Evaluation of Low-Cost Evaporative Cooling Technologies for Improved Vegetable Storage in Mali

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***Abstract*— In Mali, 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.**

This research study investigates the potential for non-electric vegetable cooling and storage devices to address the post-harvest storage challenges in rural Mali. The two classes of devices evaluated in this study are commonly known as "Evaporative Cooling Chambers" (ECCs) and "clay pot coolers", which rely upon the evaporation of water to create a cooling effect. 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.

The evaluation of six types of ECCs and clay pot coolers provided insights into user preferences as well as performance related to metrics such as interior temperature and humidity, ease of watering, and protection from animals and insects. 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 high equipment costs for refrigerators.

The reduced post-harvest losses - achieved through the improved storage environment - can lead to impacts including monetary savings, less time spent traveling to the market, and increased availability of vegetables for consumption. Based on this research, the key factors (operating conditions, need, and value) that should be assessed to determine the suitability of evaporative cooling devices for a specific context were identified and discussed.

***Keywords*— Vegetables; Cooling; Storage**

I. Introduction

Mali's horticulture sector plays a vital role in supporting the country's human nutrition and health, income generation for farmers, and poverty alleviation [1]. 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.

Vegetables are living, breathing parts of plants and contain 65% to 95% water [2]. 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 and physiological and biological deterioration – are affected by the handling, transportation, storage, and processing of the vegetables [3, 4, and 5]. 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 [6].

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.

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. 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.

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

- 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.

A. *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

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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. 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.

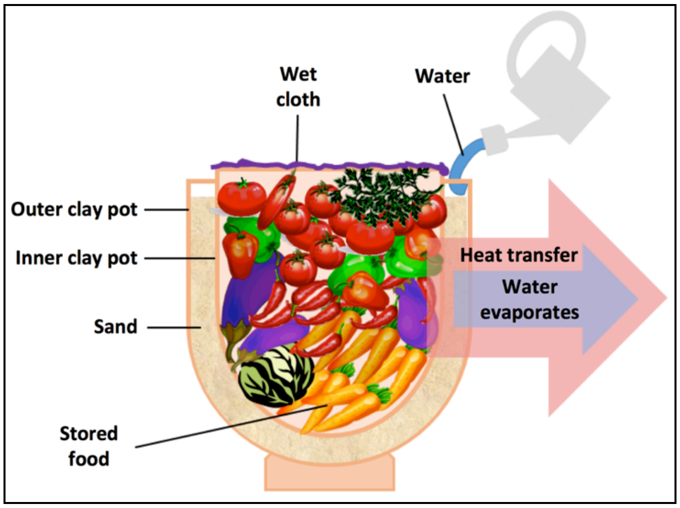

Figure 1. Diagram of a clay pot cooler with a pot-in-pot configuration, covered by a wet cloth.[2]

B. Background on Evaporative Cooling Chambers (ECCs)

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 [7 and 8] 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.

C. 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 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 [9 and 10].

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.

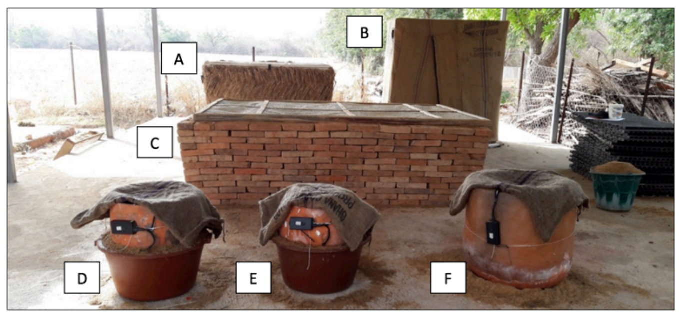

Figure 2. Above is an image of the three ECCs and three clay pot cooler devices included in this study: A) straw ECC, B) sack ECC, C) brick ECC, D) cylinder pot-in-dish, E) round pot-in-dish, and F) pot-in-pot.

II. METHODOLOGY

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?*

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. The seasonal weather during this time period ranged from the dry season and rainy season.

[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

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[3] 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).

A. *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.

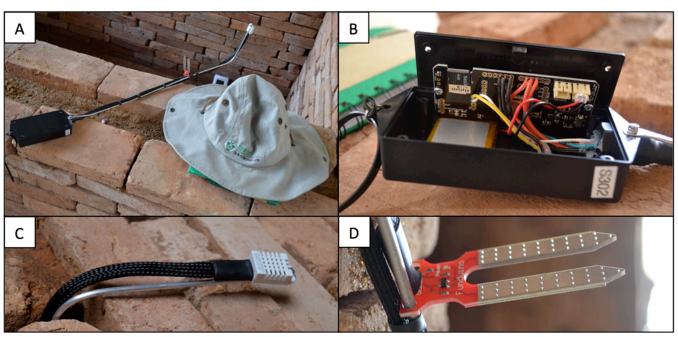

Figure 3. A) A full sensor unit on top of a brick ECC; B) Interior of sensor control box with battery, Secure Digital (SD) card, and circuit board; C) Temperature and humidity sensor D) Moisture sensor.

[3] 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.

B. *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[4]:

- 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

III. 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.

A. *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 took place from April until July. 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.

The three types of ECCs (straw, sack, and brick) displayed notably different performance, particularly in relation to the performance immediately after watering. Figures 4 and 5 show the typical daily profile of the sensor data collected.

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 4). 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.

[4] The interview questionnaires used for this study are available at: http://d-lab.mit.edu/resources/projects/evaporative-cooling

The humidity inside the ECCs is another factor that significantly impacts the shelf life of vegetables. When watered regularly the relative humidity inside the brick ECC remains consistently above 70% throughout the day (see Figure 5). In contrast, the relative humidity inside the sack and straw ECCs decreases within a few hours, and sharply increases after each watering event.

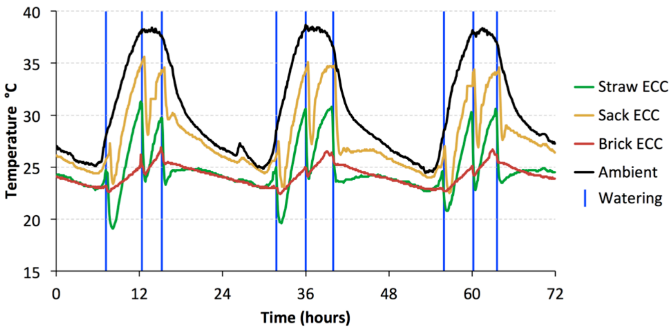

Figure 4. Typical internal daily temperature with watering for all three types of ECCs, and the ambient temperature measured by the independent sensor nearby to the ECCs is represented by the black line. A decrease in the temperature can be observed at the time of watering for each of the ECCs, indicated by the vertical blue lines.

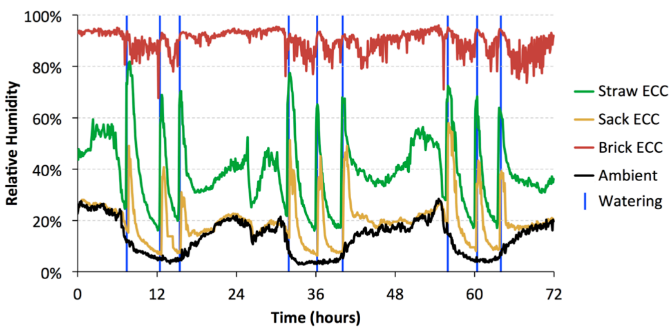

Figure 5. Typical daily relative humidity with watering for all three types of ECCs, and the ambient humidity measured from the independent sensor nearby to the ECCs is represented by the black line. An increase in the humidity can be observed at the time of watering for each of the ECCs, indicated by the vertical blue lines.

B. 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. 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.

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. The data in Figure 6 show 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.

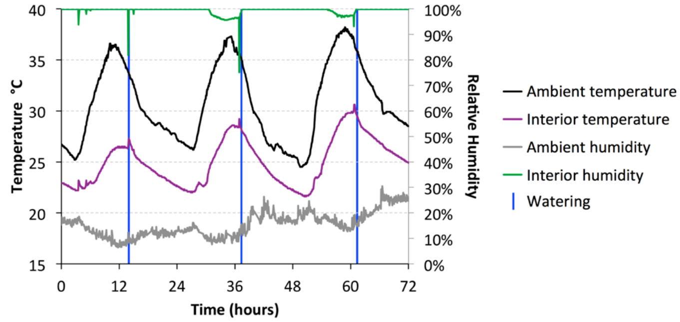

Figure 6: Typical daily temperature and relative humidity with watering for a clay pot cooler (pot-in-pot configuration). The vertical blue lines indicate when water was added.

C. ECC and Clay Pot Cooler 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 maintain a high humidity environment. To investigate the impact of watering frequency, we looked at time periods when participants did not regularly add water to the devices for several consecutive days.

When watering is stopped the straw and sack ECCs have significant reduction in the cooling effect in the first day, and the humidity inside the straw and sack ECCs is equilibrated with the ambient humidity within 13 hours and five hours, respectively. In contrast, even after watering has stopped for 15 days 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%. These results corroborate the observations in Figures 4 and 5, where a sharp decrease in temperature and increase in humidity is observed in the straw and sack ECCs when water is added in the middle of the day, but the temperature and humidity begin to equilibrate with the ambient conditions 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.

For clay pot coolers, the data shows that even 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 still provide a temperature decrease of greater than 2 °C. 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 brick ECCs and clay pot coolers were similar 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 brick ECCs and clay pot coolers.

D. ECC and Clay Pot Cooler Performance as a Function of Humidity

The ambient relative humidity has a significant effect on the performance of the ECCs and clay pot coolers. At higher relative humidity the evaporation rate of water is decreased, which reduces the cooling effect. Figure 7 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.

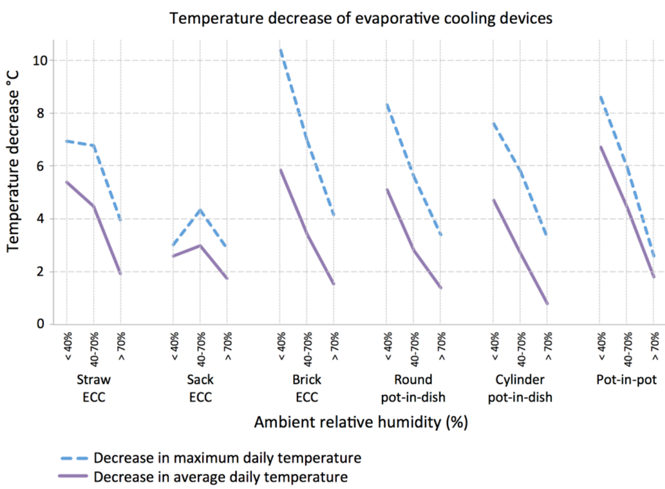

Figure 7: The decrease in the maximum daily temperature and the average daily temperature for each of the ECCs and clay pot coolers as a function of relative humidity, with regular watering. A larger decrease in the average and maximum daily temperatures indicates that the device is more effective at cooling the vegetables.

Among the ECCs, the brick ECC showed the largest decrease in the maximum daily temperature, across all relative humidity ranges; 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 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%.

Among the clay pot coolers, 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%.

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.

This data shows that, as expected, the ambient relative humidity has a significant effect on the performance of the ECCs and clay pot coolers devices – at higher relative humidity the evaporation rate of water is decreased, which reduces the cooling effect.

IV. Interview Results

Horticulture or other agriculture activities were a source of income for all of the ECC users and for 76% of the clay pot coolers users. The vegetables grown by the participants in both study groups are produced both for personal consumption and sale. Eggplant, tomatoes, hot pepper, and leafy greens are the most common vegetables reported to be stored in the ECCs and clay pot coolers. Some participants also stored beverages such as juice and drinking water in the ECCs and clay pot coolers. 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 users have an opportunity to benefit from improved storage on both ends of supply chain, as both growers and purchasers.

A. *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. Table 2 lists the most common attributes of the ECCs that respondents mentioned 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 for construction.

Table 2: Most commonly mentioned attributes of 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.

B. *User feedback on clay pot coolers*

The most common attributes of the clay pot coolers mentioned by respondents in open-ended questions about advantages and disadvantages are listed in Table 3. 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 traveling to the market.

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.

Table 3: 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.

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.

C. *Shelf life*

Based on the respondent interviews, the shelf life of eggplants and tomatoes are significantly longer in Sikasso than Mopti for all vegetables. 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. 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 for most commonly stored vegetables in Mopti (eggplant, tomatoes, peppers, and okra) is similar in each type of ECC, and no statistically significant differences could be determined. This is potentially due to the relatively small sample size for each type of device and the lack of direct comparison in many cases (many of the participants only used one type of ECC).

Household 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 4.

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 container.

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. 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 were not statistically significant, due to the large variance and lack of direct comparison between the three clay pot cooler types by individual participants

It should be noted that 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).

Table 4: 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	10-13 °C	90-95%	2-3 weeks
	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.
[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).

V. 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

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

The results of this research demonstrate 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 the 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 of the respondents reported that after receiving the clay pot coolers they were no longer using any of their previous storage methods, indicating that the clay pot coolers 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.

Table 5: 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.

VI. 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 can be used to determine if evaporative cooling devices are suitable for a specific context [11]:

- **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

To support the determination of ECCs and clay pot cooler suitability and the devices' proper construction and use we have created an interactive "*Evaporative Cooling Decision Making Tool"* and an "*Evaporative Cooling Best Practices Guide"*. 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 and supplementary data are available at: http://d-lab.mit.edu/resources/projects/evaporative-cooling

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

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