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The U.S. Government's Global Hunger & Food Security Initiative

EVAPORATIVE COOLING
FOR IMPROVED FRUIT & VEGETABLE STORAGE IN RWANDA & BURKINA FASO

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Research Report
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USAID FROM THE AMERICAN PEOPLE
HORTICULTURE INNOVATION LAB
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MIT D-Lab

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 this report.

Agribusiness Associates Inc.

Started by seasoned agribusiness professionals and led by Mr. Gurbinder Singh Gill, Agribusiness Associates Inc. is an international development consulting firm focusing on overcoming the biggest challenges in the agricultural sector. The firm has special expertise in offering comprehensive solutions to the agribusiness sector for enterprise development. Our team brings decades of experience in agricultural marketing, program development and management, agricultural technology and public-private partnerships. This research was made possible through projects implemented by Agribusiness Associates in Rwanda and Burkina Faso.

Horticulture Innovation Lab

The Feed the Future Innovation Lab for Horticulture is a global research network that advances fruit and vegetable innovations, empowering smallholder farmers to earn more income while better nourishing their communities. The program's research portfolio spans the value chain of fruit and vegetable production, from seed systems to postharvest processing, in Africa, Asia and Central America. The Horticulture Innovation Lab is funded by the U.S. Agency for International Development and led by a team at the University of California, Davis, as part of the U.S. government's Feed the Future initiative.

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Executive Summary

The horticulture sector plays a vital role in supporting human nutrition and income generation for farmers in Rwanda and Burkina Faso. A lack of affordable and effective postharvest fruit and vegetable storage solutions often leads to spoilage, loss of income, reduced access to nutritious foods, and significant amounts of time spent traveling to sell and purchase fresh produce (fruits and vegetables), particularly in rural communities. Studies conducted in Rwanda and Burkina Faso indicate that postharvest losses for perishable products like tomatoes are between 50-60%.

The objective of this research study is to investigate the potential for non-electric evaporative cooling devices to address challenges of postharvest fruit and vegetable storage in Rwanda and Burkina Faso. The two classes of devices evaluated in this study are commonly known as "Zero Energy Cooling Chambers" (ZECCs), which are generally used by horticulture farmers, farmer groups and 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, fruit and vegetable shelf life measurements, and structured user interviews to gather information about users' needs for improved postharvest storage, current methods of postharvest storage, and the performance of the evaporative cooling devices.

A brick Zero Energy Cooling Chamber (left) and a clay pot cooler (right) in Rubona, Rwanda.

Insights

The results of this research indicate that evaporative cooling devices can provide value across a range of environmental conditions and fruit and vegetable types, and uncovered the following insights in Rwanda and Burkina Faso.

Promising Results

- The devices provide increased humidity, decreased daily average temperatures, decreased peak daily temperatures, and improved temperature stability, all of which can lead to improved vegetable shelf life. All of the devices provide a minimum of the following benefits:
    - An average interior humidity greater than 95%.
    - A decrease in the average daily temperature between 1 and 3 °C.
    - A reduction in daily temperature fluctuations from 10 – 20 °C each day to less than 4 °C throughout a given day. It is important to note that even when there is not a significant decrease in the average temperature, it is beneficial to store produce in an environment with a stable temperature.
    - The peak daily temperature is reduced by 7 – 15 °C, and avoidance of peak temperatures above 30 °C.
- In Burkina Faso the clay pot in clay pot cooler design provided a larger decrease (8 °C) in the average temperature than designs with a clay pot in a dish or a plastic container in a clay pot (4 – 5 °C).
- Farmers using brick ZECCs in Rwanda reported shelf life improvements ranging from 2 to 4 times for specific vegetables compared to the shelf life in ambient conditions.
- Fruit and vegetable vendors are suffering significant financial losses due to spoilage and can benefit from evaporative cooling devices.

Barriers and Constraints to Evaporative Cooling Technology Adoption

- The high humidity in Rwanda (during the research period) limits the temperature decrease that can be achieved.
- Fungal contamination from the sides of inner clay surfaces or spreading of rot from one fruit and vegetable type to another, can accelerate deterioration. Plastic or metal inner containers may be used to avoid this issue.
- Cost of construction of ZECC and acquisition of crates is a barrier for many potential users studied.
- As the ZECC is a temporary structure, there is risk of the ZECC falling apart especially because of heavy rain.
- Organizing the construction, use, and security of shared ZECCs requires planning and coordination.

Recommendations for Scale-up

In addition to recommendations for construction, use, and dissemination that have been outlined elsewhere (Evaporative Cooling Best Practices Guide), the following recommendations were generated based on the results of this research study:

- Connect potential users with existing users of evaporative cooling devices to share advice on construction, and use, and cost of these devices.
- In addition to households and farmers, specifically, target the dissemination of evaporative cooling devices (ZECCs and clay pot coolers) to fruit and vegetable vendors and markets with permanent structures who suffer financial losses due to spoilage.

A completed brick Zero Energy Cooling Chamber in Gatisbo, Rwanda.

Introduction

In 2019, MIT D-Lab, in partnership with Agribusiness Associates Inc. and Horticulture Innovation Lab, conducted a research study on low-cost evaporative cooling devices designed to improve the postharvest storage of fresh produce. Most techniques for cooling and storing fruits and vegetables rely on electricity – which is unavailable or unaffordable in most rural areas in Rwanda and Burkina Faso – limiting access to effective and affordable postharvest storage options. The evaporative cooling devices that are the subject of this study function without the use of electricity and so are well suited for regions without electricity access, or where electricity dependent cooling and storage technologies are not affordable. Effective, affordable cooling and storage technologies have the potential to prevent food loss, increase access to fresh produce, and create opportunities for additional income generation in off-grid areas and where electricity is intermittent or prohibitively expensive (Arah, et al. 2016, Basediya, Samuel and Beera 2011, Odesola and Onwuka 2009).

This study has been conducted in collaboration with two Horticulture Innovation Lab's projects implemented by Agribusiness Associates Inc. 'Reducing Postharvest Losses in Rwanda' project is being implemented in partnership with Ministry of Agriculture and Animal Resources, Rwanda Agricultural Board, National Agriculture Development and Export Board and University of Rwanda. This Project has three Postharvest Training and Services Centers in Mulindi (Center), Busogo (North) and Rubona (South). 'Improving Postharvest Practices for Tomatoes in Burkina Faso' is being implemented in partnership with INERA. The Project has one Postharvest Training and Services Center in Kamboinsi at an INERA research station. Both projects have worked widely to increase the adoption of evaporative cooling devices.

The objective of this study is to evaluate a set of non-electric cooling and storage technologies – Zero Energy Cooling Chambers (ZECCs) and clay pot coolers – for their suitability to meet the postharvest storage needs of fruit and vegetable producers and consumers.

The challenge

Fruits and vegetables are living, breathing parts of plants and contain 65% to 95% water (Gorny 2001). Once harvested, their nutrients and water reserves begin to decline, contributing to deterioration and rot. Deterioration of fresh produce starts from the moment it is harvested and lasts until it reaches the table of the consumer. Postharvest losses – including mechanical damage, physiological, and biological deterioration – are affected by the handling, transportation, storage, and processing of the fruits and vegetables (Kumar, Basavaraja and Mahajanshetti 2006, Kader 2005, Emana, et al. 2017). The Rwanda project has conducted postharvest loss assessment studies on tomatoes, green bananas, green chilies and orange fleshed sweet potatoes, which show high quality and quantity loss across all 4 crops studied.

Storage conditions throughout the supply chain play an important role in preventing postharvest losses for fruits and vegetables. While the optimal storage conditions vary for different fresh produce, many fruits and vegetables are best stored in a cool and humid environment to prevent rot and dehydration (McGregor 1989). The Rwandan National Horticulture Strategy (December 2014) estimates that one million rural households in Rwanda grow horticultural commodities, principally for home use and sale. For most rural households, home-produced fruits and vegetables provide an important source of the micro-nutrients necessary for a healthy balanced diet.

Tomatoes are an important source of income and a key ingredient in the local cuisine of Burkina Faso and an important crop for increasing household resilience and nutrition. However, the farming of tomatoes is largely at a subsistence level and farmers face many challenges, chief among them is decreased bargaining power due to a supply glut. They are also susceptible to degradation through dehydration, rot, bruising, and fungal growth. In both cases, access to improved storage could provide benefits at several stages along the value chain including on the farms directly after harvest, at farming cooperative aggregation centers, for fresh produce vendors at markets, and in consumers' homes.

Audience for this report

Increased availability of suitable cooling and storage technologies would allow producers, distributors, and consumers to improve shelf life, leading to reduced food loss, increased access to nutritious foods, and financial savings. The results of this research report are intended to provide new information on the performance and potential of evaporative cooling devices in Rwanda and Burkina Faso.

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

While evaporative cooling postharvest storage technologies have the potential to address these challenges, more research is needed to provide evidence increasing the dissemination of evaporative cooling technologies in regions where they may be able to provide improved postharvest fruit and vegetable storage. This study looks to address this gap through the following three areas of research:

- The **Sensor Results** section of this report provides information on the interior storage conditions (temperature and humidity) that were achieved during testing of various types of evaporative cooling devices.
- The **Shelf Life Results** section provides information on the shelf life of selected fruits and vegetables stored in evaporative cooling devices compared to storage in the ambient environment.
- The **User Interview Results** section provides insights from existing users and potential users, into fresh produce purchased and produced, existing methods for fresh produce cooling and storage, need for improved cooling and storage technology, availability and cost of materials that can be used for evaporative cooling devices, and perceptions of evaporative cooling devices.

When using this report, it is important to consider the specific context, as the evaporative cooling technologies evaluated are not suitable for all contexts. Furthermore, local weather, access to water, and fresh produce 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 a need for improved postharvest storage for fruits and vegetables.

Overview of the evaporative cooling technologies

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

- Zero Energy Cooling Chambers – "ZECCs"
- Clay pot coolers – also known as "Zeer pots"

How evaporative cooling works

The ZECC 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 fruits and 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. However, the rate of evaporation of water is highly dependent on the ambient humidity. When the ambient humidity is higher, there is a less significant reduction of the interior temperature.

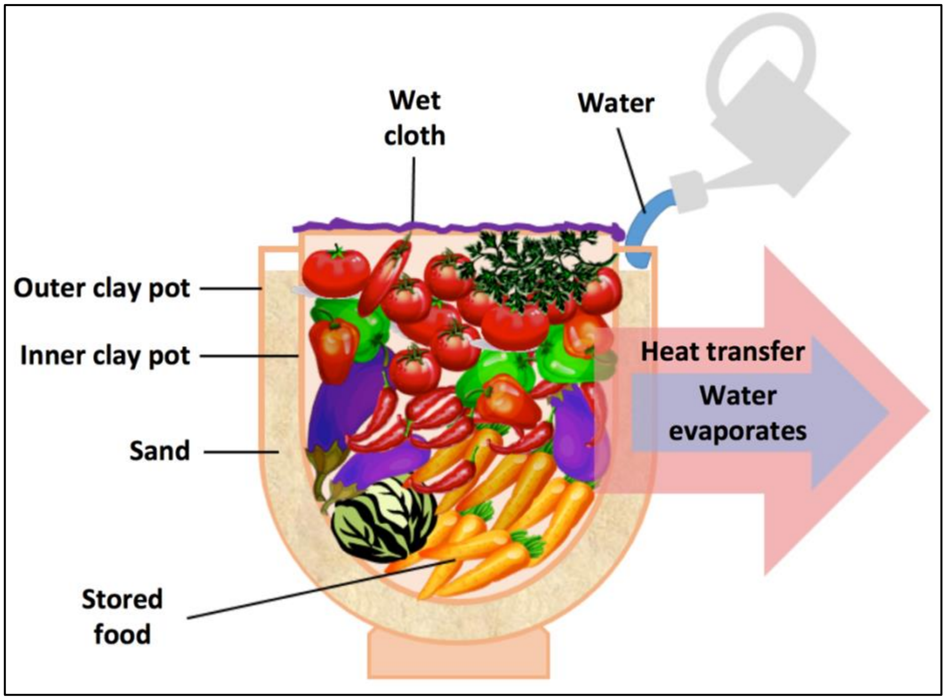

Figure 1: Diagram of a clay pot in clay pot cooler, covered by a wet cloth.[2]

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[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 ZECCs

Zero Energy Cooling Chambers (ZECCs) can be made from locally available materials including bricks, sand, wood, straw, gunny or burlap sack, and twine. Due to their relatively large size, ZECCs are typically used by larger producers or community groups. The brick ZECC was originally developed in India by Susanta K. Roy and D.S. Khuridiya in the early 1980s (Roy and Khurdiya 1982, Roy and Khurdiya 1985) to address fruit and vegetable postharvest losses, especially in rural areas without electricity. Roy and Khuridiya's ZECC 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 ZECC, food is placed in unsealed plastic containers, to keep the produce off the ZECC's floor, allow them to breathe, and allow for the circulation of cool, humid air inside the device. Details on how to construct and use a brick ZECC can be found in *Evaporative Cooling Best Practices Guide*. (Verploegen, Rinker and Ognakossan 2018). Additional images of ZECCs are available in Figure 2 of the Appendix.

Figure 2. Brick evaporative cooling device in Rubona, Rwanda.

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 in the interior pot, and both pots are covered with a lid or a damp piece of cloth. Several variations on the common pot-in-pot design were included in this study. The following configurations were tested:

- Clay pot in a clay pot (Rwanda and Burkina Faso)
- Plastic container in a clay pot (Rwanda)
- Metal container in a clay pot (Rwanda)
- Clay pot in a plastic dish (Rwanda and Burkina Faso)
- Clay pot in a metal dish (Rwanda and Burkina Faso)
- Plastic container in a clay dish (Burkina Faso)

Additional images of clay pot coolers are available in the “Sensor Results” section and in Figure 3 of the Appendix.

Figure 3. Examples of clay pot coolers included in this study
Left: A clay pot-in-pot cooler with a cloth cover and a data logger mounted on the side
Center: A clay pot in a plastic dish with the cloth cover pulled back
Right: A plastic container in a clay pot with filled with chili peppers for storage

Previous Research Results

Several studies present findings indicating that the improved storage conditions provided by evaporative cooling devices lead to improved fruit and vegetable quality – such as weight, color, firmness, and deterioration – resulting in extended shelf life. (Basediya, Samuel and Beera 2011, Ambuko, et al. 2017). Because evaporative cooling devices do not require electricity to function, they have the potential to be particularly beneficial for users in areas with limited or prohibitively expensive electricity access. Regardless of the context, the low energy consumption and use of simple materials make evaporative cooling devices an environmentally friendly alternative to refrigeration systems that use electricity.

Reports from multiple studies in India indicate that brick ZECCs 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 and Beera 2011, Kumar, Mathur and 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). Research conducted by MIT D-Lab and the World Vegetable Center in Mali showed that when the ambient humidity is < 40%, brick ZECCs and clay pot coolers can be expected to decrease in the average temperature and peak daily temperature between by 5 – 7 °C and 8 – 12 °C, respectively. This research showed that clay pot in a plastic dish configuration provides similar performance to the more common pot-in-pot design (Verploegen, Sanogo and Chagomoka 2018). Across all of the studies referenced, regardless of the ambient conditions, the brick ZECCs and clay pot coolers were shown to maintain relative humidity above 80% in the interior of the device where the fresh produce is stored. The same principle of evaporative cooling has been used with other designs and materials such as with charcoal coolers (Rathi and 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 and Onwuka 2009, Roy and Khurdiya 1985).

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 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 postharvest storage of fruits and vegetables in Rwanda and Burkina Faso and used a combination of:

- Electronic sensors to monitor the performance of the evaporative cooling devices
- Measurements of fruit and vegetable shelf life stored in evaporative cooling devices compared to storage in ambient conditions
- Structured user interviews with existing and potential users of evaporative cooling devices, fresh produce vendors, and producers of clay pots and other containers.

The research was conducted over a period of three months, February to April of 2019, at one location in the town of Kamboinse in Kadiogo Province, Burkina Faso and three locations in Rwanda (Mulindi, Rubona, and Busogo), shown in the map below.

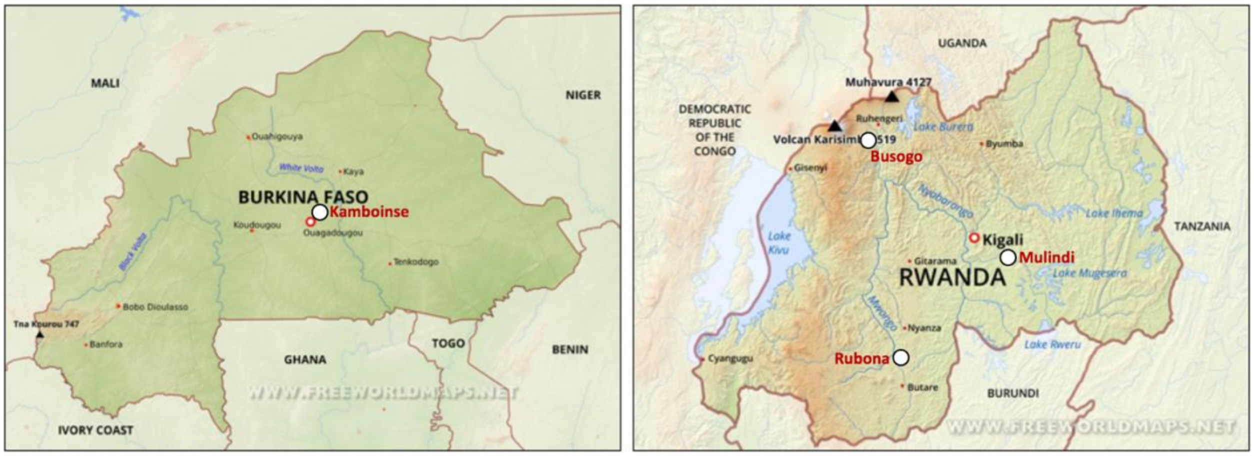

Figure 4. Left: A map of Burkina Faso. Right: A map of Rwanda. The locations where the study was conducted are labeled with white circles and red text.

The evaporative cooling devices included in this study were selected to include a range of designs constructed from locally available materials. The devices in the study were located at Postharvest Training and Service Centers (PTSCs) operated by Agribusiness Associates. The ZECCs were all installed prior to the beginning of this research study. The clay pot coolers were assembled for the purposes of this study. A list of evaporative cooling and storage devices included in the study can be found in Table 1 of the Appendix.

Electronic sensors methodology

Electronic sensors developed by Sensen were installed on the ZECCs (4) and clay pot coolers (16) monitored the following parameters:

- Exterior (ambient) temperature
- Exterior (ambient) relative humidity
- Interior temperature
- Interior relative humidity
- Sand moisture

Data for each of the five parameters were recorded every five minutes for the three months of the study period. Project staff were trained on the installation and data retrieval for the electronic sensors designed for this study. Additional information on the sensors used for data collection can be found in Figure 4 of the Appendix.

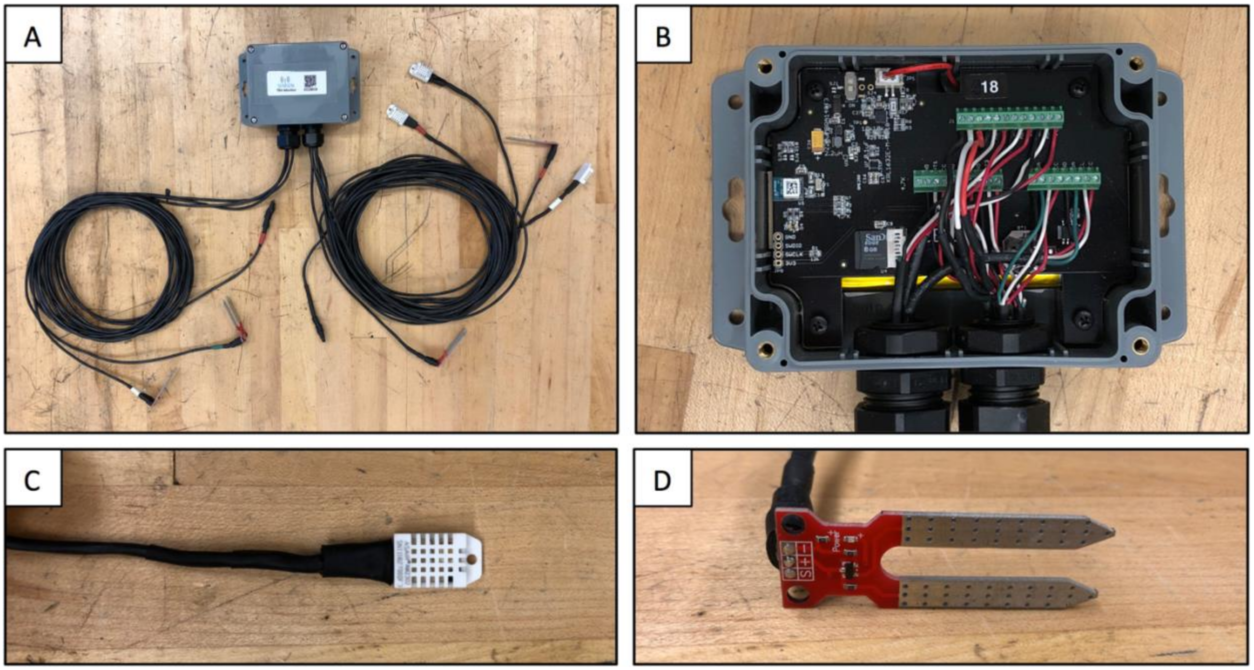

Figure 5. The sensors used for electronic data collection
A) A full sensor data logger with sensors attached; B) Interior of sensor control box;
C) Temperature and humidity sensor; D) Moisture sensor.

Fruit and vegetable shelf life methodology

Measurement of fruit and vegetable shelf life was conducted for a variety of fresh produce in each of the evaporative cooling devices included in this study. Fruits and vegetables that were recently harvested before being fully ripe were purchased, and two to five kilograms of each fruit or vegetable was weighed at the start of the experiment, then placed in each of the evaporative cooling devices and in a container in the shade exposed to ambient conditions. The fresh produce (tomatoes, mangoes, carrots, cabbage, chili peppers, and French beans) was weighed and visually inspected for evidence of fungal growth, rot, dehydration, bruising, discoloration, or other signs of deterioration every 2 – 3 days. The fresh produce was left in the chamber until signs of deterioration were observed, or the fruits and vegetables were determined to be fully ripe through visual inspection. The crops chosen are those susceptible to high losses and are grown in the different experiment sites.

User interview methodology

Structured individual interviews were conducted with ZECC users, farmers and households that are potential users of evaporative cooling devices (non-users), fresh produce vendors, and vendors of clay pots and other containers. Table 1 shows the number of each interview type conduced in Rwanda and Burkina Faso. These interviews explored:

- Types of fruits and vegetables purchased and produced
- Existing methods for fresh produce cooling and storage
- Need for improved cooling and storage technology
- Availability and cost of materials that can be used for evaporative cooling devices

Respondents were randomly selected among members of farming cooperatives whose members have received agricultural training from the Rwanda and Burkina Faso project and households in communities near the Postharvest Training and Service Centers (PTSCs). Fresh produce vendors and vendors of clay pots, plastic containers, and metal dishes were randomly selected from markets where the farmers and households purchase these products. The interview questionnaires and other data collection tools used for this study can be found in the Appendix.

Table 1: The number of each type of interview conducted in Rwanda and Burkina Faso

Country	Interview type ZECC users (farmers)	Non-users (farmers)	Non-users (households)	Fresh produce vendors	Clay pot and container vendors
Rwanda	8	55	0	10	4
Burkina Faso	0	47	32	15	15

Sensor Results

The data collected from the sensors was used to determine the temperature and relative humidity changes in the interior of the ZECCs and clay pot coolers as a function of ambient temperature and humidity, and the frequency of watering. One sensor measuring the exterior (ambient) temperature and humidity was placed near the ZECC or clay pot coolers. Sensors measuring the interior temperature and humidity were located inside the ZECC or clay pot coolers and a moisture sensor was placed in the sand layer between the two brick walls. During the period where data was being collected, water was regularly added to ensure that the sand in the evaporative cooling devices remained moist.

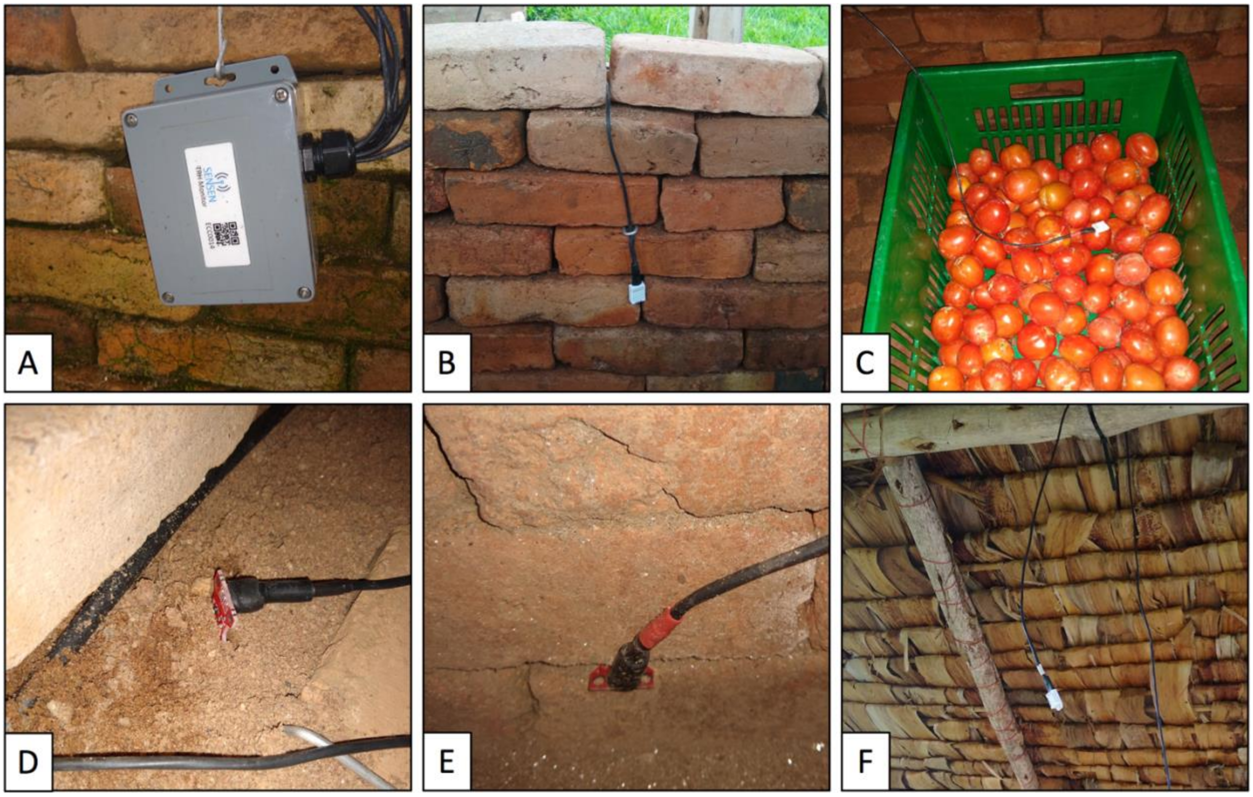

Figure 6. Sensor placement on a brick ZECC in Mulindi, Rwanda
A) Sensor data logger mounted on a brick ZECC
B) Temperature and humidity sensor mounted on the interior brick wall
C) Temperature and humidity sensor in a plastic crate containing tomatoes
D) Moisture sensor in the top of the sand layer between the two brick walls
E) Moisture sensor in at the bottom of the exterior brick wall
F) Ambient temperature and humidity sensor under the ZECC shade cover

Figure 7. Sensor placement on a clay pot coolers in Mulindi, Rwanda
A) Sensor data logger and moisture sensor mounted on a clay pot in a clay pot containing tomatoes
B) Ambient temperature and humidity sensor under the shade cover
C) Temperature and humidity sensor in a plastic container in a clay pot containing chili peppers
D) Moisture sensor in the sand layer between a metal container and a clay pot

Brick Zero Energy Cooling Chamber (ZECC) sensor data

The climates in Rwanda and Burkina Faso are significantly different, with the humidity being significantly higher in Rwanda throughout the year, including during the time when this research was conducted (average humidity of 82% and 16%, for Rwanda and Burkina Faso, respectively). The following section will compare brick ZECCs with two different designs in two different climates.

Figure 8. Left: ZECC in Mulindi, Rwanda with bricks that are stacked, a cloth cover supported by a wood and straw frame, and a structure with a tightly woven straw roof providing shade a majority of the day. Right: ZECC in Kamboinse, Burkina Faso with bricks that are held together by mortar, a plywood cover, and a wooden and straw structure that provides partial shade throughout the day.

Impact of humidity on cooling efficiency

When discussing the resulting interior storage conditions (temperature and humidity), it is important to consider the interior temperature achieved in relation to the ambient conditions. Although the ambient humidity is significantly lower in Burkina Faso, when water is added at least once per week, both ZECCs provide an average interior humidity above 90%. Furthermore, both ZECCs maintain interior humidity greater than 80% throughout the day, which is consistent with results from several other studies (Verploegen, Sanogo and Chagomoka 2018, Basediya, Samuel and Beera 2011, Odesola and Onwuka 2009).

The temperature decrease that can be achieved is highly dependent on the ambient humidity, where higher humidity significantly reduces the cooling that can be achieved through the evaporation of water. The minimum temperature that can be achieved through evaporative cooling at any specific time is called the “wet-bulb temperature” (LeRoy and Kuehn 2001). The wet-bulb temperature is dependent on the ambient temperature and humidity, where higher humidity results in a wet-bulb temperature that is closer to the ambient temperature. When evaluating the performance of an evaporative cooling device, we recommend considering the “cooling efficiency,” which is the observed temperature decrease divided by the maximum potential temperature decrease. The cooling efficiency is calculated as follows:

$$\text{Cooling efficiency} = \frac{(\text{Ambient temperature} - \text{Interior temperature})}{(\text{Ambient temperature} - \text{Wet bulb temperature})}$$

Interior temperature and humidity of brick ZECCs

Figures 9 and 10 show the ambient, interior, and wet-bulb temperature over 5-day periods for the two brick ZECCs, one in Mulindi, Rwanda and one in Kamboinse, Burkina Faso. It is important to note that even when there is not a significant decrease in the average temperature, it is beneficial to store fresh produce in an environment with a stable temperature. While the ambient temperature in Kamboinse, Burkina Faso fluctuates by more than 20 °C each day, the temperature inside the ZECC varies by less than 4 °C throughout a given day. Similarly, in Mulindi, Rwanda, the ambient temperature fluctuates by more than 10 – 15 °C each day, while the temperature inside the ZECC varies by less than 3 °C during a given day. Additionally, the peak daily temperature is reduced by 10 – 15 °C in Kamboinse, Burkina Faso and 7 – 12 °C in Mulindi, Rwanda, in both cases, avoiding peak temperatures above 30 °C. Such improved temperature stability and avoidance of high peak temperatures are expected to improve the shelf life of many fruits and vegetables.

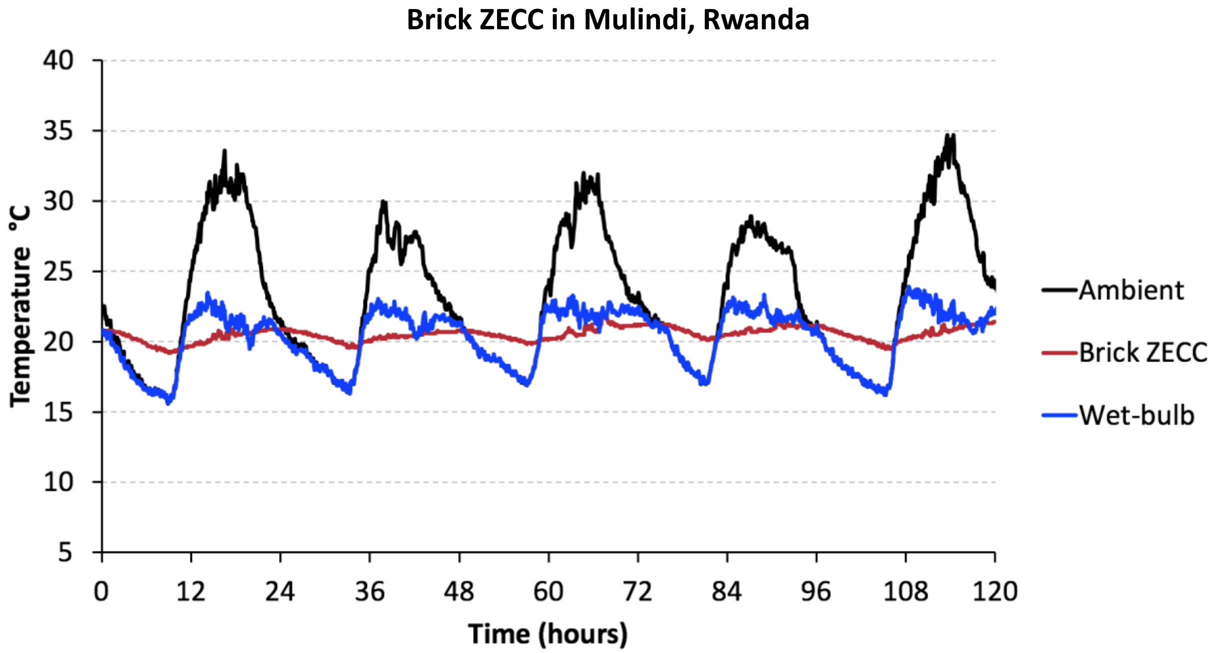

Figure 9. Typical daily ambient temperature, the interior temperature of the brick ZECC, and the wet-bulb temperature for a ZECC in Mulindi, Rwanda. The points where the wet-bulb temperature is the same as the ambient temperature corresponds to when the ambient humidity was 100%, and no evaporation can occur. Ambient humidity data over the same time period can be found in Figure 5 of the Appendix.

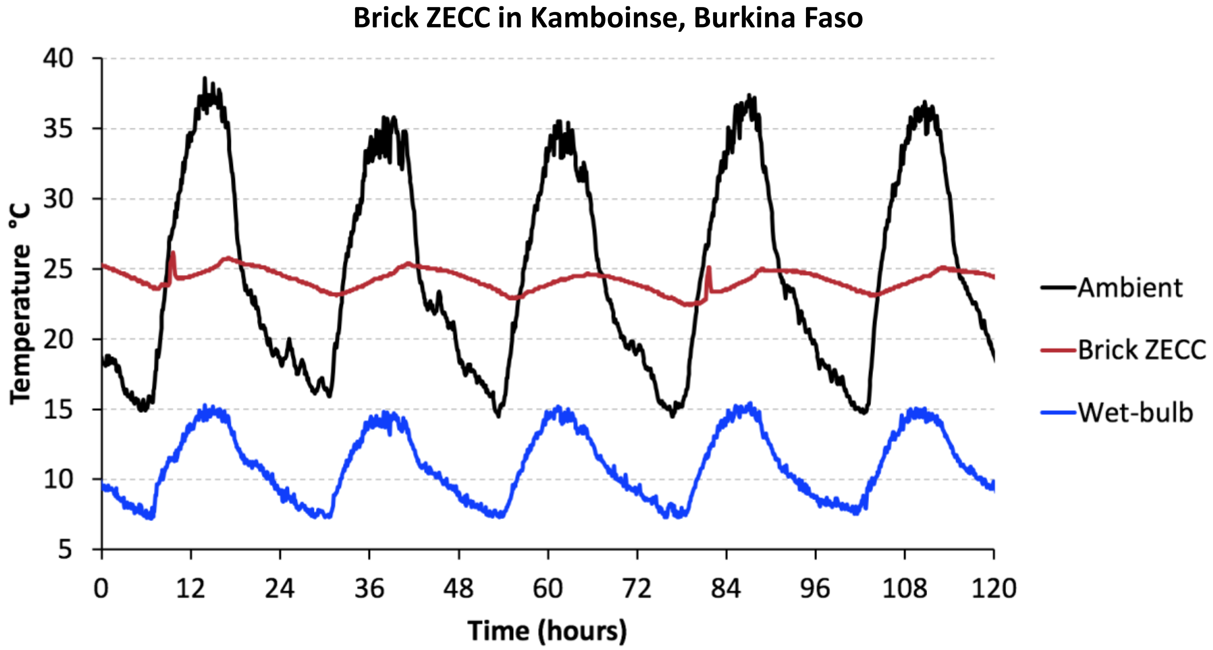

Figure 10. Typical daily ambient temperature, the interior temperature of the brick ZECC, and the wet-bulb temperature for a ZECC in Kamboinse, Burkina Faso. Ambient humidity data over the same time period can be found in Figure 5 of the Appendix.

As can be seen in Table 2, while the average ambient temperature is higher in Burkina Faso than Rwanda (25.3 °C and 22.6 °C, respectively), the average wet-bulb temperature in Burkina Faso is lower than in Rwanda (11.4 °C and 19.9 °C, respectively), yielding a theoretical temperature decrease of 13.9°C and 2.7 °C, for Burkina Faso and Rwanda, respectively. This difference is due to the significantly lower average ambient humidity in Burkina Faso (16.3%) compared to Rwanda (82.4%). While the brick ZECC in Mulindi, Rwanda only achieves a temperature drop of 2.1 °C, this is 77% of the theoretical achievable temperature drop (cooling efficiency) that can be achieved with the ambient conditions during this time period – indicating a well-designed ZECC. In contrast, the ZECC in Burkina Faso only achieves a 0.6 °C temperature decrease, yielding a cooling efficiency of only 4%. In comparison, a brick ZECC in Bamako, Mali that was the subject of previous research (Verploegen, Sanogo and Chagomoka 2018), achieved an average interior temperature of 23.9 °C, 3.9 °C lower than the average ambient temperature when ambient conditions averaged 27.8 °C and 21% relative humidity. The average wet-bulb temperature for these conditions is 14.3 °C (13.4 °C lower than the average ambient temperature), giving a cooling efficiency of 29%.

Table 2: Brick ZECC performance in Mulindi, Rwanda and Burkina Faso[1]

	Humidity	Average Temperature	Average Temperature Decrease	Cooling Efficiency	Daily Temperature Fluctuations	Decrease in Peak Daily Temperature
Ambient in Mulindi, Rwanda	82.4%	22.6 °C	-	-	15 – 20 °C	-
Interior of brick ZECC in Mulindi, Rwanda	99.9%	20.5 °C	2.1 °C	77%[3]	3 – 4 °C	7 – 12 °C
Wet-Bulb in Mulindi, Rwanda[2]	-	19.9 °C	2.7 °C	-	5 – 10 °C	-
Ambient in Burkina Faso	16.3%	25.3 °C	-	-	20 – 25 °C	-
Interior of brick ZECC in Burkina Faso	93.1%	24.7 °C	0.6 °C	4%	2 – 3 °C	10 – 15 °C
Wet-Bulb in Burkina Faso[2]	-	11.4 °C	13.9 °C	-	5 – 10 °C	-

[1] *The data used in this analysis was taken from a time period when each of the brick ZECCs had water added at least every 5 days, and the daily ambient temperature and humidity profiles did not have large fluctuations was selected for this analysis. Data was collected between January 29 and February 11, 2019, from the brick ZECC in Mulindi, Rwanda, and from the brick ZECC in Kamboinse, Burkina Faso between February 4 and February 14, 2019 (brick ZECCs are pictured above).*

[2] *The wet-bulb temperature is dependent on ambient temperature and humidity* (LeRoy and Kuehn 2001).

[3] *Due to the small difference between the ambient temperature and the wet-bulb temperature in Rwanda, the cooling efficiency is sensitive to small variations in the interior temperature of the ZECC.*

Brick ZECC design considerations

Considering the design of the brick ZECC in Kamboinse, Burkina Faso there are several reasons that the cooling efficiency is not higher, including:

- Mortar is used to secure the bricks, which reduces the surface available for water to evaporate from (mortar is less permeable to water than most bricks). Mortar was used to make the ZECC permanent as the area is prone to flash floods.
- A solid wooden cover is used to provide security (the wooden cover can be locked to the ZECC wall when closed). However, this cover does not absorb water and is not, therefore, an effective surface for evaporative cooling.
- The wooden structure with a loose straw roof does not provide good shade coverage, as light passes between the pieces of straw and the roof of the structure is not large enough or positioned to effectively prevent exposure to direct sunlight throughout much of the day.

The brick ZECCs in Rwanda were constructed using stacked bricks, a cover directly on top of the ZECC made from a wooden frame and woven straw covered in a cloth blanket and located under thatched shade covers that extend far enough past the ZECC to protect from direct sunlight for a majority of the day. While these design features improve the cooling efficiency, they are not as critical in high humidity environments, as the wet-bulb temperature limits the cooling efficiency that can be achieved. Recommended guidelines related to these considerations are provided in the section “Sensor Data: Key Takeaways.”

Figure 11. Construction of a brick Zero Energy Cooling Chamber by cooperative members in Gakenke, Rwanda.

Clay Pot Cooler sensor data

Clay pot coolers in Rwanda

Four different clay pot cooler designs were tested at three locations in Rwanda (Mulindi, Rubona, and Busogo). The materials for the clay pot coolers were purchased in Kigali in triplicate, so the three versions of each design are nearly identical (see images below).

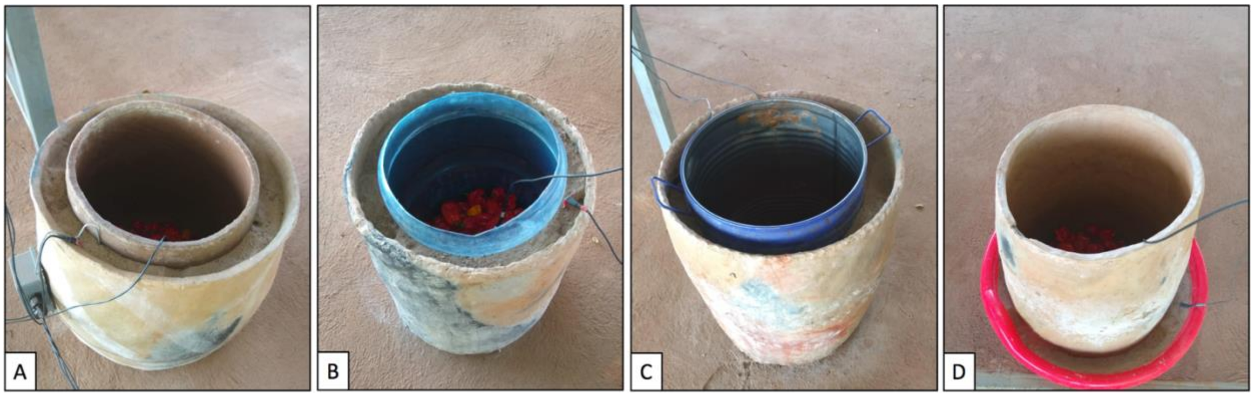

Figure 12. Examples of the 4 clay pot cooler designs studied at each of the three locations in Rwanda.
A) Clay pot in clay pot with sensor data logger attached
B) Plastic container in a clay pot
C) Metal container in a clay pot
D) Clay pot in a plastic dish
All of the clay pot coolers are covered with wet cloth when being used and have a capacity of ~ 35 liters.

By measuring the performance of these clay pot coolers in the same environmental conditions, we look to gain insights into how design variations impact the performance of the devices. Figure 13 shows the ambient temperature, the wet-bulb temperature and the interior temperature of two of the clay pot coolers, the “Pot-in-dish” and “Pot-in-pot”, and Table 3 shows a summary of the performance of all 4 devices. Similar to the data for the brick ZECC in Mulindi, Rwanda, due to the high ambient humidity – a monthly average of greater than 75% – the wet-bulb temperature is only 3.8 °C lower than the ambient temperature, limiting the amount of cooling that can be achieved through the evaporation of water. All 4 of the clay pot coolers studied in this portion of the research provided an average interior humidity greater than 95% and provide decreases in the average temperature between 1 and 3 °C. In addition to the average temperature decrease, the daily peak temperature and temperature fluctuations are both reduced. On days without significant amounts of rain[3], the ambient temperature typically fluctuates between 10 – 15 °C each day, and the temperature within the clay pot coolers has temperature fluctuations of 6 °C or less on most days while reducing the peak daily temperature by 5 – 10 °C.

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[3] On days with significant amounts of rain, the ambient temperature typically decreases significantly reducing the daily temperature fluctuations and the peak daily temperature.

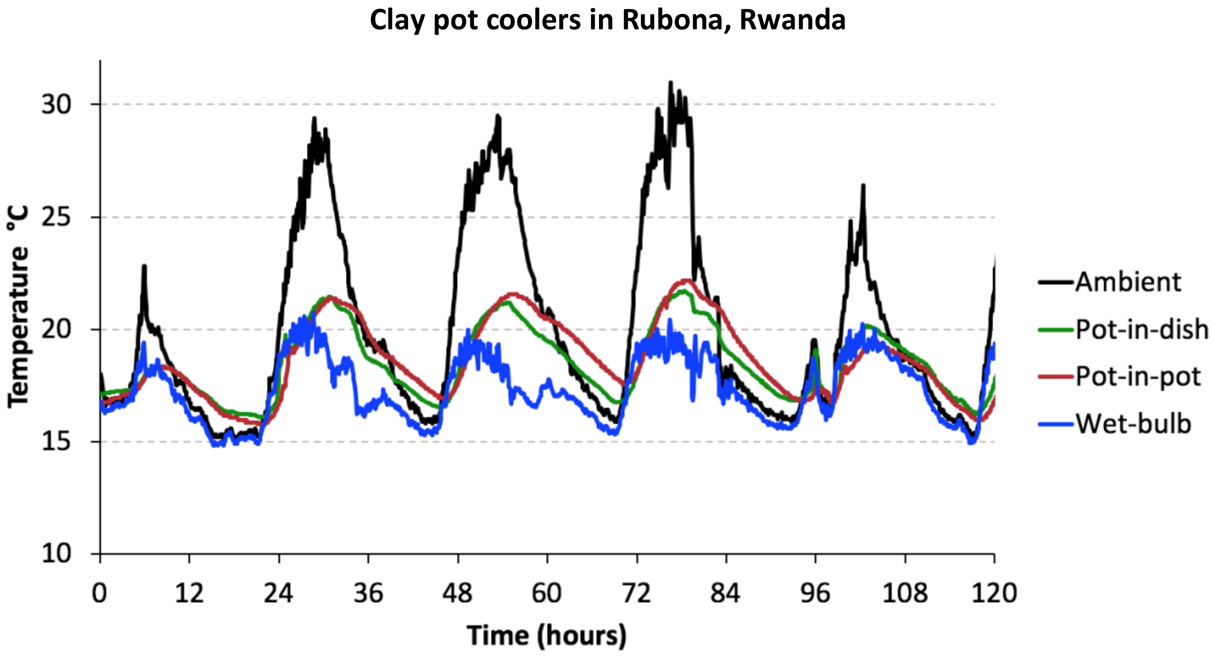

Figure 13. Typical daily ambient temperature, the interior temperature of the clay pot in a plastic dish (Pot-in-dish), the interior temperature of the clay pot in pot cooler (Pot-in-pot), and the wet-bulb temperature for a ZECC in Rubona, Rwanda. Only two of the four devices are shown in this figure for clarity, a summary comparing the performance of all four devices is shown below and in the Appendix. The points where the wet-bulb temperature is the same as the ambient temperature corresponds to times when the ambient humidity was 100%, and thus no evaporation can occur. The data in this figure was collected between March 6 and March 10, 2019.

Table 3: Clay pot cooler performance in Rubona, Rwanda[1]

	Humidity	Average Temperature	Average Temperature Decrease	Cooling Efficiency	Daily Temperature Fluctuations	Decrease in Peak Daily Temperature
Ambient in Rubona, Rwanda	76.8%	20.3 °C	-	-	12 - 16 °C	-
Clay pot in clay pot	99.9%	18.6 °C	1.7 °C	43%	4 - 7 °C	6 - 8 °C
Plastic container in clay pot	99.6%	18.5 °C	1.8 °C	47%	4 - 7 °C	6 - 8 °C
Metal container in clay pot	95.7%	18.1 °C	2.2 °C	57%	4 - 7 °C	6 - 8 °C
Clay pot in plastic dish	99.9%	18.8 °C	1.5 °C	39%	4 - 7 °C	6 - 8 °C
Wet-Bulb in Rubona, Rwanda[2]	-	16.4 °C	3.8 °C	-	-	-

[1] *The data in this table was collected between February 10 and March 13, 2019.*

[2] *The wet-bulb temperature is dependent on the ambient temperature and humidity* (LeRoy and Kuehn 2001).

Clay pot coolers in Burkina Faso

Four clay pot coolers were assembled using materials found at roadside markets in Kamboinse, Burkina Faso, images of each are shown below.

Figure 14. Examples of the 4 clay pot cooler designs studied in Burkina Faso.
A) Small clay pot in a clay pot (~ 5 liter capacity; 2,500 Fcfa; $4.28) with sensor data logger attached
B) Medium clay pot in a plastic dish (~ 20 liter capacity; 3,300 Fcfa; $5.65)
C) Large clay pot in a metal dish (~ 60 liter capacity; 13,000 Fcfa; $22.27)
D) Plastic bucket in a clay pot (~ 10 liter capacity; 2,700 Fcfa; $4.63)
All of the clay pot coolers are covered with wet cloth when being used.

The clay pot coolers in Burkina Faso showed the most significant average temperature decreases (> 4°C) of all of the devices tested in this research, particularly the small clay pot in clay pot device which provided nearly an 8 °C decrease in the average temperature (see Table 4). While this device provides the best performance, the utility for storing significant amounts of fresh produce is limited by the volume available for storage (~ 5 liters) and is best suited for household use.

Figure 15 shows a plot of the ambient temperature, the wet-bulb temperature and the interior temperature of two of the clay pot coolers, the Medium clay pot in a plastic dish “Pot-in-dish” and Small clay pot in a clay pot “Pot-in-pot” over a 5-day period. In addition to the temperature drop provided, all 4 devices significantly reduce the ambient temperature fluctuations, from over 20 °C to less than 3 °C , and the peak daily temperature, from 35 – 45 °C to 25 – 30 °C. The three devices with a clay pot as the interior chamber provided an average interior humidity of > 95%. While the plastic bucket in clay pot device provided a significant increase in humidity, 73.8% compared to an average ambient humidity of 16.8%, it is lower than the devices with a clay pot as the interior chambers. This is likely due to the inability of water to penetrate through the plastic pail, leaving the moisture from the cloth covering the device as the only source of humidity for the fruits and vegetables stored inside. Thus, when the cloth cover becomes dry, which can happen quickly in during the middle of the day when ambient conditions reach 40 °C and 10% humidity, the chamber can start to dry out. This illustrates the importance of either designing the clay pot cooler so that the water stored in the sand layer can provide moisture to maintain a high humidity environment, or to minimize the need to monitor the device to keep the cloth cover wet.

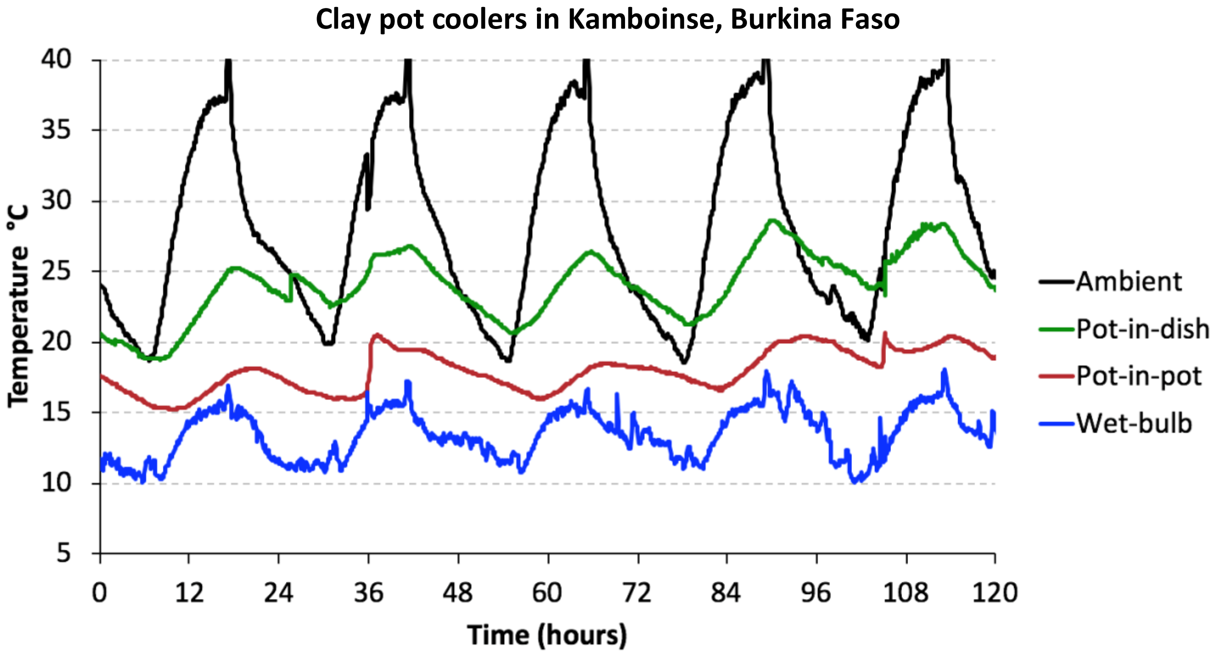

Figure 15. Typical daily ambient temperature, the interior temperature of the medium clay pot in a plastic dish (Pot-in-dish), the interior temperature of the small clay pot in a clay pot (Pot-in-pot), and the wet-bulb temperature. The data in this figure was collected between March 4 and March 8, 2019.

Table 4: Clay pot cooler performance in Kamboinse, Burkina Faso[1]

	Humidity	Average Temperature	Average Temperature Decrease	Cooling Efficiency	Daily Temperature Fluctuations	Decrease in Peak Daily Temperature
Ambient in Burkina Faso	16.8%	28.1 °C	-	-	15 - 20 °C	-
Small clay pot in a clay pot	99.9%	20.3 °C	7.8 °C	61%	3 - 6 °C	12 - 20 °C
Medium clay pot in a plastic dish	98.0%	23.7 °C	4.4 °C	35%	5 - 8 °C	8 - 11 °C
Large clay pot in a metal dish	99.9%	23.7 °C	4.5 °C	35%	5 - 8 °C	8 - 11 °C
Plastic bucket in a clay pot	73.8%	23.5 °C	4.6 °C	36%	7 - 10 °C	6 - 10 °C
Wet-Bulb in Burkina Faso[2]	-	15.4 °C	12.7 °C	-	-	-

[1] *The data in this table was collected between February 20 and March 25, 2019.*

[2] *The wet-bulb temperature is dependent on the ambient temperature and humidity* (LeRoy and Kuehn 2001).

Sensor data: Key takeaways

Impact of ambient humidity: wet-bulb temperature and cooling efficiency

When evaluating evaporative cooling devices, the temperature decrease achieved should be considered in relation to wet-bulb temperature, particularly when comparing across regions or seasons with different ambient conditions. Looking at the temperature decrease alone is not enough to provide insight into the efficacy of a ZECC or clay pot cooler design.

Summary of sensor results from brick ZECCs

A brick ZECC that has a reduced surface area available for water evaporation and was exposed to direct sunlight for a significant portion of the day showed a low cooling efficiency (4%) compared to brick ZECCs with more optimized designs that achieve cooling efficiencies ranging of 29% to 77%.

Even when evaporative cooling devices do not provide significant decreases in the average temperature, brick ZECCs provide other benefits including decreased daily temperature fluctuations, decreased peak daily temperatures, and increased interior humidity, all of which are expected to improve fruit and vegetable shelf life. For example, the ambient temperature in Kamboinse, Burkina Faso fluctuates by more than 20 °C each day, the temperature inside the ZECC varies by less than 4 °C throughout a given day. Similarly, in Mulindi, Rwanda, the ambient temperature fluctuates by more than 10 – 15 °C each day, while the temperature inside the ZECC varies by less than 3 °C during a given day. Additionally, the maximum daily temperature is reduced by 10 – 15 °C in Kamboinse, Burkina Faso and 7 – 12 °C in Mulindi, Rwanda.

Recommendations for optimized brick ZECC design

1) Stacked bricks are commonly used and recommended for a brick ZECC of this height. If a brick ZECC taller than 1.5 meters is being constructed, then it is advisable to ensure that the brick walls cannot fall over and injure anyone. Some type of reinforcement, such as a wooden and wireframe or mortar may be necessary, along with an understanding of how these modifications will impact the performance of the ZECC.

2) A water absorbent cover directly on the top of the ZECC should be used to allow for subsequent evaporation from its surface and provide additional cooling. Effective materials include cloth or woven straw mats supported by a wooden frame. If additional security is needed, the cover could include a sturdy open wire mesh attached to a wooden frame that can be locked to secure the produce inside the chamber. The cover should also be sufficiently thick so that it can absorb a significant amount of water and provide thermal insulation if it does become dry.

3) The ZECC should be located where direct sunlight is blocked for as much of the day as possible. If constructing a shade cover, the roof material should not allow light to pass through and be large enough and well positioned to block the sun as it moves across the sky. If available, a tree with thick leaf coverage is also a good option. In addition to the shade provided, the transpiration of water from the leaves provides an additional cooling effect in the area under the tree. Mango trees are well suited for this, as they have thick leaf coverage that is low to the ground and wide enough to block the sun for most of the day.

Additional guidance on the construction can be found in: "*Evaporative Cooling Best Practices Guide*" (Verploegen, Rinker and Ognakossan 2018).

Summary of sensor results from clay pot coolers

The high humidity in Rwanda limits the amount of cooling that can be achieved through the evaporation of water.

The four clay pot cooler designs in Rwanda showed similar performance in terms of the interior temperature and humidity that are provided, although greater variations in performance may be observed in lower humidity environments where a larger degree of cooling can be achieved.

The clay pot coolers in Burkina Faso showed the most significant average temperature decreases (> 4°C), particularly the small clay pot in clay pot device which provided nearly an 8 °C decrease in the average temperature. While this device provides the best performance, it is best used at the household level because of its low storage volume (~ 5 liters).

Additional research in low humidity environments is needed to better understand how design variations impact the cooling that can be achieved. In high humidity environments, there may not be a strong incentive to optimize a device for the maximum cooling effect, which is limited by the wet-bulb temperature.

In cases where significant cooling is not achieved, the shelf life of fruits and vegetables has the potential to be improved by several other factors such as the reduced temperature fluctuations, decreased daily peak temperature, and increased interior humidity that all of the brick ZECCs and clay pot coolers provide.

Shelf life Results

Rwanda fruit and vegetable shelf life data

Across the three regions in Rwanda (Mulindi, Rubona, and Busogo), fruits and vegetables were selected for inclusion in this study based on their relative importance among farmers in each region. For the shelf life experiments two fruits or vegetables were tested in the same space, so care was taken to ensure that combinations selected were compatible, particularly with respect to ethylene production and sensitivity. The fruits and vegetables studied for each region are the following:

- Busogo: cabbages and carrots
- Rubona: tomatoes and chili peppers
- Mulindi: tomatoes and mangoes / chili peppers and French beans

In all cases, the produce stored in the evaporative cooling devices showed improved shelf life compared to the produce stored in the shade in ambient conditions. Each experiment was continued until all of the produce showed signs of deterioration or were determined to be fully ripe through visual inspection. Although the ZECCs and clay pot coolers in each of the three locations in Rwanda were constructed using very similar materials and designs, there are significant variations in factors impacting the shelf life of the produce including 1) the source of the produce being tested, and 2) weather variations affecting the ambient conditions during a specific experiment (either due to different location or time). Thus, our analysis will focus on comparisons between produce purchased at the same time and stored at the same location in different devices.

Busogo: cabbages and carrots[4]

The evaporative cooling devices provided significant improvement in shelf life for carrots and cabbage compared to ambient conditions. When stored in ambient conditions, the carrots and cabbage began to show signs of degradation (fungal growth, rot, bruising, or dehydration) after eight days. In comparison, when stored in any of the four clay pot coolers, both the carrots and cabbage were still edible after 18 days and retained over 85% of their original weight. The brick ZECC provided the same shelf life for carrots (shelf life > 18 days), but the cabbage began to lose weight and spoil after 12 days, which is still an improvement over the shelf life in ambient conditions.

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[4] The cabbages and carrots were stored in separate plastic containers for the ambient and brick ZECC experiments, and stored together in the four clay pot coolers

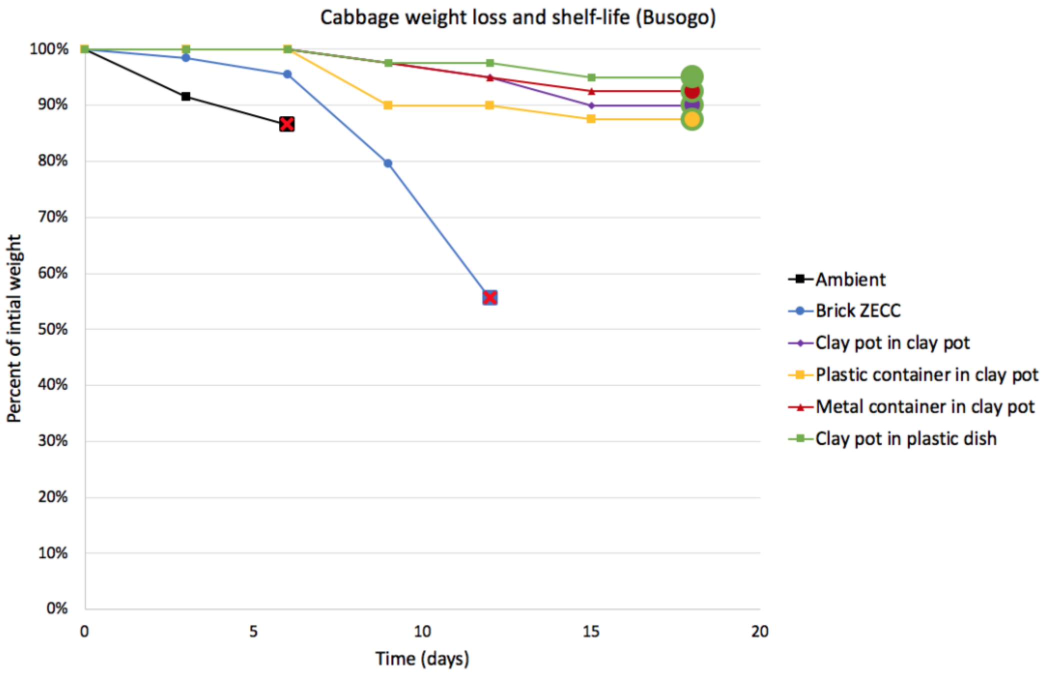

Figure 16. Weight loss and shelf life for cabbage in Busogo. The ending data points with a circle with a green border represent cabbage that was determined to be fully ripe at the conclusion of the experiment. The ending data points with a square and a red "X" represent cabbage that was fully spoiled at the point of the experiment indicated.

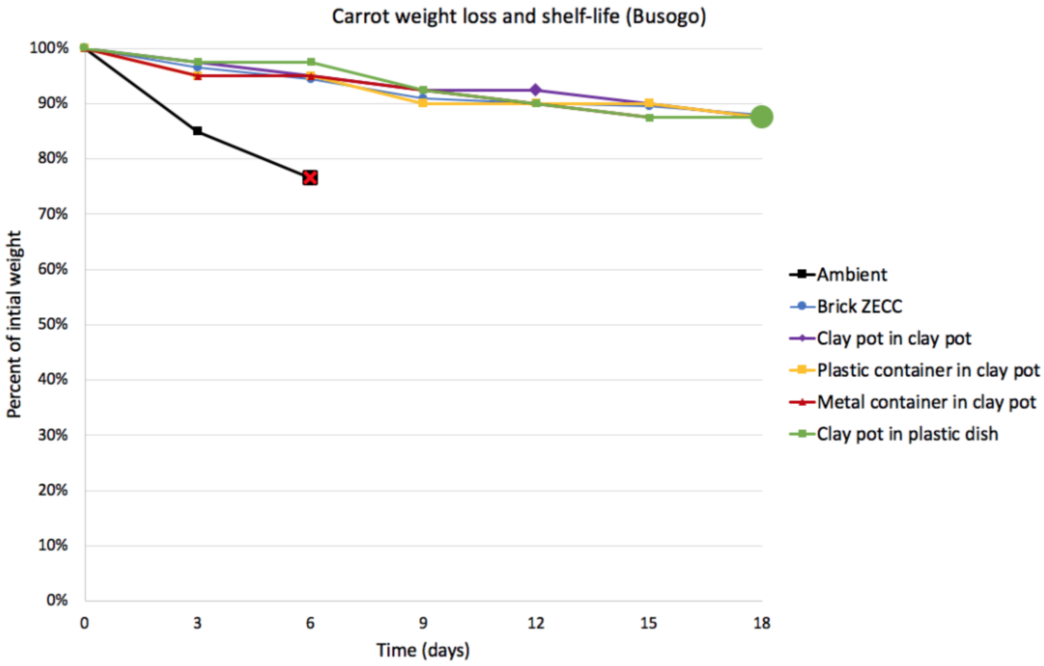

Figure 17. Weight loss and shelf life for carrots in Busogo, Rwanda. The ending data points with a circle with a green border represent carrots that was determined to be fully ripe at the conclusion of the experiment. The ending data points with a square and a red "X" represent carrots that was fully spoiled at the point of the experiment indicated.

Rubona: tomatoes and chili peppers[5]

When stored at ambient conditions over 60% of the chili peppers spoiled within 3 days, with only 5% of the chili peppers remaining unspoiled by the 9th day. When stored in the brick ZECC or clay pot coolers significant shelf life improvements were observed for the chili peppers, with minimal degradation observed until the 12th day of the experiment when they began to rapidly degrade. In contrast, the tomatoes stored in ambient conditions did not show significant signs of degradation, primarily shriveling, until the 9th day, with the tomatoes stored in the brick ZECC and clay pot coolers showing slightly prolonged shelf life (see Figure 6 in the Appendix).

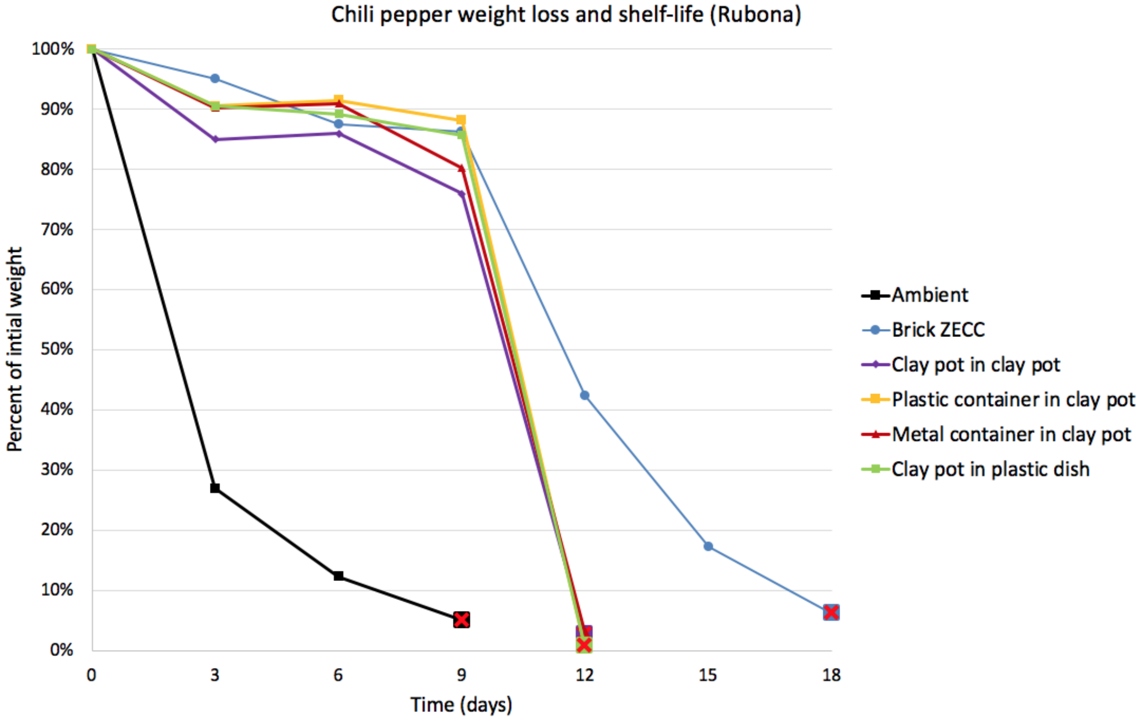

Figure 18. Weight loss and shelf life for chili pepper in Rubona, Rwanda. The ending data points with a circle with a green border represent chili pepper that was determined to be fully ripe at the conclusion of the experiment. The ending data points with a square and a red "X" represent chili pepper that was fully spoiled at the point of the experiment indicated.

Mulindi: tomatoes, mangoes, chili peppers, and French beans[6]

In Mulindi, the primary cause of spoilage for mangoes and tomatoes in the evaporative cooling devices was bruising and fungal growth at the area of the fruit or vegetable in contact with the inner surface of the chamber. This was particularly an issue with devices where the inner pot

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[5] The tomatoes and chili peppers were stored in separate plastic containers for the ambient and brick ZECC experiments, and stored together in the four clay pot coolers

[6] Two sets of experiments were conducted, the first with tomatoes and mangoes peppers were stored in separate plastic containers for the ambient and brick ZECC experiments, and stored together in the four clay pot coolers, and the second with chili peppers and French beans stored in separate plastic containers for the ambient and brick ZECC experiments, and stored together in the four clay pot coolers.

was made of clay. This could illustrate the importance of properly cleaning the interior chamber that is in contact with the fruits or vegetables. The devices with a metal or plastic interior chamber may be able to provide benefits in this regard, due to their smoother surface, which is easier to keep clean. Further research with a larger sample size is needed to validate this hypothesis.

Unlike the chili peppers from the experiment in Rubona, when stored in ambient conditions the chili peppers in Mulindi did not begin to show significant signs of degradation until the 10th day of the experiment. By the third day, the French beans stored in ambient conditions showed greater weight loss than those stored in the brick ZECC and clay pot coolers and spoiled after the 7th day. The French beans stored in the brick ZECC and clay pot coolers remained unspoiled after the 13th day and retaining 75 – 95% of their original weight. Both the chili peppers and the French beans had less weight loss when stored in the clay pot coolers as compared to the brick ZECC (see Figure 7 in the Appendix).

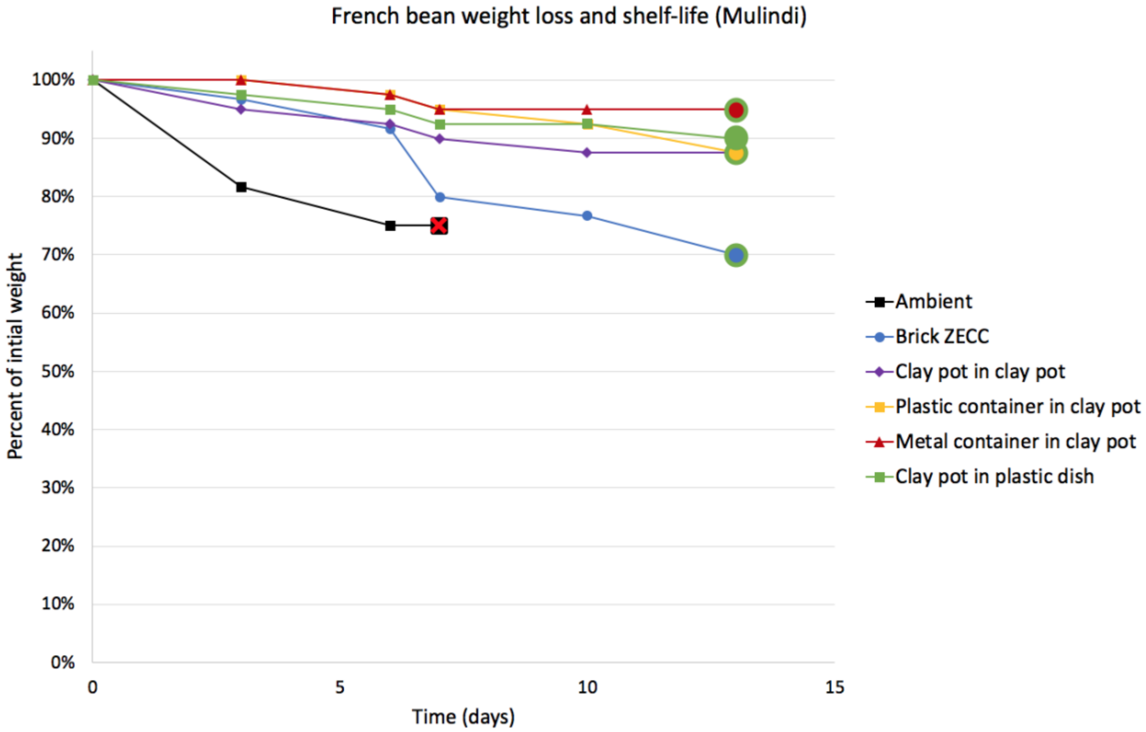

Figure 19. Weight loss and shelf life for French bean in Mulindi, Rwanda. The ending data points with a circle with a green border represent French bean that was determined to be fully ripe at the conclusion of the experiment. The ending data points with a square and a red "X" represent French bean that was fully spoiled at the point of the experiment indicated.

Table 5: Number of days until 50% of the fruits and vegetables are fully ripe* or spoiled**

		Storage condition					
Location	Product	Ambient	Brick ZECC	Clay pot in a clay pot	Plastic container in a clay pot	Metal container in a clay pot	Clay pot in a plastic dish
Mulindi	Tomatoes	12	12	12	12	12	12
	Mangoes	12	12	12	12	12	12
Mulindi	Chili Peppers	10	10	10	10	10	10
	French Beans	10	13	13	13	13	13
Rubona	Tomatoes	12	15	15	15	15	15
	Chili Peppers	3	12	12	12	12	12
Busogo	Cabbages	9	15	18	18	18	18
	Carrots	9	18	18	18	18	18

**The numbers in green indicate that at this point 50% or more of the produce was fully ripe. Ripeness is measured objectively according to a maturity index based on physical characteristics of the fruit or vegetable.*

***The numbers in grey indicate that at this point 50% or more of the produce had spoiled.*

Data on the weight loss and shelf life of the fruits and vegetables in these experiments can be found in Figures 5, 6, and 7 of the Appendix.

Fruit and vegetable shelf life: Key takeaways

Across all of the regions, there is a greater incidence of degradation due to dehydration (weight loss, cracking, and shriveling) for fruits and vegetables stored in ambient conditions, as compared to those stored in evaporative cooling devices, which provide a high humidity environment.

While these shelf life experiments provide an indication that evaporative cooling devices can improve fresh produce shelf life in multiple contexts, further research is needed to gain more conclusive evidence of the value that evaporative cooling devices can provide, and a deeper understanding of the factors that influence fruit and vegetable preservation in these devices.

When measuring the shelf life of fruits and vegetables, it is important to compare storage in an evaporative cooling device to that of the same fruits and vegetables in ambient conditions or other alternative methods of storage. Such comparative shelf life experiments should be conducted at the same location and time (to ensure the ambient conditions are the same), and with the same source of the fruits and vegetables. Additionally, care should be taken to account for the impacts of having multiple fruits and vegetables stored together, such as ethylene production and sensitivity, fungal contamination, spreading of rot from one fruit or vegetable to another in close proximity.

Figure 20. Nibagwire Claudine is the President of the Dufatanye-Nyanza cooperative, in Nyanza District of Rwanda. Claudine shared, "After being trained by the Project in May 2018 on small scale postharvest handling practices, I was motivated to build a ZECC to protect the produce against both weight loss, quality loss and price decrease. Since then, we are saving time as we used to harvest and deliver to the market immediately fearing the losses and the full day was busy but now we harvest and store the produce in the ZECC and continue our farm activities. We are now selling our vegetables twice a week on Mondays and Thursdays. If all the produce is not sold, we can store it back in the ZECC."

Interview Results

Users of evaporative cooling devices, fresh produce vendors, and producers of clay pots and other containers were interviewed to gain insights into:

- Types of fruits and vegetables purchased and produced
- Existing methods for fresh produce cooling and storage
- Need for improved cooling and storage technology
- Availability and cost of materials that can be used for evaporative cooling devices

Interviews with clay pot and container vendors

Fifteen vendors were randomly selected who sold clay, plastic, and metal containers in the Kadiogo province of Burkina Faso and were interviewed to gain an understanding of what products are available and how much they cost. All of the vendors specialize in selling either clay containers, or both metal and plastic containers. Clay pot prices range from 500 – 5,000 ($0.86 – $8.60) for various size pots, with smaller pots (~ 5 – 15 liters) averaging ~1,200 Fcfa ($2.06) and larger pots (~ 50 – 100 liters) averaging 4,200 Fcfa ($7.19). These clay pots are primarily sold to households for storing water because, in the Sahel region, it is common knowledge that storing water in a clay pot will keep it cooler than if it is stored in a plastic or metal container. Plastic dishes, buckets, and baskets, and metal dishes of various sizes ranging from 30 – 70 cm in diameter can be purchased for between 600 Fcfa ($1.03) and 4,500 Fcfa ($7.71); and an average price of 2,400 Fcfa ($4.11). These containers are primarily sold to women for washing clothes, dishes, and storing food. All of the vendors selling plastic and metal containers said they would deliver those products to their customers, but only a third of vendors reported that they would deliver clay pots to customers. This is likely because the clay pots are heavier and more fragile than plastic or metal containers. While the price is similar across the clay, plastic, and metal containers of similar size, the convenience of transporting plastic or metal containers may provide some advantages.

Interviews with current users of evaporative cooling devices

Five farmers and three cooperative leaders who are current ZECC users in Rwanda were interviewed about what they store in the ZECC and how it compares to other storage methods. All of the ZECC users report that it provides improved shelf life compared to storage in ambient conditions. The most common fruits and vegetables stored in ZECCs were amaranthus, cabbages, carrots, and tomatoes. Other produce these respondents stored in the ZECCs includes sweet potato, sweet peppers, pineapples, chayotes, beetroots, eggplants, French beans, chili peppers, spinach, peas, and passion fruits. Some specific shelf life improvements that were reported are shown in Table 6 below.

Table 6: Fresh produce shelf life reported by individual farmers

Produce	Shelf life in ambient conditions	Shelf life in brick ZECC
Carrots	2 days	4 days
Amaranthus	1 day	4 days
Cabbage	3 days	14 days
Tree tomato	6 days	10 days

Users reported their ZECCs can store 35 – 200 kg, with an average storage volume of 100 kg; and cost between 30,000 – 64,000 RWF, with an average cost of 46,000 RWF.

Interviews with potential users of evaporative cooling devices

Interviews were conducted with 57 farmers who are non-users of ZECCs in Rwanda, and in Burkina Faso 47 farmers, 13 public servants, and 19 traders, artisans, or private sector workers who are not currently using ZECCs or clay pot coolers. The farmers were randomly selected among members of cooperatives that the Project works with, and the non-farmer respondents were randomly selected from the communities surrounding the farming cooperative.

Interviews with farmers in Rwanda

All of the farmers interviewed in Rwanda are members of cooperatives, and 25% are also members of savings groups. Table 7 below shows the most common crops grown by the farmers interviewed in Rwanda. The crops are separated by those that are suitable for storage in evaporative cooling devices and those that should not be stored in high humidity conditions.

Table 7: Most commonly grown crops among farmers interviewed in Rwanda

Produce[1]	
Amaranthus	49.1%
Cabbage	47.4%
Sweet potato	45.6%
Eggplant	42.1%
Carrot	26.3%
Tomato	22.8%
Sweet pepper	14.0%
Beetroot	7.0%
Avocado	5.3%

Crop[2]	
Maize	45.6%
Cassava	36.8%
Onion	15.8%

[1] Friuts and vegetables that are suitable for storage in evaporative cooling devices

[2] Crops that are not suitable for storage in evaporative cooling devices due to their sensitivity to high humidity conditions.

These farmers grow the crops for a combination of personal consumption and sale. The fruits and vegetables that are sold are typically taken to local or district markets by bicycle or by foot. These markets are 1 – 6 km from the respondent's home. Many of these farmers purchase fruits – such as pineapples, mangos, bananas, and passion fruit – as well as fruits and vegetables that they do not grow for themselves.

The storage method used by the farmers interviewed in Rwanda is primarily keeping the fresh produce in a shady and well-ventilated place. Most of the respondents stated that they would prefer a ZECC or refrigerator if they could afford it, and some respondents indicated that a lack of electricity access was also a barrier for using a refrigerator. For respondents who desired a ZECC, the cost of materials is the most common reason for not having one.

Interviews with farmers in Burkina Faso

The primary harvest season for tomatoes in Burkina Faso is December through March, which are grown for both personal consumption and sale. The farmers interviewed in Burkina Faso sell an average of 18,000 kilograms of tomatoes per week with an average of ~ 15% tomatoes spoiling before they are able to be sold. All of the farmers reported selling their tomatoes right after harvest for prices of ranging from between 7,000 Fcfa ($12) and 25,000 Fcfa ($43) per 100 kilograms, depending on the market conditions. Fifty percent of the farmers interviewed are members of farming cooperatives or savings groups. In addition to tomatoes, most farmers (79%) also grow onions, along with some farmers growing eggplants (28%), cabbages (19%), carrots (15%) (11%), and chili peppers (11%). None of the farmers interviewed used either refrigerators or ZECCs for vegetable storage, as they were sold soon after harvest to avoid large amounts of spoilage. For fruit and vegetable storage in their homes, these farmers used straw or plastic baskets with an average capacity of 6 kilograms, costing an average of 1,000 Fcfa ($1.70). All of the respondents would prefer a refrigerator but cited either the lack of electricity of the high cost as the reasons for not currently having a refrigerator. Because these farmers sell their crops immediately after harvest there may not be significant value that ZECCs can provide; however, further investigation could provide insights into potential benefits that improved storage could provide, including reduction in the need to travel to the market everyday to sell the harvest and improved negotiating position with vendors purchasing the produce from farmers.

Interviews with non-farmers in Burkina Faso

Among the heads of households interviewed that are not farmers, 40% were traders, 40% work in public service, and the remain 20% with various private sector jobs. Five percent are members of savings groups. Someone from these households travels an average of 2 km to the local market to purchase fruits and vegetables including tomatoes (96%), onions (75%), cabbages (50%), eggplants (28%), and chili peppers (22%). There was a wide range in the frequency of traveling to the market to purchase fruits and vegetables, ranging from everyday (25%) to once per week (16%), with an average of three trips to the market per week among this respondent group. Forty six percent of the households use a refrigerator for storage with an average capacity of 12 kilograms and 60% of the households use straw or plastic baskets with an average capacity of 7 kilograms (some households reported using both a refrigerator and baskets for fruit and vegetable storage). The refrigerators, costing an average of 220,000 Fcfa ($375), provided an average shelf life of 13 days for tomatoes, eggplants, and cabbages; while the straw and plastic baskets, costing an average of 1,200 Fcfa ($2), provided an average shelf life of 3 days for tomatoes, eggplants, and cabbages. One respondent within this group reported using a clay pot to store tomatoes, providing a shelf life of 7 to 10 days. All of the respondents that are currently using straw and plastic baskets would prefer a refrigerator but cited the cost as being the major barrier to purchasing one. Among the respondents that are currently using refrigerators a majority reported that there is no other method of storage that they would prefer, with two respondents saying that they would prefer a solar refrigerator to avoid power cuts, and one woman having recently heard about ZECCs said she would prefer this storage method due to the lack of electricity consumption. Further research would be required to determine what benefits improved shelf life would provide to these households in order to determine a clay pot cooler capable of storing 5 to 10 kilograms of tomatoes can provide enough value to justify its cost.

Table 8: Current storage methods used by non-farmers in Burkina Faso

Storage method	Percent using	Average Capacity	Average Cost	Average fruit and vegetable shelf life
Refrigerator	46%	12 kilograms	220,000 Fcfa ($375)	13 days
Straw or plastic basket	60%	7 kilograms	1,200 Fcfa ($2)	3 days

Interviews with fruit and vegetable vendors

Fresh produce vendors in Rubona, Rwanda

Interviews were conducted with 10 randomly selected fresh produce vendors at Nyanza market in Rubona. The most common fruits and vegetables being sold were carrots, eggplant, tomatoes, and French beans. Most vendors purchase their fresh produce directly from farmers who come to the market to sell their produce. Some vendors also travel to other larger markets to purchase produce at bulk prices. The vendors sell their produce at mark-ups of 50% – 100% from their purchase price. The price that vendors pay for the produce and their selling price typically varies by a factor of 2, where the price in the peak harvest season is typically half of the low season. Most vendors sell a variety of fruit and vegetable types and at volumes anywhere between 5 – 50 kg of a given fruit or vegetable per day, and report losing between 10% – 50% of the fruits and vegetables that they purchase per day.

All of the vendors interviewed are currently storing their fruits and vegetables where they are exposed to ambient conditions under the shade of the market stall, either in baskets, sacks, or on tables. Over half the vendors said they would prefer to store their fruits and vegetables in a cold room or shared warehouse, and the remaining 40% responded that they were not aware of any other options for improved storage.

Fresh produce vendors in Kadiogo, Burkina Faso

Fifteen randomly selected fresh produce vendors from three markets were interviewed, all of whom primarily sell tomatoes, as well as some who also sell cabbage, eggplant, and onions. Tomatoes are purchased by the vendors from nearby wholesalers in 100 kg boxes for 7,500 – 60,000 Fcfa ($12.85 – $102.78), depending on the season. Most vendors sell 35 – 200 kg of tomatoes per day, with a margin between 2,000 and 5,000 Fcfa ($3.43 – $8.56) per 100 kg box (mark-up ranging from 7 – 57%). These vendors reported the tomato spoilage ranging from 1.5 kg – 10 kg per day (3 – 12 % of vegetables sold), with an average of 4 kg per day of tomatoes that spoil. Daily tomato spoilage of 4 kg per day results in the loss of 370 – 1,600 Fcfa ($0.63 – $2.73) per day, which is a significant portion of the sales compared with the margin calculated. Additionally, given that prices for clay pots and other containers reported from vendors at markets, a clay pot cooler with a capacity of 35 – 70 kgs can be constructed for under 10,000 Fcfa ($17.13). For vendors that need to store more than 70 kg of tomatoes per day, more than one clay pot cooler may be needed. If these clay pot coolers can reduce tomato spoilage by 50%, they would pay for themselves in two to eight weeks depending on the season.

Potential of evaporative cooling devices to benefit fresh produce vendors

Clay pot coolers or small brick ZECCs could provide single-vendors storage for one or more compatible fruit and vegetable types. One key consideration regarding the practicality for vendors to use clay pot coolers for tomato storage at markets is the portability of the devices. If the markets have permanent structures, the clay pot coolers can be stored overnight or permanent ZECCs could be constructed. However, in cases where vendors move to different locations, the clay pot coolers would have to be transported each day.

The markets where the vendors interviewed in Rwanda and Burkina Faso sell their produce are permanent markets, allowing for the possibility of constructing a brick ZECC to meet the storage needs of a single vendor, or for a group of vendors, with a need to store similar fruits and vegetables. Such a permanent structure could serve as a shared warehouse allowing for produce that did not sell on a given day to be stored overnight. While the shelf life experiments in this and other studies show that a well-designed and maintained ZECC can provide significant shelf life improvements, organizing the construction, use, and security of a shared storage facility requires planning and coordination. Alternatively, individual vendors could construct clay pot coolers for storing smaller amounts of fresh produce near where they are selling their produce, and if they have access to secure storage space, the clay pot coolers would not have to be transported away from the market each day.

For vendors that purchase fruits and vegetables in suitable boxes or crates (where there are holes for ventilation in the side and bottom of the container), there is the potential to cover the container with a wet cloth to produce some measure of an evaporative cooling effect. This is a potential area for future research to evaluate the performance of a device with such a design.

Figure 21. Tomatoes in a crate used for transportation and storage.

Conclusions and Recommendations

The objective of this work is to evaluate if evaporative cooling technologies show promise for improving fresh produce cooling and storage in Rwanda and Burkina Faso. In this study, we investigated two classes of evaporative cooling devices: Zero Energy Cooling Chambers (ZECCs) and clay pot coolers. In the previous sections, we presented the results from:

- **Electronic sensors** that provide information on the interior storage conditions (temperature and humidity) that were achieved during testing of various types of evaporative cooling devices.
- **Shelf life** experiments that provide information on the shelf life of selected fruits and vegetables stored in evaporative cooling devices compared to storage in the ambient environment.
- **Interviews** with existing and potential users of evaporative cooling devices, fresh produce vendors, and producers of clay pots and other containers. The interviews explored fruits and vegetables purchased and produced, existing methods for fresh produce cooling and storage, need for improved cooling and storage technology, availability and cost of materials that can be used for evaporative cooling devices, and perceptions of evaporative cooling devices.

Summary of findings

The results of this study indicate that low-cost evaporative cooling devices, such as clay pot coolers and brick ZECCs, can improve fruit and vegetable storage shelf life by providing a stable storage environment with reduced temperatures and high humidity. These conditions reduce water loss and spoilage in the produce studied (tomatoes, mangoes, carrots, cabbage, chili peppers, and French beans) and could have important benefits for households, farmers, and fresh produce vendors. Specific key results are listed below.

Limited cooling in high humidity environments: It is well understood that the evaporative cooling is highly sensitive to ambient humidity. In this research, the wet-bulb temperature (the minimum temperature that can be achieved through evaporative cooling) was compared to the interior temperature of the devices to determine the cooling efficiency. The results showed that in Rwanda, while the cooling efficiency of clay pot coolers were ~ 40 – 60%, the average temperature decrease was only 1 – 2 °C. In contrast, the low humidity environment in Burkina Faso allowed for temperature decreases of 4 – 8 °C to be achieved with cooling efficiencies of 35 – 60%.

Impacts of design on performance: Some specific results demonstrate the impact of evaporative cooling device design on performance:

- A brick ZECC that has a reduced surface area available for water evaporation and was exposed to direct sunlight for a significant portion of the day showed a low cooling efficiency (4%) compared to brick ZECCs with more optimized designs that achieve cooling efficiencies ranging of 29% to 77%.
- Even when evaporative cooling devices do not provide significant decreases in the average temperature, brick ZECCs and clay pot coolers provide other benefits including increased interior humidity, decreased temperature fluctuations, and decreased peak daily temperatures, all of which are expected to improve fruit and vegetable shelf life.
- The four clay pot cooler designs in Rwanda showed similar performance in terms of the interior temperature and humidity, although greater variations in performance may be observed in lower humidity environments where greater cooling can be achieved.
- The clay pot coolers in Burkina Faso showed the most significant average temperature decreases (> 4°C), particularly the small clay pot in clay pot device, which provided nearly an 8 °C decrease in the average temperature. While this device provides the best performance, the volume available for fruit and vegetable storage is limited (~ 5 liters).

Improvements in fresh produce shelf life: Shelf life improvements are dependent on the ambient conditions, the specific fruit and vegetable types, and the time they were harvested in the maturation cycle. Given this context, specific results from this research include:

- Carrots and cabbage saw greater benefits than either tomato experiment.
- Chili peppers saw a greater shelf life improvement in Rubona than Mulindi.
- Besides ethylene compatibility (sensitivity and production), fungus or rot from one fruit or vegetable type can accelerate deterioration in another type.
- Contact with the walls of the inner chamber can cause degradation if the surface is not clean.

Benefits reported by ZECC users: Farmers who have constructed brick ZECCs were satisfied with their investment and reported shelf life improvements ranging from ~2 times the shelf life in ambient conditions (tree tomato) to a shelf life improvement of over 4 times the shelf life in ambient conditions (cabbage).

Potential for evaporative cooling devices to provide benefits to fresh produce vendors: Fresh produce vendors in Rubona, Rwanda, and Kadiogo, Burkina Faso suffer high rates of spoilage. Because the vendors surveyed sell at daily markets with permanent locations (as opposed to traveling each day to sell at different weekly markets), there is the potential to construct brick ZECCs or store clay pot coolers at these locations to help the vendors avert food spoilage and financial losses.

Recommendations

In addition to recommendations for construction, use, and dissemination that has been outlined elsewhere (Evaporative Cooling Best Practices Guide), the results of this study point to additional specific areas where continued efforts can be made to increase and improve the usage of evaporative cooling devices in Rwanda and Burkina Faso:

Communicate best practices for construction and use of evaporative cooling devices to enable local practitioners and users to create locally appropriate designs. If users have a firm understanding of the basic mechanisms for the functioning of evaporative cooling devices, they can tailor the design for the storage volume to their needs and optimize performance within the constraints of the locally available materials and cost considerations.

Connect potential users with existing users of evaporative cooling devices to share information on the value that these devices can provide, advice on constructing a ZECC, and the costs of ZECC construction. These efforts have the potential to increase adoption rates of these technologies.

Specifically target fresh produce vendors for the adoption of evaporative cooling devices. This research showed that there is potential for fresh produce vendors to benefit financially from the use of evaporative cooling devices. Target the dissemination of evaporative cooling devices to fresh produce vendors at markets with permanent structures who suffer financial losses due to spoilage.

Continued research on evaporative cooling device performance has the potential to identify how to optimize the design of these devices for factors including the locally available materials, the storage volume required, cost, and performance.

Additional research on the impact of design modifications on evaporative cooling device performance in order to optimize the use of locally available materials, while achieving the required storage volume, cost, and performance. This research should be focused on low humidity environments. In high humidity environments, there may not be a strong incentive to optimize a device for the maximum cooling effect, which is limited by the wet-bulb temperature.

Research on evaporation using suitable boxes or crates (where there are holes for ventilation in the side and bottom of the container). There is the potential to cover the container with a wet cloth to produce some measure of an evaporative cooling effect. This is a potential area for future research to evaluate the performance of a device with such a design.

Additional research on the shelf life benefits that evaporative cooling devices have as a function of the specific fruit and vegetable types and climate conditions.

- Fruit and vegetable shelf life varies significantly with the type of fruit, how ripe it is when harvested, and the ambient conditions (the value that evaporative cooling devices provide is in the relative shelf life improvement compared to storage in ambient conditions).
- Basic experiments should be done using locally available materials to ensure that the devices provide improvements in fruit and vegetable shelf life that justify their cost prior to commencing dissemination efforts.

Dissemination efforts that need to be refined and tested

- Dissemination of information directly to users for self-construction and use
- Training and support to local entrepreneurs for the construction and sales of evaporative cooling devices to users

Figure 22. A completed brick Zero Energy Cooling Chamber in Ngoma, Rwanda.

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