct evaporative cooling, where heat is removed as water evaporates from the surface of the storage device. The evaporative cooling effect causes a decrease in temperature and an increase in the relative humidity[1] inside the storage device, conditions that increase the shelf life of many vegetables (Kader, 2005). Water must be added at regular intervals to maintain the cooling effect. The watering frequency required can vary from several times a day to only a few times a week, depending on the storage device's material and design as well as the weather conditions.



Above: Diagram of a clay pot cooler with a pot-in-pot configuration, covered by a wet cloth.[2]

[1] All references to humidity in this report are referring to the relative humidity, not the absolute humidity

[2] Adapted from Peter Rinker, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=33444154, Accessed January 3, 2018

Background on ECCs

Straw ECC

Sack ECC

Brick ECC

Evaporative cooling chambers (ECCs) can be made from locally available materials including bricks, sand, wood, straw, gunny or burlap sack, and twine. Due to their relatively large size, ECCs are typically used by larger producers or community groups with up to 50 members. The World Vegetable Center's process for constructing a straw ECC begins with the frame of a box made of wooden planks. The bottom is covered with wooden planks, the four sides are then covered with locally available straw, and a straw mat is used to cover the top of the structure. Similarly, the sack ECC begins with the frame of a box made of wooden planks. The top, bottom, and three of the sides are partially covered with wooden planks, leaving one side opened to allow access to the interior. The box is then covered with gunny or burlap sacks. The brick ECC was originally developed in India by Susanta K. Roy and D.S. Khuridiya in the early 1980s (Roy & Khurdiya, 1982; Roy & Khurdiya, 1985) to address fruit and vegetable post-harvest losses, especially in rural areas without electricity. Roy and Khuridiya's ECC design is composed of a double brick wall structure, supported by a base layer of brick, and covered with a straw mat. The space in between the two brick walls is filled with sand, which retains the water that is added. Inside the ECC, food is placed in unsealed plastic containers, which keep the vegetables off the ECC's floor and allows them to breathe and be exposed to the cool, humid air inside the device. Additional images of ECCs are available in Figure 3 of the Appendix.

Background on Clay Pot Coolers

Clay pot coolers have been used for centuries to help farmers reduce food spoilage and waste, increase their income, and limit the health hazards of spoiled foods. Clay pot coolers are typically used at the household level due to their simple construction and relatively small size. The pot-in-pot design, commonly known as a "Zeer pot," was popularized in 1995 by Mohammed Bah Abba in Nigeria and is composed of two clay pots with the same shape but different sizes. One pot is placed inside the other (Longmone, 2003; Oluwasola, 2011) and the space between the two containers is filled with sand, which retains the water added. Food is placed inside the interior pot, and both pots are covered with a lid or a damp piece of cloth.

The pot-in-dish design is a variant of the clay pot cooler: a clay pot is placed on top of a plastic or metal dish filled with sand. Vendors of clay pots and community members in Mali reported use of the pot-in-dish configuration for vegetable storage during interviews conducted as part of background research for this research project. Because the pot-in-dish configuration is used in the study locations, it was included in the study to determine their performance relative to the more widely studied pot-in-pot configuration. To our knowledge, this is the first systematic study of the pot-in-dish configuration for a clay pot cooler. Additional images of clay pot coolers are available in Figure 4 of the Appendix.

Clay pot coolers

Round clay pot-in-plastic dish | Cylinder clay pot-in-plastic dish | Cylinder clay pot-in-clay pot

Previous Research Results

Several studies present findings indicating that the improved storage conditions provided by evaporative cooling devise led to improved vegetable quality – such as weight, color, firmness, and deterioration – resulting in extended shelf life. (Basediya, Samuel, & Beera, 2011; Ambuko, Wanjiru, Chemining'wa, Owino, & Eliakim, 2017). However, the rate of evaporation of water is highly dependent on the ambient humidity, resulting in a less significant reduction of the interior temperature when the ambient humidity is higher.

Because evaporative cooling devices do not require electricity to function, they have the potential to be particularly beneficial for users in areas with limited electricity access, as well as for those on-grid but for whom electricity costs are prohibitively high. Regardless of need and context, due to their low energy consumption and use of simple materials, devices such as ECCs and clay pot coolers are more environmentally friendly than refrigeration systems that use electricity that contributes to global warming.

Reports from multiple studies in India indicate that brick ECCs can provide temperature reductions of 10-15 °C when the ambient temperature is greater than 35 °C and the ambient relative humidity is less than 40% (Basediya, Samuel, & Beera, 2011; Kumar, Mathur, & Chaurasia, 2014). In a separate study, clay pot coolers demonstrated temperature reductions of 5-10 °C when the ambient temperature is greater than 40 °C and the ambient relative humidity is less than 30% (Morgan, 2009). Across all of the studies referenced, regardless of the ambient conditions, the brick ECCs and clay pot coolers were shown to maintain a relative humidity above 80% in the interior of the device where the vegetables are stored. The same principle of evaporative cooling has been used with other designs and materials such as with charcoal coolers (Rathi & Sharma, 1991; Noble, 2003) and devices that use synthetic materials to hold and allow for the evaporation of water (Kitinoja, 2016). Another design – commonly referred to as a janata cooler – consists of a metal or plastic container placed inside of a clay pot or dish, with a wet cloth covering any exposed surface of the inner container (Odesola & Onwuka, 2009; Roy & Khurdiya, 1985).

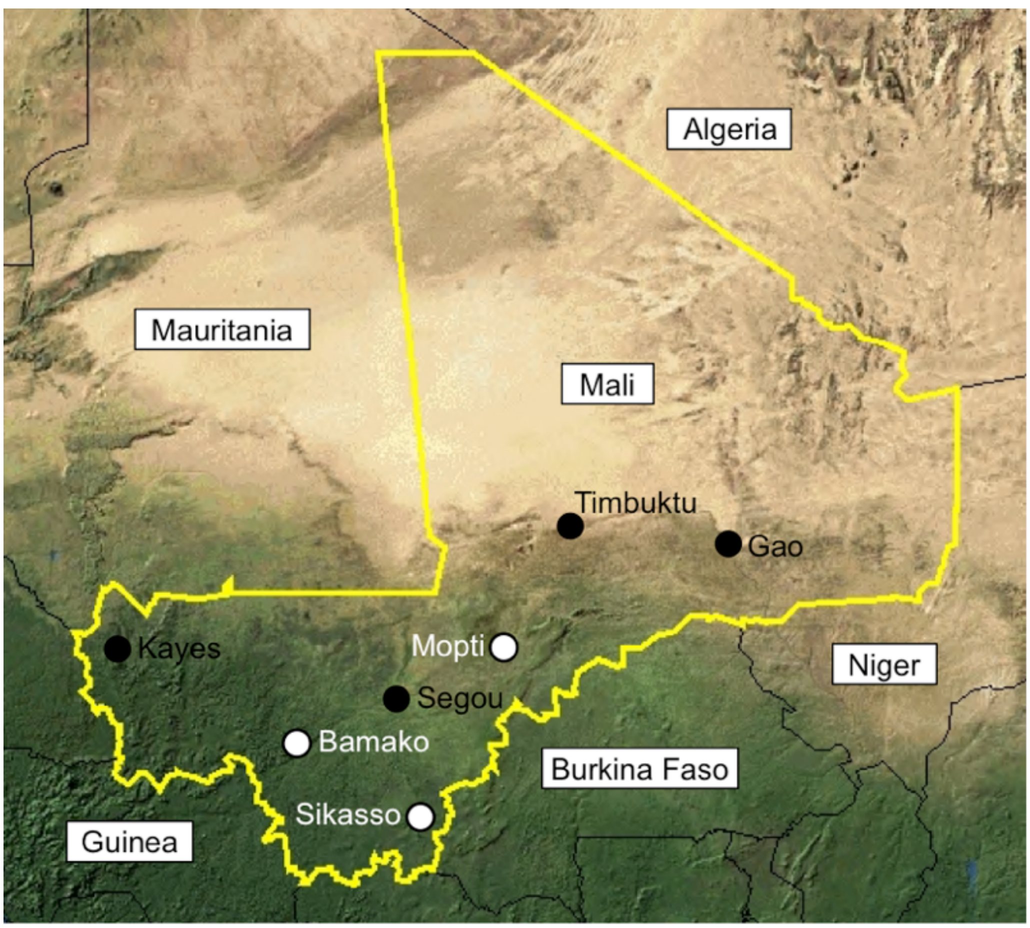
Improved vegetable storage is needed when the ambient temperature is greater and the humidity is lower than the ideal storage conditions for a specific vegetable. When assessing the potential benefits of a cooling and storage device for a given context, it is essential to consider how the storage conditions that can be achieved within the device compare to the conditions without the device. For example, the ideal storage conditions for tomatoes are between 18 °C and 22 °C with a humidity between 90% and 95%; if the ambient conditions present an average temperature of 35 °C and relative humidity of 20%, a storage device that provides conditions with an average temperature of 30 °C and greater than 80% humidity can provide a significant increase in shelf life for tomatoes (McGregor, 1989).

Study Design

The objective of this study is to evaluate a set of non-electric cooling and storage technologies for their suitability to improve the post-harvest storage of vegetables in rural Mali, to answer the question: *Does this technology effectively meet the needs of the intended users?*

Methodology and Data Collection

This study used a combination of electronic sensors and structured user interviews (with individuals and groups) to gather information about users' needs for improved post-harvest vegetable storage, current methods of post-harvest vegetable storage, and the performance of the evaporative cooling devices. The research was conducted over a period of 5 months, during February to July of 2017, in three regions of Mali: Mopti, Bamako, and Sikasso (see map below).



A satellite image of Mali (outlined in yellow). The locations where the study was conducted are labeled with white circles and white text[3]*.*

[3] Image of map adapted from: http://johan.lemarchand.free.fr/cartes/cartes-mali.html, Accessed March 3, 2018

Evaporative cooling devices evaluated in this study

The evaporative cooling devices included in this study were selected to include a range of designs constructed from locally available materials, and a variety of sizes chosen to meet a wide range of user needs. The ECCs included in the study were located at horticulture Best Practice Hubs[4] in Sikasso and Mopti, as well as research facilities in Bamako. The ECCs at the Best Practice Hubs were all installed prior to the beginning of this research study. The clay pot coolers were distributed to households in the Mopti region as well as to research facilities in Bamako. A list of vegetable cooling and storage devices included in the study can be found in Table 1 below.

Table 1: Evaporative cooling and storage devices evaluated in this study. The table below indicates the number of each cooling and storage device type and where it is located.

Evaporative cooling device	Region			Total
	Sikasso	Bamako	Mopti	
Straw ECC	4[a]	2[b]	2[a]	**8**
Sack ECC	4[a]	2[b]	2[a]	**8**
Brick ECC	1[a]	2[b]	2[a]	**5**
Round pot-in-dish	-	3[b]	17[c]	**20**
Cylinder pot-in-dish	-	3[b]	21[c]	**24**
Pot-in-pot	-	3[b]	29[c]	**32**
Totals	**9**	**15**	**73**	**97**

[a] Located at World Vegetable Center horticulture Best Practice Hubs (13 ECCs).
[b] Located at World Vegetable Center research facilities (6 ECCs and 9 clay pot coolers).
[c] Located at participant households (67 clay pot coolers).

[4] The World Vegetable Center operates Best Practice Hubs in Mali as a platform to bring research findings closer to farmers, help farmers express their opinions during validation of technologies, and facilitate dialogue between farmers, researchers, extension service providers, vegetable traders, and inputs suppliers.

Sampling

For both the ECC and clay pot cooler portions of the study, regions were selected that have limited or no electricity access and a need for improved vegetable storage. The evaporative cooling devices were used by study participants to either store vegetables that they produce themselves or for vegetables that were purchased for consumption. The study began in March 2017 during the dry season and continued through the beginning of the rainy season in July in order to monitor the performance of the ECCs throughout seasonal variations in temperate and humidity in each region (see Figure 2 the Appendix).

The ECC portion of the study took place across three regions of Mali (Sikasso, Bamako, and Mopti), which each have different climates. As you move north in the country, the temperature increases while relative humidity decreases. The specific sites within these regions (see Table 1 in the Appendix) were selected due to the presence of ECCs in operation at Best Practice Hubs or research facilities managed by the World Vegetable Center prior to this study. At the launch of the study, groups of 20-30 members of horticulture cooperatives associated with the Best Practice Hubs were convened for the researchers to provide overview of the ECCs and the goals of the study, as well as to gather background information on the community's vegetable storage needs. Based on recommendations from the World Vegetable Center staff, individuals from the horticulture cooperative who are well informed about vegetable production and post-harvest storage techniques were selected to be in charge of the operation and maintenance of the ECCs. At the end of the study period, a total of 21 horticulture cooperative members participated in the in-depth interviews.

The clay pot cooler portion of the study took place with households in the Mopti region and at research facilities in Bamako. Mopti was selected for the household portion of the study because it has the driest climate among the regions where World Vegetable Center has staff members and due to the proximity to artisans who manufacture clay pots that were used in the study. In order to sample a range of household profiles, we selected participants from three communities in the Bankass and Koro Cercles in the Mopti region:

- Tanoussagou, a rural farming village with no access to the electricity grid
- Ogotene, a peri-urban farming community with limited (< 30%) electricity grid access
- Bankass, a densely populated small city with high rates (> 85%) of grid electricity access

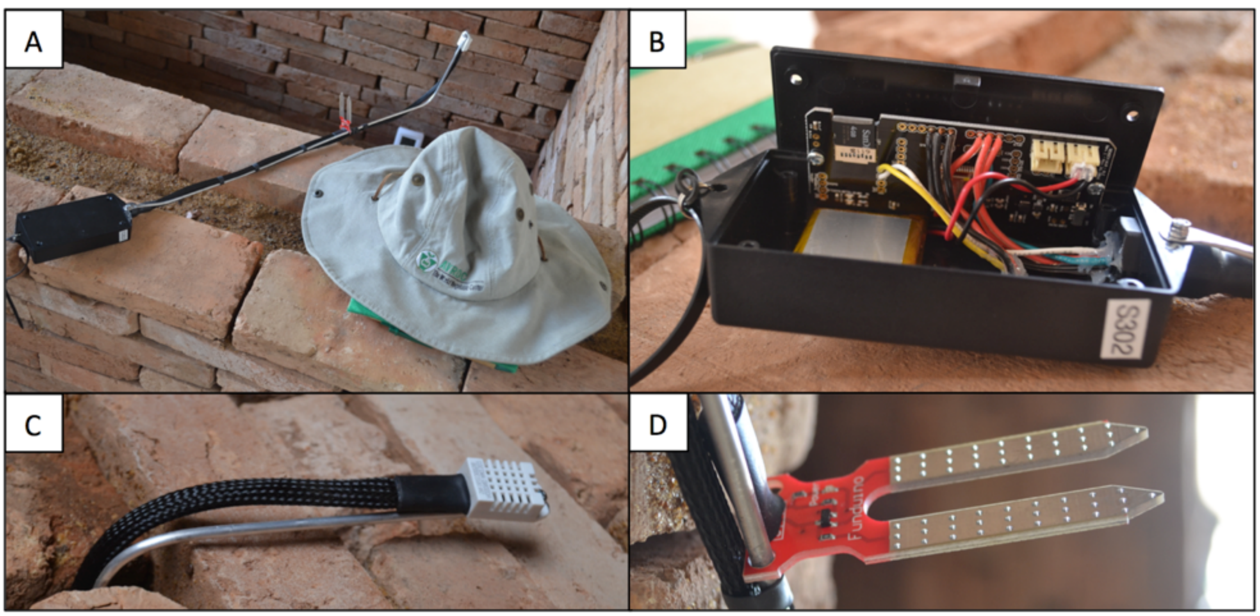
Within these communities, the 67 participants were selected using a random sampling approach.

Electronic Sensors

Electronic sensors installed on the ECCs and clay pot coolers monitored the following parameters:

- Exterior (ambient) temperature
- Exterior (ambient) relative humidity
- Interior temperature
- Interior relative humidity
- Sand moisture (only brick ECCs and clay pot coolers)

Data for each of the five parameters were recorded every five minutes for the 3 to 5 months of the study period. Technicians from the World Vegetable Center were trained on the installation and data retrieval for the electronic sensors designed for this study (see Figure 6 in the Appendix). Additional information on the sensors used for data collection can be found in Figure 7 of the Appendix.



A) A full sensor unit on top of a brick ECC; B) Interior of sensor control box with battery, Secure Digital (SD) card, and circuit board; C) Temperature and humidity sensor D) Moisture sensor.

User Interviews

Structured individual interviews were conducted with members of the 67 households that received clay pot coolers and group interviews with 21 members of the six community groups that had access to ECCs. The interviews were conducted after the participants had been using the evaporative cooling devices for a minimum of three months and explored:

- Need for cooling and storage technology
- Existing methods for vegetable cooling and storage
- Suitability of the cooling and storage technologies being evaluated for various vegetables (fruits and leaf vegetables)
- Usage of the evaporative cooling devices provided

The interview questionnaires and other data collection tools used for this study can be found in the Appendix.

Left: Interview with Mrs. Setou Mariko, the President of women's group in Bledougou, Sikasso; Right: Group interview with members of a farming cooperative in Bledougou, Sikasso

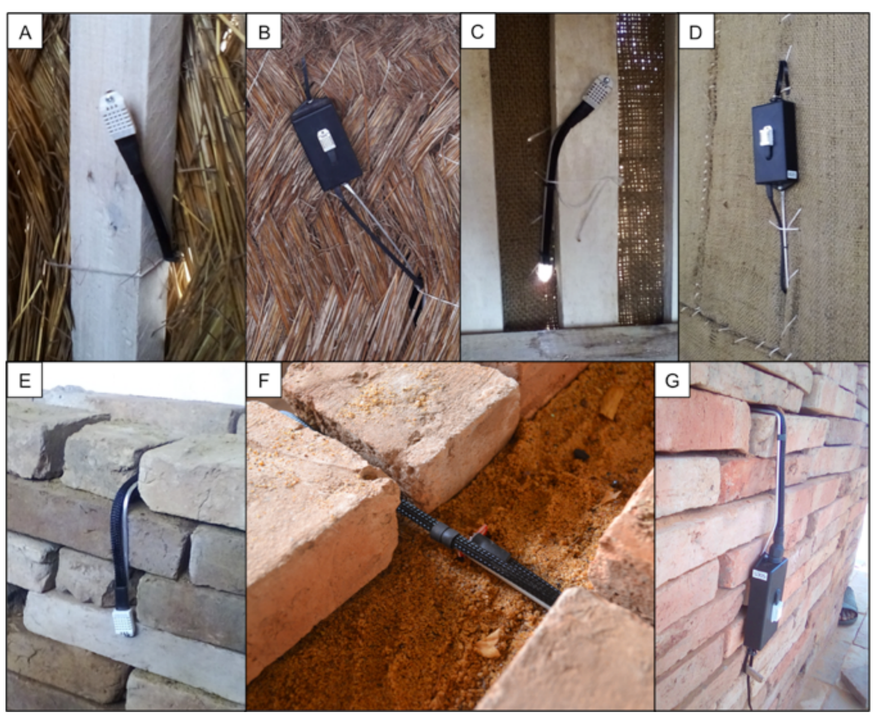
Sensor Results

The data collected from the sensors were used to determine the temperature and relative humidity changes in the interior of the ECCs and clay pot coolers as a function of ambient temperature and humidity, and the frequency of watering. Through the course of the study, 32% of the sensors stopped collecting data due to leakage of water into the control box. Despite these challenges, data was collected on the 21 ECCs for an average of 114 days and on the 76 clay pot coolers for an average of 65 days.

Evaporative Cooling Chamber (ECC) Sensor Data

The sensors measured the performance of the ECCs over the study period during which time the weather conditions varied in each region due to seasonal changes. In Bamako and Sikasso data collection on the ECCs took place from February to July and in Mopti data collection on the ECCs and clay pot coolers took place from April until July. See Figure 2 in the Appendix for average ambient weather conditions during these months in each region. One sensor measuring the exterior (ambient) temperature and humidity was affixed to the outside of the control box, which was mounted on the exterior of the ECC. A second sensor measuring the interior temperature and humidity was located inside the ECC. This interior sensor was connected to the control box by a 50 cm aluminum rod and wiring, which passed through a small hole in the straw, sack, or brick wall of the ECCs. In the case of the brick ECC, a moisture sensor was placed in the sand layer between the two brick walls.

Images on the right:
A) straw ECC interior sensor
B) straw ECC exterior sensor
C) sack ECC interior sensor
D) sack ECC exterior sensor
E) brick ECC interior sensor
F) brick ECC moisture sensor
G) brick ECC exterior sensor



Additionally, at the Bamako (Sotuba and Samanko) research stations an additional sensor was placed at a separate location about five meters from any of the ECCs. This independent sensor was used to determine if the exterior temperature and humidity sensor on the ECC was impacted by the close proximity to the ECC. These results indicate that when the ECC was watered at least once per day, the exterior temperature recorded near the outside to the ECC was reduced by 0.5 to 2 °C. In the ECC performance results discussed in the following sections, the data for the ambient temperature was recorded from the independent sensors nearby to the ECCs.

ECC watering frequency

The ECCs in this study were located either at research facilities in Bamako or Best Practice Hubs in Mopti or Sikasso. One of the objectives of the study was to monitor the user behavior related to the frequency of adding water to the ECCs and clay pot coolers. We were able to identify instances when the user added water to the ECCs by observing sharp increases in relative humidity in the straw and sack ECCs, and through increases in the moisture of the sand for the brick ECCs. In this section, we describe the observed frequency of watering by the users, which has a significant impact on the interior temperature and humidity (discussed in the following sections).

The process of adding water to the brick ECCs is the least time consuming, taking less than five minutes. This process includes pouring water from a bucket in the area containing sand between the two brick walls, and sprinkling water onto the straw cover of the brick ECCs. Relatively little water is spilled during the process of watering the brick ECC. The watering of the straw and sack ECCs is more time consuming, as water needs to be splashed or sprayed into the sides and top of these ECCs. It can take between 10 and 20 minutes to fully wet the sides of the straw and sack ECCs and a significant amount of water is wasted, running off of the sides of these ECCs and spilling onto the floor. The sack ECC is particularly challenging, as the sack material does not easily absorb water when dry: the fibrous nature of the sack surface creates a hydrophobic surface and beading of water droplets is observed. Additionally, the height of the sack ECCs in this study require the user to stand on a stool or chair to reach the top of the sack ECC.

In Mopti and Sikasso, World Vegetable Center staff members frequently visit the Best Practice Hubs where the ECCs are located to work with community members on improving their horticulture practices. For this study, 1 to 3 individuals from the community were recruited to be responsible for watering and monitoring the ECCs. Participants were instructed to add water three times each day to the ECCs until the straw, sack, or sand between the bricks was completely wet. This allowed the evaporation of water to cool the ECCs throughout the day, even if no vegetables were being stored in the ECCs. Solar water pumps located nearby the ECCs provided reliable access to water throughout the year.

While the amount of water added to each ECC was not systematically measured, the following observations and user feedback were recorded. Out of the six Best Practice Hubs where ECCs are located, four regularly added water to the ECCs (at least once a day for a majority of study period), and two of the participating locations watered the ECCs less frequently. In Bamako, researchers consistently watered the ECCs 1 to 3 times per day throughout the study, with the exception of one three-week period during which the ECCs were intentionally not watered to investigate how the performance would change over time without watering. The impacts of variations in watering frequency are discussed in a later section.

ECC performance as a function of relative humidity with regular watering

The three types of ECCs (straw, sack, and brick) displayed notably different performance, particularly in relation to the performance immediately after watering. Figures 1 and 2 show the typical daily profile of the sensor data collected.

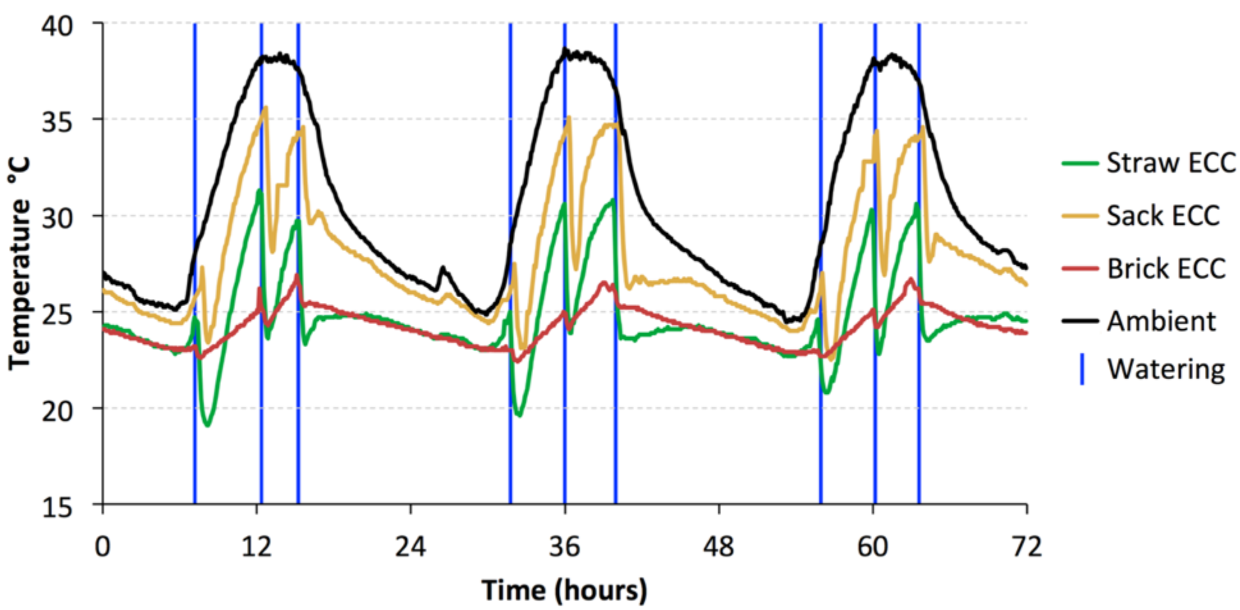


Figure 1: Typical internal daily temperature with watering for all three types of ECCs, and the ambient temperature measured by the independent sensor nearby to the ECCs is represented by the black line. A decrease in the temperature can be observed at the time of watering for each of the ECCs, indicated by the vertical blue lines.

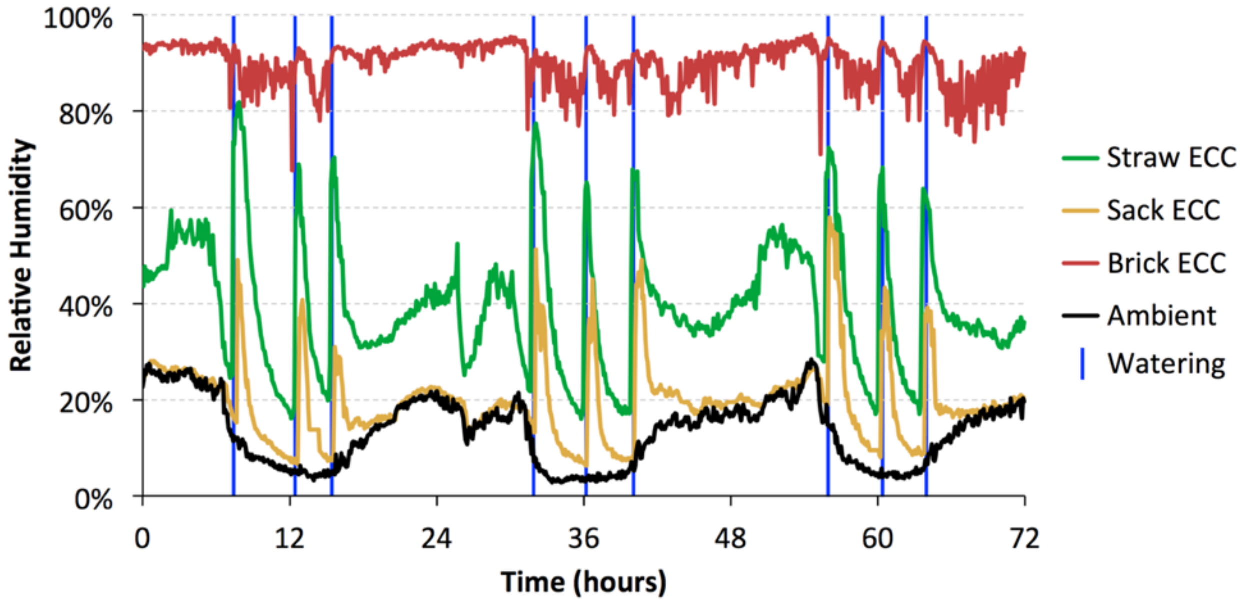


Figure 2: Typical daily relative humidity with watering for all three types of ECCs, and the ambient humidity measured from the independent sensor nearby to the ECCs is represented by the black line. An increase in the humidity can be observed at the time of watering for each of the ECCs, indicated by the vertical blue lines.

A decrease in the temperature can be clearly observed when water is added to the storage device for all three types of ECCs (see Figure 1). The effect is more pronounced for the straw and sack ECCs than for the brick ECC. For all of the ECCs, the cooling effect is more pronounced during the daytime when the temperature is the highest, the relative humidity is the lowest, and the watering is occurring. This has the effect of decreasing maximum temperature, when the vegetables are most susceptible to spoilage. When watered three times a day, all of the ECCs maintain an interior temperature that is lower than the ambient temperature throughout the day. Due to the large thermal mass of the thick brick and sand walls, the brick ECC shows the greatest stability in temperature, which is favorable for vegetable storage. Additionally, when watered regularly the relative humidity inside the brick ECC remains consistently above 70% throughout the day (see Figure 2). In contrast, the relative humidity inside the sack and straw ECCs decreases within a few hours, and sharply increases after each watering event.

The ambient relative humidity has a significant effect on the performance of the ECCs. At higher relative humidity the evaporation rate of water is decreased, which reduces the cooling effect. Figure 3 shows: 1) the decrease in the maximum daily temperature at the interior of the storage device compared to the ambient temperature and 2) the decrease in the average daily temperature at the interior of the storage device compared to the ambient temperature, as a function of the ambient relative humidity for each of the ECCs and clay pot coolers, both of which are important for increasing the shelf life of vegetables.

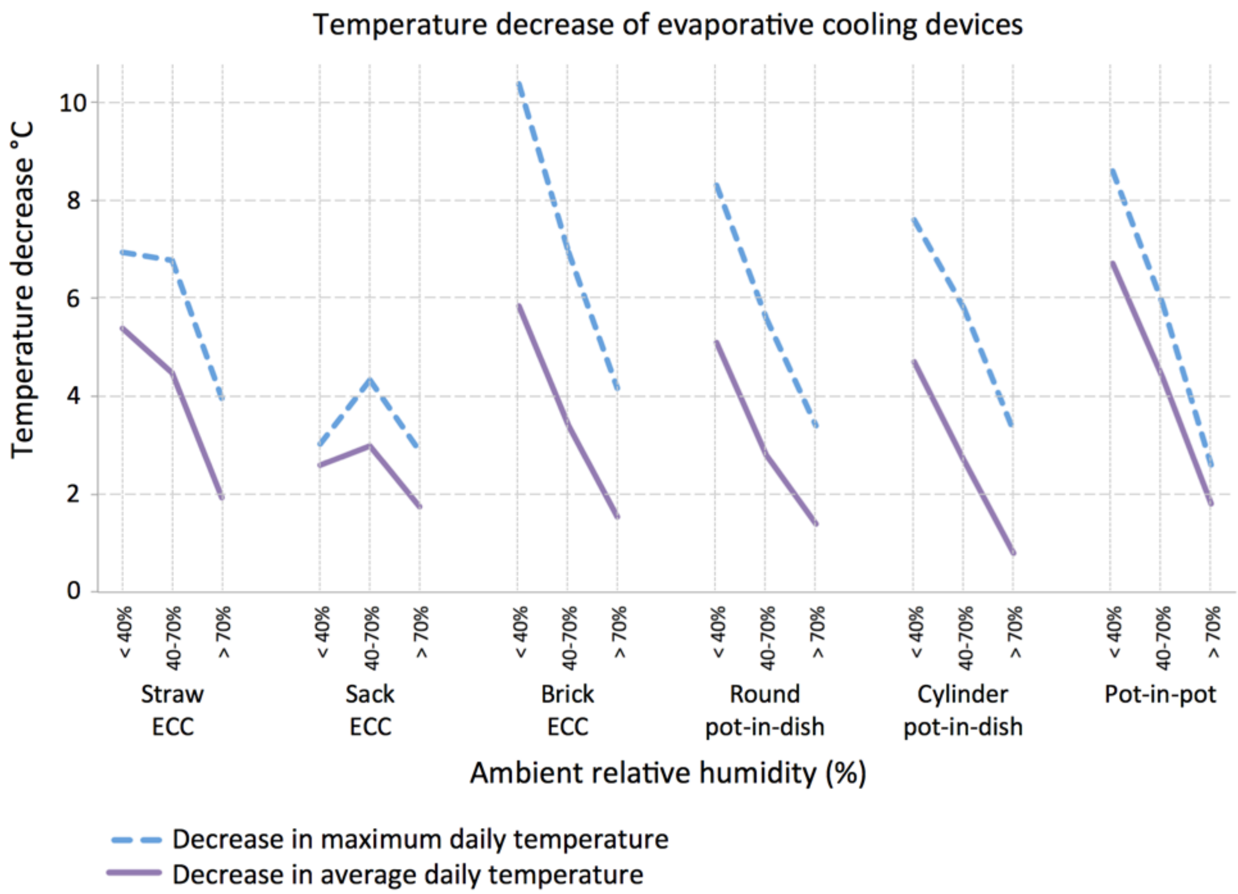


Figure 3: The decrease in the maximum daily temperature and the average daily temperature for each of the ECCs and clay pot coolers as a function of relative humidity, with regular watering. A larger decrease in the average and maximum daily temperatures indicates that the device is more effective at cooling the vegetables. See Figures 8 and 9 in the Appendix for additional details and plots with individual daily data points.

Across all relative humidity ranges, the brick ECC showed the largest decrease in the maximum daily temperature, ranging from a decrease of 10.4 °C when the ambient humidity is less than 40%, to 4.2 °C when the ambient humidity is greater than 70%. The straw ECC showed the second largest decrease in the maximum daily temperature, with a decrease of 6.9 °C and 4.0 °C when the ambient humidity is less than 40% and greater than 70%, respectively. The straw and brick ECCs show a similar decreases in the average daily temperature, ranging from 5.8 °C when the ambient humidity is less than 40%, to 1.5 °C when the ambient humidity is greater than 70%. This observed decrease in the maximum and average daily temperatures across the brick and straw ECCs with increasing ambient humidity is due to the reduced evaporation of water with higher humidity.

The sack ECC showed the poorest cooling performance, with temperature decreases ranging from 4.3 °C to 2.9 °C for the maximum daily temperature, and 3 °C to 1.8 °C for the average daily temperature. Interestingly, the sack ECC showed a smaller temperature decrease when the humidity was less than 40% than when the humidity was between 40% and 70%, which does not agree with the expectation that the lower humidity leads to increased evaporation and a greater temperature decrease. The explanation for this unexpected result is related to difficulties observed in adding water to the sack surface, which are most pronounced when the ambient humidity is low. The challenges faced by the technicians and participants resulted in less water being added to the sack when the ambient humidity was less than 40%, reducing the water available for evaporative cooling. However, once the humidity reaches a certain threshold, the sack fibers become more absorbent, allowing for complete watering to be achieved with less effort, resulting in the greater temperature decreases observed for the sack ECC in the humidity range of 40% to 70% than the humidity range below 40%.

The humidity inside the ECCs is another factor that significantly impacts the shelf life of vegetables. A list of vegetables that store well in the high humidity environment provided by EECs can be found in the "*Evaporative Cooling Best Practices Guide*". Figure 4 shows the relative humidity inside each of the ECCs as a function of the ambient relative humidity for each of the ECCs. The brick ECC shows an average daily humidity above 80% – even with an ambient humidity below 20% – and maintains an interior humidity near 100% throughout the day when the ambient humidity is above 50%. The straw ECC shows an increased average interior humidity, but less pronounced than the brick ECC, particularly when the ambient humidity is less than 40%. The humidity inside the sack ECC increased significantly compared to the ambient humidity only in the hours immediately following the addition of water (see Figure 2), resulting in an average daily humidity that is only slightly greater than the ambient humidity. In some cases, the average daily humidity inside the sack ECC is actually lower than the ambient humidity.

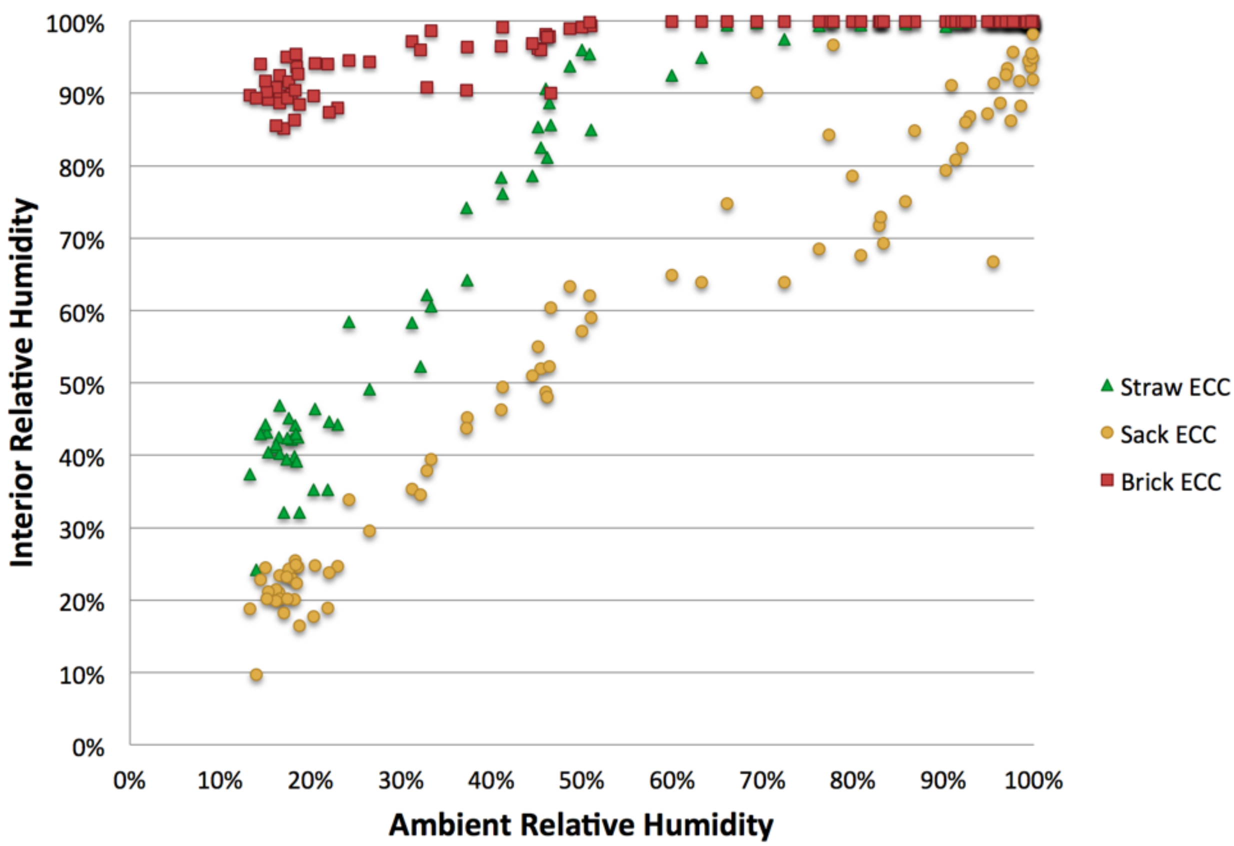


Figure 4: The relative humidity inside each of the ECCs as a function of the ambient relative humidity. Each data point on the plot indicates the average interior and ambient humidity for a single day. Data was only included when the ECC was watered at least once during previous day, and the day in question.

ECC performance as a function of watering frequency

While a simple storage vessel alone can reduce temperature fluctuations, the evaporation of water is required to achieve a decrease in the average temperature and to maintain a high humidity environment. To investigate the performance of the ECCs without regular daily watering, the researchers were instructed to not add water to one set of ECCs in Bamako (one of each type) for a period of 15 days.

Figures 5 and 6 show the average daily temperature reduction and relative humidity of each type of ECC for the 15 days following the last addition of water. This data shows that the straw and sack ECCs have significant reduction in the cooling effect in the first day after watering is stopped, compared to the brick ECC. Similarly, while the average daily humidity inside the brick ECC remains greater than the ambient for over 15 days, the humidity inside the straw and sack ECCs is equilibrated with the ambient humidity within 13 hours and five hours, respectively (see Figure 10 in the Appendix).

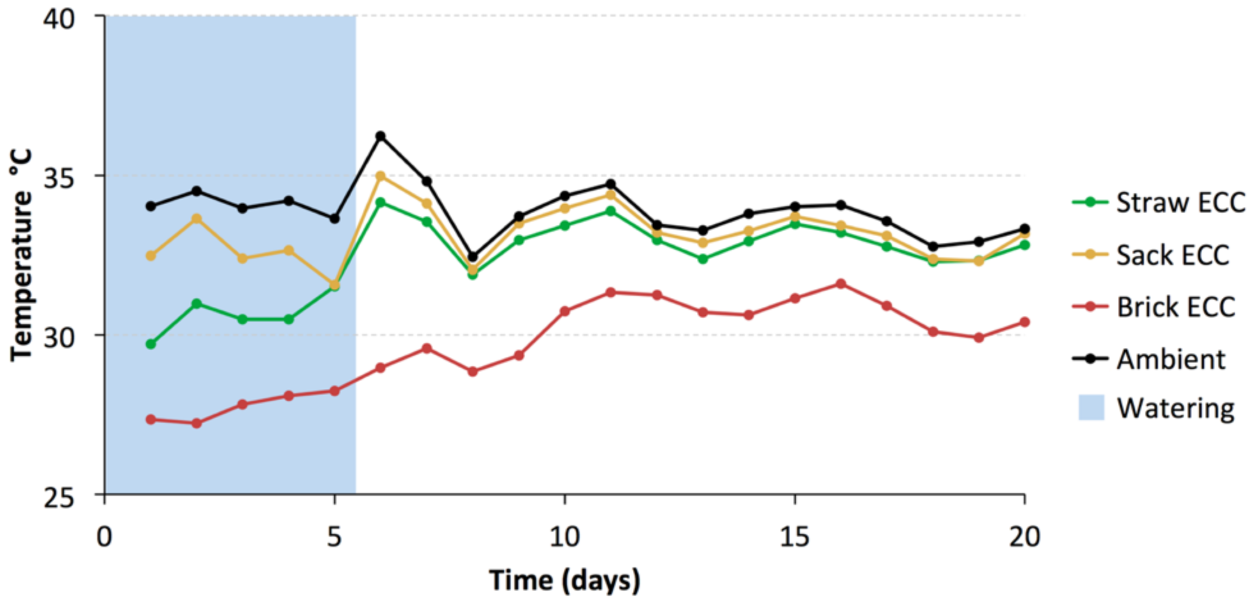


Figure 5: The average daily temperature as a function with and without regular watering (watering only occurs prior to the 5th day, indicated by the blue shaded area). An hourly plot of the temperature and humidity throughout the 20 days is available in Figure 10 in the Appendix.

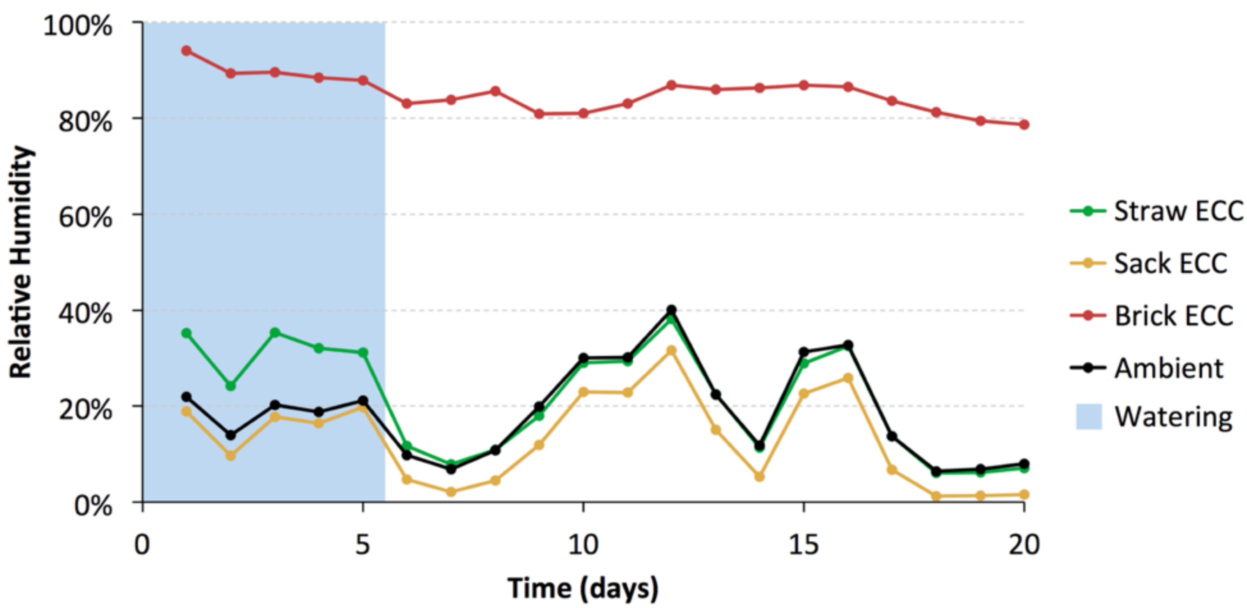


Figure 6: The average daily humidity as a function with and without regular watering (watering only occurs prior to the 5th day, indicated by the blue shaded area). An hourly plot of the temperature and humidity throughout the 20 days is available in Figure 10 in the Appendix.

Even after watering has stopped, the brick ECC is able to maintain an average temperature that is at least 2 °C less than the ambient daily average temperature, and an average daily interior humidity between 75 and 95%. Furthermore, the brick ECC maintains an interior humidity between 50% and 90% throughout the day, even when the ambient humidity is between 0% and 15% and it has been more than 10 days after the last watering.

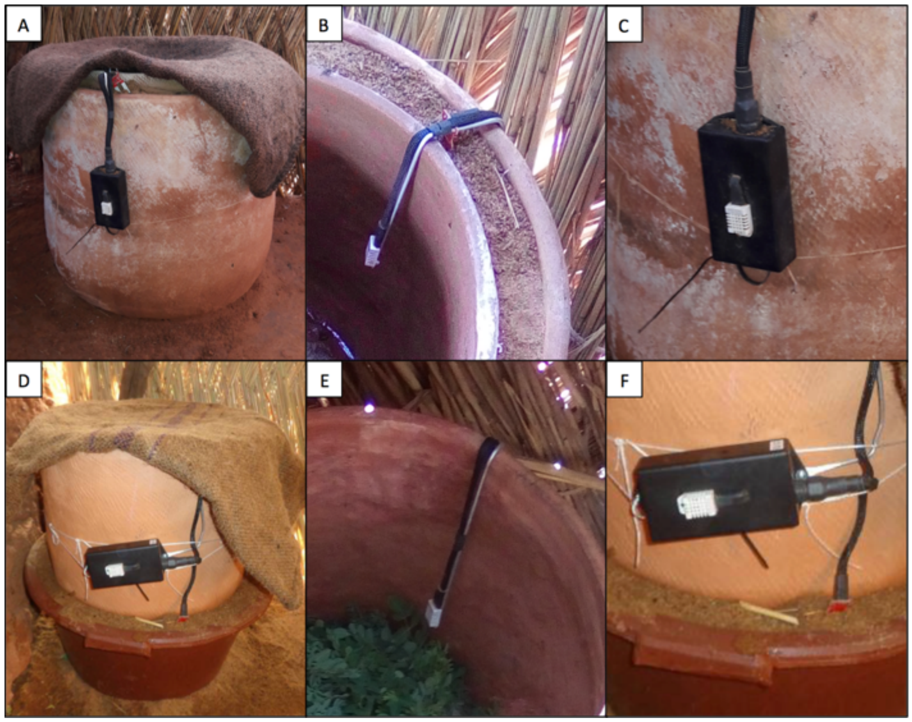
These results corroborate the observations in Figure 1, where a sharp decrease in temperature is observed in the straw and sack ECCs when water is added in the middle of the day (when the temperature is the highest and the relative humidity is the lowest), but the temperature begins to rise within 1 to 2 hours, indicating that a majority of the water has evaporated.

The brick ECC has a thick (~10 cm) and absorbent layer of sand that can retain water, as opposed to the thinner sack and straw layers. Because the straw and sack ECCs are not able to hold as much water as the brick ECC, they need to be watered more frequently. This has a significant impact on the amount of time and effort that is required upon the part of the user to maintain cool and humid environment inside the ECC.

Clay Pot Cooler Sensor Data

Over the three to five month study period, sensors were also used to measure the performance of 67 clay pot coolers at users' households in Mopti and 9 clay pot coolers at research facilities in Bamako. During this time, the weather conditions varied due to seasonal changes: data collection began in March during the dry season and continued through the beginning of the rainy season in July. Throughout this time, the ambient humidity – in both Bamako and Mopti – steadily increased allowing for the performance to be measured across a wide ambient humidity range.

Images on the right:
A) Pot-in-pot cooler
B) Pot-in-pot moisture and interior sensors
C) Pot-in-pot exterior sensor
D) Pot-in-dish cooler
E) Pot-in-dish interior sensor
F) Pot-in-dish moisture and exterior sensors



Clay pot cooler watering frequency

One of the objectives of the study was to monitor the user behavior related to the frequency of adding water to the clay pot coolers, which could be identified by sharp increases in the moisture of the sand between the inner pot and the outer pot or dish. Using the moisture sensor, we were able to observe the frequency with which the users watered their clay pot coolers, which has a significant impact on the interior temperature and humidity (discussed in the following sections). Participants were instructed to water the clay pot coolers 1 to 3 times per day to keep the sand wet and allow for the evaporation of water from the clay pot coolers throughout the day.

At the beginning of the study, over 75% of the participants added water to the clay pot cooler at least once per day. As the study progressed, the number of participants that watered the clay pot coolers decreased, with just over 50% of the participants adding water regularly (at least once per day) to the clay pot coolers throughout the entire study time period. The reasons users decreased the frequency of watering later in the study period could include changes in the need for vegetable cooling, decreased performance of the clay pot coolers as the ambient humidity increased steadily in the later months of the study, or simply because they forgot or became tired of adding water to the clay pot coolers. None of the study participants mentioned having difficulties accessing water for keeping the sand in the clay pot coolers wet.

Clay pot cooler performance as a function of humidity with regular watering

The three types of the clay pot cooler cooling and storage devices displayed the same primary trends in performance, with some differences in relation to the magnitude of the average daily temperature decrease. Figure 7 shows the typical daily profile of the sensor data collected.

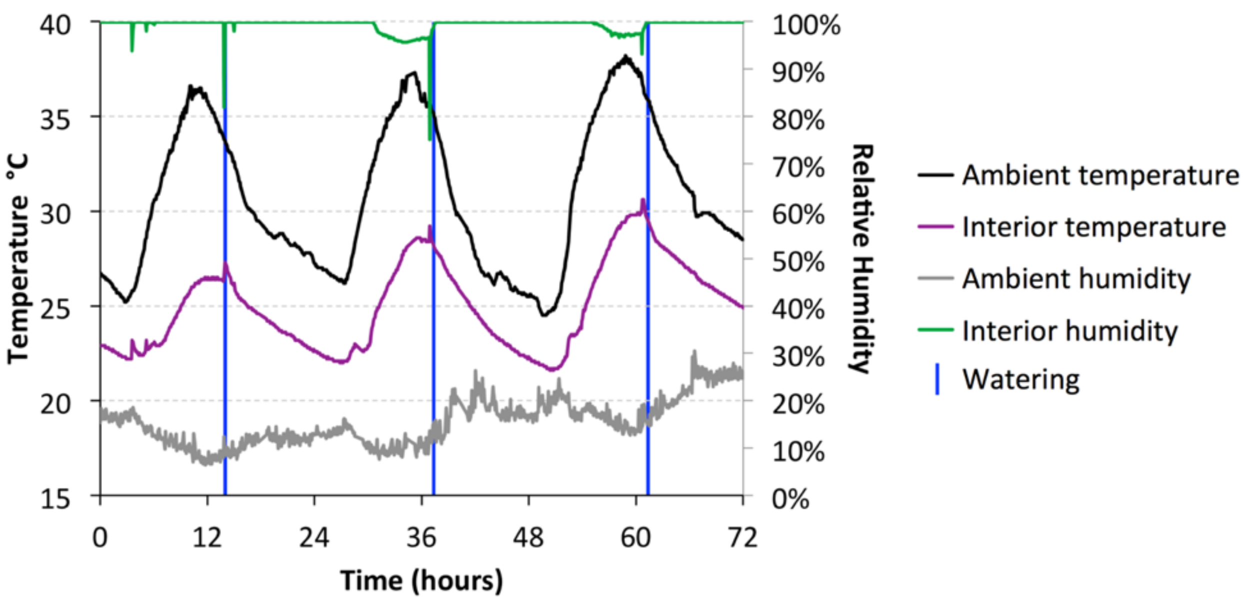


Figure 7: Typical daily temperature and relative humidity with watering for a clay pot cooler (pot-in-pot configuration). The vertical blue lines indicate when water was added.

The data in Figure 7 shows that the average interior temperature of the clay pot cooler is reduced, with the cooling effect being most pronounced during the day when the temperature is the highest and the relative humidity is the lowest. This has the effect of decreasing maximum temperature, when the vegetables are most susceptible to spoilage/damage.

Similar to the ECCs, the placement of the exterior temperature sensor on the side of the clay pot coolers had an impact on the temperature recorded compared to the ambient temperature in the location where the clay pot coolers was located. In order to estimate this effect, an additional sensor was placed at a separate location about five meters from any of the clay pot coolers at the Sotuba and Samanko research stations in Bamako. The results indicate that when the clay pot cooler was regularly watered the average exterior temperature recorded near the outside to the clay pot cooler was reduced by 0.5 to 0.9 °C compared to the ambient temperature measure from an independent sensor nearby to the clay pot coolers. Because we did not have the resources to place an independent sensor near the ECCs in the participants' households, the clay pot cooler performance results discussed in the following sections use the exterior temperature sensor located on the side of the pot; thus, the actual ambient temperature was most likely up to 0.9 °C hotter than reported.

When watered frequently enough to keep the sand from becoming dry, all of the clay pot coolers showed a significant decrease in temperature and an increase in interior relative humidity (see Figures 3 and 7). The pot-in-pot devices showed the greatest decrease in the average daily temperature across all humidity ranges, ranging from 6.9 °C when the ambient humidity is less than 40%, to 1.8 °C when the ambient humidity is greater than 70%. The pot-in-dish devices showed a slightly lower decrease in the average daily temperature, ranging from 5.1 °C when the ambient humidity is less than 40%, to 0.8 °C when the ambient humidity is greater than 70%. The three types of clay pot coolers showed a similar decrease in the maximum daily temperature ranging from 8.6 °C when the ambient humidity is less than 40%, to 2.6 °C when the ambient humidity is greater than 70%. This data shows that, similar to the ECCs, the ambient relative humidity has a significant effect on the performance of the clay pot coolers devices – at higher relative humidity the evaporation rate of water is decreased, which reduces the cooling effect.

Similar to the brick ECCs, when the clay pot coolers are regularly watered and then covered with a wet cloth the average daily interior humidity is above 80%, even when the ambient humidity is less than 20%, and the interior humidity is maintained near 100% throughout the day when the ambient humidity is greater than 50% (see Figure 11 of the Appendix).

It is important to note that participants received only ~ 1 hour of training on how to operate the clay pot coolers. Photographs of the clay pot cooler placement within the household show that many of the clay pot coolers were in sub-optimal locations, either partially exposed to direct sunlight or placed close to a wall or corner where they were not exposed to air flow or wind. Thus, it would be expected that the clay pot coolers should provide an even greater temperature decrease if placed in a more optimal position.

Clay pot cooler performance as a function of watering frequency

In order to achieve a decrease in the average temperature and to maintain a high humidity environment, water must be added to the clay pot coolers. To investigate the performance of the ECCs without regular daily watering, we looked at time periods where the participants did not add water to the clay pot coolers. Figure 8 shows the average daily temperature decrease and humidity, as a function of when water was added to the clay pot cooler.

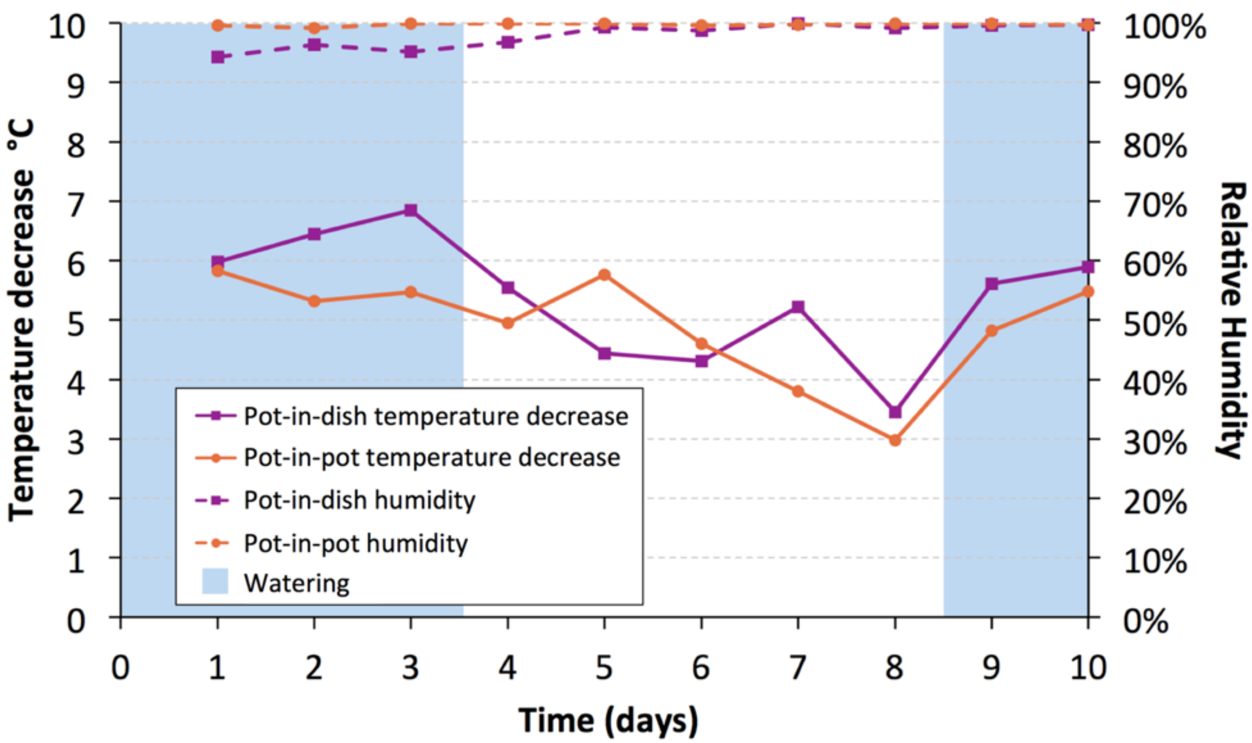


Figure 8: The average daily temperature and humidity as a function with and without regular watering (watering occurs prior to the 4th day and resumes on the 9th day, indicated by the blue shaded area). A detailed plot of the temperature and humidity throughout the 10 days is available in Figure 12 of the Appendix. The average daily ambient temperature was between 29 – 35 °C and the humidity was less than 40% for both of the clay pot coolers throughout the time shown in this figure.

This data shows that after five days without watering there is no impact on the interior humidity, which remains above 95% throughout the day. In the five days after watering was stopped, the average daily temperature decrease followed a downward trend (although not monotonic). By the fifth day without watering, each of the clay pot coolers showed over a 2 °C reduction in the temperature decrease achieved. Once watering was resumed the temperature decrease returned to the magnitude (over 5 °C) prior to period when watering did not occur.

Overall, the performance of the clay pot coolers were similar to that of the brick ECC in terms of the temperature decrease achieved, temperature and humidity stability, and the ability to maintain a high humidity environment with infrequent watering. There was no evidence watering more than once per day had a significant impact on the performance of the clay pot coolers.

Interview Results

Evaporative Cooling Chamber (ECC) User Interview Data

The 21 respondents for the ECC portion of the study were all between 35 to 70 years old; a majority (60%) were women; and horticulture or other agriculture activities were a source of income for all respondents. All respondents were affiliated with the World Vegetable Center Best Practice Hubs and report benefiting from trainings ranging from best practices for composting and fertilization to operating vegetable nurseries and integrated pest management techniques.

Corn, sorghum, and millet are the most important staple crops for the participants; and eggplant, tomatoes, hot pepper, and okra are the most common vegetables produced and were reported to be stored in the ECCs (see Table 2), which are primarily grown in the World Vegetable Center Best Practice Hubs.

Table 2: List of the most common items stored by participants in ECCs and clay pot coolers.

	ECCs	**Clay pot coolers**
Vegetables and fruits (overall)	100%	100%
Eggplant	90%	100%
Tomato	86%	100%
Hot pepper	48%	96%
Cucumber	10%	85%
Sweet pepper	0%	33%
Melon	0%	30%
Okra	43%	28%
Mango	10%	19%
Leafy greens (overall)	48%	92%
Cabbage	0%	85%
Sweet potato leaves	19%	61%
Amaranth leaves	48%	18%
Moringa leaves	0%	10%
Parsley	0%	9%
Beverages (overall)	33%	43%
Juice	19%	27%
Drinking water	29%	24%
Milk	0%	15%

All of the respondents reported growing vegetables for both personal consumption and for sale. Vegetables produced for sale are transported to the village or to market either by foot, bicycle, tricycle, or animal trucks depending on the volume of the production and access to the various modes of transportation. Less than 20% of the respondents purchase vegetables from the market, with the rest relying on their own production as their only source of vegetables.

Prior to having access to the ECCs located at the World Vegetable Center Best Practice Hubs, members of the horticulture cooperatives stored vegetables with several methods, such as spreading them on a wet sack or sand, or in metal, plastic, or wood containers. Due to reasons ranging from concerns about the security of their vegetables in the ECCs and distance from their homes to the Best Practice Hub, many participants continue to use their previous methods of vegetable storage. Additionally, many farmers dried their hot peppers and okra and processed them into powder, in order to allow for relatively long conservation (1-6 months) before being consumed or sold in the market.

Participants in Sikasso reported that there were periods of time where the ECCs were not frequently used because there were not many crops being harvested that required post-harvest storage. In Sikasso the months of February and March are some of the driest months of the year – and when the ECCs are best suited to provide effective cooling – but because there is not a large need for vegetable storage during this time the ECCs cannot provide a significant benefit to the community during this time. The primary harvest season is in July and August, when the relative humidity is the highest and the ECCs will perform the worst. This illustrates the importance of evaluating the overlap of the seasonal weather conditions (and subsequently ECC performance) with the seasonality of the post-harvest vegetable storage needs.

Shelf life of vegetables in ECCs

Based on the respondent interviews, the shelf life of eggplants and tomatoes are significantly longer in Sikasso than Mopti for all vegetables (see Table 2 in the Appendix). This difference is likely due to the significant variations in weather conditions between the two regions, which impacts the storage conditions experienced by the vegetables in the ECCs. The average ambient conditions throughout the study 5 month period were more favorable for vegetable storage in Sikasso than in Mopti, as Sikasso is situated in the Sudan-Savanna zone while Mopti is part of the hotter sand dryer Sahel-Saharan zone in Mali. Similarly, the eggplants and tomatoes in the straw and sack ECCs in Sikasso experienced ambient conditions that were an average of over 2 °C lower and 20% higher humidity than the vegetables in the straw and sack ECCs in Mopti. Because of the favorable ambient conditions for vegetable storage (higher humidity and lower temperature) the ECCs provide less value in Sikasso, as the need for improved storage is not as great and the higher humidity reduces the temperature decrease inside the ECCs.

The reported shelf life of the vegetables most commonly stored in the ECCs in Mopti is compared in Table 3 for each of the ECC types. The reported shelf life for each vegetable is similar in each type of ECC, and no statistically significant differences could be determined.

Table 3: Comparison of the shelf life of eggplants, tomatoes, hot pepper, and okra in each of the three ECC types in Mopti.

Vegetable	Reported shelf life (days)[a]			Optimal storage conditions		
	Straw ECC	Sack ECC	Brick ECC	Temperature	Humidity	Shelf life[b]
Eggplant	8 ± 3	9 ± 2	10 ± 3	12 °C	90-95%	1 week
Tomato	6 ± 1	7 ± 1	8 ± 2	18-22 °C	90-95%	1-3 weeks
Hot pepper	14 ± 9	12 ± 5	10 ± 5	0-10 °C	60-70%	6 months
Okra	5 ± 1	7 ± 1	7 ± 1	7-10 °C	90-95%	7-10 days

[a] The first number in the shelf life is the mean, followed by the standard deviation. See Table 3 in the Appendix for additional details, including the maximum, minimum and sample size.
[b] The shelf life listed is under the optimal storage conditions listed (McGregor, 1989).

User feedback on ECCs

In response to a multiple-choice question about their overall impression of the ECCs, the participants rated the brick ECC as the highest, followed by the sack ECC, and the straw ECC rated the lowest (see Table 4 in the Appendix). Table 4 lists the most common attributes of the ECCs mentioned by respondents in open-ended questions about the advantages, disadvantages, convenience, and considerations for adoption for each ECC. For respondents who would consider adopting the straw ECC, the primary reason was the availability and affordability of straw. For respondents who would consider adopting the sack ECC and brick ECC, the primary reason was the cooling effectiveness and improved shelf life of the vegetables that the participants observed during the study, compared to their previous storage methods. The brick ECC was also rated the highest on the categories of ease of watering and protection from animals and insects. However, the brick ECC was the lowest rated on access and affordability of the materials (bricks) needed to construction.

Table 4: Most commonly mentioned attributes of the ECCs and user perceptions[a]

Attribute	Straw ECC	Sack ECC	Brick ECC
Cooling effectiveness	Low	Medium	High
Protection from animals and insects	Low	Low	High
Ease of watering	Medium	Low	High
Materials access and affordability	High	Medium	Low
Overall rating	Low	Medium	High

[a] The attributes listed were mentioned by respondents in response to a series of open-ended questions for each type of ECC about the advantages, disadvantages, convenience, and considerations for adoption for personal use.

Clay Pot Cooler User Interview Data

The 67 participants for the clay pot cooler portion of the study were all between 25 to 65 years old; a majority (83%) were women; and 76% are active in horticulture. The most common source of income for the households selected for this study includes farming, trading, and civil service work (see Table 1 for the distribution of the study participants). Sixty seven percent (67%) of the participants reported benefiting from training in areas such as best practices for composting and crop fertilization, operating vegetable nurseries, and agriculture post-harvest agricultural processing. Millet, groundnut, and cowpea are the most important staple crops grown by the participants; and eggplant, tomatoes, hot pepper, onion, and okra are the most common vegetables produced. The vegetables grown by the participants are produced both for personal consumption and sale. Most of the participants that received clay pot coolers also purchase vegetables from the market (87%), which is in contrast to the less than 20% of the ECC users who purchase vegetables from the market. These households have an opportunity to benefit from improved storage on both ends of supply chain, as both growers and purchasers.

Previous storage methods

The most common methods of vegetable storage used by the participants prior to receiving the clay pot coolers were baskets woven from dried grass or straw, or metal, plastic, and wood containers (see Table 5). Woven baskets are often suspended hanging above the ground to prevent insects or animals from eating the vegetables. Other methods of storage included placing the vegetables near the family water jar, and on top of wet sand or sack, which achieves a cooling effect through the evaporation of water. Users reported the primary benefit of storage methods such as the woven baskets and other containers were that they do not require electricity, but the disadvantages were that they do not provide a long storage life for the vegetables, they require frequent monitoring to avoid infestation by insects or animals.

Table 5: Previous methods used by participants before the clay pot coolers

Type of storage	% of users
Woven baskets	49%
Metal, plastic, and wood containers	41%
Near the family water pot	10%
On top of wet sand or sack	6%
Refrigerator	3%

Over half of participants had a connection to grid electricity in their home (52%), and most of those (76%) had a refrigerator, (which makes 40% of the total participant group with a refrigerator). However, only two participants (3%) used a refrigerator for vegetable storage. Participants using refrigerators for vegetable storage reported good performance for storing vegetables without spoilage, but noted the high electricity costs. Additionally, some participants who had refrigerators reported not using them for vegetable storage either because of limited space or that vegetables result in undesirable odors that affect the juice being stored in refrigerators for sale. This data indicates that refrigerators are not a viable solution for vegetable storage for populations with the profile of the participants of this study. Furthermore, this illustrates that evaporative cooling devices such as ECCs and clay pot coolers have the potential to benefit both on-grid and off-grid populations.

Clay pot cooler usage and shelf life of vegetables

The participants used the clay pot coolers to store a wide range of products (see Table 2 for details). The vegetables most commonly stored in the clay pot coolers were eggplant, tomato, hot pepper and cucumber – with 100%, 100%, 96% and 85% of the respondent storing these vegetables, respectively. Ninety-two percent of the participants stored at least one type of leafy green, such as cabbage, sweet potato leaves, amaranth leaves, moringa leaves, or parsley in the clay pot cooler. Other commonly stored vegetables include sweet pepper, okra, melon, and mango. In addition to vegetables and leafy greens, nearly half (46%) of the participants also used the pots for storing beverages such as milk, juice, and water. A few (8%) of the participants used the clay pot coolers to store eggs or meat.

Participants were asked about the shelf life of the five most commonly stored vegetables (eggplant, tomatoes, hot pepper, cucumber, and cabbage) in their previously storage method and the clay pot cooler that they received as a part of this study. Because the ambient weather conditions vary across seasons, the participants were asked to report the shelf life of each vegetable in each storage method in both the dry season and rainy season. A summary of these responses is shown in Table 6. For all of the vegetables the average reported shelf life was slightly longer in the rainy season compared to the dry season, for both the previously used storage method and the clay pot coolers. This result is expected, as the more humid and cooler ambient conditions in the rainy season are more favorable for the storage of the vegetables in question.

Despite large variance in the shelf life data collected from the participant interviews, it can be determined that the clay pot coolers provide improved shelf life compared to the previous methods of storage used by the participants. The average reported shelf life of the vegetables was 87% longer in the clay pot coolers than in the previous methods of storage, for all of the vegetables in both the rainy and dry season. This result is expected based on the sensor data, which show an average decrease in temperature and an increase in humidity inside the clay pot coolers as compared to the ambient temperature outside the clay pot coolers – which are the conditions that the vegetables are exposed to in the most common storage methods such as a woven basket or metal and plastic containers.

Table 6: Shelf life of common vegetables stored in clay pot coolers in Mopti

Vegetable	Season	Reported shelf life (days)[a]		Optimal storage conditions		
		Previous[b]	Clay pot cooler	Temperature	Humidity	Shelf life[c]
Eggplant	Dry	5 ± 3	10 ± 5	12 °C	90-95%	1 week
	Rainy	6 ± 3	12 ± 6			
Tomato	Dry	4 ± 2	9 ± 4	18-22 °C	90-95%	1-3 weeks
	Rainy	6 ± 2	10 ± 5			
Hot pepper	Dry	5 ± 2	9 ± 5	0-10 °C	60-70%	6 months
	Rainy	6 ± 3	11 ± 6			
Cucumber	Dry	5 ± 3	9 ± 4	10-13 °C	95%	10-14 days
	Rainy	6 ± 4	13 ± 7			
Cabbage	Dry	4 ± 2	8 ± 6	0 °C	98-100%	3-6 months
	Rainy	5 ± 3	9 ± 6			

[a] The first number in the shelf life is the mean, followed by the standard deviation. See Table 3 in the Appendix for additional details, including the maximum, minimum and sample size.

[b] The shelf life reported for the previous method of storage used by the participant, including woven baskets, metal and plastic containers, near the family water jar, on top of wet sand or sack.

[c] The shelf life listed is under the optimal storage conditions listed (McGregor, 1989).

In addition to the average shelf life reported for vegetable storage in clay pot coolers compared to the previous methods of storage, it is useful to look at the over 500 direct comparisons of the shelf life for vegetables from individual participants (see Table 3 in the Appendix for the full data set of reported shelf life by the participants). For the dry season, 87% of the participants indicated a longer shelf life for specific vegetables in the clay pot cooler, compared to their previous method of storage. Six percent (6%) of respondents indicated the same shelf life with the clay pot cooler as their previous method of storage, and 7% of respondents indicated a longer shelf life with their previous method. Similarly, in the rainy season, 63%, 21%, and 16% of the participants indicated the shelf life for specific vegetables in the clay pot cooler, was longer, the same, and shorter, respectively, in comparison to their previous method of storage. The differences in shelf life between the three types of clay pot coolers was not statistically significant, due to the large variance and lack of direct comparison between the three clay pot cooler types by individual participants (see Table 6 in the Appendix for details).

User feedback on clay pot coolers

Overall, the participants perceived all of the clay pot coolers favorably. In response to a multiple-choice question about their overall impression of the clay pot coolers over 95% of the participants rated the clay pot coolers either “good” or “very good”, with only two participants giving the clay pot coolers a rating of “fairly good”, and none giving the rating of “not good” (see Table 5 in the Appendix for details).

The most common attributes of the clay pot coolers mentioned by respondents in open-ended questions about advantages and disadvantages are listed in Table 7. Nearly all of the participants listed increased shelf life (increased freshness and reduced spoilage) of the vegetables as a key advantage of the clay pot coolers. A majority of the participants also indicated their vegetables benefited from improved protection from animals and insects when stored in the clay pot cooler, which is a common problem for the previous storage methods such as woven baskets, plastic and metal containers, and vegetables spread on a wet sack or sand or near the family water pot. Other advantages the participants cited as a consequence of the improved storage include increased monetary savings, an increased availability of vegetables for their family, improved hygiene of the vegetables, convenience, and less time spent travelling to the market.

Table 7: Most commonly mentioned advantages and disadvantages of the clay pot coolers[a]

Advantages	All clay pot coolers	Round pot-in-dish	Cylinder pot-in-dish	Pot-in-pot
Increased shelf life	97%	94%	100%	97%
Protection from animals and insects	69%	82%	67%	62%
Saves money	31%	24%	33%	34%
Increased availability of vegetables	37%	35%	24%	48%
Hygienic storage of vegetables	13%	18%	14%	10%
Convenient	10%	0%	5%	21%
Less time spent going to market	7%	6%	14%	3%

Disadvantages	All clay pot coolers	Round pot-in-dish	Cylinder pot-in-dish	Pot-in-pot
Water seepage into the inner pot	13%	29%	19%	0%
Difficulties adding water	3%	0%	5%	3%

[a] The attributes listed were mentioned by respondents in response to open-ended questions about the advantages and disadvantages of the clay pot coolers. The total number of respondents was 67, with 21, 17, and 29 respondents for the cylinder pot-in-dish, round pot-in-dish, and pot-in-pot, respectively.

The most commonly cited disadvantage of the clay pot coolers was the seepage of water into the inner pot, and several participants noted that the water inside the storage area caused cabbage to spoil. It is interesting to note that participants with the pot-in-pot storage devices did not report water seepage. It is likely that the water seepage was only observed in the clay pot coolers with a pot-in-dish configuration due to the plastic dish, which is impermeable to water. In the case of the pot-in-pot configuration the outer pot is permeable to water, allowing for excess water to leave through the bottom of the pot, instead of seeping into the inner pot. For the pot-in-dish configuration, the seepage of water into the interior pot could potentially be avoided by drilling a series of small holes into the plastic dish – allowing for excess water to drain from the bottom once the sand is saturated. However, this could reduce the dish's utility to function for other tasks such as washing clothes or preparing food. A few participants also reported having difficulty adding water to their clay pot coolers.

Additionally, 90% of participants reported that they were no longer using any of their previous storage methods after receiving the clay pot coolers, indicating that the 50 liter capacity of the clay pot coolers used in this study is sufficient to meet the vegetable storage needs of most households.

When asked if they would consider purchasing a clay pot cooler, a majority of the respondents (63%) indicated "yes" they would, with 29% and 8% replying "maybe" and "no", respectively. However, because the researchers conducting the interviews could not provide details on the price and availability of the clay pot coolers in the regions, most participants indicated that their purchasing decision would be based on the affordability and availability of clay pot coolers. Further research directly testing the market for clay pot coolers will be needed to determine the willingness to pay for different customers profiles.

Construction and Cost

In order for evaporative cooling chambers (ECCs) or clay pot coolers to be widely disseminated in a particular region, it is critical that they can be constructed using locally available and affordable materials. While there is no single "right way", to construct an ECC or clay pot cooler, there are general principles and certain best practices that should be considered to maximize the performance of the devices.

In this section, we will describe the key elements and associated costs of constructing evaporative cooling devices to evaluate their potential cost-effectiveness.

Much of the basic construction protocol for evaporative cooling devices can be communicated pictorially, and many of the design considerations do not have rigid constraints, allowing for the possibility of disseminating the principles for constructing an ECC or clay pot cooler to prospective end users or producers. As the scope of this research study was not to develop detailed instructions for constructing ECCs and clay pot coolers – and previous work has been done by others in this area – we provide references to practical resources for constructing of evaporative cooling devices in the "*Evaporative Cooling Best Practices Guide*" accompanying this report.

Evaporative Cooling Chamber (ECC) Construction and Cost

Regardless of the type of ECC, the cost can vary significantly based on desired size and local cost of materials. Because ECCs can be constructed over a range of sizes, it is important to select an appropriate size according to need, to avoid over-building and spending more money than is needed. Below is a list of the key materials needed for constructing each type of ECC:

- Straw ECC: wood and nails or screws for a frame, straw to cover the surfaces of the ECC, and rope or twine to secure the straw
- Sack ECC: wood and nails or screws for a frame, sack to cover the surfaces of the ECC, and rope or twine to secure the sack
- Brick ECC: enough for two layers of brick around the sides and bottom of the ECC (typically 400-800 bricks), sand to fill the space between the two brick walls, and a cover for the top of the ECC made of wood and straw or cloth

If the user does not have a shady place where the ECC can be placed, then a shade cover will need to be made. This typically consists of a wood or metal frame and a combination of straw and plastic. An expanded list of materials required for each type of ECC can be found in Table 7 of the Appendix.

When constructing and using an ECC, the placement is critical. The ECC must be located in a shaded area and exposed to air flow or wind to remove water vapor. Brick ECCs in particular are time consuming to move and the selection of an appropriate location is particularly important when planning the construction of an ECC. Any structures that are required to accommodate these requirements should be considered as a part of the cost of the ECC.

The three ECC types in this study (straw, sack, and brick) were made large enough (1000 – 2500 liters) to serve the needs of the cooperatives that the World Vegetable Center works with. The total cost to construct each ECC and their size is shown in Table 8.

At a cost of roughly $100, the straw ECC was the least expensive to construct, but also the smallest design. The larger sack and brick ECCs cost $215, and $260, respectively. When considering these costs, the size of the ECCs should be considered; the sack and brick ECCs used in this study had over twice the storage volume as the straw ECCs. Additionally, while the straw and sack ECCs located under the covered area of the World Vegetable Center Best Practice Hub, the brick ECC required a shade cover to be constructed (at a cost of about $45), due to its large footprint and inability for it to be easily moved. The largest cost for the straw and sack ECCs is the wood frame, and the bricks comprise the majority of the cost for constructing the brick ECC. The availability of straw can vary seasonally, with the price typically increasing during the rainy season. The bricks were purchased from a women's cooperative in Mopti where special clay soil to manufacture burnt bricks is available. Transportation costs of the components were not included in the costs listed here, but should be taken into account when calculating the cost to build each type of ECC in a specific context.

Table 8: Cost and size of evaporative cooling chambers (ECCs) and clay pot coolers

Evaporative cooling device	**Storage volume**		**Cost (USD)**	
	Range	**This study**	**Range**	**This study**
ECC (straw)	250 - 4000 L	1000 L	$50 - $250	$100
ECC (sack)	250 - 4000 L	2500 L	$50 - $250	$215
ECC (brick)	500 - 5000 L	2500 L	$70 - $350	$260
Round pot-in-dish	10 - 150 L	50 L	$6 - $35	$23
Cylinder pot-in-dish	10 - 150 L	50 L	$6 - $35	$23
Pot-in-pot	10 - 100 L	50 L	$10 - $50	$40

Clay Pot Cooler Construction and Cost

The cost of a clay pot cooler can vary significantly based on desired size and local cost of materials. It is important to select an appropriate size according to need to avoid spending more money than is needed. A list of materials required for each type of clay pot cooler can be found in Table 8 of the Appendix.

Clay pot coolers must also be placed where they are in the shade and exposed to air flow or wind to remove water vapor. Larger clay pot coolers with a pot-in-pot configuration can be heavy and difficult to move when assembled, so the location should be considered prior to assembling the clay pot cooler. Any structures that are required to accommodate these requirements should be considered as a part of the cost of the clay pot cooler.

Clay-pots are made with special type of clay soil, and wherever the clay soil is present, local manufacturers often exist or could be trained in clay-pot manufacturing. Clay pot coolers will likely be most accessible and affordable in areas where clay pots are already being made and sold. In Mali, clay is most readily available along the Niger River, and there are several businesses that manufacture a wide range of earthenware products at these locations. A women's cooperative near in Mopti produced the pots used in this study.

Earthenware products – typically made using locally available clay – are present in most households in Mali. Clay pots are commonly used to store water for drinking and it is well known that water stored inside the pot is cooled, which is desirable for drinking water. This occurs through the same evaporative cooling mechanism as the clay pot coolers for vegetable storage. This creates a situation where the general concept of using clay pots and water to create a cooling effect is widely understood in both rural and urban areas throughout Mali.

The clay pot coolers in this study were relatively large (50 liters), as the vegetable storage need of the participants were unknown at the beginning of the study. In all but one case the participants reported that the size of the clay pot coolers they received was large enough to meet their vegetable storage needs. The total cost to construct each clay pot cooler is shown in Table 8.

For this study, the pot-in-dish configuration cost $23 and the pot-in-pot configuration $40, not including transportation costs. Even for pots of comparable size, this cost could likely be lowered because the pots for this study were custom ordered to specifications to ensure uniformity for this research study. For this study, the transportation cost was an additional $5 per unit (not included in the costs listed above), and should be taken into account when calculating the total cost of a clay pot cooler in a specific context. It could be possible to lower the total cost of the clay pot cooler by using clay pots being manufactured at a larger scale, using existing supply chains for transportation, and relying on the end user to transport the pots from the point of purchase to their home.

Based on a survey of typical market prices for clay pots and plastic dishes, we expect that the components to construct clay pot coolers, ranging from 10 liters to 150 liters in capacity, could cost between $6 and $50. Clay pot coolers with the pot-in-pot configuration will typically cost more than a comparably sized pot-in-dish configuration, as the outer clay pot is more expensive than a plastic dish that could hold a similar sized inner pot.

Given the wide availability of both clay pots and plastic dishes, local business could assemble the necessary components for constructing clay pot coolers and market them specifically for vegetable storage to customers with vegetable storage needs. This could be done by either custom designing combinations of the appropriate containers or selecting components among those already locally available. Furthermore, households with a need for improved vegetable storage could potentially assemble a clay pot cooler from materials that they either already have in their home or are available at a local market. This latter scenario also presents the possibility where a household may not even need to make a new purchase to create a clay pot cooler, as existing materials could be repurposed. This could be particularly attractive for users that may only have intermittent vegetable storage needs.

Additionally, there are other designs that can adapt the clay pot cooler concept to achieve the same goals. For example, the janata cooler consists of a metal or plastic container placed inside of a clay pot, with a wet cloth covering any exposed surface of the inner container (Odesola & Onwuka, 2009; Roy & Khurdiya, 1985). This design prevents water from seeping into the area where vegetables are stored and can also be used to control the interior humidity if desired. Each alternative design will have its own advantages and disadvantages, including cost, performance, and usability.

In all cases, the potential to use locally available materials for ECCs, clay pot coolers, or other evaporative cooling designs, reduces the distribution challenges for disseminating the technology compared to importing and distributing a new device in a market.

Conclusions and Recommendations

The main objective of this work is to evaluate if evaporative cooling technologies show promise for improving vegetable cooling and storage in Mali. In this study, we investigated two classes of evaporative cooling devices: evaporative cooling chambers (ECCs) and clay pot coolers. In the previous sections we presented the results from:

- Sensors to measure the changes in temperature and humidity inside the devices as a function of ambient conditions and the frequency of watering.
- Interviews with study participants about their vegetable production and consumption, their usage and perception of the evaporative cooling devices, and the impact of the ECCs and clay pot coolers in the shelf life of vegetables compared to their previous methods of vegetable storage.
- Analysis of the cost to construct each type of evaporative cooling device.

Summary of Findings

The results of this study indicate that evaporative cooling devices such as ECCs and clay pot coolers have the potential to benefit off-grid populations who have limited electricity access, as well as on-grid populations in Mali who face high electricity and/or equipment costs for refrigerators, by offering a low-cost option for improved vegetable cooling and storage. Evaporative cooling can improve vegetable storage shelf life by providing:

- A stable storage environment with low temperature and high humidity, which reduces water loss and spoilage in most vegetables
- Protection from animals and insects that contaminate and eat the vegetables

Interviews with study participants indicated that reduced vegetable degradation – achieved through the improved storage environment – can lead to impacts such as:

- Financial savings due to reduced food loss
- Less time and money spent travelling to the market
- Increased availability of vegetables for a family
- Improved hygiene of the vegetables
- Convenience

In the following sections we will review the key results for each class of evaporative cooling device (ECCs and clay pot coolers). The key characteristics for each device studied are shown in Table 9, and the major conclusions from the comparison of the devices in each class are:

- The brick ECC showed better performance than the straw and sack ECCs
- The different configurations of type of clay pot coolers (pot-in-pot and pot-in-dish) showed similar performance

Table 9: Summary of key characteristics for each evaporative cooling device

Evaporative cooling device	Average temperature decrease*	Humidity range*	Minimum watering frequency	Protection from animals and insects	Storage volume	Cost
ECC (straw)	5.4 °C	30-50%	1-3 times per day	No	250-4000 L	$50 - $250
ECC (sack)	2.6 °C	10-30%	1-3 times per day	No	250-4000 L	$50 - $250
ECC (brick)	5.8 °C	80-100%	once per 1-7 days	Yes	500-5000 L	$70 - $350
Round pot-in-dish	5.1 °C	80-100%	once per day	Yes	10-150 L	$6 - $35
Cylinder pot-in-dish	4.7 °C	80-100%	once per day	Yes	10-150 L	$6 - $35
Pot-in-pot	6.7 °C	80-100%	once per day	Yes	10-100 L	$10 - $50

*For the data provided, the ambient relative humidity was less than 40% and the average daily temperature was between 29 °C and 37 °C. *See Figures 8 and 9 in the Appendix for additional details*.

Evaporative cooling chambers (ECCs)

Due to the typical size of ECCs, they are most suitable for farming groups, farming cooperatives, or larger producers. This situation typically requires the organization of a single point person or team to be responsible for watering the ECCs and ensuring the security of the vegetables stored at the ECC location. These considerations are not as critical for the clay pot coolers – typically used by individual households – which does not require considerations beyond the typical determination of household responsibilities and securing household items.

The data from the sensors and user interviews indicate that brick ECCs are superior to the straw and sack ECCs across a range of factors including:

- Stable low temperature and high humidity storage environment
- Protection from insects and animals
- Easy and frequency of watering, as well as the quantity of watering required
- Storage life and overall preference reported from users

The data from the sensors show that when the ambient humidity is low (< 40%), brick ECCs can be expected to provide a decrease in the average temperature and maximum daily temperature between 5 – 7 °C and 9 – 12 °C, respectively; while maintaining an average interior humidity above 80% (see Figure 3 and Table 9). As expected, the evaporative cooling effect is reduced for all of the ECCs with increasing ambient humidity.

For a given volume the cost for construction for this study was comparable for each type of ECC; however, this could vary significantly depending on the local availability and cost of the relevant materials. Participants reported that they would have the most difficulty accessing materials to construct a brick ECC.

Among the three types of ECCs, the brick ECC was the most promising technology based on insight from beneficiaries, and the performance measured by the sensors (temperature decrease and humidity increase). Compared to a brick ECC, the straw and sack ECCs do not provide as stable a low temperature and high humidity storage environment, require a greater frequency and amounts of watering, and do not protect as well against insects and animals. Due to these considerations, straw and sack ECCs are not recommended, but could provide some benefits if bricks are not locally available and there are no other vegetable storage options.

Clay pot coolers

The three different types of clay pot coolers that were distributed to households as a part of this study received similar user feedback and showed similar performance. All clay pot coolers provide a stable low temperature and high humidity storage environment for vegetables, and good protection from animals and insects.

Nearly all of the participants (97%) listed increased shelf life of the vegetables as a key advantage of the clay pot coolers compared to their previous methods of storage. Individual comparisons against previous storage methods showed that the clay pot coolers provided an average increased shelf life of 87% for the most common vegetables (eggplant, tomatoes, hot peppers, cucumbers, and cabbage), in both the rainy and dry seasons. However, the differences in shelf life between the three types of clay pot coolers could not be determined to be statistically significant, due to the large variance and lack of direct comparison by individual participants.

In low humidity (< 40%) environments with maximum daily temperature between 29 °C and 37 °C, a decrease in the average temperature between 4 – 6 °C and 5 – 8 °C can be expected for the pot-in-dish and pot-in-pot configurations, respectively. Similar to the ECCs – and in alignment with the theoretical expectations – the cooling effect decreases as the ambient humidity increases (see Figure 3 and Table 9). Regardless of the ambient humidity, the sensor results indicate that clay pot coolers consistently maintain an average interior humidity above 80%, which prevents dehydration and spoilage for many vegetables.

Clay pot coolers with a pot-in-dish configuration provide comparable performance to the pot-in-pot configuration, across a majority of the metrics measured. While the pot-in-dish configuration has less surface area exposed for the evaporation of water (due to the inability of water to permeate the plastic and evaporate), and subsequently a smaller cooling effect than the pot-in-pot configuration; both configurations performed very similarly on other metrics such as interior humidity, ease of watering, and protection from animals and insects.

Ninety percent of participants reported that after receiving the clay pot coolers they no longer used any of their previously used storage methods, and indicated that the 50 liter capacity of the clay pot coolers used in this study is sufficient to meet the vegetable storage needs of most households. When asked if they would consider purchasing a clay pot cooler, a majority of the respondents indicated they were interested, but their purchasing decision would be based on the affordability and availability of clay pot coolers. The pot-in-dish configuration could provide a more accessible and affordable option, as the components are common in most households (as opposed to the pot-in-pot that may have to be custom designed to fit in each other), and could be set-up for intermittent use, for households that have sporadic needs for improved vegetable storage.

Suitability of Evaporative Cooling Devices

Evaporative cooling devices such as evaporative cooling chambers (ECCs) and clay pot coolers are not suitable for all contexts, and several factors should be assessed to determine if a device will meet user needs in a particular setting. Below is a list of key considerations, adapted from "*A Review of Porous Evaporative Cooling for the Preservation of Fruits and Vegetables*" (Odesola & Onwuka, 2009):

- **Operating conditions:** Specific conditions are required for evaporative cooling devices to operate effectively:
  - Low relative humidity (less than 40 %)
  - High temperature (daily maximum above 25 °C)
  - Access to water, which must be added for evaporative cooling to work
  - Availability of shady, well-ventilated locations for ECCs and clay pot coolers
- **Need:** The storage conditions provided by evaporative cooling devices must meet users' needs. Potential users should consider:
  - Optimal storage conditions for different vegetables
  - The scale of vegetable storage needed
  - Variations in the need for vegetable cooling and storage throughout the year
- **Value:** The cost of the ECC or clay pot cooler must be affordable and justified by the benefits that will be realized due to its improved storage. Potential users should evaluate:
  - Local availability and affordability of materials to construct an ECC or clay pot
  - Potential benefits of evaporative cooling devices, such as time and money saved, increased vegetable availability, improved hygiene, and convenience

In the following sections, we discuss these considerations along with specific insights from research conducted by MIT D-Lab.

Operating conditions

Several key considerations are important for determining if an evaporative cooling device will provide effective cooling and storage. ECCs and clay pot coolers provide the most benefits when they are used in low ***humidity*** climates (less than 40% relative humidity), the ***temperature*** is relatively hot (maximum daily temperature greater than 25 °C), ***water*** is available to add to the device between one and three times per day, and the device can be located in a ***shady and well-ventilated area***.

If any of these key criteria cannot be met at the time when improved vegetable storage is needed, then ECCs or clay pot coolers may not provide sufficient benefits to justify their use. In general, evaporative cooling devices are best suited to provide these benefits in dry and hot climates. A Koppen climate classification map can be found in Figure 1 of the Appendix, showing the regions of the world where these climate conditions are present.

Need for improved post-harvest vegetable cooling and storage

These technologies have the potential to provide benefits for people along several points of the vegetable post-harvest value chain, including farmers, traders, and consumers. However, the specific vegetable storage needs of a particular user should be considered before deciding to use an evaporative cooling device such as an ECC or clay pot cooler. Some key considerations include:

What type of vegetables or other products are in need of improved storage?

ECCs or clay pot coolers provide benefits if post-harvest vegetable spoilage is the result of exposure to high temperatures, low humidity, animals, or insects. Vegetables particularly vulnerable to these conditions include eggplants, tomatoes, leafy greens, peppers, and okra. Non-electric evaporative cooling devices – such as ECCs and clay pot coolers – are **not** suitable for items that require sustained temperatures below 20 °C (medicine, meat, and dairy products) or foods that require a low humidity environment (onions, coffee, garlic, millet, and other grains).

What volume of vegetables needs to be stored at any one time?

It is necessary to estimate the volume of vegetables in need of improved storage at any given time to determine the appropriate size of the evaporative cooling device. If the vegetables can fit into a clay pot with a capacity of 150 liters or less, then a clay pot cooler is most appropriate. Individuals or groups that need to store larger amounts of vegetables can consider an ECC (see Table 9).

How often is improved vegetable storage needed?

Variations in the need for improved vegetable storage can arise due to seasonal growing and harvest cycles, vegetable production surpluses relative to local demand, and climate variations. It is important to determine if proper operating conditions exist for evaporative cooling to effectively provide benefits during the time when vegetable storage is needed, and if the need for improved vegetable storage is frequent enough that the value an ECC or clay pot cooler can provide is greater than its cost.

Value that ECCs and clay pot coolers provide in relation to their cost

To determine if there is enough benefit to justify investing in an ECC or clay pot cooler, the cost of constructing an appropriate evaporative cooling device must be determined. The construction of an ECC or clay pot cooler requires that the relevant materials are locally available and affordable. A description of the materials needed to construct ECCs and clay pot coolers can be found in the "*Construction and Cost*" section of this report and further details are available in the "*Evaporative Cooling Best Practices Guide*" accompanying this report.

The benefits must be greater than the cost to justify the construction or purchase of an ECC or clay pot cooler. Among the benefits that should be considered when making this determination are:

- Financial savings due to reduced food loss
- Time and money saved traveling to the market
- Increased availability of vegetables for a family
- Improved hygiene of the vegetables
- Convenience

Additionally, an end user must either be able to afford the cost of the device or have access to a financing plan that will allow for them to pay for the device after the financial benefits of improved storage have accumulated.

Overall, the evaporative cooling and storage technologies discussed here have the potential to provide effective post-harvest vegetable storage in an appropriate context. Based on this research and the considerations outlined in this section, we have developed an interactive Microsoft Excel-based "*Evaporative Cooling Decision Making Tool*" to help determine if evaporative cooling devices are suitable for a particular context and guide the calculation of potential financial savings.

Recommendations

The most important first step is for prospective users, producers, or promoters of ECCs and/or clay pot coolers to carefully consider the suitability of evaporative cooling devices for the specific context of interest (see the previous section). The key elements for increasing the usage of evaporative cooling devices are **awareness, availability, quality, and affordability** in the **appropriate** regions. Prospective users can explore purchasing or constructing an appropriate device using locally available materials (see the "*Evaporative Cooling Best Practices Guide*" accompanying this report).

If evaporative cooling devices have the potential to meet the vegetable cooling and storage needs for a large number of prospective users in a community or region, a business or market facilitator could produce, distribute, and/or promote suitable devices. In order to increase the dissemination of these beneficial technologies the following steps should be taken:

- Identify specific end user profiles who could benefit from evaporative cooling technologies
- Raise awareness of the benefits and suitability of the technology among prospective end users
- Increase availability of appropriately designed clay pots – organized production and distribution can increase availability, quality, and affordability

Government agencies, NGOs, and civil society organizations acting as market facilitators could promote this technology through awareness and training campaigns targeted at both businesses (that could be prospective ECC or clay pot cooler producers) and end users. Both the producers and end users of evaporative cooling devices need to be well-trained in order to understand the usefulness of evaporative cooling technologies for improving vegetable shelf life, and best practices for construction and use of the devices.

Training of a woman on pot watering and monitoring in Bankass, Mopti

Training of a group of study participants to use clay pot coolers in Tanoussagou, Mopti

Additional research is needed to determine what the most effective strategies for increasing the availability and usage of evaporative cooling devices, including investigation of:

- Locations where evaporative cooling devices provide the most value
- Factors that lead producers or entrepreneurs to construct and sell evaporative cooling devices
- Distribution strategies that are most effective in generating sales
- Factors that lead users to adopt evaporative cooling devices
- How evaporative cooling devices are used and quantification of the benefits they provide to users

Additional Resources

The following additional resources are available at:
http://d-lab.mit.edu/resources/projects/evaporative-cooling

- **Evaluation Appendix:** Additional details on the study methodology and data referenced in the report.
- **Evaporative Cooling Decision Making Tool:** An interactive Microsoft Excel-based decision making tool to help determine if evaporative cooling devices are suitable for a specific context, and to guide the calculation of potential financial savings.
- **Evaporative Cooling Best Practices Guide:** Provides guidance on best practices for determining the suitability of evaporative cooling technologies for a specific context, construction and usage of clay pot coolers and evaporative cooling chambers, and dissemination approaches.

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Dr. Verploegen received a PhD from the Massachusetts Institute of Technology in Polymer Science in Technology. Eric joined D-Lab in 2014 to expand D-Lab's research efforts in the area of off-grid energy. He has over 10 years of experience developing technologies for the energy sector, including waste remediation systems for the oil and gas industry and solar cells. He is passionate about helping organizations based in off-grid regions identify technologies, products, and distribution strategies to increase energy access in their communities.

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References

Ambuko, J., Wanjiru, F., Chemining'wa, G. N., Owino, W. O., & Eliakim, M. (2017). *Preservation of Postharvest Quality of Leafy Amaranth (Amaranthus spp.) Vegetables Using Evaporative Cooling*. Journal of Food Quality.

Basediya, A. l., Samuel, D. K., & Beera, V. (2011). *Evaporative cooling system for storage of fruits and vegetables - a review* (Vol. 50). Journal of Food Science and Technology.

Emana, B., Afari-Sefa, V., Nenguwo, N., Ayana, A., Kebede, D., & Mohammed, H. (2017). *Characterization of pre- and postharvest losses of tomato supply chain in Ethiopia* (Vol. 6). Agriculture & Food Security.

Gorny, J. R. (2001). *A summary of CA and MA requirements and recommendations for fresh-cut (minimally processed) fruits and vegetables*. Postharvest Horticulture Series, University of California, Davis.

Kader, A. A. (2005). *Increasing Food Availability by Reducing Postharvest Losses of Fresh Produce*. Proceedings 5th International Postharvest Symposium.

Kitinoja, L. (2016). *Innovative Approaches to Food Loss and Waste Issues*. Frontier Issues Brief for the Brookings Institution's Ending Rural Hunger project.

Kumar, A., Mathur, P. N., & Chaurasia, P. B. (2014). *A Study on the Zero Energy Cool Chamber for the Storage of Food Materials* (Vol. 5). International Research Journal of Management Science & Technology.

Kumar, D. K., Basavaraja, H., & Mahajanshetti, S. B. (2006). *An Economic Analysis of Post-Harvest Losses in Vegetables in Karnataka* (Vol. 61). Indian Journal of Agricultural Economics.

Longmone, A. (2003). *Evaporative Cooling of Good Products by Vacuum* (Vol. 47). Food Trade Review.

Matsumoto-Izadifar, Y. (2008). *Mali – Beyond Cotton, Searching for "Green Gold"*. OCED Development Center.

McGregor, B. (1989). *Tropical Products Transport Handbook*. USDA Office of Transportation, Agricultural Handbook.

Morgan, L. (2009). *Clay Evaporative Coolers Performance Research*. Practical Action.

Noble, N. (2003). *Evaporative Cooling*. Practical Action.

Odesola, I. F., & Onwuka, O. (2009). *A Review of Porous Evaporative Cooling for the Preservation of Fruits and Vegetables*. (Vol. 10). The Pacific Journal of Science and Technology.

Oluwasola, O. (2011). *Pot-in-pot Enterprise: Fridge for the Poor*. UNDP: Growing Inclusive Markets.

Rathi, R., & Sharma. (1991). *Few More Steps Toward Understanding Evaporating Cooling and Promoting Its use in Rural Areas*. A Technical Report. Delhi, India.

Roy, K. S., & Khurdiya, D. S. (1982). *Keep vegetables fresh in summer* (Vol. 27). Indian Horticulture.

Roy, S. K., & Khurdiya, D. S. (1985). *Zero Energy Cool Chamber* (Vol. 43). India Agricultural Research Institute: New Delhi, India. Research Bulletin.

World Health Organization. (2018). *Nutrition Landscape Information System (NLiS)*. http://apps.who.int/nutrition/landscape/report.aspx?iso=mli (accessed April 10, 2018).