Forced-air evaporative cooling chamber for postharvest fruit and vegetable pre-cooling and storage

In many countries, a significant portion of the food produced (30%-50%) is lost before it reaches the table. Improved fruit and vegetable storage has the potential to reduce food loss, provide farmers and produce vendors with increased flexibility to sell their produce during favorable market conditions, and improve access to nutritious food in the communities.

A team from MIT has developed and tested an innovative design that retrofits common shipping containers to provide a lower-cost alternative to refrigerated cold rooms and a better-performing alternative to non-climate-controlled environments. This solution, which relies on forced-air evaporative cooling, has the potential to provide an effective, low-cost solution for postharvest fruit and vegetable storage in low-income regions with hot and dry climates. The rapid cooling rates achievable with forced-air evaporative cooling have significant potential for providing value at the pre-cooling stage, especially because this technology can be deployed near the farm gate, reaching produce shortly after harvest.

The team has deployed pilot chambers in Kenya and India, the technology is ready for broader dissemination and commercialization, which will be achieved through publishing publicly available open-source designs of the technology and engagement and support of early adopters and promoters of the technology.

Eric Verploegen, CoolVeg Foundation, MIT D-Lab Affiliate
Leon Glicksman, Massachusetts Institute of Technology Building Technology Program

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Introduction

In Sub-Saharan Africa, over 50% of fruits and vegetables produced are lost or wasted before consumption, and nearly 20% of the waste can be attributed to insufficient post-harvest and storage [1]. In India, 30% of the fruits and vegetables cultivated annually are lost due to insufficient availability of effective post-harvest storage [2]. In the state of Gujarat alone, annual post-harvest fruit and vegetable losses totaled $1.8 billion [3]. These challenges are often most pressing in hot and dry regions of the world, where fruits and vegetables are most susceptible to rapid spoilage and cooling solutions are the most expensive to operate. For many farmers and traders, the lack of adequate storage directly leads to loss of produce and income. In 2012 the Food and Agriculture Organization (FAO) estimated that post-harvest losses reduce the income of 470 million smallholder farmers by at least 15 percent [4]. In Nigeria, 76% of the tomatoes produced are lost, with transportation, handling, and storage being the stage in the value chain where the greatest losses occur [5]. Additionally, the inability to store their harvest often prevents farmers from selling their produce at times when they can receive the best price for their product. For example, farmers in India could receive prices three to five times higher for their eggplants and tomatoes if they were able to effectively store their harvest overnight and sell them in the morning at local markets. Additionally, inadequate postharvest storage can disrupt supply chains and limit consistent local access to high-quality nutritious food.

Additionally, there are environmental benefits to improving fruit and vegetable cold chains. Global food loss and waste generate 4.4 billion tCO2 equivalent annually, accounting for about 8% of total anthropogenic GHG emissions [6]. The deployment of this solution will reduce food loss and GHG emissions associated with farming, storage, and transportation activities. For example, in Nigeria, the inefficient or non-existent cold chains lead to 38% of tomatoes being lost in postharvest handling, transportation, and storage, resulting in $1.2 billion of value lost and over 1.5 million tCO2 equivalent generated [5].

One of the most critical and unaddressed stages in the postharvest supply chain for fruits and vegetables is immediately after harvest, commonly referred to as “pre-cooling” [7]. An hour delay in leaving produce at field conditions, often as high as 35°C, can lead to a loss in shelf-life of about 1 day – even with optimal storage conditions later in the supply chain [8]. It is well established that forced-air cooling is advantageous for pre-cooling applications, as the greater airflow rates increase the cooling rates of the produce being stored [7, 9].

To address these issues, significant improvements are needed at several stages in fruit and vegetable cold chains, ranging from pre-cooling at or near the farm gate to cold storage at markets, along with temperature-controlled options for short and long-term transportation. Currently, the most common solutions for postharvest storage of fruits and vegetables targeted at serving smallholder farmers and vendors include:

1) **Non-climate-controlled storage options** such as sacks, baskets, or crates, typically placed in the shade are inexpensive and widely available, but many fruits and vegetables have short shelf-life in hot and dry environments with these storage methods.
2) **Passive evaporative cooling chambers** such as brick or charcoal cooling chambers function through the evaporation of water from the wetted outer surface of the devices reducing the temperature and increasing the humidity inside the chambers [10]. These technologies require little or no electricity, but they are limited in the cooling rates and temperature reductions they can achieve.

3) **Refrigerated cold rooms**, typically functioning through a vapor compression cycle, can provide a controlled low-temperature environment. Recent developments using thermal batteries have reduced costs for off-grid applications, but the cost of installation and operation limits their affordability in many segments of horticulture value chains.

Our team from MIT began collaborating with the University of Nairobi in 2019 with an initial focus on optimizing charcoal evaporative cooling chambers. With Kenya having recently instituted a ban on the production of wood charcoal, we began searching for materials with the potential to replace charcoal as the passive evaporative cooling material on the outer surface of a storage room. Materials including vermiculite, pearlite, and sand were considered, but keeping these materials constrained without damaging them proved challenging. For smaller devices, like clay pot coolers, passive evaporative cooling is effective because the small size provides a high surface-to-volume ratio, and adding an active cooling system would significantly increase the cost. However, for larger storage rooms, with over 2 metric tons of produce, the cooling rate that can be provided by passive evaporative cooling is severely limited and not sufficient for many applications, particularly for produce recently harvested with a need for removal of field heat. The high equipment costs and energy consumption associated with cold rooms using mechanical refrigeration create a barrier to deploying these technologies in low-income communities, regardless of the business model being used. Seeking higher performing approaches to passive evaporative cooling with lower cost than mechanical refrigeration, we turned to active evaporative cooling – or forced-air evaporative cooling.

Forced-air evaporative cooling is commonly used for industrial and residential settings in dry regions and functions by forcing the warm dry ambient air through an evaporative cooling pad. As the air passes through the wetted pad water evaporates, reducing the temperature of the air and increasing the relative humidity. Evaporative cooling pads are specifically designed to maximize the evaporation of water into the air that passes through. They can be made from a range of porous materials that retain water, and the most common is corrugated cellulose pads.

Forced-air evaporative cooling uses equipment that is less complex and less expensive than systems using mechanical refrigeration, while also being four times less energy intensive [11]. Reducing the energy consumption reduces the operating cost for on-grid systems and for off-grid applications, the cost of a solar PV system can be significantly reduced. Systems based on evaporative cooling cannot provide the low-temperature storage environments (below 10°C) that are possible with a refrigerated cold room. However, most fruits and vegetables do not require storage temperatures this low and can greatly benefit from cool and humid environments, provided by evaporative cooling based systems. Using forced air enables the proposed innovation to provide superior pre-cooling performance, particularly in hot and dry climates, along with improved shelf life during transportation and during short-term storage.

20’ shipping container based forced-air evaporative cooling chamber

The idea for the forced-air evaporative cooling chamber grew out of a recognition of the respective limitations of room-sized passive charcoal cooling chambers and refrigerated cold rooms. The new forced-air evaporative cooling chamber developed at MIT is designed for the storage of fruits and vegetables and to be used in hot, dry regions – where evaporative cooling is most effective and postharvest challenges are most acute. Forced-air evaporative cooling is commonly used for industrial and residential settings in dry regions and uses evaporative cooling pads which are specifically designed to maximize the evaporation of water into the air that passes through. Devices using evaporative cooling are limited in the minimum temperature that can be achieved by the humidity of the ambient air. Lower humidity allows for more water to evaporate resulting in greater cooling of the air passing through the system. The forced-air evaporative cooling chamber developed at MIT combines the principles and materials used in commercially available evaporative coolers, the use of a standard shipping container as the structure for the chamber, with innovative airflow and insulation arrangements. Basing the design on a used standard 20’ or 40’ shipping container reduces construction costs, allows for the chamber to be mobile, and eases construction and replicability.

Using forced air as opposed to passive evaporative cooling allows this design to cool produce faster and reach lower temperatures than charcoal evaporative cooling chambers while reducing water consumption by shielding the evaporative cooling media (charcoal walls or the corrugated cellulose pads) from sunlight and the ambient environment and allowing for water to be recycled. Furthermore, the cooling pads are more durable and require less maintenance than a charcoal wall making the overall cost similar to a charcoal evaporative cooling chamber.

By using simple fans, water pumps, and evaporative cooling pads, which are less expensive and less energy-intensive than refrigeration equipment, this approach is roughly half the cost of a typical refrigerated cold room with the same storage capacity. The chamber functions by forcing the hot dry ambient air through the wetted evaporative cooling pad, producing cool, humid air, which is directed through stacks of vegetable crates inside the container, removing heat from the produce, and then vented out of the chamber. By forcing air through the crates of produce, this design can cool produce faster than either passive evaporative cooling or a typical cold room. The chamber is specifically designed for the storage of produce in standard vegetable crates (~60 cm x 40 cm x 25 cm). The arrangement of crates on either side of a central aisle of the chamber allows for easy access to all of the produce and for different types of fruits and vegetables to be stored in separate compartments. The chamber design, specifically the arrangement of the evaporative cooling unit, produce crates, thermal insulation, and airflow ducting is what makes this design effective.

Comparison with refrigerated cold rooms

The key advantages of the forced-air evaporative cooling chamber compared to refrigerated cold rooms are lower cost, faster cooling rates, and higher humidity in the storage environment. The primary advantage of refrigerated cold rooms is that they can achieve lower temperatures than systems based on evaporative cooling. However, many fruits and vegetables of interest do not require the low temperatures (below 10°C) achievable with refrigerated cold rooms. In the past five years, there have been significant advances in the development and deployment of refrigerated cold rooms for off-grid settings. Recent advancements, including the use of water or ice batteries for thermal storage, are particularly encouraging for improving efficiency and reducing the need for chemical batteries. Evaporation cooling has an important role to play as well. The key areas where evaporative cooling-based systems differ from refrigerated cold rooms include:

Cost

Relying on fans, a water pump and evaporative cooling pads — instead of expensive and energy-intensive compressors for mechanical refrigeration — the forced-air evaporative cooling chamber can be built at half the cost of a similarly sized refrigerated cold room. Furthermore, evaporative cooling systems require neither compressors nor refrigerants, thereby reducing the complexity and cost of the equipment and supplies, and requiring less technical expertise for maintenance and repair. Additionally, access to capital is currently a major challenge for many entrepreneurs working to scale technologies to improve cold chains across Africa. With lower upfront costs than a refrigerated cold room, the forced-air evaporative cooling chamber has the potential to be deployed more widely with less investment.

Cooling rate

One of the most critical and unaddressed stages in the postharvest supply chain for fruits and vegetables is the time immediately after harvest, when what is commonly referred to as “precooling” makes a significant difference in the shelf life of produce. The rapid cooling rates achievable with forced-air evaporative cooling have significant potential at the precooling stage, especially because this technology can be deployed near the farm gate, reaching produce shortly after harvest. Refrigerated cold rooms typically rely on room cooling through conduction and natural convection, resulting in significantly slower cooling rates. This process is less beneficial to freshly picked fruits and vegetables and, even where available and affordable, cold rooms are rarely situated close enough to farms to provide precooling.

Minimum temperature

The minimum temperature that can be achieved with evaporative cooling is highly dependent on the relative humidity. Lower relative humidity allows for more effective cooling, while higher humidity limits cooling potential. In hot and dry regions, temperature drops of greater than 10 degrees Celsius can be expected and are well-suited to keeping many fruits and vegetables fresh. Refrigerated cold rooms, on the other hand, can achieve temperatures sufficiently low to safely store dairy products, meat, and certain medicines; refrigeration equipment and power supply must be available and affordable. However, most fruits and vegetables do not require storage temperatures this low and can greatly benefit from cool and humid environments, provided by evaporative cooling based systems.

Humidity
Systems based on evaporative cooling generate cool and humid air, whereas refrigeration systems remove moisture from the air, creating a low-humidity environment. Most fruits and vegetables — including leafy greens, tomatoes, eggplants, okra, mangoes, and melons — prefer high-humidity environments to avoid dehydration. In contrast, foods such as onions, garlic, and cereal grains require low-humidity environments to avoid microbial and fungal growth. The ideal humidity of produce being stored should be considered when selecting a storage method. For most fruits and vegetables, the higher humidity environment of an evaporative cooling-based system is beneficial.

Open-source designs

Our team chose to make the designs publicly available to reach the widest audience and achieve the greatest impact. After the design was piloted in Kenya and India, we published the detailed design documentation on the website, How to Build a Fruit & Vegetable Cooling Chamber. This documentation includes dimensional design schematics; diagrams for the airflow, plumbing and electrical systems, along with a bill of materials; guidance for sourcing; and a recommended order of construction. Full design documentation for the 20' shipping container based forced-air evaporative cooling chamber is available on the MIT website: https://www.cooling-chamber.mit.edu/chamber-designs.

Figure 1 shows a head-on cross-sectional schematic of the airflow system of the 20' forced-air evaporative cooling chamber. The general dimensions and physics of the airflow system in the proposed mobile forced-air evaporative cooling chamber will be very similar and the results detailed in this document are expected to translate to the new design.

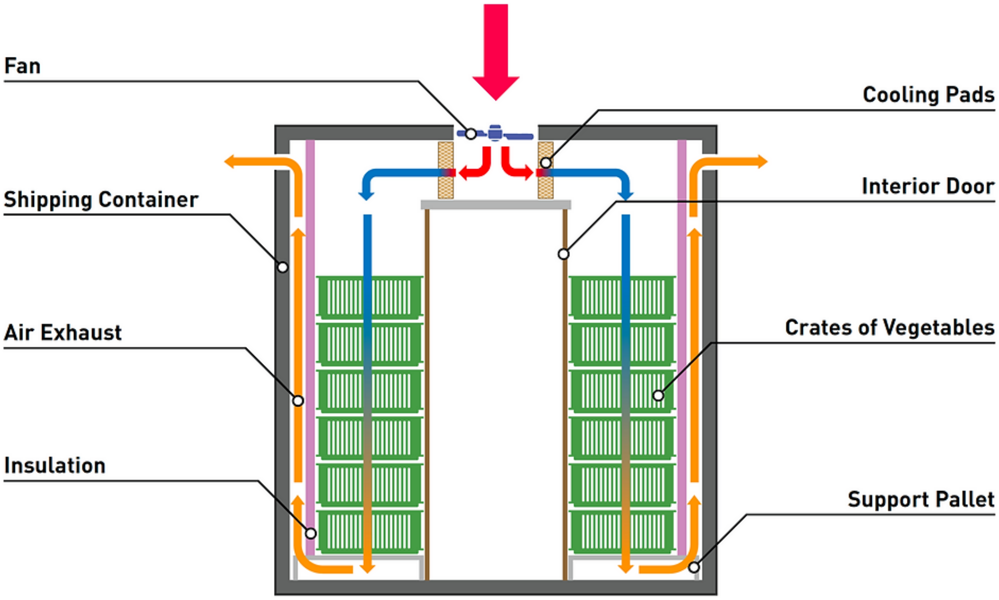

Figure 1. Cross-section schematic of the forced-air evaporative cooling chamber. This design is based on retrofitting a used standard 20’ or 40’ shipping container in order to reduce construction costs, allow for the chamber to be mobile, and improve ease of construction and replicability. Key features include:

- **Arrangement of produce** on either side of a central aisle within a shipping container. The width of a standard shipping container is well-suited to allow for the necessary ducting, insulation, two rows of standard produce crates on each side of the aisle, and an aisle that is wide enough for a person to comfortably place and remove crates, which allows for easy user management.
- **Customized evaporative cooling unit** running the length of the chamber, to optimize space use inside the shipping container and evenly distribute the cool, humid air. The maximum cooling capacity can be adjusted by simple variations in the evaporative cooling media.
- **Air ducting arrangement** that prevents the cool air from escaping through the bottom of the chamber, reduces the heat that enters the chamber through the side walls, allowing for the cooling unit to be turned off when the target interior conditions are reached while minimizing airflow and energy losses.

Figures 2 and 3 show example CAD drawings of the chamber. Comprehensive CAD drawings are available here: https://www.cooling-chamber.mit.edu/section-2

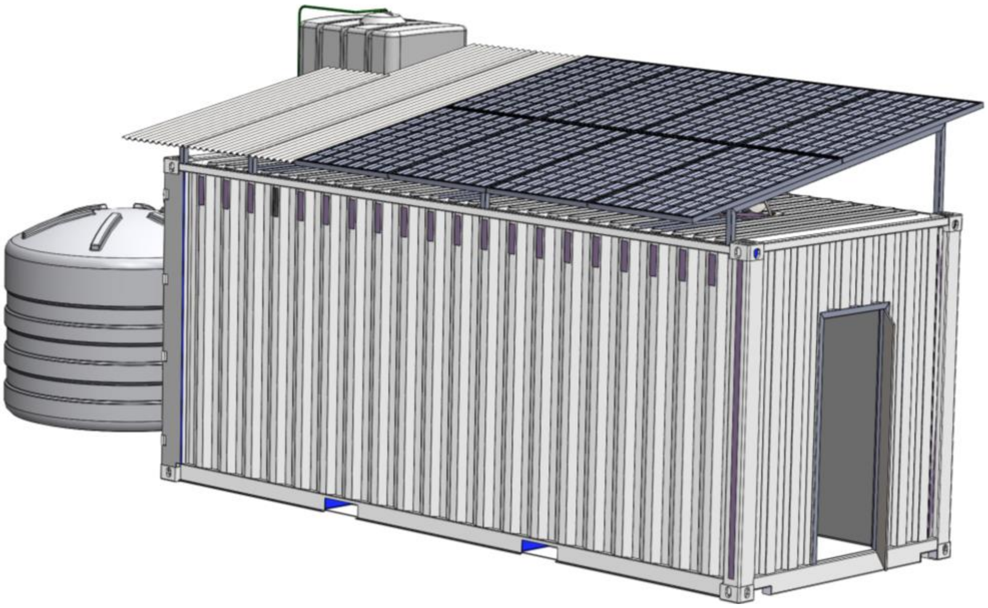

Figure 2: Perspective view of the container with the solar panels and roof visible. The lower water tank is visible on the left side of the image behind the container and the upper water tank is visible at the top of the container protruding from behind the roof. On the front of the container, the open entrance door is visible.

Figure 3: Perspective section view of the front of the chamber exposing the interior and showing the interior insulation (purple), evaporative cooling pads (brown in grey casing), crates for storing vegetables (green), and the sliding doors separating the compartments where vegetables are stored from the center aisle.

Thermal Performance

Due to the similarities in the geometry of the airflow pathways, the thermal performance of the system proposed mobile forced-air evaporative cooling chamber is expected to be very similar to that of the 20’ shipping container based forced-air evaporative cooling chamber that was previously developed and tested.

Heat and mass transfer models

Before the initial prototype chamber was constructed, heat and mass transfer models were developed to inform the design of the system. The following key areas were considered:

- Airflow rate and pressure drop through the system. What aspects of the system create the greatest pressure drop?
- Performance of the evaporative cooling pad. What is the expected temperature and flow rate of the air exiting the evaporative cooling pad?
- Heat removal from the stored produce. How quickly can heat be removed from the produce being stored in the chamber?

Airflow rate and pressure drop

When designing this type of system it is important to ensure that the power being used to drive the fan has the maximum benefit. To achieve this, the greatest pressure drop should be across the produce itself and not elsewhere in the system. Figures 4 and 5 show a cross-section of one side of the chamber’s airflow system and the pressure at key points throughout the system, respectively. In this model, the crates filled with vegetables were approximated by a porous media with the thermal properties of tomatoes and 50% porosity. This model was used to determine the appropriate dimensions of the airflow channels before and after the crates filled with vegetables in this system. For the geometry selected, the pressure drop across the crates is approximately an order of magnitude greater than any other part of the system, avoiding wasted energy due to unnecessary airflow constraints.

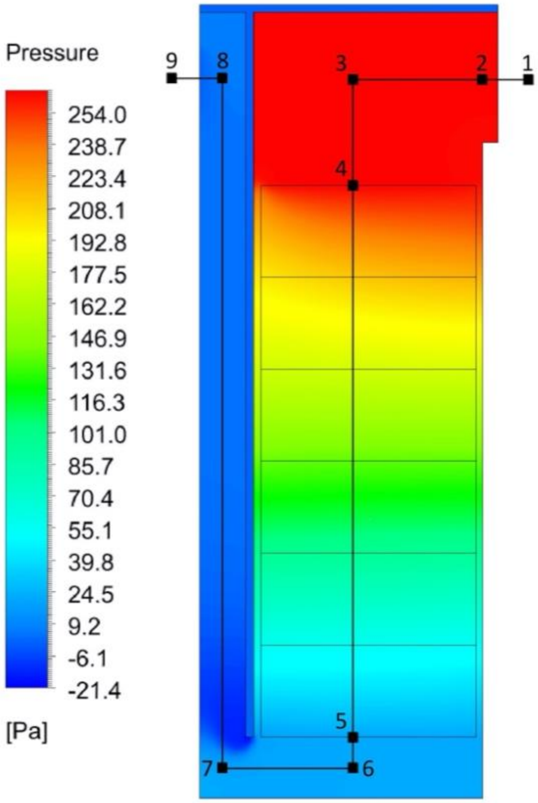

Figure 4. The figure to the left shows the pressure contours for a cross-section of the shipping container model. The contours indicate the pressure above or below atmospheric pressure (101,325 Pa). The solid squares indicate points where the pressure is measured.

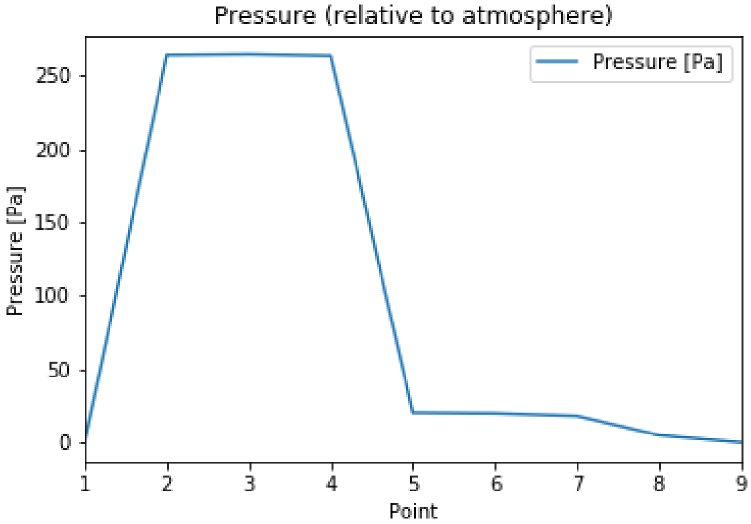

Figure 5. The figure to the left shows the pressure for each of the points identified in Figure 4. The largest pressure drop is across the stack of crates filled with produce (between points 4 and 5).

Heat removal from the stored produce

With rapid pre-cooling as a major need for target users of forced-air evaporative cooling chambers, heat transfer modeling was conducted to approximate the expected cooling rates that could be achieved with the system.

Heat transfer due to conduction through the walls, floor, and ceiling of the chamber was taken into account in this model, along with radiation from direct sunlight and the surrounding environment.

For these simulations, the initial condition begins with the chamber and its contents in equilibrium with the ambient temperature, 33°C. With an ambient relative humidity of 40% yielding a wet-bulb temperature of 23°C. With an evaporative cooler efficiency of 76%, the air entering the storage area from the evaporative cooler (inlet temperature) is 25°C. The solar irradiance was set constant at 400 W/m^2. No diurnal temperature change for ambient air was included in the simulation.

The results shown in Figure 6 show the impact of the airflow rate on the cooling rate of produce stored in the chamber. This simulation is used to select fans for the system considering the impacts of power consumption on airflow and cooling rate. The results shown in Figure 7 show the impact of crate positions in a vertical stack on the cooling rate. These results show that faster cooling rates can be achieved with shorter stacks of crates filled with produce. This information will allow users to intentionally place in arrangements that prioritize their cooling needs.

A forced-air evaporative cooling system can cool produce more quickly in the critical hours after harvest than cooling in the typical refrigerated cold room. Based on our heat and mass transfer models, the use of forced-air will allow for over 3,000 kg of fresh produce to be cooled by 8°C in less than six hours while stored inside of a 20’ shipping container. In contrast, typical refrigerated cold rooms require 10 - 15 hours to achieve a similar temperature decrease. Although our design will not achieve the same temperature as a refrigerated cold room, cooling below 20°C is not required for the storage of most fruits and vegetables. With our design, the most recent produce added to the chamber, stacked on top, will be cooled fastest.

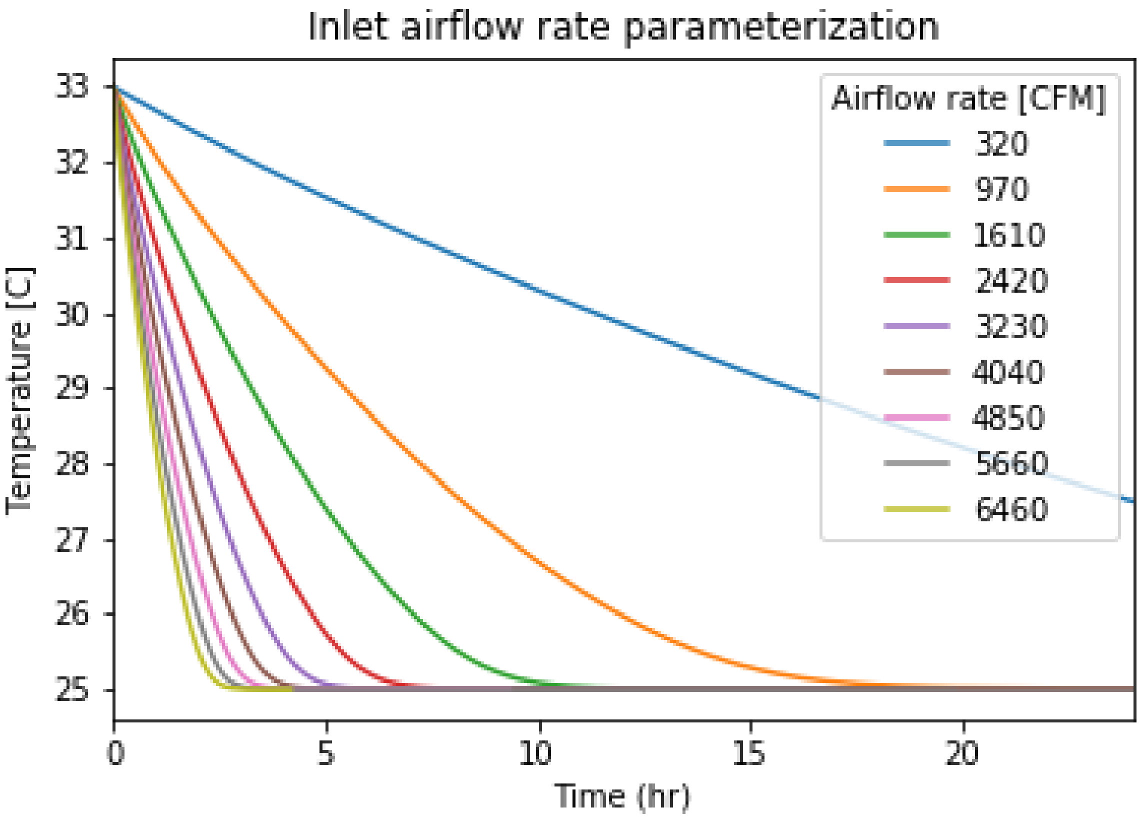

Figure 6. Data from computational fluid dynamics (CFD) simulations of the average temperature of crates of vegetables as a function of time in one-half of the 20’ shipping container (84 crates). The inlet velocity varies from 320 to 6,460 cubic feet per minute (CFM). For each simulation, the initial condition begins with the chamber and its contents in equilibrium with the ambient temperature, 33ºC, and the air entering the storage area from the evaporative cooler (inlet temperature) is 25ºC.

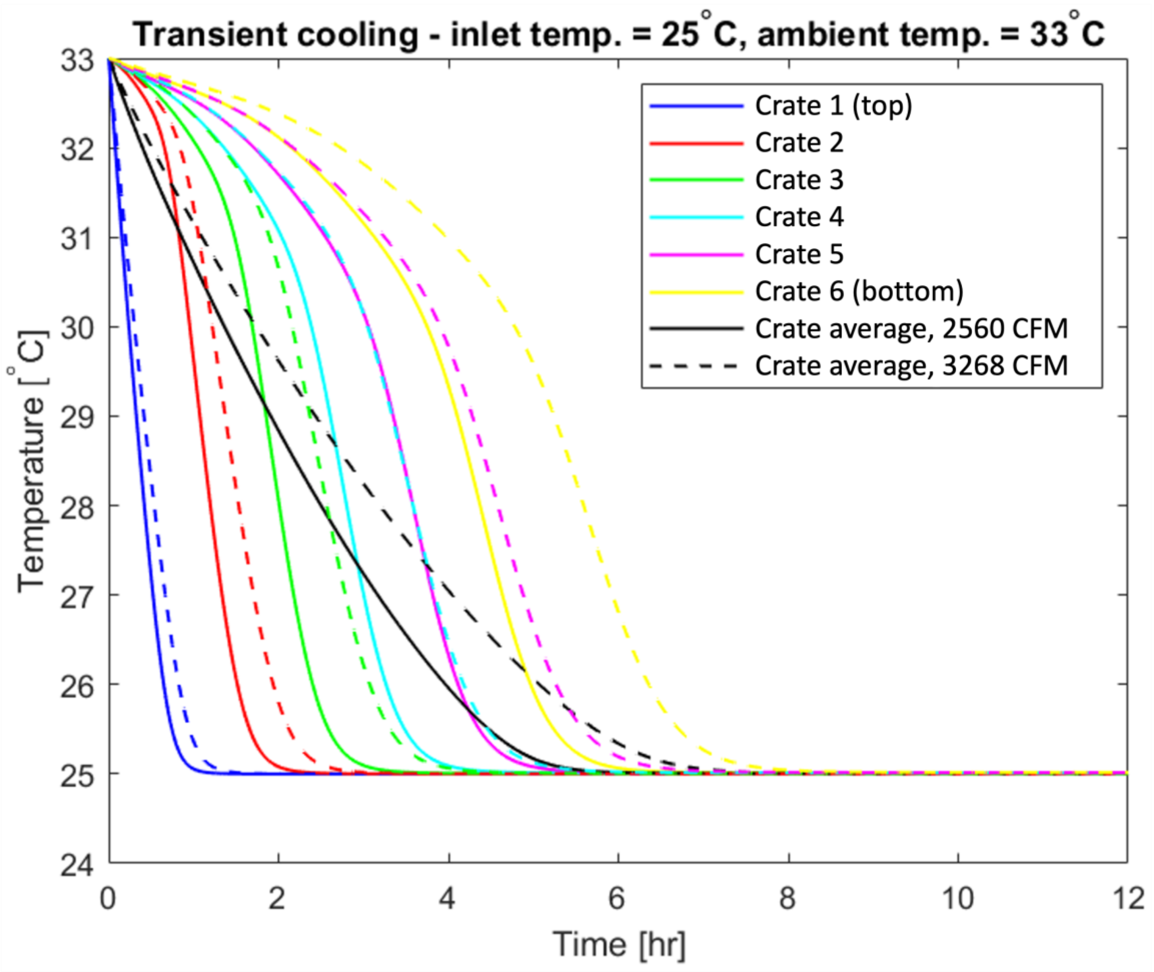

Figure 7. Data from computational fluid dynamics (CFD) simulations of the temperature of crates of vegetables as a function of time in one-half of the 20' shipping container (84 crates). The temperature of individual crates as a function of height in a stack (colored lines) is shown along with the average temperature of all 6 crates (black lines). The solid lines are a simulation using 3,268 CFM and the dashed lines are a separate simulation using 2,560 CFM. For both simulations, the initial condition begins with the chamber and its contents in equilibrium with the ambient temperature, 33°C, and the air entering the storage area from the evaporative cooler (inlet temperature) is 25°C.

Prototype chambers at MIT

A prototype forced-air evaporative cooling chamber was constructed on MIT's campus in Cambridge, Massachusetts in 2021 using a 10' shipping container. Experiments, using 225 mL water bottles as a thermal approximation for tomatoes, were conducted to validate the heat transfer models. Over a 5-day period, the average ambient temperature was 21.6°C, the average ambient relative humidity was 60%, and the average temperature inside crates filled with water bottles was 18.0°C, a 3.6°C decrease in the average temperature. This corresponds to an average evaporative cooling efficiency of 70%. These results along with similar experiments provided confirmation that the system could operate as expected at a full-scale geometry.

Results from the prototype chamber in Cambridge over a 5-day period showed an average decrease in temperature of 3.6°C and an average evaporative cooling efficiency of 70% (see Figure 8).

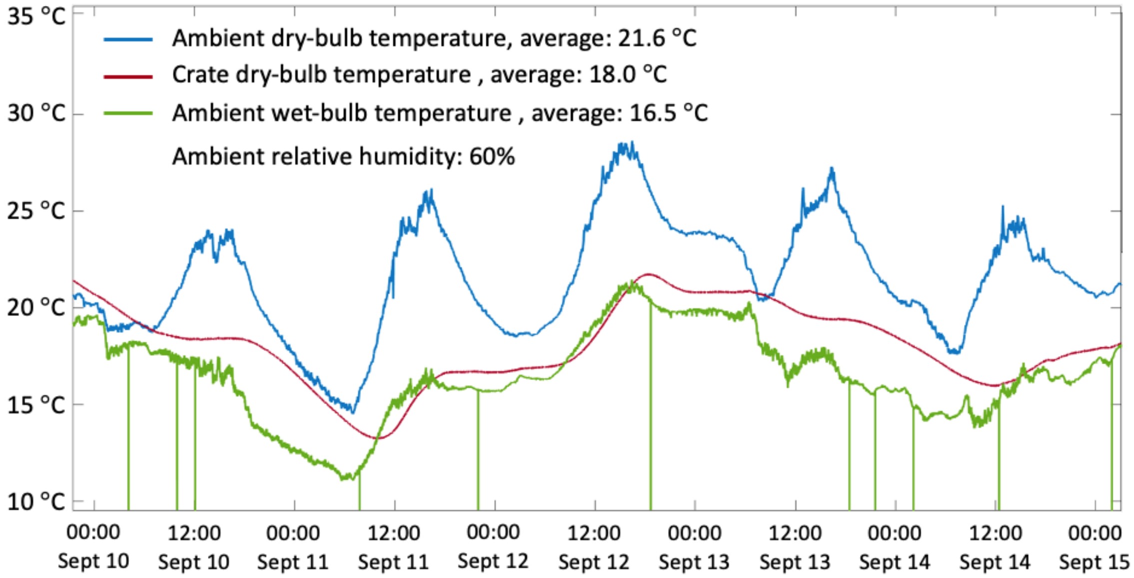

Figure 8: Data from forced-air evaporation cooling chamber at MIT
Comparison of the ambient dry-bulb temperature (blue line), the ambient wet-bulb temperature (green), and the dry-bulb temperature measured inside the crates filled with water bottles (red). The average temperatures over this 5-day experiment (September 10th – September 15th 2021 were:

- Ambient dry-bulb temperature (blue line): 21.6°C
- Ambient wet-bulb temperature (green): 16.5°C
- Crate dry-bulb temperature (red): 18.0°C

The average ambient relative humidity was 60%

The average evaporative cooling efficiency was 70%, defined as:

$$\frac{Ambient\ dry\ bulb\ -\ Crate\ dry\ bulb}{Ambient\ dry\ bulb\ -\ Ambient\ wet\ bulb}$$

Pilot chamber in Kenya

A pilot chamber was constructed with the cold storage provider Solar Freeze in Kenya. An image of this chamber located near Kibwezi, Kenya is shown in Figure 9. This chamber operates fully off-grid using solar photovoltaic (PV) panels with battery backup.

Figure 9: The front of the pilot forced-air evaporative cooling chamber in Kibwezi, Kenya, showing the custom entrance, the solar PV panels above the chamber, and the upper water storage tank (black rectangle above the upper right corner of the container).

Data were collected in July 2022 from the 20' shipping container in Kenya (see Figure 10). Over a 4-day period, the average ambient temperature was 22.6°C, the average ambient relative humidity was 56%, and the average temperature inside the chamber was 17.5°C – a 5.1°C decrease in the average temperature – there was no produce inside the chamber during this data collection period. This corresponds to an average evaporative cooling efficiency of 82%. In addition to the reduction in the average daily temperature, the chamber is also able to reduce the fluctuations in the temperature throughout the day. While the ambient temperature during this experiment varied by up to 15°C, the interior temperature varied between 5 and 7 °C each day. These results along with similar data collection provided confirmation that the evaporative cooling unit is able to deliver the expected cooling to the chamber. Further testing, while the chamber is filled with produce, is planned.

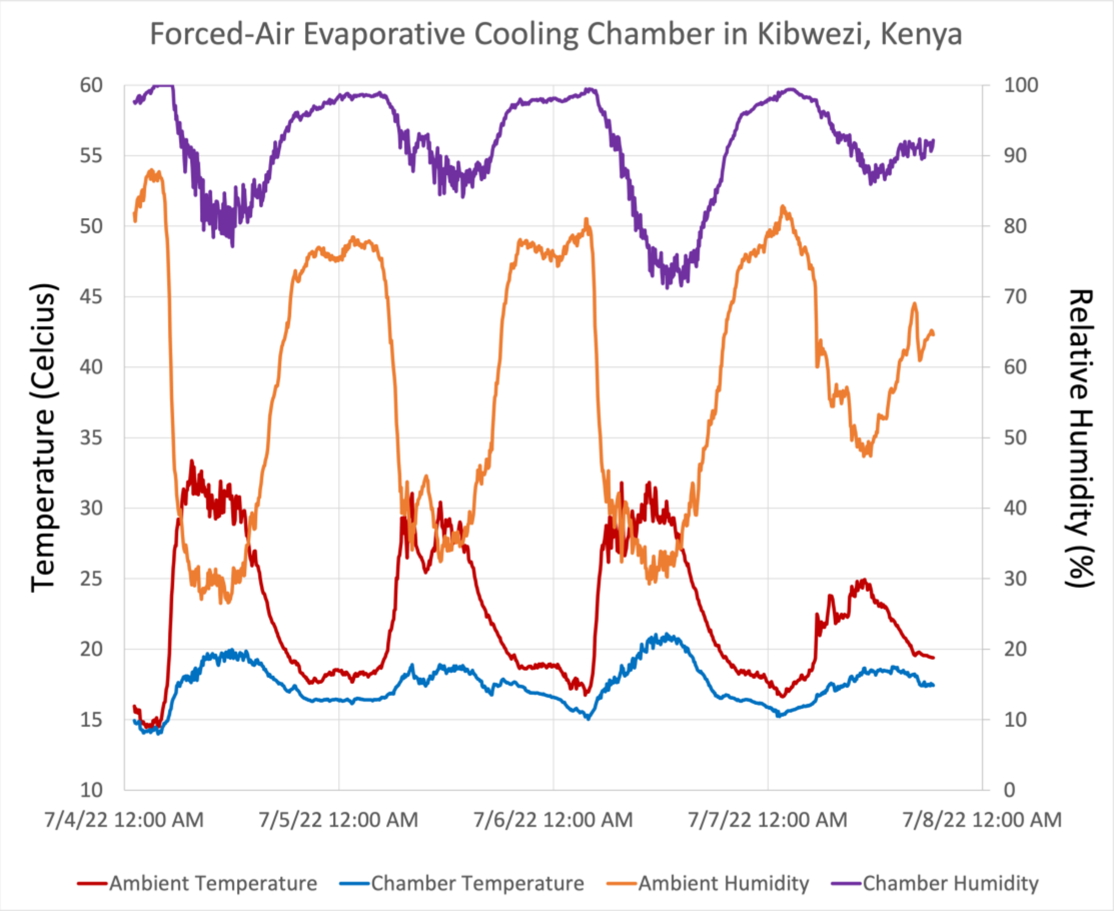

Figure 10: Temperature and humidity data from the forced-air evaporative cooling chamber in Kibwezi, Kenya over 2 days. The temperature and humidity recorded inside and outside of the chamber are:

- Average ambient dry-bulb temperature: 22.6°C
- Maximum ambient dry-bulb temperature: 33.4°C
- Average ambient relative humidity: 56%
- Average ambient wet-bulb temperature: 16.4°C
- Average dry-bulb temperature inside the chamber: 17.5°C
- Maximum dry-bulb temperature inside the chamber: 21.1°C
- Average humidity inside the chamber: 91%

The average evaporative cooling efficiency was 82%, defined as:

$$\frac{Ambient\ dry\ bulb\ -\ Crate\ dry\ bulb}{Ambient\ dry\ bulb\ -\ Ambient\ wet\ bulb}$$

Pilot chamber in India

A pilot chamber was constructed with the non-profit organization Hunnarshala Foundation in Kenya. An image of this chamber located near Bhuj, India is shown in Figure 11. This chamber is located near a reliable electrical grid connection and was configured as a fully AC system. In the absence of solar panels above the chamber, a roof was fabricated to prevent water from entering the opening where the fans are mounted into the ceiling of the chamber.

Figure 11: The rear of the pilot forced-air evaporative cooling chamber in Gujarat, India, showing the two water storage tanks.

Data were collected in May 2022 from the 20' shipping container in India (see Figure 12).During the time of this experiment, the average temperature inside the container was 26°C and the temperature outside the container was 33°C, and the relative humidity was 87% inside the chamber and 45% outside the chamber.

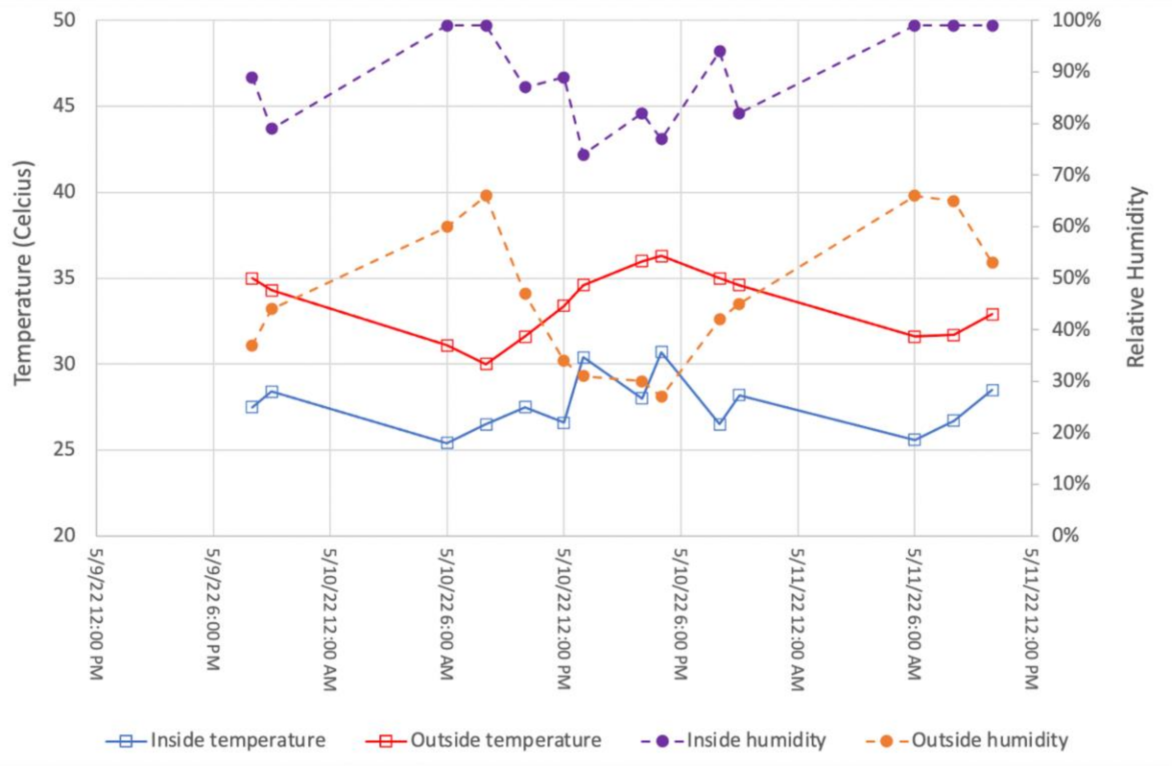

Figure 12: Temperature and humidity data from the forced-air evaporative cooling chamber in Gujarat, India over 2 days. The evaporative cooling unit was turned on and off every three hours: 50% capacity factor.

The temperature and humidity recorded inside and outside of the chamber are:

- Average ambient dry-bulb temperature: 33.5°C
- Maximum ambient dry-bulb temperature: 36.6°C
- Average ambient relative humidity: 46%
- Average ambient wet-bulb temperature: 24.6°C
- Average dry-bulb temperature inside the chamber: 27.3°C
- Maximum dry-bulb temperature inside the chamber: 31.0°C
- Average humidity inside the chamber: 89%

The average evaporative cooling efficiency was 69%, defined as:

$$\frac{Ambient\ dry\ bulb\ -\ Crate\ dry\ bulb}{Ambient\ dry\ bulb\ -\ Ambient\ wet\ bulb}$$

Vegetable Shelf-life

The key performance factor to consider is the shelf-life of relevant fruits and vegetables in the storage chamber compared to storage in ambient conditions or competitive technologies. Additionally, cooling rate, final temperature, and humidity within the storage environment are all relevant performance metrics that vary based on the produce being stored. For example, when stored in the cool and humid environment provided by evaporative cooling chambers, the shelf-life of carrots can be extended from 5 days to 18 days[8], tomatoes from 2 days to 20 days [12], mangoes from 6 days to 10 days, and leafy greens from 1 day to 4 days [12, 13]. Our forced-air evaporative cooling chamber is well suited to cool produce rapidly in the critical hours after harvest and we will look to target markets where the rapid removal of field heat is a pressing need [7, 8].

Vegetable shelf life: results from the pilot chamber in Kenya

A shelf-life experiment was conducted in Kenya with spinach stored inside the forced-air evaporative cooling chamber and spinach stored outside the chamber for 6 days (See Figure 13). Significant wilting of the spinach stored outdoors in the shade can be seen by the second day, and the spinach is completely spoiled by the third day. The spinach stored in the forced-air evaporative cooling chamber only shows moderate wilting by the third day and is still saleable after the fifth day.

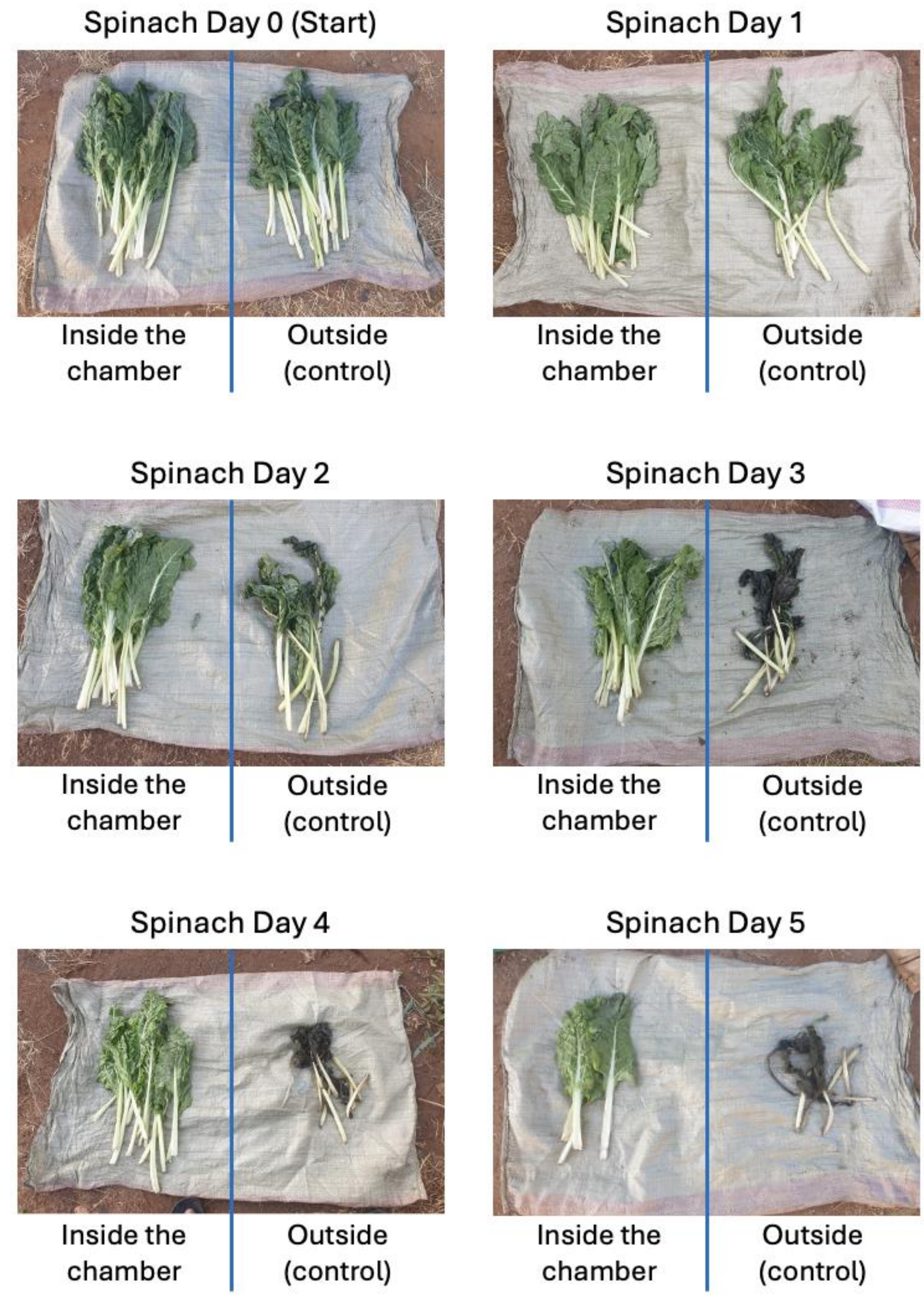

Figure 13: The progression of spinach stored inside the chamber compared with spinach stored outside the chamber over 6 days.

Vegetable shelf life: results from the pilot chamber in India

Hunnarshala Foundation conducted a shelf-life experiment with 12 vegetables in the pilot forced-air evaporative cooling chamber in Gujarat, India with vegetables acquired from local markets. All of the fruits and vegetables showed longer shelf life when stored inside the chamber. The results showed reductions in spoilage ranging from 13% to 50% for various vegetables after 2 days of storage in the chamber, compared to produce stored in crates outside of the chamber as a control. (see Figure 14).

Vegetable	Control	Chamber	Improvement
Alfalfa	50%	17%	33%
Coriander	70%	20%	50%
Cucumber	30%	15%	15%
Cabbage	15%	2%	13%
Cauliflower	18%	2%	16%
Eggplant	38%	12%	26%
Tomatoes	50%	10%	40%
Chili pepper	17%	5%	22%
Ladyfingers	20%	1%	19%
Ridge gourd	30%	8%	22%
Papaya	24%	8%	16%
Spinach	60%	20%	40%

Figure 14: Shelf-life data from experiments run on the pilot forced-air evaporative cooling chamber in Gujarat, India. For the control, vegetables were placed in plastic crates in the shade in ambient conditions near the chamber. The data in the table for the control and the chamber represent the amount of produce that had spoiled after two days of storage. During this experiment the evaporative cooling unit was cycled on and off every three hours, giving a 50% capacity factor. During the time of this experiment the average temperature inside the container was 26°C and the temperature outside the container was 33°C; and the relative humidity 87% inside the chamber and 45% outside the chamber.

Cost

The cost to construct and operate the proposed solution should be less than that of competitive technologies, normalized by the storage capacity. Commercial evaporative cooling technologies designed for household or industrial use typically use four times less energy than vapor-compression refrigerators and are less expensive to build [11]. By replacing the refrigeration unit of a cold room with an evaporative cooler, we can reduce the cost, complexity, and energy consumption of the system.

Operators of produce storage chambers typically gather revenue by charging customers a daily fee for storing crates. Given this, it is most useful to think of storage capacity as the number of standard-sized crates that can be stored in each chamber at one time, as opposed to the interior volume of a chamber.

Our initial estimates and the data gathered from the construction of the two pilot chambers indicate that the novel forced-air evaporative cooling chamber is a significantly lower-cost solution than refrigerated cold rooms. Our team also obtained information on the capacity and total system cost from three organizations operating stationary off-grid cold storage facilities with capacities greater than two metric tons serving low-income farmers:

- Coldhubs chamber cost: $32,000, capacity: 150 crates ($213/crate)[*]
- Solar Freeze chamber cost: $15,000, capacity: 100 crates ($150/crate)[*]
- FreshBox chamber cost: $12,000, capacity: 75 crates ($160/crate)[*]
- MIT chamber cost estimate: $11,000, capacity: 150 crates ($73/crate)[*]
- MIT chamber cost in India: $12,100, capacity: 168 crates ($78/crate)[†]
- MIT chamber cost in Kenya: $15,000, capacity: 168 crates ($89/crate)[‡]

Our initial projections for the MIT chamber with a 150-crate storage capacity in a 20' shipping container was $6,500 for capital materials and labor costs, and $4,500 for a 1.6 kW solar powered system with 12 kWh of battery backup and a charge controller. This total projected cost for this off-grid system, totaling $11,000.

In Kenya, we constructed a fully off-grid pilot chamber capable of storing 168 crates. The total cost of this chamber was $15,000 including materials, labor costs, and a 4-kW solar powered system with 16 kWh of battery backup. Some of the construction costs for this system could be minimized in the future. Due to sourcing and scheduling challenges, the evaporative cooling pads were sent from India to Kenya via air freight at a cost of $1,900, which could be reduced significantly by purchasing larger quantities of the pads with longer lead times. The off-grid power system was intentionally oversized for pilot purposes and the cost of this equipment ($5,600) can be reduced when the power requirements are better understood and optimized.

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[*] Data obtained in early 2020, includes the cost of a solar PV + battery power system for a fully off-grid system

[†] Data obtained from the construction of pilot chamber in 2022 in Gujarat, India. Includes a solar PV + battery power system for a fully off-grid system with an estimate cost of $4,000

[‡] Data obtained from the construction of pilot chamber in 2022 in Kibwezi, Kenya. Includes the cost of the installed solar PV + battery power system for a fully off-grid system.

In India, pilot chamber we constructed is capable of storing 168 crates and cost $8,100, including materials and labor costs. This chamber is located in an area with reliable grid access, so an off-grid power system was not necessary. We expect that an off-grid solar PV system for this system could be purchased for $4,000 yielding a total off-grid system cost of $12,100.

Initially, for both pilot chambers we sought to purchase DC fans and water pumps in order to avoid the need for a DC-to-AC inverter. When we were unable to find suitable DC fans after several months of searching, we decided to use AC fans, an AC water pump, and an inverter. For the chamber in Kenya, the off-grid power system was intentionally oversized for pilot purposes to ensure that we would be able to operate the chamber and gather data without interruption. The cost of this equipment ($5,600) can be reduced when the power requirements are better understood and optimized.

Improved sourcing – providing longer lead times, and ordering in larger quantities when constructing multiple chambers – will lead to reduced transportation costs and more favorable pricing.

Conclusions and Next Steps

In search of a cost-effective solution for pre-cooling fruits and vegetables in dry regions, we leveraged forced-air evaporative cooling and created a chamber design based on a standard 20’ shipping container that has a storage capacity of 168 standard vegetable crates. This design provides more rapid cooling and lower temperatures than passive evaporative cooling at a lower cost than a refrigerated cold room.

During the initial design process, heat and mass transfer modeling was used to estimate the cooling rates and optimize the airflow pathway to ensure uniformity of airflow through the crates, avoid air bypass, and optimize energy consumption.

In 2022, pilot chambers were constructed in Kenya and India in collaboration with Solar Freeze and Hunnarshala Foundation, respectively. During field testing, these chambers were able to provide temperature decreases of up to 10°C and significantly extend the shelf-life of a range of fruits and vegetables. The cost of constructing the fully off-grid chamber powered by solar PV panels in Kenya was $15,000, roughly half the cost of refrigerated cold rooms with similar storage capacity. The on-grid chamber in India cost $8,100 to construct, and the estimated cost of converting to an off-grid system is an additional $4,000.

As of December 2024, both chambers are operational, and testing has begun. Solar Freeze has deployed the off-grid chamber near Kibwezi, Kenya, and is commercially operating the chamber with customers in the areas surrounding Kibarani town. Customers include local farmers, local produce vendors, and traders coming from other regions to buy and sell produce. Hunnarshala has deployed the on-grid chamber at an organic farm near Bhuj, India, nearby farmers and vendors are benefiting from storing produce in the chamber.

Our team produced detailed design documentation to enable others to replicate this approach and published them on the website: https://www.cooling-chamber.mit.edu/
We are continuing to gather data on the performance and usage of the two existing chambers and are interested in engaging with organizations that have an interest in replicating this design.

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The team will continue to update this document as new data and other information becomes available.

Authors and Acknowledgments

About the Authors

Eric Verploegen, PhD, **CoolVeg Foundation Inc.**

Dr. Verploegen is a materials scientist and international development professional with extensive expertise in the energy sector and post-harvest fruit and vegetable storage. Prior to founding CoolVeg, Eric worked at MIT D-Lab from 2014 to 2023 as an instructor and principal investigator on numerous global development projects, working with collaborators in over 10 countries across Africa and South Asia. Eric previously worked as a Senior Research Scientist at Soane Energy developing chemical and mechanical oilfield waste management technologies and as a post-doctoral researcher at Stanford University developing materials for renewable energy applications. Eric has a Bachelor of Science in Materials Science and Engineering from Cornell University, a Ph.D. in Polymer Science and Technology from the Massachusetts Institute of Technology, and he completed a certificate program in innovation and entrepreneurship from the Stanford Graduate School of Business.

Leon Glicksman, **Massachusetts Institute of Technology**

Prof. Glicksman received his BS and PhD from MIT and MS from Stanford. He has been teaching at MIT since 1966 and is a Professor of Building Technology and Mechanical Engineering. He founded the MIT Building Technology Program and served as head for 24 years. He was a founding member of the MIT Energy Initiative. Glicksman devoted his later research to developing energy-efficient, sustainable building technologies and compatible designs in programs in China, India, Japan, and Europe, including the use of natural ventilation in commercial buildings and sustainable housing for residents in low-income areas of India and Nepal. He published over 250 papers and three books, the latest is Modeling and Approximation in Heat Transfer. He has developed and taught courses in energy and heat transfer. Among his awards are the Melville Medal of the American Society of Mechanical Engineering, the Robert T. Knapp Award, and the ASME Heat Transfer Memorial Award. He is a fellow of ASME and ASHRAE.

Contact information:
Eric Verploegen: eric@coolveg.org
Leon Glicksman: glicks@mit.edu

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