Portable and Mobile Forced-Air Evaporative Cooling Chambers for Smallholder Farmers and Produce Vendors

CoolVeg Foundation - Technical Report

Efficiency for Access Research and Development Fund

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Acknowledgments

Efficiency for Access is a global coalition working to promote affordable, high-performing, and inclusive appliances that enable access to clean energy for the world's poorest people. It is a catalyst for change, accelerating the growth of off and weak-grid appliance markets to boost incomes, reduce carbon emissions, improve quality of life, and support sustainable development. Current Efficiency for Access Coalition members have programmes and initiatives spanning 62 countries and 34 key technologies. It is co-chaired by UK aid from the UK government via the Transforming Energy Access platform and the IKEA Foundation. www.efficiencyforaccess.org

CoolVeg Foundation has received support from the Efficiency for Access Research and Development Fund. The Efficiency for Access Research and Development Fund is supported by UK aid from the UK government via the Transforming Energy Access platform and the IKEA Foundation. The Efficiency for Access Research and Development Fund aims to accelerate the availability, affordability, efficiency, and performance of a range of appliances that are particularly suited to rural developing country contexts and promote social inclusion.

Since its inception, the Efficiency for Access Research and Development Fund has supported 38 projects with over £5 million in funding. Energy Saving Trust manages the Efficiency for Access Research and Development Fund. The Efficiency for Access Coalition is coordinated jointly by CLASP and the UK's Energy Saving Trust.

The IKEA Foundation is a strategic philanthropy that focuses its grantmaking efforts on tackling the two biggest threats to children's futures: poverty and climate change. It currently grants more than €200 million per year to help improve family incomes and quality of life while protecting the planet from climate change. Learn more at www.ikeafoundation.org.

This project was a collaboration between CoolVeg, Artisana, and ColdHubs.

CoolVeg Foundation

CoolVeg Foundation is a nonprofit organization dedicated to developing and deploying technologies for preserving fruits and vegetables in low-income off-grid settings in arid regions across Africa and South Asia. These underutilized technologies improve fruit and vegetable shelf-life, increasing access to these nutritious foods, reducing food loss, and saving community members precious time and money. CoolVeg was founded in 2022 by Eric Verploegen to increase access to and adoption of these technologies through collaborations with businesses, research institutions, NGOs, and government agencies. A recent spinout from the Massachusetts Institute of Technology (MIT), the CoolVeg team members have led research projects related to evaporative cooling for postharvest fruit and vegetable storage in 7 countries across Africa and South Asia.

ColdHubs

ColdHubs Limited is a Nigerian company that provides solar-powered, walk-in cold storage units for farmers and food vendors to reduce post-harvest losses of perishable goods. They offer a "pay-as-you-store" service, allowing users to store their produce for a daily fee, extending shelf-life and increasing income. ColdHubs primarily serves smallholder farmers and market vendors, many of whom are women, and aims to improve food security and livelihoods in Nigeria and other West African countries.

Artisana

Artisana Centre For Habitat & Technologies Private Limited was incorporated in 2023 and is based in Bhuj, Gujarat, India. Artisana's work includes reviving traditional building techniques, especially those using earth-based materials, and for promoting eco-friendly and disaster-resilient construction.

Contributions to the project activities were made by the following individuals:

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Chamber design: Eric Verploegen (CoolVeg) and Leon Glicksman (MIT).

Chamber construction: Cambridge - Eric Verploegen (CoolVeg) and Sucheta Baliga (CoolVeg); India: Mahavir Acharya (Artisana), Karamshi Rangani (Artisana), Hari Bhai (Artisana), and Raja Bhai (Artisana); Nigeria: Paul Mbonu (ColdHubs) and Francis Jeremiah (ColdHubs).

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Data analysis and report preparation: Eric Verploegen (CoolVeg), Sucheta Baliga (CoolVeg), and Leon Glicksman (MIT).

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Cover photo: Members of the CoolVeg and Artisana teams in front of a portable forced-air evaporative cooler in Bhuj, Gujarat, India; Photo credit: Dan Sweeney, CoolVeg.

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Executive Summary

In many countries, a significant portion of the food produced (30%-50%) is lost before it reaches the table. Forced-air evaporative cooling chambers have the potential to provide an effective, low-cost solution for postharvest fruit and vegetable storage in low-income regions with hot and dry climates. Our innovative design uses simple and widely available materials to create forced-air evaporative cooling chambers that are a lower-cost alternative to refrigerated cold rooms and a better-performing alternative to non-climate-controlled environments. Access to improved fruit and vegetable storage will reduce food loss, provide farmers with increased flexibility to sell their produce during favorable market conditions, and improve access to nutritious food in the communities. This document outlines the design of innovative forced-air evaporative cooling chambers:

- Portable chambers for use in stationary applications
- Mobile chambers for use in transportation applications.

These chambers are specifically engineered for smallholder farmers and vendors to facilitate postharvest storage of fruits and vegetables. With support from the Efficiency for Access Research and Development Fund, several versions of these chambers were constructed, tested, and deployed in India and Nigeria.

The portable chamber design that has been piloted in Zaria, Nigeria, is capable of cooling 500 kg of vegetables by 10 °C in less than 6 hours, while requiring less than 200 Watts of electrical power. 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. Evaporative coolers are less expensive, more energy-efficient, and easier to maintain than refrigeration-based systems. As a result, CoolVeg's off-grid forced-air evaporative cooling chambers cost about 60% less than traditional cold rooms of similar size. By lowering the cost of pre-cooling and storage of fruits and vegetables with an energy-efficient, affordable, and effective technology, forced-air evaporative cooling chambers have potential for addressing an unmet need in the early stages of fruit and vegetable supply chains in low-income regions.

CoolVeg's portable forced-air evaporative cooling chambers can be easily, quickly, and affordably constructed using commonly available materials and are capable of rapidly cooling produce in the critical hours after harvest. The portable version of the chamber can be easily carried by several people and lifted onto a small truck for transportation to remote locations, providing a cooling solution immediately after harvest. CoolVeg's mobile cooling chambers provide an option to rapidly cool produce *during* transportation, filling a critical and underserved link in fruit and vegetable cold chains in many countries.

CoolVeg is looking to build on the work presented here by commercializing these technologies in Nigeria, India, and other arid regions in need of improved fruit and vegetable storage.

Introduction

CoolVeg develops and disseminates innovative forced-air evaporative cooling chambers for smallholder farmers and vendors to facilitate postharvest storage of fruits and vegetables. Technical and financial support from the Efficiency for Access Research and Development Fund enabled CoolVeg to develop the next generation of portable and mobile evaporative cooling-based storage chambers for use on farms, at vegetable markets, and in transportation applications. Through this project, several versions of these chambers were constructed, tested, and deployed in India and Nigeria. This document describes the design of the chambers, the results from this research project, and their potential for commercialization.

Need for Postharvest Storage Solutions

Across Sub-Saharan Africa, 54 million tonnes of fruits and vegetables are lost or wasted per year, accounting for 52% of the total production, the greatest percentage of food loss for any crop category[1]. These challenges are particularly pressing in hot and dry regions of the world – conditions where fruits and vegetables spoil the quickest. Improvements in cold chain infrastructure are necessary in many regions to address fruit and vegetable losses; however, suitable technologies are not available and affordable for many low-income farmers, retailers, and traders.

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” [2]. An hour delay in leaving produce at field conditions, often 35°C, can lead to a loss in shelf-life of about 1 day – even with optimal storage conditions later in the supply chain [3]. Technologies with the ability to affordably and effectively pre-cool fruits and vegetables will provide significant value and have the potential to reduce food losses.

Nigeria

The Sahel, with a population of over 400 million people, is one of the poorest regions of the world, with most parts of the region experiencing hot and dry weather for over 8 months per year. Of the estimated 180 million people living in rural, off-grid communities within the dry regions of Africa's Sahel, approximately one-third reside in the 12 states of Northern Nigeria.

In Northern Nigeria, there are over one hundred thousand smallholder farmers, retailers, and wholesalers of fresh fruits and vegetables, aged between 18-70 years. Women constitute a majority of the small plot gardeners, providing 75% of the labor in production and nearly 100% of the labor in the sales of fruits and vegetables. Most of these small farmers and retailers are food insecure, with an average monthly income of $60.

Revenue in the vegetable market in Nigeria is expected to amount to $27.10 billion in 2024. The market is expected to grow annually by 13.53% resulting in a market of $45.02 billion in 2028 [4].

The combined domestic production of fruits and vegetables in 2020 was 41.2 million metric tonnes [5]. Currently, 40% of fruits and vegetables grown in Nigeria are lost between when they are harvested and when they arrive at the market [6]. Additionally, inadequate postharvest storage can disrupt supply chains, leading to lost time and money for farmers and limiting consistent local access to high-quality nutritious food.

The tomato cold chain in Nigeria faces particularly significant challenges, with a total of 76% of the tomatoes grown being lost without being consumed. Half of these losses (38% of the total production) occur during the postharvest handling, transportation, and storage of tomatoes, resulting in $1.2 billion of value lost and over 1.5 million tCO_2 equivalent generated [6]. With only 10% to 15% cold chain utilization for fruits and vegetables [5], there is a huge market opportunity for new solutions to reduce food loss and increase profits for farmers and other actors along the supply chain.

Our conversations with the CEOs from ColdHubs, Coldbox Store, and Alyx Limited in Nigeria indicate that the vast majority of produce is not handled through a proper cold chain. There are relatively few businesses working to address these issues. This is highly problematic for tomatoes and other perishable crops, as the hot and dry climate in these regions is particularly unfavorable for tomato transportation and storage. These companies also list access to capital and large capital costs as the largest barriers to the growth of their cold storage businesses. With capital costs 50% or lower than refrigerated cold rooms, these conditions present an opportunity for forced-air evaporative cooling chambers to enter this untapped market.

India

Gujarat and Rajasthan are among the most arid regions in India, making them well-suited for forced-air evaporative cooling. There are 3.6 million marginal or smallholder farmers in the state of Gujarat [7] and 3 million marginal or smallholder farmers in the state of Rajasthan [8]. In Gujarat and Rajasthan, the rural population living below the poverty line is 21.5% and 16.1%, respectively [9]. In Gujarat, 21,250,000 metric tonnes of fruits and vegetables are produced annually, on a land area of 1,035,400 Ha. This production amounts to $2.9 billion of annual value [9]. In Rajasthan, 2,436,000 metric tonnes of fruits and vegetables are produced annually, on a land area of 220,400 Ha. This production amounts to $278 million of annual value [9]. In India, 30% of the fruits and vegetables cultivated annually are lost due to insufficient availability of effective postharvest storage [10]. In the state of Gujarat, annual postharvest fruit and vegetable losses totaled $1.8 billion [11].

For farmers in Gujarat or Rajasthan, India, who need to sell their produce at certain times of the day to receive a good price, the lack of adequate storage presents logistical challenges that need to be overcome to avoid food loss. Vendors and wholesalers without suitable storage often sell their produce at the end of the day at discounted prices to avoid spoilage overnight. Improved storage would allow these traders to keep produce fresh throughout the day and overnight, allowing for fresh inventory to be available at all times. Additionally, inadequate postharvest storage can disrupt supply chains, leading to lost time and money for farmers and limiting consistent local access to high-quality and nutritious food.

Existing Solutions for Fruit and Vegetable Storage

Current approaches for fruit and vegetable storage in low-income settings include non-climate-controlled storage options, evaporative cooling, and refrigeration-based storage options. Forced-air cooling is often used in industrialized settings, but is not commonly used in low-income communities.

Non-climate-controlled storage options

Inexpensive and readily available non-climate-controlled storage solutions, such as sacks, baskets, or crates placed in the shade, offer limited shelf-life for many fruits and vegetables in hot and dry climates. Despite being the most economical choice, their inadequacy in preserving produce in target regions makes them prime candidates for replacement.

Evaporative cooling

Evaporative cooling is the process where water absorbs heat when it evaporates, resulting in a cooling effect. This phenomenon is the basis for how sweating cools the human body. The wet-bulb temperature is the lowest temperature that can be achieved through the process of evaporative cooling, and is dependent on the air temperature and relative humidity. In drier environments, where there is less moisture in the air, water evaporates more rapidly. This faster evaporation leads to quicker cooling and a lower wet-bulb temperature. Consequently, greater temperature reductions – the difference between the ambient temperature and the wet-bulb temperature – are possible in low-humidity conditions. Evaporative cooling offers the most significant advantages in hot and dry environments. This is due to two factors: greater temperature reductions are achievable, and fruits and vegetables are more prone to degradation under such conditions.

Passive evaporative cooling relies on natural convection or wind to drive the evaporation of water, offering limited control and is highly dependent on the climate and architecture of the cooling device. Active evaporative cooling uses mechanical systems such as fans to force air through wet media. Active evaporative cooling provides more consistent and controllable cooling, but requires electricity to operate the fans that generate the air flow. For both passive and active evaporative cooling, continuous cooling necessitates the relevant surfaces or media to remain consistently wet. This can be accomplished either through manual wetting or by employing a mechanical system equipped with a pump and a basic irrigation setup.

Passive evaporative cooling chambers such as clay pot coolers, brick evaporative cooling chambers, charcoal cooling chambers, and Zero-Energy Cooling Chambers (ZECCs) function through the evaporation of water from the wetted outer surface of the devices, reducing the temperature and increasing the humidity inside the chambers [12], see Figure 1. These technologies require little or no electricity, but are typically not well-suited for mobile applications and are not able to deliver the rapid cooling rates required for pre-cooling applications [12, 13]. Larger devices with a smaller surface-to-volume ratio have challenges with achieving useful cooling rates for large volumes of produce. Charcoal evaporative cooling chambers provide benefits over storage in ambient environments (lower temperature and higher humidity), but rely on environmentally harmful charcoal, consume large amounts of water, and are limited in the cooling rates and temperature reductions they can achieve. Furthermore, after being promoted for several decades, there has not been widespread adoption of these technologies, likely due to a combination of the mediocre cooling performance and the inability of businesses to centrally manufacture and distribute the technology.

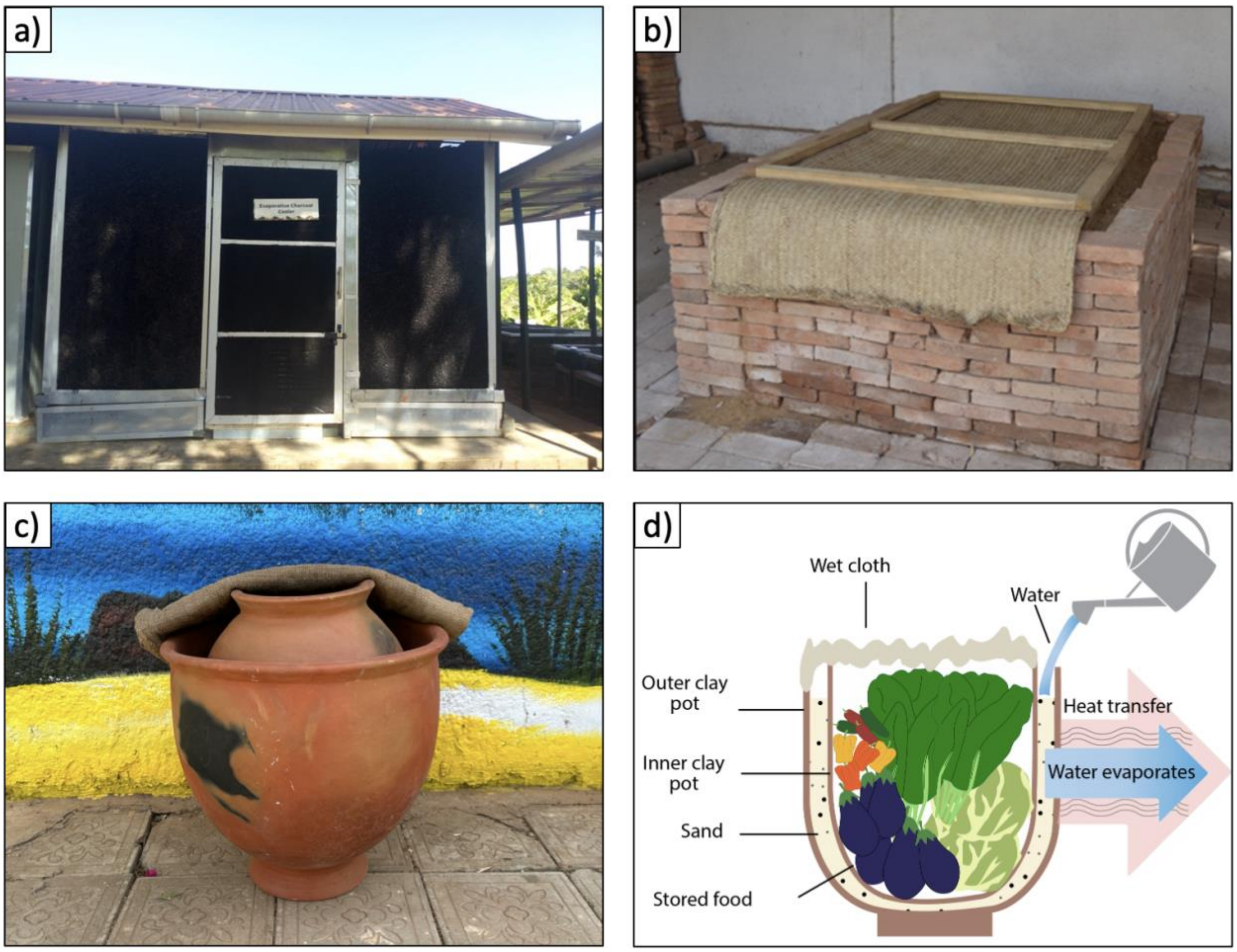


Figure 1. a) A charcoal evaporative cooling chamber in Karurumo, Kenya - also known as a “evaporative charcoal cooler (ECC)”, b) a brick evaporative cooling chamber in Bamako, Mali - also known as a “Zero Energy Cooling Chamber (ZECC)”, c) a clay pot cooler in Niamey, Niger - also know as a “Zeer pot”, and d) schematic showing the evaporative cooling principle of clay pot coolers. Water evaporates creating a cool and humid environment inside the inner pot where vegetables are stored. The photographs were taken by Eric Verploegen and the clay pot cooler schematic is based on work by Peter Rinker, Movement e.V. and redesigned by Melissa Mangino.

Active evaporative cooling systems, often called “air coolers” or “swamp coolers”, are commercially available in many arid regions for residential and commercial use. The key component of these off-the-shelf devices consists of a cooling pad that has been designed to allow air to flow through the wetted media, a water pump to irrigate the water over a cooling pad, a fan to blow air through the cooling pad, and a casing to hold the components described, along with a water reservoir, in the proper configuration (see Figure 2).

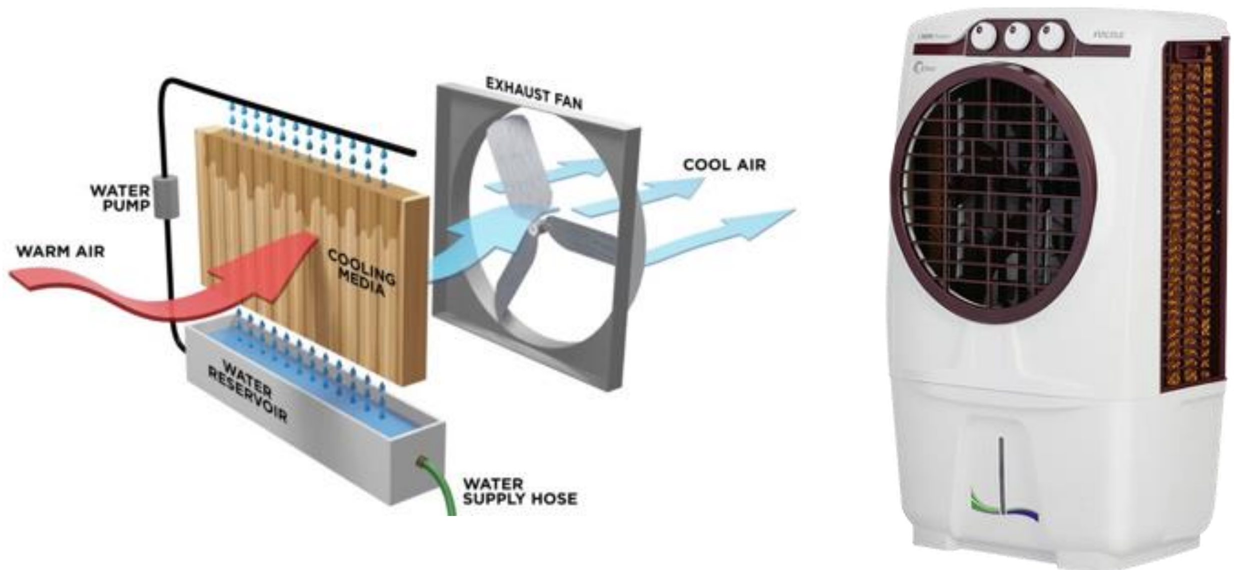


Figure 2. Left: schematic of active evaporative cooling - as air passes through the porous corrugated cellulose cooling media, water evaporates and cools the air [14], and right: a common commercially available evaporative cooler available for $160 in India [15].

Refrigerated cold rooms

Refrigeration systems, functioning through a vapor compression cycle or mechanical refrigeration, are effective in providing a controlled low-temperature environment that provides significant shelf-life extensions for many fruits and vegetables. Refrigerators or freezers for household use are typically not large enough to meet the needs of farmers, and walk-in refrigerated cold rooms are better suited for storing crates of produce. With most refrigerated cold rooms having a capacity of more than 2 metric tonnes and costing more than $20,000, they are often unaffordable for individual farmers or vendors. When deployed in off-grid settings, the energy consumption of the refrigeration equipment requires a significant investment in solar panels, batteries, and other electrical components. Additionally, maintaining imported refrigeration equipment often proves challenging in many rural, low-income areas due to the need for specialized parts and skilled technicians.

To increase the affordability of this technology for smallholder farmers in low-income communities, businesses operating refrigerated cold rooms typically rent space to farmers for storing fruits and vegetables (storage-as-a-service). The typical fee charged by businesses ranges from $0.20 to $1.00 per crate per day, depending on demand, the value of the produce being stored, and the customer type. However, businesses operating with a storage-as-a-service model often struggle to make this service both affordable to their customers and profitable for their business due to the costs associated with typical vapor-compression refrigeration equipment, staffing the chamber to manage inventory and collect payments, and electricity to power the system.

The high costs and energy consumption associated with refrigerated cold rooms create a barrier to deploying these technologies in low-income communities, regardless of the business model being used.

Forced-air cooling

In the context of fruit and vegetable storage, forced-air cooling is the process of rapidly pushing or drawing cool air through containers of produce, which significantly speeds up the cooling process compared to traditional room cooling. It is well established that forced-air cooling is advantageous for pre-cooling applications, as the high airflow rates increase the cooling rates of the produce being stored [1]. The rapid cooling rates achievable with forced-air evaporative cooling have significant potential to improve fruits and vegetable shelf-life at the pre-cooling stage, especially near the farm gate, reaching produce shortly after harvest.

In developed regions, forced-air cooling is utilized in many large cold rooms. However, in low-income regions, most refrigerated cold rooms rely on room cooling. This method involves passive and active air convection within the storage space, rather than directing air through produce containers. This is a missed opportunity to provide faster cooling rates with a relatively small increase in energy consumption. However, implementing forced-air cooling requires careful arrangement of produce to maximize the airflow through the crates or other packaging where produce is stored.

User Profiles and Needs

Forced-air cooling technology is best-suited in markets with an unmet need for fruit and vegetable storage and a hot, dry climate where evaporative cooling will be effective. Key markets include the African Sahel, East Africa, the Middle East, Pakistan, and India. With CoolVeg's mission of providing solutions to low-income communities, we narrowed our focus to markets in these regions, where we would be able to test the technology, and upon scale, would provide maximum benefit to the local communities of those regions.

From the outset, we aimed to get an understanding of the value chain for fruits and vegetables – from harvest to sale – to define our users. This would then help us to design the chamber according to their needs and constraints, both in Nigeria and India.

The Kaduna region of Nigeria, where part of this project took place, is one of the major tomato-producing states in Nigeria. Here, our partner ColdHubs, which would construct the chambers, is also the user of the chamber, which meant our user research for context and design constraints was limited to members from the ColdHubs team working on this project. ColdHubs currently has 58 walk-in cold rooms in 28 states, serving 11,000 customers, with each
3-tonne cold room having a storage capacity of 150 crates. Additionally, ColdHubs has constructed two 100-tonne facilities with the ability to store 5,000 crates of produce. They described the supply chain as shown in Figure 3 and as follows:

- Individual smallholder farmers harvest their crops, with tomatoes being one of the most harvested crops
- The produce is then bought by different distributors who consolidate it and take it to the ColdHubs' 100-ton cooling facility that serves as an aggregation point. The distributors hire transporters to pick up the produce from the smallholder farms using a combination of refrigerated and non-refrigerated trucks. The produce is typically stored in wooden/woven baskets, which often damage the skin of the tomatoes. Farms can be up to 100 km away from the cooling facility
- Once the produce arrives at the ColdHubs 100-ton facility, distributors pay a fee of ~200 Naira per crate per day of produce stored (~$0.14/crate/day)
- From the ColdHubs 100-ton facility, the produce is transported to markets in Lagos in ColdHubs' refrigerated trucks

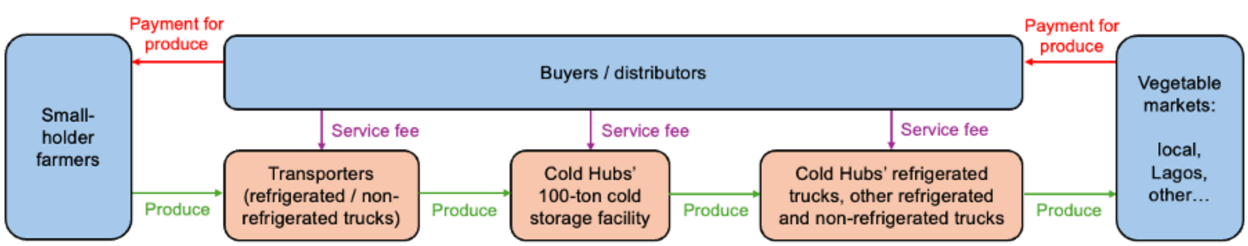


Figure 3. A graphical representation of the supply chain relating to smallholder farmers who use ColdHubs' 100-ton in Zaria, Kaduna, Nigeria.

Together, we decided that for this project, we would concentrate on Kaduna state as it has a well-suited climate for evaporative cooling and farms close enough to the cold room so as to test a mobile chamber design. The tomatoes currently arrive at the cold room at ~35 °C, at which point they are cooled to 12 °C. This not only adds load to the cold room, but there is a lot of spoilage during transport. The mobile chamber would be able to reduce the temperature from 35 to 25 °C, thus decreasing spoilage and also lowering the cooling burden on the cold room. ColdHubs would be the operator of the mobile chamber and charge a service fee for the transportation of produce. We could thus test two different designs - a portable chamber for cold

storage at the farms, and a mobile cooling chamber for pre-cooling produce during transportation from the farm gate to the 100-ton cold room.
In India, more specifically Gujarat, during the harvest season, farmers harvest their produce two to five times a week on average. They sell their produce on the same day, either by transporting it themselves to the local market, or have transporters who pick up and drop their produce at the market. The local market is run by the Agricultural Produce Market Committee (APMC), established by the government of India for fair trade between farmers and buyers. They buy from the farmers and then sell to local vendors as well as distributors/exporters through auctions held either on the same day or the next day. During the auctions held twice a day, once at 4 am for produce from the previous day and once at 3 pm for same day produce, vendors come to the APMC to buy the fruits and vegetables. Most of the local vendors buy during the morning auction, whereas the bigger distributors buy in the evening. The vendors then transport the produce to their local shops, where they sell it to the final customers. These shops can either be actual full-sized stores, permanent stationary carts, or smaller transport vehicles like *autorickshaws* or tempos.

We gathered this supply chain information by speaking to the following people:

- Multiple staff members at Artisana
- Different kinds of farmers – organic, regular, trust-foundation-based farming organization, large-scale (100-acre+ farming area), and small-scale (1-10 acres)
- 5 APMC agents
- 7 local vendors who operated out of physical stores, stationary carts, movable carts, and small-transportation vehicles

We were thus able to identify our three distinct users – farmers, vendors and APMC wholesalers. Apart from some very large-scale farmers (farming area of 100 acres or more), our target users did not have access to any kind of cold storage solutions. They were all used to dealing with their produce on the same day and discarding spoiled produce within two days. On average, the farmers lost about 15% of their produce, the vendors about 25-35% and the wholesalers about 20%. We clearly recognized that there was a need for cold storage, but an important question was whether the behavior change needed to move them from dealing (harvesting, telling, and discarding) with their produce on a daily basis to storage was feasible. Another key factor we realized was that all these users had very different storage needs, ranging from 15 crates to 40 crates, which guided our chamber designs.

Forced-Air Evaporative Cooling Chamber Design

The chambers developed for this project aim to combine the cool and humid environment provided by evaporative cooling and the rapid cooling rates of forced-air cooling, while maintaining relatively low energy consumption and equipment costs. The design process for both the portable and mobile chambers developed for this project builds on the CoolVeg team's prior work at MIT, with support from the Abdul Latif Jameel Water and Food Systems Lab (J-WAFS), where they developed a forced-air evaporative cooling chamber based on a 20' shipping container [16], see Figure 4. Detailed design documentation is available 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.

Figure 4. A forced-air evaporative cooling chamber constructed by MIT D-Lab and Solar Freeze, near Kibwezi, Kenya. This chamber has a storage capacity of 168 vegetable crates (> 3,000 kg of produce) and is fully powered by the solar PV panels (above the chamber) and a battery storage system. This chamber is used by farmers and vendors who pay a fee to store their produce in the chamber.

The key innovation in each of these forced-air evaporative cooling chambers is the carefully designed airflow pathway to maximize the cooling rate, maximize the energy efficiency, and minimize heat intrusion when the evaporative cooling system is turned off. In this system, ambient hot, dry air is pulled into the chamber by a fan and forced through a wetted pad, producing cool, humid air. The cool, humid air is then directed through stacks of vegetable crates inside the container – removing heat from the produce – and then vented out of the chamber. There are several key specifications that are important to optimize the system's performance, including the airflow rate of the evaporative cooler, minimizing air bypassing the crates, having sufficient openings at the bottom of the crates, and avoiding flow constriction in unintended locations. These items will be discussed in more detail in the "Evaporative Cooler Specifications and Airflow Pathway" Section.

Five portable chambers were built for use in stationary applications, along with one mobile chamber for use in transportation applications (see Table 1). Images of the portable chambers deployed in India and Nigeria are shown in Figure 5.

The portable chambers are designed for use at settings including small farms, local produce aggregation points, farming cooperatives, and in retail settings (either individual or groups of retailers). Although they do not have built-in wheels for transportation, they can be deployed in a wide range of locations, including rural areas with poor road networks. Weighing between 100 and 150 kilograms when empty, these chambers can be lifted by ~ 6 people onto a truck or carried for short distances for precise placement. This flexibility also allows for the chamber to be moved to different locations at various times of the year, where the need for improved storage is the greatest.

The mobile chamber built in Nigeria for this project was constructed on a custom-built trailer and can be towed by a farm tractor, van, or truck. While the approach gives versatility, there is potential to retrofit an existing vehicle, such as a cargo tricycle or small truck, which may be more cost-effective, particularly if the mobile chamber will be in use for the majority of the year.

Table 1. A list of the 6 chambers that were constructed as part of this project. The portable chambers are designed for use in stationary applications, and the mobile chamber is designed for use in transportation applications.

Chamber type	Application	Storage capacity	Location	Power system
Portable	Research	25 crates	Cambridge, United States	On-grid
Portable	Wholesaler	25 crates	Anjaar, Gujarat, India	On-grid
Portable	Farmer	20 crates	Kodki, Gujarat, India	On-grid
Portable	Vendor	15 crates	Bhuj, Gujarat, India	Off-grid
Portable	Farmer	25 crates	Zaria, Nigeria	On-grid
Mobile	Transportation	32 crates	Zaria, Nigeria	Off-grid

Figure 5: Top left: Portable cooling chamber with a storage capacity of 25 crates in Zaria, Kaduna, Nigeria; Top right: Portable cooling chamber with a storage capacity of 25 crates in Bhuj, Gujarat, India; Bottom left: Portable cooling chamber with a storage capacity of 15 crates in Bhuj, Gujarat, India; Bottom right: Portable cooling chamber with a storage capacity of 20 crates in Bhuj, Gujarat, India.

Best practices for use

Below are some key considerations when determining if the type of forced-air evaporative cooling chamber discussed here is appropriate for your context.

1. Climate: Where these chambers work

The chamber provides the most value in hot, dry climates where the process of evaporative cooling can deliver the largest decrease in temperature. Ideal conditions for this type of cooler are a typical maximum daily temperature of greater than 30°C and relative humidity of less than 50% during the hottest times of the day. The forced-air evaporative cooling chamber provides an environment with over 80% relative humidity, average temperatures as much as 10°C below the ambient temperature, and it can decrease the maximum daily temperature by up to 15°C.

2. Storage suitability: What benefits from storage in these chambers

Fruits and vegetables such as tomatoes, eggplants, peppers, carrots, mangoes, and leafy greens have a short shelf-life in hot and dry climates and benefit from the cooler and more humid environment provided by the forced-air evaporative cooling chamber. Agricultural products like cereal grains and onions will rot in the humid conditions present in these chambers and should be stored using other methods.

3. Need: Who will benefit from these chambers

The target users for these chambers are anyone who regularly faces food (fruits and vegetables) loss or degradation due to the lack of adequate storage solutions. Furthermore, fruits and vegetable farmers, vendors, and wholesalers who are forced to travel long distances or travel more frequently to avoid food loss would also benefit from having a local storage option that allows them to have greater flexibility and control over how they manage their inventory.

Comparison with competitive technologies

Below is a comparison of forced-air evaporative cooling with competitive technologies, highlighting the key features motivating the use of this approach. Designed for use in hot, dry regions for fruit and vegetable storage, forced-air evaporative cooling chambers provide a lower-cost alternative to refrigerated cold rooms and a better-performing alternative to passive evaporative cooling systems and non-climate-controlled environments. By directing cool air through stacks of vegetable crates inside the container, forced-air evaporative cooling is able to achieve faster cooling rates than passive evaporative cooling or refrigeration-based systems relying on room cooling. These rapid cooling rates are particularly beneficial to avoid degradation in the critical hours after harvest.

Solutions based on passive evaporative cooling provide a cool and humid environment, but are inefficient in their water use. The large wetted surfaces of these devices are exposed to the ambient environment and must be constantly kept wet to prevent heat intrusion through the thermally conducting walls of the chamber if they were to become dry. In contrast, by using an insulated chamber with a forced-air evaporative cooling system, water consumption can be reduced significantly compared to a passive evaporative cooling system. When a target temperature has been reached, a forced-air cooling system can be turned off with minimal heat intrusion, saving both water and energy. Furthermore, the water irrigating the walls of a charcoal cooling chamber cannot be recycled due to the presence of abrasive charcoal dust that would damage the water pump, leading to a significant waste of water.

Commercially available 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. Refrigeration equipment and replacement parts typically need to be imported, and skilled technicians are necessary for the maintenance of the systems. In contrast, the key components of the forced-air evaporative cooler – fans, water pumps, and evaporative cooling pads – are locally available in most arid regions and do not require specialized tools or skilled technicians to repair or replace. By replacing the refrigeration unit of a cold room with an evaporative cooler, the cost and energy consumption of the system can be significantly reduced, particularly in off-grid settings.

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°C can be expected and are well-suited to keeping many fruits and vegetables fresh. Provided that a sufficient power supply is available, refrigerated cold rooms can be designed to achieve specific setpoints for temperature below 0°C if desired. Due to their ability to achieve lower temperatures, refrigerated cold rooms offer greater versatility than evaporative cooling, as they can safely store a wider array of perishable goods, including dairy products, meats, and certain medicines.

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, making evaporative cooling an attractive storage option. However, it is important to note that microbial and fungal growth can be accelerated in high-humidity environments. Thus, it is important to carefully control the humidity when storing foods such as onions, garlic, and cereal grains.

While evaporative cooling cannot provide temperatures as low as a refrigerated cold room, most fruits and vegetables do not require storage temperatures below 15°C, and greatly benefit from cool and humid environments provided by forced-air evaporative cooling.

Evaporative Cooler Specifications and Airflow Pathway

The most critical aspect of this chamber design is optimizing the airflow of the system in order to maximize the cooling rate and the energy efficiency. To maximize airflow through the crates storing the produce intended to be cooled, it is important to ensure:

1) The evaporative cooler is appropriately sized
2) Areas where air can bypass the crates are minimized
3) Unnecessary airflow restrictions are avoided

It is important that the area of greatest flow restriction is the crates filled with produce. If any other parts of the airflow pathway provide greater airflow resistance, the cooling rate and the energy efficiency with both be reduced. Figure 6 highlights the key areas of the air flow pathway.

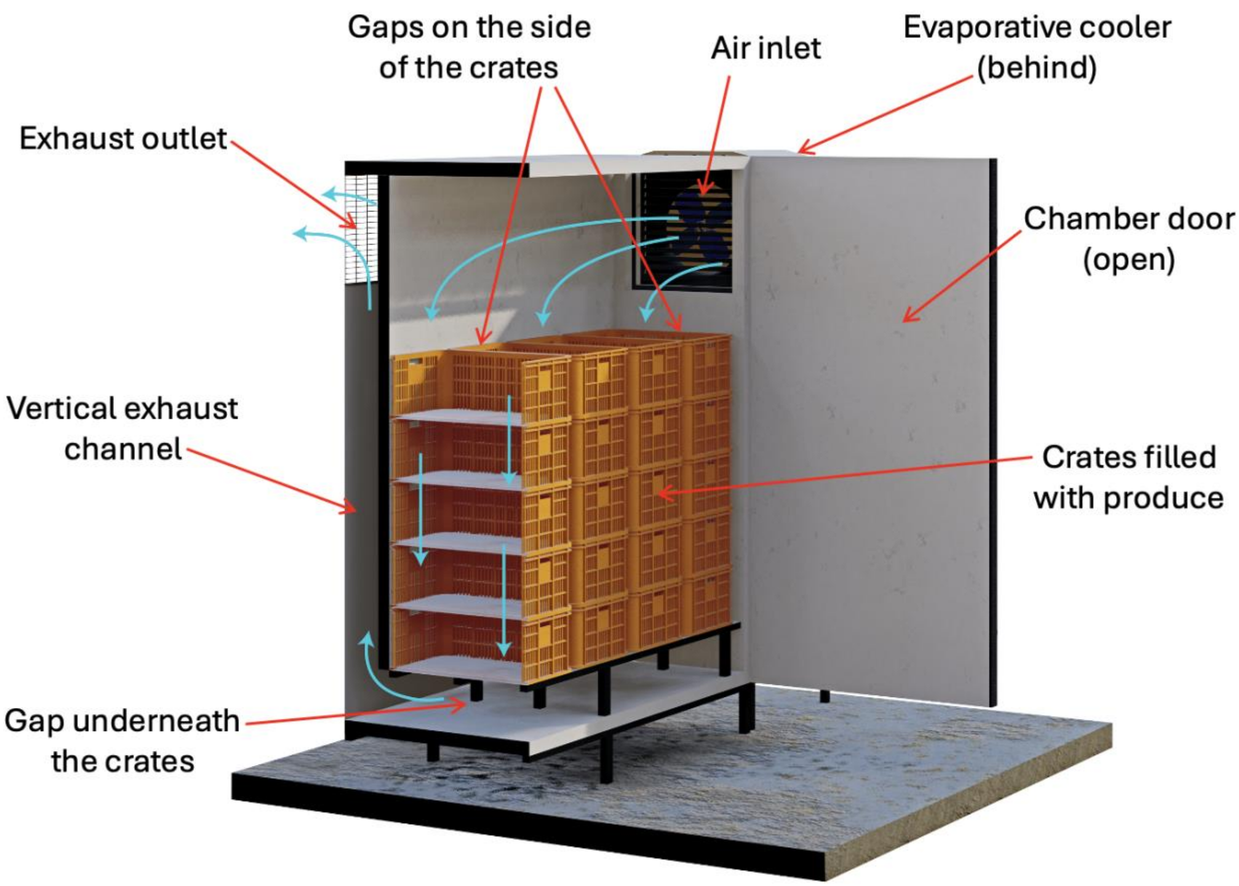


Figure 6. Schematic of CoolVeg's forced-air evaporative cooling chamber. This cross-section shows the chamber with the door in the open position, exposing the crates from the side and the front. The key components of the system are labeled (red arrows), and the air flow pathway is shown in blue arrows: air entering the chamber from the evaporative cooler, being directed downward into and through the stacks of crates, air existing from the bottom of the crates and flowing up the vertical exhaust channel and out the exhaust outlet on the rear of the chamber.

Evaporative cooler

The flow rate of the air exiting the evaporative cooler will be determined by the fan power and the resistance provided by the evaporative cooling pads and elements in the downstream air path. The chamber designs for the portable and mobile cooling chambers described here both specify the use of off-the-shelf evaporative coolers, and these devices typically list the volumetric airflow rate in cubic meters per hour (CMH) or cubic feet per minute (CFM) range. These listings are for the airflow rates when there is no resistance and the airflow rate in practice will be less than these listings when used in an application such as this fruits and vegetable cooling chamber.

As a rough guide, for a chamber capable of storing 25 crates – arranged as 5 stacks of crates, each 5 crates high – the target listed airflow rate for an evaporative cooler is in the range of 4,000 - 8,000 CMH (2,300 - 4,700 CFM). Evaporative coolers with power consumption between 150 and 300 Watts generally have airflow rates in this range. If the storage capacity is altered, the airflow rate should be adjusted by the same magnitude to achieve the same performance. These ranges are general guidance, note that the greater the airflow rate the faster the cooling rate and the greater the power consumption. Evaporative coolers with lower airflow capabilities will use less power and cool the contents more slowly. Given these considerations, an evaporative cooler and chamber size can be designed to find the appropriate balance between cooling rate and power consumption for a given context.

Linear airflow velocity rate at the crates

In addition to considering the volumetric airflow rate listed for the selected evaporative cooler, the linear velocity of air flowing through the crates is a useful metric for understanding the rates of cooling that can be achieved. An airflow meter, pictured on the left [17], is a relatively inexpensive tool that can provide valuable information on the airflow rate at various points in the chamber's airflow pathway. The recommended linear velocity of the air being directed downward and entering the crates is ~0.5 meters per second (m/s). As noted above, a wide range of airflow rates can be used with the knowledge that the cooling rate and power consumption will be impacted.

Entrance into the chamber

When attaching the evaporative cooler to the main chamber, avoid having any blockage of the air exiting the evaporative cooler. For example, the hole cut in the side of the chamber where the evaporative cooler will be mounted should be larger than the outlet of the evaporative cooler. The evaporation cooler should be mounted on the side of the chamber with the fan blowing directly into the chamber.

Gaps on the sides of the crates

To ensure that as much of the air flows through the crates storing the vegetables, the gaps between the crates and the inner walls of the chamber should be minimized. Unnecessary space around the crates can allow air to bypass the vegetables, reducing the cooling rate and wasting energy. From a practical perspective, there must be some gap between a stack of crates and the chamber wall, or between adjacent stacks of crates, so that the crates can be easily placed in the chamber and removed. However, when these gaps are more than 2 cm, a significant portion of the air coming from the evaporative cooler is able to bypass the crates and exit the chamber. We recommend that the horizontal space between a given crate and adjacent crates or the chamber walls should be less than 1 cm in each direction. For example, the interior of the chamber intended to hold five crates, each measuring 60 cm long, and 40 cm wide, could be designed as follows:

- 61 cm front to back, for a 60 cm long crate (0.5 cm gap on each side)
- 202 cm interior width, for a chamber holding 5 crates, each 40 cm in width (0.33 cm gap on each side of each stack of crates)

Openings at the bottom of the crates

It is important that the crates being used have openings (holes, gaps, or cutouts) in the bottom that allow for sufficient airflow. If the openings are too small or there is too little open cross-section, then the airflow will be unnecessarily restricted. The goal is to have the openings restrict the airflow less than the vegetables in the crates. As a rough guide, if the total cross-sectional area of the openings at the bottom of the crate is more than 50% of the area of the bottom of the crate, this should be sufficient. Note that fewer openings or holes that are large in size provide less airflow resistance than a greater number of small openings.

Space under the crates and the vertical channel on the rear of the chamber

The rack supporting the crates should be sufficiently high to keep the crates at least 20 cm from the bottom of the chamber. The cutout at the bottom of the rear panel should be at least 20 cm from the bottom of the chamber to the start of the panel. This should roughly align with the metal rack supporting the crates. If following the designs provided (see appendix), this will not need to be actually “cut out” as the panel dimensions specified will leave the desired gap. The exhaust channel running up the rear of the chamber should be at least 15 cm deep and run the full length of the chamber from left to right (~200 cm), giving a total cross-sectional area of 0.3 m^2. If following the designs provided (see appendix), this channel is created by securing a simple metal sheet to the rear of the chamber.

Exhaust outlet

The final exhaust location - where the air exits the chamber will be determined by the distance from the top of the rear metal sheet and the bottom of the ceiling panel. To prevent debris, insects, or animals from entering the chamber through the exhaust channel, a screen covering the exhaust location should be installed. This distance should be at least 30 cm to allow for a screen to cover this area without restricting air flow.

Chamber Materials and Construction Guidance

Materials for construction

The portable chambers were designed to be as simple as possible using materials that can be readily sourced in many locations. The 2 most critical components are 1) an off-the-shelf evaporative cooler and 2) insulation panels to form the chamber body.

The following is a full list of materials and components needed for constructing a forced-air evaporative cooling chamber:

- An evaporative cooler to provide cool and humid air (details described above).
- Insulation panels:
  - Material: expanded polystyrene (EPS), extruded polystyrene (XPS), and polyurethane foam (PUF) are all suitable.
  - Clad in aluminum or galvanized steel on the inside and outside to prevent rust.
  - Thickness: 50 mm. The panels can be thicker if desired, but thinner panels are not recommended as the structural integrity and thermal performance will be negatively impacted.
  - Color: The panels should be white or reflective to minimize the heat absorbed through radiation from direct sunlight and the surrounding environment.
- Brackets to hold panels together.
  - Right angle brackets for most junctions.
  - Hinges for the doors.
- Metal rack to support the crates inside the chamber.
  - 40 mm steel square tube.
  - Galvanized, polymer-coated, or painted for rust protection.
- Metal rack to support the chamber off the ground.
  - 40 mm steel square tube.
  - Galvanized, polymer-coated, or painted for rust protection.
- Sealant for the insulation panel junctions.
  - There are several options that can be used to seal the panel junction, but the high-humidity environment must be considered. Given this consideration, caulk or other sealants that are intended for wet or humid environments is preferred to duct tape.
- Weather stripping or refrigerator door gasket to seal the chamber door.
  - The adhesive used to secure the gasket should be able to withstand getting wet and repeated opening and closing of the doors.
- Screens to protect the air outlets.
  - Metal or plastic mesh.
  - Openings 1-2 mm in size.
    - The opening supporting the screen should be oversized relative to the air outlet channel to prevent the screen from restricting airflow.
  - A coarser support structure (e.g., chicken wire) is recommended to support the finer screen and prevent damage to the finer screen.

For a mobile chamber, the same materials listed above will be needed, and the chamber dimensions can be designed to fit on a selected trailer or vehicle. In addition to the trailer or truck bed on wheels, a metal shell is recommended to protect the evaporative cooler and insulation panels from damage while in transit. More details are provided in the next section.

Dimensional Diagrams and 3D Renderings

The dimensions of both the portable and mobile chambers are based on the outer dimensions of the crates being stored. The most common vegetable crates used in Nigeria have a length, width, and height of 60 cm x 40 cm x 23 cm. The mobile chamber constructed in Nigeria was also designed for carts of this size. In India, the most common vegetable crates have a length, width, and height of 54 cm x 36 cm x 29 cm. The dimensions of the insulating panels were adjusted to accommodate this crate size. Dimensional diagrams and renderings can be found in the appendix for these various chamber configurations discussed.

Mobile Forced-Air Evaporative Cooling Chamber

In addition to the portable forced-air evaporative cooling chambers for stationary applications, a mobile cooling chamber was constructed for use in transportation applications in Nigeria. This chamber used the same core design principles as the portable chamber and was mounted on a custom-built trailer, shown in Figures 7, 8, and 9. Dimensional diagrams and renderings can be found in the appendix for the mobile trailer-based forced-air cooling chamber.

Figure 7: A trailer-based mobile forced-air evaporative cooling chamber, with the steel exterior side doors visible. The insulation chamber is housed inside the exterior metal shell and can be seen through the exhaust vents at the top of the side doors.

Figure 8: A trailer-based mobile forced-air evaporative cooling chamber with the front and right side visible. Two evaporative coolers are located in an enclosed front compartment, visible through the square windows in the front of the chamber.

Figure 9: Vendors loading produce into a trailer-based mobile forced-air evaporative cooling chamber. The chamber has a storage capacity of 32 crates, or 640 kgs of produce.

Results and Discussion

The design of CoolVeg's portable forced-air evaporative cooling chambers has several key features that are attractive for deployment in low-income, rural, and arid regions, including:

- Can be constructed using materials that are locally available in most target markets
- A construction process that is simple and requires few specialized skills
    - A portable chamber capable of storing 500 kgs of produce can be constructed by two people in 2-3 days.
    - Skills required include:
        - Simple metal working (cutting and welding).
        - Basic electrical knowledge, if installing a solar + battery power system.
- The portable chamber is light enough to be easily deployed in rural areas
    - 100 to 150 kgs when empty (crates, interior metal rack, and evaporative cooler removed)
    - Can be lifted by ~ 6 people onto a small truck for deployment in rural areas and carried for short distances for precise placement.
- Utilizes the evaporative cooling effect to provide a cool and humid storage environment when used in hot and dry regions.
- Carefully designed airflow pathway to maximize the cooling rate and energy efficiency.

This section will discuss data collected regarding the following topics:

- Thermal performance of the cooling chambers and refrigeration-based solutions
    - The storage environment that can be provided.
    - The cooling rate that can be achieved.
- Energy efficiency of the cooling chambers and refrigeration-based solutions.
    - The energy requirement to achieve the improved storage environment and cooling rates.
- Fruit and vegetable shelf-life
    - Comparison of the shelf-life of fruits and vegetables when stored inside the forced-air evaporative cooling chamber and storage in ambient conditions.
- User research and feedback
    - Potential users' perception of the forced-air evaporative cooling chambers.
    - The impact of using the cooling chamber on users' lives and finances.
- Cost and scalability
    - The cost to manufacture and operate the cooling chambers.
    - The potential for commercializing the cooling chambers.

Because the primary features of the evaporative cooler and the airflow pathway are nearly identical between the portable and mobile cooling chambers, the sections covering the thermal performance, energy efficiency, and impacts on fruits and vegetable shelf-life do not make a distinction between the two applications.

Thermal Performance

The evaluation of the performance of the forced-air evaporative cooling chambers begins with determining the temperature and humidity of the storage environment, followed by the time it takes for the produce being stored to reach this temperature, i.e., the cooling rate. A cool and humid storage environment is known to provide significant shelf-life improvements compared to hot and dry storage conditions [3].

Testing and monitoring equipment

Electronic sensor systems were used to monitor the temperature and relative humidity in the storage area of the chambers and the ambient air outside of the chambers. The data logging platforms used are all capable of storing data locally and transmitting it to the cloud when a cellular signal is available:

- Cambridge, United States: (https://docs.particle.io/boron/)
- Zaria, Nigeria: (https://www.ubibot.com/ubibot-ws1pro/)
- Gujarat, India: (https://en.wikipedia.org/wiki/ESP32)

For all of the systems, two types of sensors were used:

- BME20 temperature, pressure, and relative humidity: (https://www.sunfounder.com/products/bme280-barometric-pressure-sensor-module)
- Waterproof DS18B20 temperature sensors (https://www.adafruit.com/product/381)

Using these instruments, the temperature, cooling rate, relative humidity, and temperature differential with ambient conditions was evaluated as a function of design parameters to allow for the optimization of the system. The most extensive testing was conducted on the prototype chamber in Cambridge due to the reproducibility enabled by the controlled indoor environment. Data from the chambers built and deployed in India and Nigeria were collected, analyzed, and compared to the data from the Cambridge chamber.

Experiments were conducted using the portable chamber in Cambridge, United States

A total of 26 experiments were conducted using the evaporative cooling system and the prototype chamber constructed in Cambridge. Additionally, 10 experiments were conducted in the same chamber, but using a refrigeration-based air conditioning unit instead of an evaporative cooler to allow for direct comparisons in the cooling rates and power consumption of the two technologies.

The majority of the experiments with the evaporative cooler used the following protocol:

1) An equilibration phase so that the temperature inside the chamber is roughly the same as the ambient environment (within 1°C).
2) A cooling phase where the evaporative cooler is turned on at the selected fan speed and allowed to run until the 10 gallons of water in the reservoir is exhausted. This typically takes between 6 and 12 hours, depending on the fan speed and the ambient conditions.
3) A re-heating/equilibration phase begins once the water in the evaporative cooling reservoir is exhausted. The fan speed in the re-heating phase is typically the same as the fan speed used during the cooling phase. In addition to equilibrating the temperature of the contents of the chamber with the ambient environment, the re-heating phase provides additional data on the heat transfer physics of the system.

Twenty-five (25) plastic crates measuring 60 cm long, 40 cm wide, and 25 cm tall are filled with 80 water bottles each (225 mL), totaling 450 kg. Water bottles of this size were selected to approximate the thermal properties of tomatoes. In the majority of the experiments, the 25 crates are arranged in a 5x5 grid, with five stacks of crates, each 5 crates tall. Sensors were placed inside water bottles at several locations within the chamber. The data used for the analysis of the cooling rates is taken from sensors inside the water bottles placed in the top crate in the central stack of crates, the middle crate in the central stack of crates, and the bottom crate in the central stack of crates. Additional sensors were placed to measure the air temperature at several locations through the chamber, including:

- The space above the crates, where the cool air from the evaporative cooler first enters the chamber.
- On the outside of the water bottles inside the crates, including adjacent to the water bottles, are sensors measuring the water temperature.
- The space below the crates, before the air is exhausted out of the chamber.
- At several positions outside the chamber, to measure the ambient conditions.

The "7/8 cooling time" is a standard metric for pre-cooling that we will use when discussing the cooling time in these experiments. It measures the time required for the temperature within water bottles to decrease by 87.5% (7/8) of the initial temperature difference. This difference is calculated between the starting temperature of the water bottles and the temperature of the air exiting the evaporative cooler.

The representative data in Figure 10 shows that the chamber is capable of cooling the contents of the chamber (450 kg of water bottles in plastic crates) by more than 5°C with a 7/8 cooling time of just over 6 hours. The relative humidity inside the chamber was increased by more than 30% to ~73% (see Figure 11).

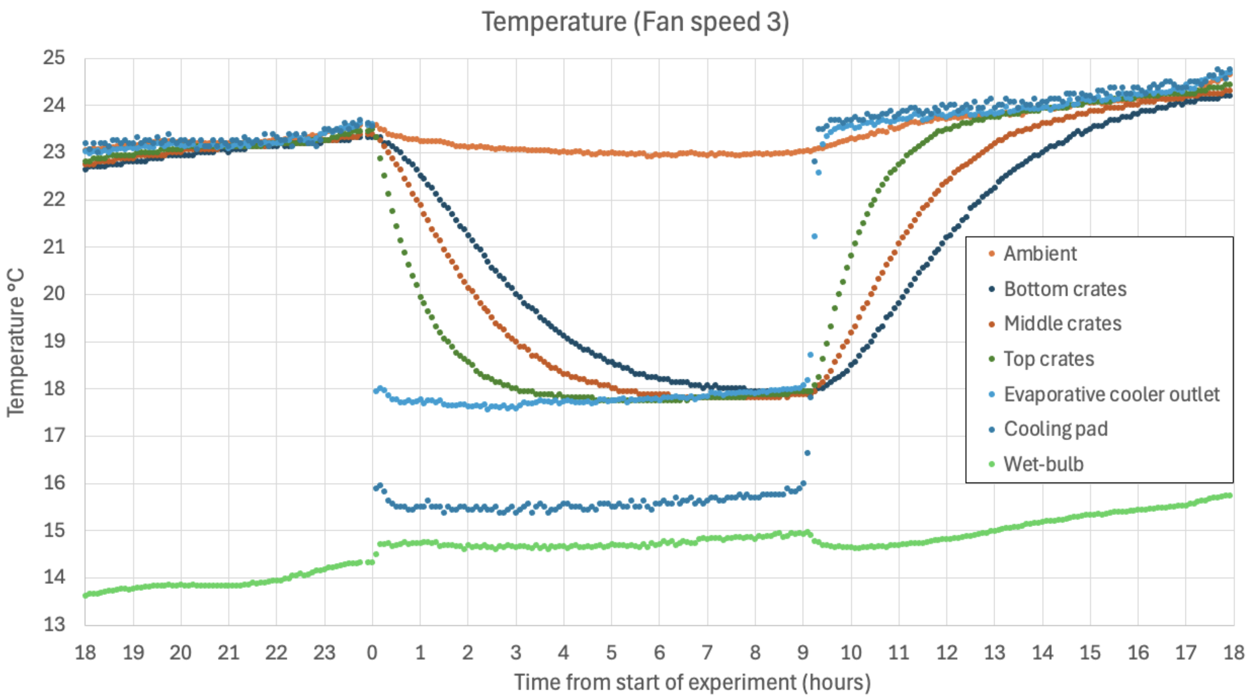


Figure 10: The temperature at several positions inside and outside of the forced-air evaporative cooling chamber on the MIT' campus. After 9 hours, the water irrigation over the cooling pad was turned off while the evaporative cooler's fan remained on to reheat the contents of the chamber. The reheating curve for the water bottles stored in the chamber follows the same trajectory as the cooling curve, but in the opposite direction. Initial heat transfer modeling results corroborate the behavior observed in these experiments. The relevant temperature and cooling times for this experiment are listed below.

Initial temperature:	23.49°C
Temperature of the air exiting the evaporative cooler:	17.57°C
ΔT (initial temperature – evaporative cooler temperature):	5.92°C
7/8 cooling temperature:	18.31°C
ΔT (initial temperature – 7/8 cooling temperature):	5.18°C
Top crate 7/8 cooling time:	2.63 hours
Middle crate 7/8 cooling time:	4.72 hours
Bottom crate 7/8 cooling time:	6.05 hours

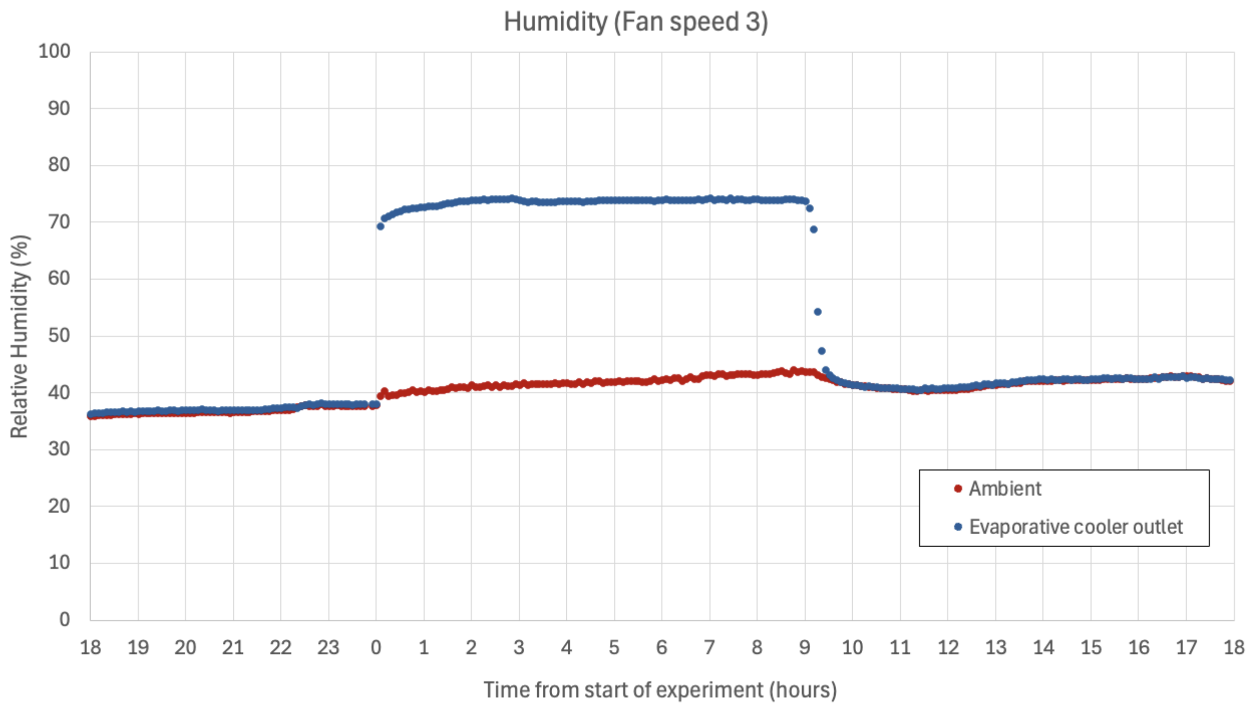


Figure 11: The relative humidity at two positions inside and outside of the forced-air evaporative cooling chamber on the MIT campus. After 9 hours, the water irrigation over the cooling pad was turned off while the evaporative cooler's fan remained on to reheat the contents of the chamber, leading to a decrease in the relative humidity inside the chamber.

The evaporative cooler has three fan speed settings. Data was analyzed from experiments with the fan speed at the "high" and "low" settings. For the experiments with the air conditioner, the thermostat was set to 14°C, and the exhaust channel in the rear of the chamber was sealed with an insulating panel. The table below shows the results from a set of 12 experiments with the four conditions listed in the column headers. Because vegetable crates are rarely stacked in refrigerated cold rooms in an arrangement that completely fills the chamber, we tested a configuration where 10 crates were removed, leaving three stacks, each 5 crates high. This arrangement is shown in Figure 12 and noted as "Air conditioner 15 crates" in Table 2. This arrangement was not replicated with the evaporative cooler, as it would never be used in practice, as it would allow for the majority of the air to bypass the vegetables in the crates. This data shows that the cooling rate is significantly faster when the evaporative cooler is used and the cooling rates observed in this study are in alignment with times reported in the literature, 1-10 hours for forced-air cooling and 20-100 hours for room cooling [2].

Table 2. Data collected from pre-cooling tests conducted in Cambridge, United States, comparing the results when using an evaporative cooler with an air conditioner. All tests were conducted using the same chamber, quantity of water bottles, and sensor positions. The only changes involved swapping the evaporative cooler for the air conditioner, closing the air exhaust channel when using the air conditioner, and the removal of 10 crates of water bottles for the "air conditioner 15 crates configuration".

	Evaporative cooler		Air conditioner	
	High fan 25 crates	Low fan 25 crates	25 crates	15 crates
Initial temperature	21.6 °C	21.8 °C	22.2 °C	20.3 °C
Temperature of the air exiting the evaporative cooler/AC	14.0 °C	14.7 °C	14.1 °C	14.5 °C
ΔT (initial temperature – evaporative cooler/AC temperature)	7.5 °C	7.0 °C	8.1 °C	5.8 °C
7/8 cooling temperature	15.0 °C	15.6 °C	15.1 °C	15.3 °C
ΔT (initial temperature – 7/8 cooling temperature)	6.6 °C	6.2 °C	7.1 °C	5.1 °C
Top crate 7/8 cooling time	2.4 hours	2.4 hours	5.7 hours	5.7 hours
Middle crate 7/8 cooling time	4.1 hours	4.6 hours	17.0 hours	16.2 hours
Bottom crate 7/8 cooling time	5.7 hours	6.4 hours	39.1 hours	11.7 hours

Table 3 shows the ratio of the 7/8 cooling times for 6 configurations.

- While we did not conduct experiments with only 15 crates while the evaporative cooler was being used to cool the contents of the crates, the values for the "High fan (15)" and "Low fan (15)" configurations were obtained by using the data from the middle crate of the "High fan (25)" and "Low fan (25)" configurations, respectively.
- In the AC (15) configuration, the middle crate cooled the slowest, and thus this value was used as the figure of merit for this configuration (highlighted in orange).

Table 3. A comparison of the 7/8 cooling times when using an evaporative cooler and an air conditioner with various fan speeds and crate configurations. Details of the "High fan (15)", "Low fan (15)", and "AC (15)" configurations are provided in Figure 12.

Ratio of 7/8 cooling times for the slowest cooling crate		High fan (15) 4.1 hours	Low fan (15) 4.6 hours	High fan (25) 5.7 hours	Low fan (25) 6.4 hours	AC (15) 16.2 hours	AC (25) 39.9 hours
High fan (15)	4.1 hours	-	0.89	0.73	0.64	0.25	0.11
Low fan (15)	4.6 hours	1.12	-	0.81	0.72	0.29	0.12
High fan (25)	5.7 hours	1.38	1.23	-	0.89	0.35	0.15
Low fan (25)	6.4 hours	1.56	1.39	1.13	-	0.40	0.16
AC (15)	16.2 hours	3.93	3.51	2.85	2.52	-	0.41
AC (25)	39.9 hours	9.46	8.54	6.87	6.08	2.4	-

Some key observations from this analysis of the cooling times include:

- The 7/8 cooling time is only 13% slower when using the low fan speed of the evaporative cooler compared to the high fan speed. This is due to the relatively small difference in the airflow velocities between these settings. The high fan setting provides an estimated face velocity of 0.56 meters per second, and the low fan setting provides an estimated face velocity of 0.44 meters per second.
- The 7/8 cooling time using the evaporative cooler is significantly faster than either configuration while using the air conditioner. The evaporative cooler on the high fan setting provides a 7/8 cooling time that is 6.87 times faster than the AC (25) configuration when considering the slowest cooling crate in each configuration. Additionally, the evaporative cooler on the high fan setting provides a 7/8 cooling time that is 2.85 times faster than the AC (15) configuration when considering the slowest cooling crate in each configuration, while noting that the AC (15) configuration cools 40% less mass.

Figure 12: Left: the crate configuration for the "High fan (15)" and "Low fan (15)" tests, where only the top three rows of crates are considered, represent the cooling of 15 crates. Right: the crate configuration for the "AC (15)" tests, where two stacks of crates were removed to allow for airflow between the remaining stack of crates. This type of configuration is commonly used in cold rooms.

Heat transfer modeling of the forced-air evaporative cooling chamber

To gain a deeper understanding of the heat transfer considerations we have, we compared experimental data with a heat transfer model. Several assumptions were made to simplify that model. Assuming that all of the vegetables in the crates are initially at a uniform temperature Tb_0 (starting temperature of the vegetables). At time zero, air at Ta_0 (the temperature of the inlet air, exiting the evaporative cooler and entering the cooling chamber), which has been cooled by evaporation, flows uniformly downward through the crates. Heat is transferred from the warm vegetables to the cool air. As the cooling process take place, the cool inlet air begins to reduce the temperature of the vegetables. The temperature of the air increases as it moves down through the crates as it absorbs heat from the vegetables. The crates of vegetables at the top level are in contact with the coolest air, so these vegetables cool fastest. As the vegetables cool, the vertical temperature distribution of the vegetables changes with time. The vertical temperature distribution of the air also changes with time. The analysis presented here will be used to predict the time variation of the vegetables at each vertical location. To carry out this analysis, the time variation of the air at each vertical location must also be found.

It will be assumed that the temperature of each individual vegetable is uniform throughout. That is, the surface temperature and the interior temperature are the same, although that temperature will change with time. At each vertical cross-section, all of the vegetables are assumed to have the same temperature. For the experiments at MIT, water bottles were used to simulate the thermal mass of vegetables. At each vertical cross-section, the air velocity is assumed to be constant, and the vegetables are uniformly distributed. Conduction heat transfer will be neglected in the vertical direction and the cross-sectional directions. Therefore, the only heat transfer mechanism considered is convection between the air and the surface of the vegetables, or water bottles in the case of the experiments at MIT.

Figure 13 shows the experimental results of the tests at the MIT campus using water bottles to simulate vegetables. At the beginning of the test, all of the water bottles are at a uniform temperature, and cool air is introduced at the top of the chamber. The figure shows the time variation of the water bottle temperature at three locations: the top, the middle – 0.5 m from the top, and the bottom – 1 m from the top. Predictions using a numerical solution of the heat transfer model described were made from the model and are included on the same plot [18]. The agreement between the model and the experimental data is quite good, considering that there is an uncertainty in the heat transfer correlation for the geometry of the bottles.

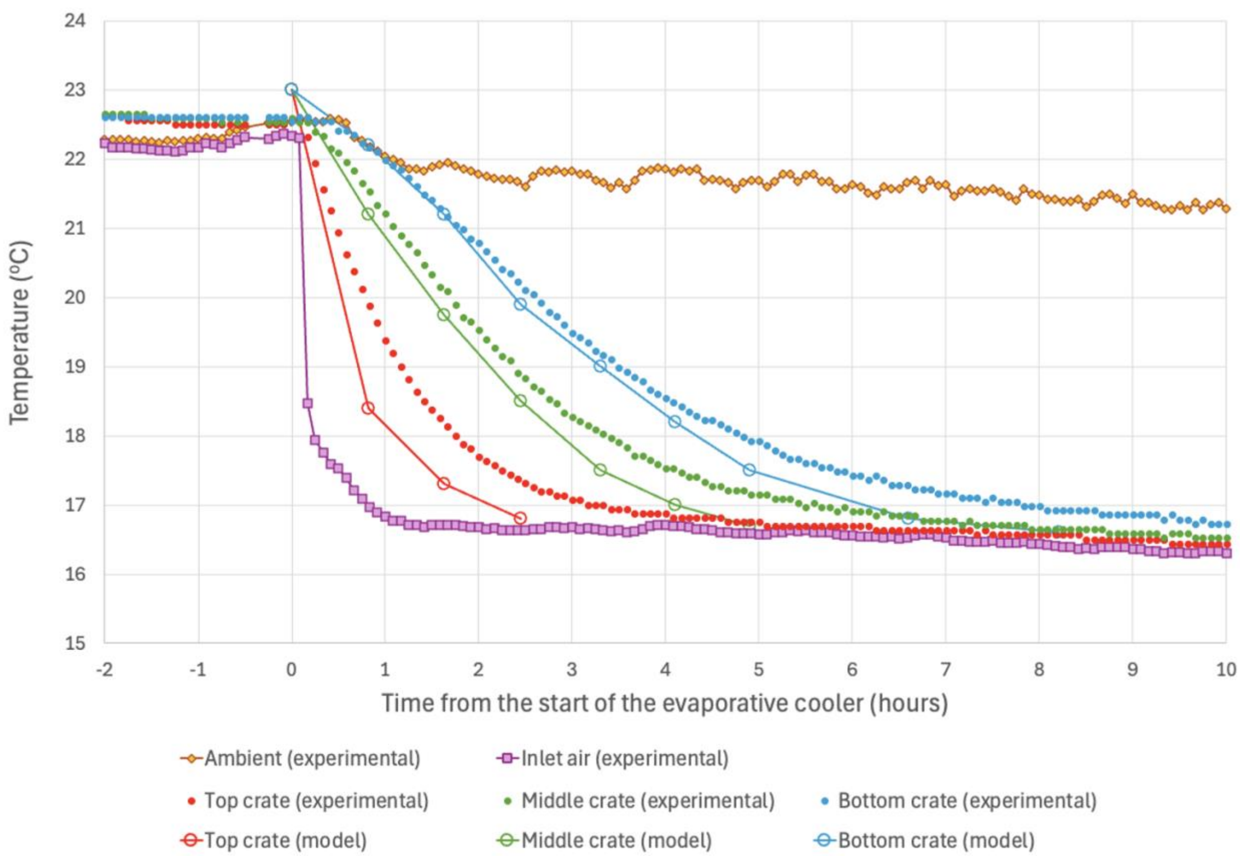


Figure 13: A plot of experimental data collected at the MIT campus compared with the heat transfer model. The ambient is the air temperature around the chamber, and the inlet air is the temperature being blown into the chamber by the evaporative cooler. The data for the top, middle, and bottom crates was collected using waterproof temperature probes placed inside water bottles at the specified locations. The data from the model was calculated using the numerical solution presented in a previous publication[18].

The heat transfer model can also be used to predict the influence of the flow rate, or face velocity, on the time constant at the bottom of the crates. The velocity influences the heat transfer coefficient as well as the mass flow rate of the air. Figure 14 shows the time constant, defined as the time at which the temperature has cooled 67%, or exp^{-1}, between the initial and final temperatures. The non-linear relationship between the face velocity and the time constant indicates that there are diminishing returns for increasing the face velocity to speeds greater than 0.6 m/s. When designing a chamber and selecting the fan speed for a specific application, this non-linearity should be taken into account to optimize the tradeoff between the energy efficiency and cooling rate.

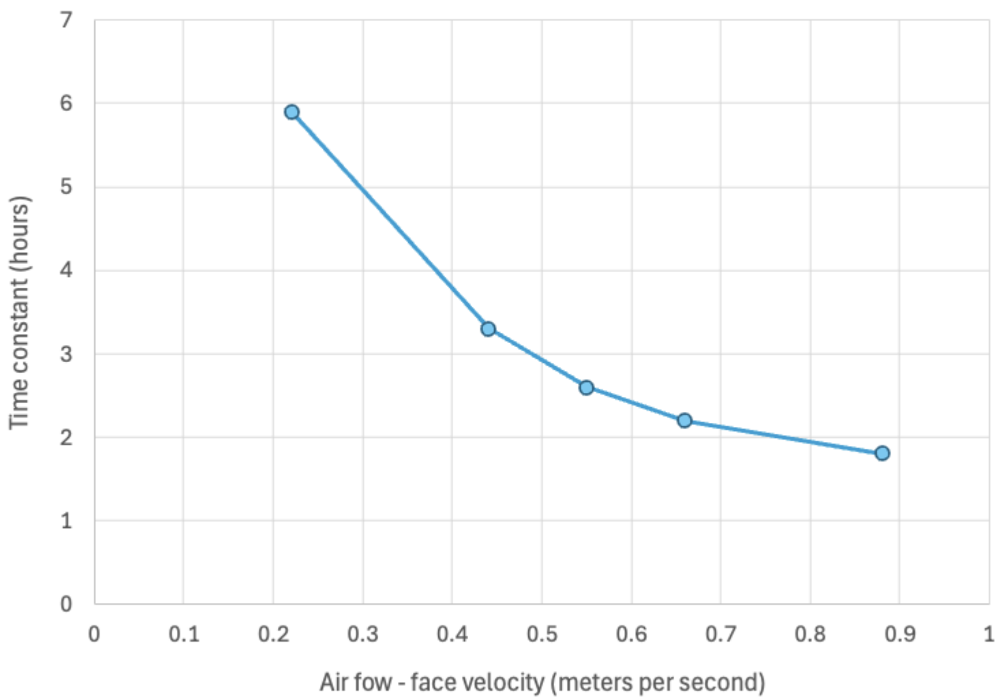
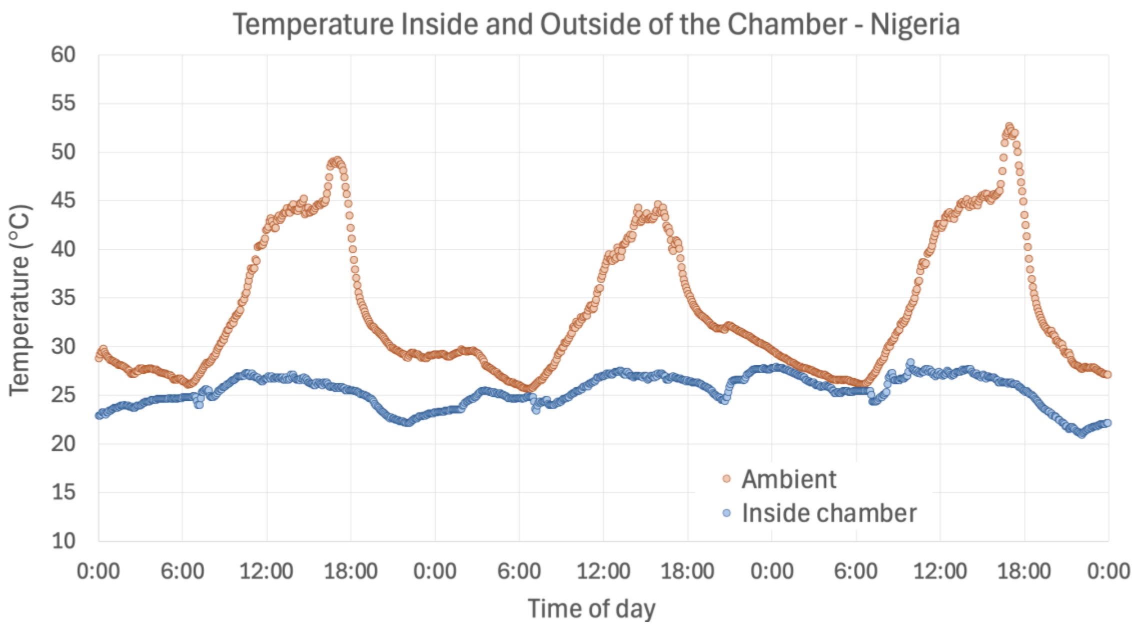


Figure 14: The time constant at the bottom as a function of the face velocity of the cooling air.

Data from the chambers in Zaria, Kaduna, Nigeria

Data from the portable chamber in Nigeria was gathered using sensors placed inside and outside the chamber. Figure 15 shows that during the hottest time of the day, the temperature inside the chamber is more than 15 °C lower than the ambient temperature. The relative humidity inside the chamber is more than 30% higher than outside the chamber during the hottest time of the day, when fruits and vegetables are most susceptible to spoilage.



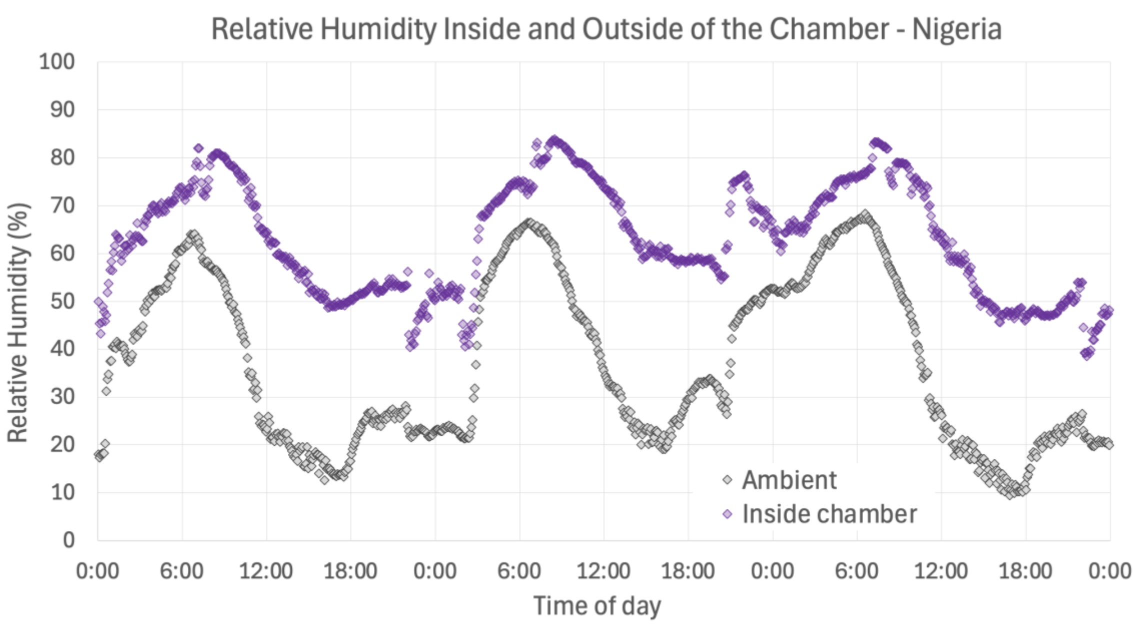
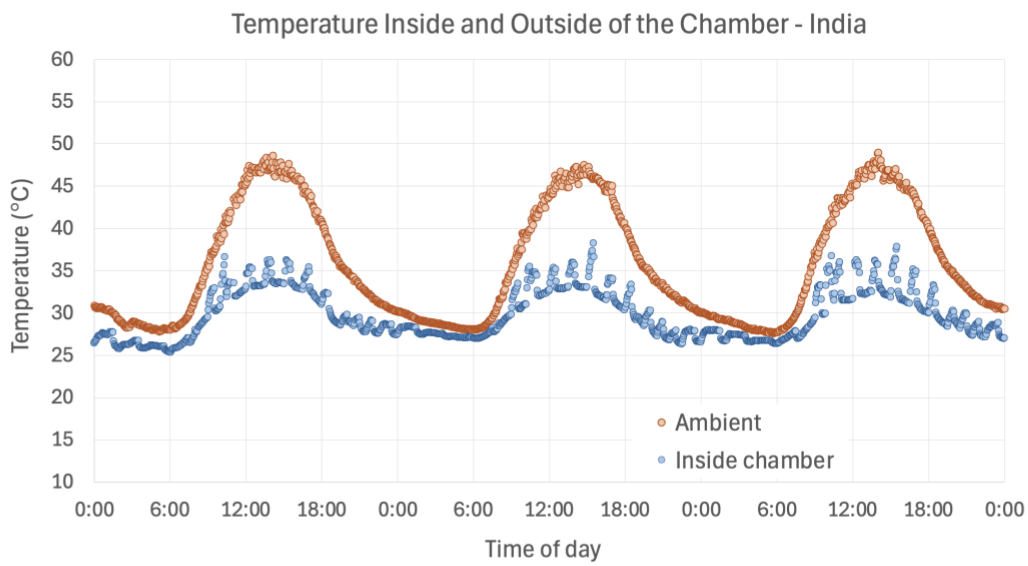


Figure 15. Representative plots of the temperature (top) and relative humidity (bottom) inside and outside of the evaporative cooling chamber in Zarai, Nigeria, over a 3-day period.

Data from the chambers in Bhuj, Gujarat, India

Data from portable chambers in India was gathered using sensors placed inside and outside the chamber. Figure 16 shows that during the hottest time of the day, the temperature inside the chamber is more than 12 °C lower than the ambient temperature. The relative humidity inside the chamber is above 80% through the majority of the day, while the relative humidity outside the chamber is below 30% during the hottest time of the day, when fruits and vegetables are most susceptible to spoilage. The small increases in the air temperature inside the chamber that are observed in the plot below are a result of cycling the evaporative cooler on and off throughout the day with a timer to reduce energy consumption.



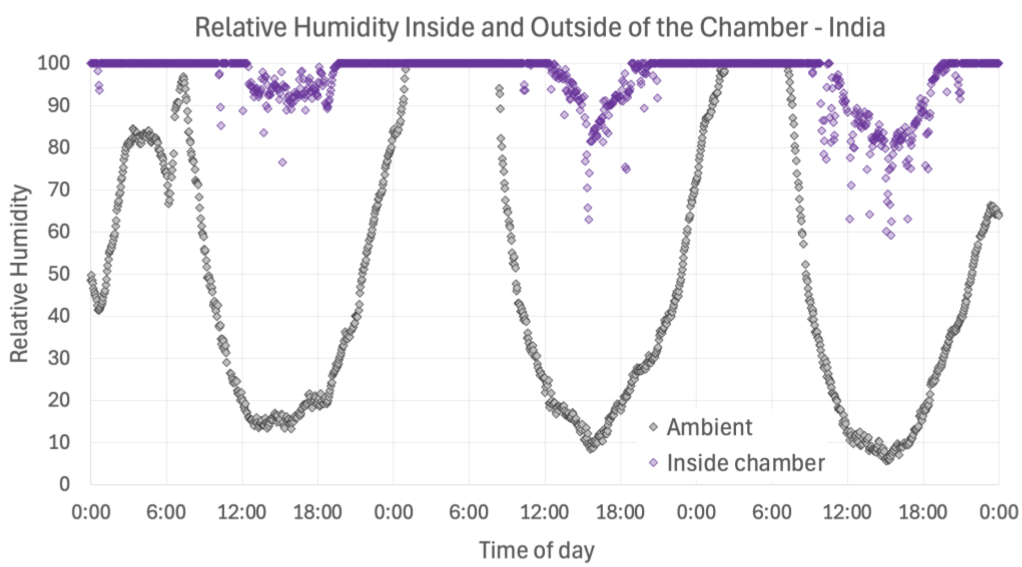


Figure 16. Representative plots of the temperature (top) and relative humidity (bottom) inside and outside of the evaporative cooling chamber in Bhuj, India, over a 3-day period.

Energy Efficiency

This section discusses the energy consumption required to achieve the storage environments and cooling rates observed. This data consists of quantitative measurements of:

- Peak power consumption (kW)
- Energy consumption during steady-state storage (kWh)
- Energy consumption during initial cooling (kWh)
    - The calculation of the power consumption during the initial cooling phase is dependent on the cooling rate

The storage volume of a cooling chamber can measured by:

- The chamber's total internal volume (m^3).
- The number of vegetable crates that can be stored in a given version of the forced-air evaporative cooler and the volume of each crate (m^3). This is a more practical representation of the chamber's storage capacity than total internal volume.
- The storage capacity in terms of the weight of produce that can be stored (kg).

The power consumption was monitored using a P3 P4400 Kill A Watt Electricity Usage Monitor (https://shop.p3international.com/products/kill-a-watt) that measures instantaneous power consumption and records cumulative power consumption.

Peak power consumption

The peak power consumption of the evaporative coolers used for the portable chambers in this project was the following: 127 Watts (Cambridge), 185 Watts (India), and 195 Watts (Nigeria). The power consumption of the evaporative coolers did not have significant variations as a function of the stage of cooling; however, the power consumption of the coolers is impacted by the back pressure provided by the chamber. The power consumption of the evaporative coolers is reduced by ~ 5% when the cooler is pushing air through stacks of crates, compared to when it is operating in an open room.

Figure 17 shows a plot of the power consumption as a function of time while the air conditioner was in use during a cooling test in Cambridge. The peak power consumption of the air conditioner used in the experiments in Cambridge is over ~600 Watts, while the power consumption is ~250 Watts when the contents of the system have reached the temperature of the thermostat setting. In these experiments, the evaporative cooler was operated using a consistent amount of power while operating. In contrast, the air conditioning unit utilized a thermostat to cycle on and off to prevent ice buildup when the target temperature at the exit of the unit is reached. In practical operation, the evaporative cooler would be used at constant power for the initial cooling of produce, and then can be cycled on and off once the target temperature has been reached, further reducing the energy consumption of the system.

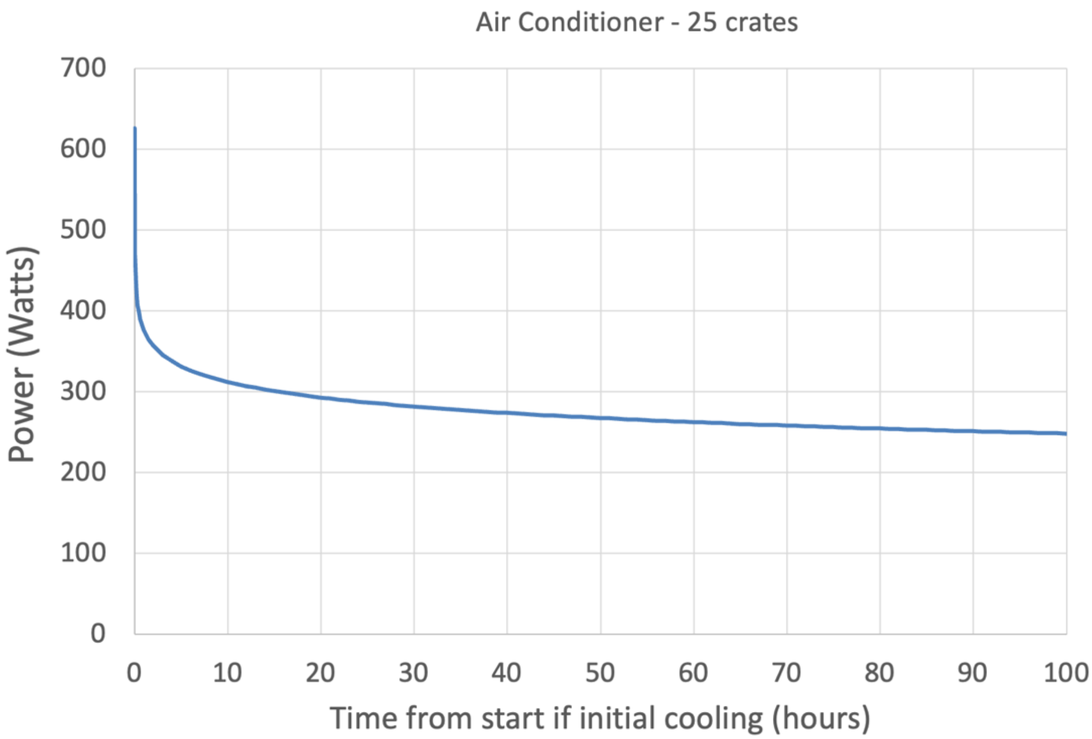


Figure 17: The power consumption of the air conditioner used in the cooling chamber experiments as a function of time.

Energy efficiency during steady-state storage

The steady-state storage energy efficiency is the energy required to maintain a specified temperature after this temperature has been reached. The discussion in this section focuses on the daily energy consumption per cubic meter of storage capacity (kWh/m^3). The daily energy consumption (kWh) is the average daily power consumption (kW) multiplied by 24 hours (h). In the forced-air evaporative cooling chamber designs developed for this project, the practical storage capacity is between 40% and 60% of the total internal volume. This value is typically much lower (30% - 40%) for walk-in style cold rooms. Practical storage capacity is a more relevant measure than the internal volume of a cold storage chamber, as it does not include volume above a height that is practical for storing produce, space between crates that may be intentionally left to allow access to produce, etc. It is important to note that these metrics are only indicative of the energy consumption of the cooling unit while maintaining a specified temperature and the size of the chamber; this metric does not take into account the cooling rate or the temperature that can be achieved. Table 4 lists the energy consumption for both the:

- Internal volume of the chambers (the interior dimensions of the chamber)
- Practical storage capacity (the number of crates of a given volume that can be stored in the chamber)

Table 4. The daily energy consumption for nine cooling chambers, including several forced-air evaporative cooling chambers (FAECCs), an air conditioning-based chamber, and a commercially available refrigerator in Nigeria. *Assumes that vegetables are removed from crates and placed directly in the refrigerator. **Assumes 50% capacity factor during steady-state operation.

Cooling chamber energy efficiency	Power consumption		Daily Energy Consumption (kWh/m³)	
	Peak	Average	Internal chamber volume	Practical storage capacity
FAECC in Cambridge (25 crates)	127	127	1.34 (kWh/m³)	2.54 (kWh/m³)
Air conditioner-based cooling chamber in Cambridge (25 crates)	600	250	2.63 (kWh/m³)	5.00 (kWh/m³)
Air conditioner-based cooling chamber in Cambridge (15 crates)	600	250	2.63 (kWh/m³)	8.33 (kWh/m³)
Portable FAECC in India (25 crates)	352	352	3.65 (kWh/m³)	5.99 (kWh/m³)
⁺Portable FAECC in India (25 crates)	185	185	1.92 (kWh/m³)	3.15 (kWh/m³)
Portable FAECC in India (20 crates)	185	185	2.19 (kWh/m³)	3.94 (kWh/m³)
Portable FAECC in India (15 crates)	185	185	2.45 (kWh/m³)	5.25 (kWh/m³)
Portable FAECC in Nigeria (25 crates)	195	195	1.90 (kWh/m³)	3.39 (kWh/m³)
700-Liter capacity refrigerator in Nigeria*	700	375**	12.86 (kWh/m³)	12.86 (kWh/m³)
20' shipping container based FAECC in Kenya (168 crates)	1,500	1,500	1.38 (kWh/m³)	3.88 (kWh/m³)

Key observations from the data in Table 4 include:

- The daily energy consumption of the air conditioner is greater than the evaporative cooler in the same chamber.
- Note that the internal volume is the same for the AC 25 crates and 15 crates configurations, while removing 10 crates changes the practical storage capacity.
- The daily energy consumption per cubic meter (m^3) of the 700-liter refrigerator in Nigeria is significantly higher than that of the other cooling chambers.
- ⁺The portable FAECC in India with 25 crates could easily be outfitted with the same 185 W evaporative cooler that is used for the 20-crate and 15-crate chambers.
- The choice of evaporative cooler impacts the daily energy consumption for short-term storage, but greater airflow rates above a minimum requirement to maintain the desired temperature do not provide significant value for short-term storage.
- Greater airflow rates and higher energy consumption increase cooling rates, discussed below.

Energy efficiency during pre-cooling

When considering the energy efficiency during the pre-cooling, the primary use case is for the forced-air evaporative cooling chamber being developed as part of this project; it is important to consider the instantaneous power consumption, but also the duration of time that the device must be operating to achieve the desired pre-cooling. Key metrics related to the energy efficiency of the cooling chamber in different configurations are listed in Table 5. When the chamber is completely filled with 25 cases, the evaporative cooler is 17 times more efficient than the air conditioner in cooling the chamber contents; 0.73 kWh from the evaporative cooler compared to 12.8 kWh for the air conditioner. This is due to both the higher energy consumption of the air conditioner and the slow cooling rate (more than 39 hours) of the bottom crates while the air conditioner is in use. When only 15 crates are placed in the chamber (three stacks of five crates) when the air conditioner is being used, the energy efficiency is significantly improved, but is still nearly 9.3 times more energy-intensive than pre-cooling the same number of crates with an evaporative cooler; 0.53 kWh from the evaporative cooler compared to 4.9 kWh for the air conditioner. The table below also displays the energy efficiency values for the practical storage capacity in kWh/m^3 and kWh/kg.

Table 5. Analysis of data collected from pre-cooling tests conducted and power consumption measurements in Cambridge, United States, comparing the results when using an evaporative cooler with an air conditioner. Both "25 crate" results used the same configuration, and the "15 crate" results use the configurations described in Figure 12. The energy efficient metrics presented in this table are based on the practical storage capacity (the number of crates that can be placed in the chamber and the internal volume of the chamber is not considered for this analysis.

Energy efficiency during pre-cooling	25 crates		15 crates	
	Evaporative cooler	Air conditioner	Evaporative cooler	Air conditioner
7/8 cooling time (hours)	5.7 hours	39.1 hours	4.1 hours	16.2 hours
Average energy consumption (Watts)	127 Watts	302 Watts	127 Watts	327 Watts
Energy consumption for 7/8 temperature (Watt-hours)	0.73 kWh	12.8 kWh	0.53 kWh	4.9 kWh
Practical storage capacity of the chamber (cubic meters)	1.20 m^3	1.20 m^3	0.72 m^3	0.72 m^3
Energy efficiency value (kWh/m^3)	0.60 Wh/m^3	10.61 kWh/m^3	0.73 kWh/m^3	6.81 kWh/m^3
Practical storage capacity of the chamber (kg)	450 kg	450 kg	270 kg	270 kg
Energy efficiency value (Wh/kg)	1.62 (Wh/kg)	28.45 (Wh/kg)	1.95 (Wh/kg)	18.16 (Wh/kg)

Fruit and Vegetable Shelf-Life

Shelf-life studies were conducted with the forced-air evaporative cooling chambers in India and Nigeria. For each of the experiments, a portion of the vegetables purchased was placed in the chamber, and a portion was placed in an open basket placed in the shade to act as a comparison (control). The comparison of the quality of the two sets of produce over time is the core of the shelf-life study. Because the shelf-life of most fruits and vegetables is sensitive to the specific variant of fruit or vegetable, the time they were harvested, and the temperature and humidity where they are stored, this head-to-head comparison is critical for obtaining reliable results.

The following metrics were recorded on each day of the test, including “Day 0” when the test started:

- Weight loss (in reference to the weight of the vegetables on the first day)
- Visual Quality
- Rot
- Saleability

Other than the quantitative weight loss metric, the remaining qualitative metrics are subjective ratings assigned by the research team. Our primary metric for determining the shelf-life of the batch of produce is when 50% or more of the produce is still sellable.

The following vegetables were included in shelf-life studies as part of this project:

- Carrot (India)
- Cauliflower (India)
- Cluster bean (India)
- Cucumber (India and Nigeria)
- Eggplant (India)
- Green beans (Nigeria)
- Ivy Gourd (India)
- Leafy greens (India and Nigeria)
    - Cabbage (Nigeria)
    - Coriander (India)
    - Green onion (Nigeria)
    - Spinach (India)
- Okra (India and Nigeria)
- Pepper - bell (Nigeria)
- Pepper - green chili (India)
- Pepper - hot cherry (Nigeria)
- Pepper - hot chili (Nigeria)
- Red onion (Nigeria)
- Tomato (India and Nigeria)

Shelf-life studies in Nigeria

After initial testing of the portable chamber to confirm the thermal performance was as expected, a variety of vegetables were placed in the chamber. The first test included 10 vegetables, and began on April 12, 2025, at ColdHubs' facility in Zaria, Kaduna State, Nigeria. The second test focused on 5 key vegetables and was started on April 25, 2025.

Table 6 shows that the shelf-life of all the vegetables was significantly extended when stored in the portable forced-air evaporative cooling chamber. For most of the vegetables, the shelf-life was extended by 4 or more days, and was three times longer in the chamber than outside of the chamber. The set of images in Figure 18 shows side-by-side comparisons of tomatoes, bell peppers, okra, and cucumbers (from the 2nd test) after 6 days.

Table 6. The shelf-life of selected vegetables was compared between storage outside of the chamber in the shade with storage in the forced-air evaporative cooling chamber. Only 5 of the 10 vegetables were included in the second shelf-life test.

Forced-air evaporative cooling chamber shelf-life tests in Zaria, Nigeria Shelf-life (days) is defined as saleability >= 50%				
Vegetable	Shelf-life test #1		Shelf-life test #2	
	Stored outside	Stored in the FAECC	Stored outside	Stored in the FAECC
Tomato	2	6	2	9
Hot chili pepper	2	6	-	-
Bell pepper	2	6	2	9
Cabbage	6	22	-	-
Cucumber	1	14	2	8
Green onion	2	5	2	8
Green beans	1	5	-	-
Okra	1	4	1	6
Hot cherry pepper	2	5	-	-
Red Onion	14	100+	-	-

Tomatoes, bell peppers, and cucumbers each had an average shelf-life of 2 days when stored in the shade. The shelf-life extensions achieved range from 2.5 times longer for hot cherry peppers when stored in the forced-air evaporative cooling chamber, as compared to storage in the shade, and cabbage lasting an average of 9 times longer in the chamber. Tomatoes, hot chili peppers, bell peppers, cabbage, green onion, green beans, and okra all lasted between 3 and 5 times longer when stored in the chamber as compared to storage in the shade.

Notably, the shelf-life of red onions was extended from 14 days when stored in the shade, as compared to more than 100 days in the chamber. This result was surprising to the CoolVeg team, as we had seen poor results when storing red onions in passive evaporative cooling technologies such as clay pot coolers, as rot would occur due to the humidity remaining near 100% at all times. However, due to the constant airflow in the FAECC and the humidity that was elevated compared to the ambient conditions, but rarely reaching 100%, the red onions are showing few signs of degradation after more than 3 months of being stored in the cooling chamber. This dramatic increase in shelf-life is particularly advantageous for farmers as they will be able to store their red onions from the harvest time – when prices are the lowest – until several months later, when prices increase as the supply is significantly lower.

Figure 18: The shelf-life of tomatoes, bell peppers, cucumbers, and okra stored in the forced-air evaporative cooling chamber and outside of the chamber in the shade. The degradation of the samples stored in the shade is clearly visible, while the samples stored in the chamber are still fresh and edible and salable after 6 days.

Shelf-life studies in India

The shelf-life studies in India did not show results as compelling as in Nigeria. In nearly all cases, the condition of the vegetables was better, and the shelf-life was longer, inside the chamber, as compared to storage in ambient conditions, but the differences were often only 1-2 days. We suspect several factors contribute to the less significant improvements, including:

1) The ambient humidity in India reached 100% most nights, which allows the control samples stored outside the chamber in Bhuj, India, to last longer than those from Zaria, Nigeria.
2) The humidity inside the chamber was at or near 100% for the entire day when the chamber was in operation. We have seen negative impacts of consistent high-humidity environments' passive evaporative cooling technologies, such as clay pot coolers. We found that opening the cover of a clay pot cooler several times a day reduced the occurrence of mold and rot. We are looking at options for initially reducing the humidity inside the chamber to allow users to have greater control over the chamber's environment.

User Research and Feedback

During our user research, we identified users in both Nigeria and India. In the below sub-sections, we will describe them separately in the context of users in the state of Kaduna, Nigeria and for users in Gujarat, India. These will include the methodology of collecting data, assumptions for choosing the final users, the interviews and responses, and finally, the feedback about the chambers. The following subsections are discussed below:

- Methodology
- Insights from user research and user interviews
- Feedback and insights after demonstration and usage

Methodology

In Nigeria, as previously stated, our initial user research was conducted with the ColdHubs team members, who gave us he needed information about the value chain and the design constraints for the chambers based on their previous engagement with their customers who use their cold storage facilities. Once the chambers were ready to be deployed, 46 farmers and retailers from the surrounding areas of the Kaduna cold room facility were invited to attend a demonstration of the portable and mobile chambers. The demonstration was conducted at a time when the chamber, while a shelf-life experiment was in progress. The farmers and vendors in attendance were able to see the chamber in action and compare the condition of produce kept inside and outside the chamber. CoolVeg and ColdHubs had prepared a list of questions to facilitate a group discussion and collect information regarding their harvesting/buying details, their storage needs, and their selling process. This included a section to record their immediate feedback upon seeing the demonstration of the portable and mobile chambers. For the mobile chamber, one of the ColdHubs staff members drove the trailer with fresh vegetables in the chamber to the nearby farm areas and markets and identified potential users in the area. This was done over a period of 10 days, and high-level feedback was collected. Following the demonstrations, individual interviews with 16 potential users were conducted to gather more detailed information about the respondents' perception of the technologies and their interest in purchasing the chambers for a selected purchase price for the chambers to gauge whether the chamber was affordable to the users.

In India, after getting a basic understanding of the value chain from Artisana team members, we created a user research interview document for each of the three main user types. We then traveled to Bhuj in Gujarat, where Artisana helped identify potential users in each category. Each interview was about 45 minutes on average, conducted in person, in Hindi- a language everyone was comfortable in. The answers were noted down and then transcribed.

For the user research, we conducted 17 interviews, and we had to choose 3 users to deploy the chambers in the final stage. We had also pre-decided certain criteria that the users needed to fulfil. These included:

a) A clear interest in the cooling chamber.
b) A need for cold storage in their daily activities.
c) A willingness to purchase after a successful trial of the chamber.
d) A daily handling of vegetables known to thrive in cold storage, including tomatoes, leafy greens, chilies, and eggplants.
e) A willingness to manage and secure the safety of the various sensors we would deploy.

We selected one stakeholder each – an organic farmer having 1.5 acres of farming land, a local vendor who sells fruits and vegetables through a stationary cart, and an Agricultural Produce Market Committee (APMC) wholesaler.

Once the chambers were ready to be deployed, a more in-depth interview was conducted with each of them. This included their harvesting/buying details, their storage needs, their selling process, the various pricing strategies they employ, along with questions related to their expectations for the cooling chamber. The users were also provided with detailed instructions on how the chambers were to be used, how the crates should be loaded with produce, and general maintenance of the chambers. For tracking usage of the chamber, we created a simple recording document seen below, both in English and Gujarati (the local language of the users in Bhuj). This underwent multiple iterations so as to make it as simple as possible for the users.

IN			OUT		
Date	**Produce Name**	**Quantity**	**Date**	**Produce Name**	**Quantity**

A mid-line interview was similarly conducted approximately a month after the users had begun using the chambers, with the questions very similar to the baseline interview. This was done so that we could analyze the difference in their pricing, behaviors, and other changes that could be observed before and after using the chamber. Unfortunately, due to non-conducive weather and it being a period where a lot of vegetables weren't being harvested, we didn't receive substantial feedback. Our users are still testing the chambers, and we will continue to follow up with them to collect detailed feedback.

Insights from user research and user interviews

The insights for India came from interviews with multiple stakeholders as well as in-depth interviews with the three users chosen for deployment. Since each user had specific storage requirements, the insights, along with snippets from their interviews, have been condensed into bullet points below.

1. Farmer – Mauji Bhai
    - Organic farmer with 1.5 acres of farming land.
    - Most harvested crops – tomato, papaya, chili, guava, mango.
    - Harvests his crops every 2-3 days in the mornings and sells the produce in the afternoon.
    - On the days that he isn't selling, he cannot harvest his crops as he has no storage, which means they would become spoiled. Harvesting every day isn't feasible for him, as the transport costs are high.
    - He would like to harvest every day and then be able to store the produce safely until the selling day. This would increase his revenue while keeping transport costs the same.
    - When he doesn't harvest every day, his ripe crops get eaten by birds and vermin; ~25% of his harvest is thus lost.
    - Unsold produce is distributed for free to his family and friends.
    - He expected that a chamber capable of storing 20 crates of produce would be enough for his storage needs.

2. Local vendor – Dhaval Jawaharlal Bhai
    - Sells different varieties of fruits and vegetables all year round, and keeps a stock ranging between 20-100kgs for each variety of produce. Of this, he loses 25% of his stock every day in the summer, and 15-20% in the monsoon and winter seasons due to a lack of cold storage.
    - Expensive fruits and vegetables like broccoli, dragon fruit, etc. are bought in very small quantities, as if they get spoiled, he incurs a big loss.
    - Reasons for wanting the chamber:
        - To buy more produce without worrying about spoilage.
        - To reduce losses incurred due to spoiled fruits and vegetables.
        - To buy more expensive and better-quality fruits.
        - To do supply-demand and cost analysis for pricing and inventory management, which is currently impossible with daily trading.

During our conversations, Dhavalji mentioned that he has fewer customers when it is very hot, as they are unwilling to spend time shopping from stationary carts outside, or unwilling to linger around. In response to this customer behavior and opportunity for the chamber to provide additional value, the CoolVeg team modified the cooling chamber design so that the cool and humid exhaust air from the chamber could be used to provide improved thermal comfort to areas near it. Even after the cool and humid air from the evaporative cooler is passed through the crates of warm produce, it is still cooler than the ambient air. These modifications directed the exhaust air over the top of the chamber towards the areas where the shop employees, the produce on display for sale, and the customers are located. He believed this would improve the customer experience, leading to more sales and making it more comfortable for him as well.

3. APMC Wholesaler – Sahadev Singh

- Interested in the portable chamber to prove that the technology works, in which case he would want to get multiple larger capacity chambers, both for his store as well as his farm.
- Deals with over 1 ton of vegetables every day, of which about 25% gets spoiled.
- Wasn't interested in the chamber to reduce spoilage, but mostly to store produce to a point where the demand would be greater than the supply, and get higher prices for them.

For Nigeria, there was no specific user research done. All insights and feedback gathered were conducted after demonstrations of both chambers were made to the farmers and retailers.

Feedback and insights after demonstration and usage

In Nigeria, a total of 16 interviews were conducted. These were with potential users identified during the initial demonstration of the portable chamber and during the mobile chamber display during the trailer drive. 50% of those interviewed currently rent space within the ColdHubs 100-ton cooling facility to store their produce. The produce is typically stored for 7-10 days. The biggest challenge they face with storing at the cooling facility is the time and cost required to transport the produce.

Of the 16 interviewees in Nigeria, there were 10 farmers, 2 retailers, and 4 who conducted both farming and retail activities, see Figure 19. Of note, several farmers mentioned they would like to start or re-start retail operations if they had storage capabilities at their farm, as it would provide them flexibility of time and additional opportunities to conduct retail operations. Close to 60% were interested in owning the portable chamber, mostly to prevent spoilage and increase their income. 75% of the respondents who currently use ColdHubs storage preferred owning the portable chamber instead of renting space, mainly to avoid the additional transportation time. 50% of the interested respondents preferred an off-grid chamber, and 25% specifically mentioned needing financing options. After observing an increase in shelf-life of red onions to 60+ days, members of an association of 30+ red onion farmers and retailers were also interested in buying the chamber. Of the respondents who were identified during the display of the mobile chamber, 44% were interested in owning the mobile chamber.

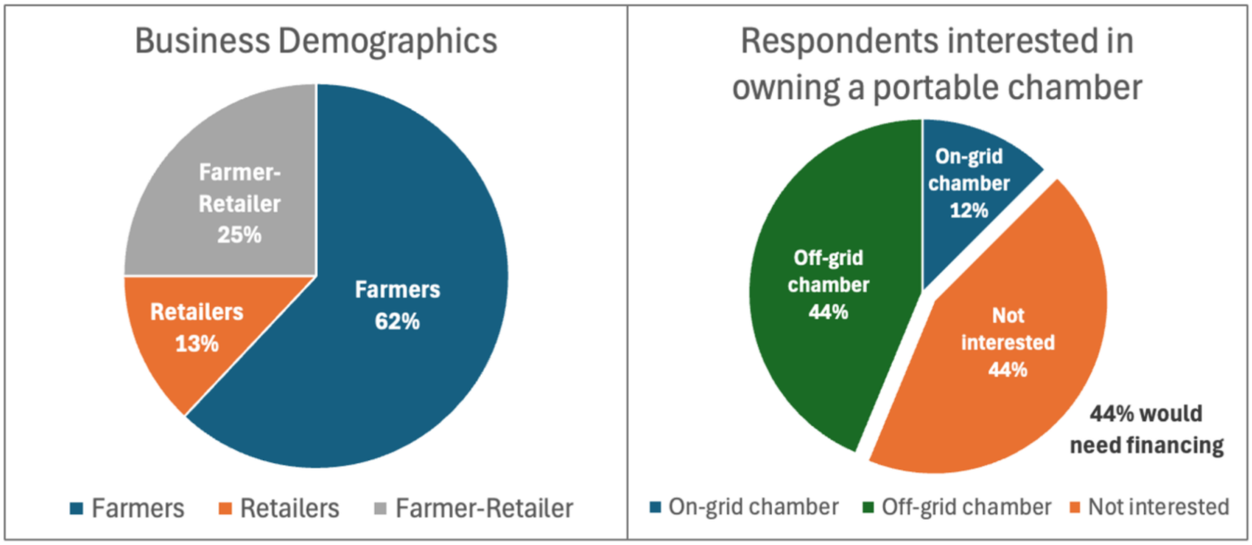


Figure 19: Left: The distribution of the business activities conducted by the 16 interview respondents. Right: The distribution of interview respondents who are interested in an on-grid portable cooling chamber (7), off-grid portable cooling chamber (2), and who are not interested in buying a portable chamber (7).

In India, the deployment of the chambers was delayed due to additional shelf-life experiments conducted, which also then led to a period where not many vegetables were being harvested. Of note, the willingness to purchase, as well as the impacts on their income and their business activities, would need a minimum of another 6 months of field testing. We still managed to conduct mid-line interviews with the farmer and the vendor, and have included some preliminary feedback gathered.

1. Farmer – Maujibhai
   - The summer was hotter than last year, and the high temperatures led to a poor harvest season.
   - He was unable to fully test the chamber and used it to store just about 8-10 crates of mangoes; the capacity is 20 crates.
   - His electricity bill has increased 10x from ~50 Rs to 500 Rs after installing the chamber, but he thinks it's a small price to pay to prevent spoilage.
   - He would prefer an on-grid chamber if he were to consider buying it, but he thinks it's too soon to say.

2. Local Vendor – Dhavalji
   - He noticed a 50% decrease in spoilage, especially in tomatoes, okra, and eggplants.
   - He was initially hesitant to store produce in the chamber during the day, as he thought it might affect his sales if the produce wasn't visible to his customers. He was happy to report that wasn't the case, and as long as a small portion was on display, he could keep the rest inside the chamber. This further helped in keeping the produce fresh for longer
   - He now uses the chamber both during the day and for overnight storage.

- The chamber – specifically designed to direct the exhaust air towards the area where produce is strewn while on display – has been able to provide additional cooling for Dhavalji's customers and himself during the day, from the cold and humid air directed from the exhaust. He has been pleasantly surprised by this.
- His electricity bill has more than doubled since using the chamber from ~700Rs to ~1800Rs. He is considering using a solar-powered chamber after the trial period, as this seems to him like a significant cost.
- He observed that the leafy greens do not seem to be impacted positively by the chamber, and continues to store them outside.
- He is willing to buy the chamber with financing, once the trial period is completed. He seems unsure about on-grid or off-grid, as the price is almost double for an off-grid chamber, and he does have electricity, but the running costs for on-grid are higher.
- He has already recommended getting this chamber to his network of vendors.

Cost and Scalability

Affordability of cooling solutions is particularly critical when targeting low-income vegetable vendors and farmers. There are several factors to consider when determining affordability, including:

- The up-front cost
- The operating and maintenance costs
- The lifetime of key components
- The value that the solution provides to the user, particularly in terms of financial returns

Table 7 lists the cost of the 5 forced-air evaporative cooling chambers (FAECCs), along with a shipping container based FAECC, and two refrigeration-based solutions. This table provides the up-front cost and the cost normalized by the available storage capacity ($/kg) for on-grid deployments, as well as off-grid deployments, where the cost of an off-grid power system is included (solar panels, batteries, inverter, charge controller, and wiring).

Table 7. The cost listed for the off-grid power systems assumes a 100% capacity factor for the FAECCs and a 50% capacity factor for the refrigerated chamber. The cost for the 3-tonne cold room in Nigeria was quoted with the standard off-grid power system, and the capacity factor is not known.

Chamber cost	Chamber cost		Cost per storage capacity	
	On-grid	Off-grid*	On-grid	Off-grid
Portable FAECC in India (25 crates)	$1,100	$2,000	2.20 ($/kg)	4.00 ($/kg)
Portable FAECC in India (20 crates)	$1,000	$1,850	2.50 ($/kg)	4.63 ($/kg)
Portable FAECC in India (15 crates)	$900	$1,700	3.00 ($/kg)	5.67 ($/kg)
Portable FAECC in Nigeria (25 crates)	$1,300	$2,300	2.60 ($/kg)	4.60 ($/kg)
Mobile FAECC in Nigeria (32 crates)	-	$13,000	-	20.31 ($/kg)
700-Liter capacity refrigerator in Nigeria	$1,100	$3,000	4.58 ($/kg)	12.50 ($/kg)
20' shipping container based FAECC in Kenya (168 crates)	$10,500	$15,000	3.13 ($/kg)	4.46 ($/kg)
3-tonne refrigerated cold room in Nigeria (150 crates)	-	$52,000	-	17.33 ($/kg)

The portable FAECCs and the FAECC based on a 20' shipping container, both for use in stationary applications, have a cost between $4.00 and $5.70 per kilogram of storage capacity as off-grid systems. In comparison, the 700-liter refrigerator in Nigeria with a 240 kg capacity costs $12.50 per kilogram of storage capacity, which is between 2.2 and 3.1 times more expensive than the forced-air evaporative cooling chambers in an on-grid setting. When considering operating these chambers in an off-grid setting, the 700-liter refrigerator in Nigeria is between 1.5 and 2.1 times more expensive than the forced-air evaporative cooling chambers. The greater cost reduction for the FAECCs when deployed in an off-grid setting is due to the lower energy consumption of the evaporative cooling unit, compared to the refrigeration unit.

The design and construction of the mobile FAECC in Nigeria are not comparable to the portable chambers and have not been optimized. We are specifically looking to identify suitable vehicles that are widely available in key markets to use as the base for the mobile chambers, as opposed to a custom-fabricated chassis.

In addition to considering the cost as a function of storage capacity, it is also important to consider the affordability in terms of the up-front cost as a factor in the affordability of the technology. Both the farmer and vendor in India indicated that they would require financing or other financial arrangements to purchase the portable chamber and spread out the cost of purchase over time. Similarly, more than half of the respondents in Nigeria indicated they would require financing to purchase a portable chamber. Even with financing, the potential users are careful about the amount of money they are committing to the purchase of a postharvest solution, making a lower-cost solution with a smaller storage capacity more attractive than a larger and more expensive chamber, even if the normalized cost per storage capacity is the same.

Another important factor in the affordability of these cooling chambers is the cost of operating the chamber. For the portable forced-air evaporative cooling chambers, the most significant cost is the maintenance of the evaporative cooler, specifically the cooling pads. The evaporative cooling pad should be cleaned roughly every 6 months – which is easily done by removing the pads and spraying them with water from a hose to remove any debris or other deposits. The cooling pads have an expected lifetime of 2 to 3 years. For locally purchased evaporative coolers, it can be expected that the vendor will offer replacement pads, which typically cost around $50. Other key components have long lifetimes, such as the evaporative cooler (10 to 20 years) and insulation panels (over 25 years). The components of an off-grid power system also have relatively long lifetimes: solar panels (25-30 years), batteries (3-10 years), inverters (10-15 years), and charge controllers (5-15 years). By the time a majority of these components begin to fail, the cooling chamber will have already provided value well above the initial purchase price, and replacement with newer and more advanced components will likely be affordable to allow for further use of the system.

One common method for determining if a technology provides sufficient value to be affordable is determining the financial payback period. This can be done by estimating the financial savings the chamber provides – e.g., food loss averted, reduced cost of transporting produce, new business opportunities enabled by having increased shelf-life – with the cost of the system. A target of a 2 to 3-year payback period is a reasonable amount of time for financing this type of system. If the chamber was purchased with financing and the user is receiving monthly financial benefits in excess of their loan payments, the system would be considered to have a strong value proposition and be affordable in the long term.

Commercial outlook for the portable cooling chambers

The forced-air evaporative cooling chambers will provide value in the target markets by reducing postharvest losses at key points along the supply chain and further increasing farmers' income by improving their access to markets. The rapid cooling rates achievable with forced-air evaporative cooling have significant potential at the pre-cooling stage, especially because this technology can be deployed near the farm gate, reaching produce shortly after harvest. This technology is suitable for regions with an unmet need for fruit and vegetable storage and a hot, dry climate where evaporative cooling will be effective. Key geographies include the African Sahel, East Africa, the Middle East, Pakistan, and India.

With a population of over 100 million people in the 12 states in Northern Nigeria, we aim to reach annual sales of 1,000 chambers within the next 5 years in partnership with ColdHubs. We are aiming to build an initial inventory of 20 chambers and conduct a marketing campaign to raise awareness about this technology and begin selling the chambers. The revenue generated from the sale of the prototype 20 chambers will be reinvested to continue production, marketing, and sales of additional evaporative cooling chambers. If this initial phase of commercialization proves successful, ColdHubs and CoolVeg will form a new company focused on forced-air evaporative cooling technologies, with the 25-crate portable chamber as its flagship product. This company will lead in the production, distribution, sales, and marketing of both portable chambers for stationary applications & mobile chambers for transportation applications. While additional product development is needed to optimize the usability and cost of the mobile chambers, addressing this critical and unaddressed link in the value chain holds great potential for reducing postharvest losses and increasing income for farmers and vendors. The company will raise funds through equity and debt investment rounds. Beyond the commercialization of this technology with ColdHubs in Northern Nigeria, CoolVeg aims to disseminate this technology across the West African Sahel and other arid regions in need of improved fruit and vegetable storage.

The portable forced-air evaporative cooling chambers have the potential to benefit hundreds of thousands of smallholder farmers across Gujarat and Rajasthan. Deploying this technology at the 854 Agricultural Produce Market Committees (APMCs) in Gujarat and Rajasthan has the potential to benefit nearly one hundred thousand small produce vendors. CoolVeg will continue to gather data from the 3 users (farmer, retail vendor, and wholesaler) to identify the user(s) who see the greatest value proposition of the technology. CoolVeg will then identify a manufacturing partner in Gujarat and establish a company to market and sell the chambers.

Conclusions

This report describes the development and testing of portable and mobile forced-air evaporative cooling chambers for use in off-grid arid regions. This solution leverages the following features:

- The unique suitability of evaporative cooling to provide energy-efficient cooling when used in dry regions.
- The ability of forced-air cooling to dramatically increase the cooling rate compared to room cooling.
- A carefully designed airflow pathway to maximize the cooling rate and energy efficiency.
- The use of commonly available materials and a chamber design that allows for relatively quick and simple construction of the cooling chamber.
- Can be powered by an off-grid power system consisting of solar PV panels, batteries, and an inverter.
- The portable cooling chamber can be easily carried by several people and lifted onto a small truck for transportation to remote locations.
- The mobile cooling chamber provides an option to rapidly cool produce *during* transportation.

These design features provide a solution that has the capacity to cool 500 kg of produce by 10°C in under 6 hours, while using less than 200 Watts of electricity. This cooling efficiency is nearly 10 times more energy-efficient than using a refrigeration-based air conditioner with room cooling. As a result of being constructed from low-cost materials and the lower energy consumption, CoolVeg's off-grid forced-air evaporative cooling chambers cost about 60% less than traditional cold rooms of similar size. The portable and mobile solutions can both be operated off-grid, allowing them to be deployed in remote areas and meet the needs of farmers who have no other options for improved storage and reducing food loss.

In Nigeria, the shelf-life of many vegetables – including tomatoes, peppers, cucumbers, cabbage, green onions, and green beans – was extended by 4 or more days, and was three times longer in the chamber than outside of the chamber. Additionally, the shelf-life of red onions was extended from 14 days when stored in the shade, as compared to more than 100 days in the chamber.

In India, the condition of the vegetables was better when stored inside the chamber, as compared to storage in ambient conditions, but the differences were often only 1-2 days. A potential reason for these observations is that the humidity inside the chamber was at or near 100% for the entire day when the chamber was in operation, which can negatively impact the shelf-life. An area for improvement is providing mechanisms for users to reduce the humidity inside the chamber to allow users to have greater control over the chamber's environment. Despite the less dramatic shelf-life improvements, the chamber users reported significant decreases in spoilage and increased profit after using the chamber.

The deployment of this solution has the potential to generate economic, nutritional, and environmental benefits. The availability of a more cost-effective postharvest storage solution for perishable fruits and vegetables will make improved storage more accessible and affordable for farmers, reducing food spoilage and loss. With more affordable storage solutions and a reduction in food loss, farmer incomes will increase, and local access to nutritious foods will be improved through a greater and more consistent supply of food. This solution also provides several environmental benefits, including reducing net water usage across the fruit and vegetable value chain. Storing water-intensive crops, such as leafy greens or tomatoes, in a forced-air evaporative cooling chamber for a week uses less than 1% of the water it takes to grow the crops. Thus, food loss that is averted by using the chambers reduces net water usage across the fruit and vegetable value chain.

CoolVeg will work with our existing partners in India and Nigeria to commercialize the portable chambers in the respective markets. The team is exploring options to adapt the mobile chamber to be based on an existing vehicle, such as a cargo tricycle or a small truck. As an open-source technology, CoolVeg will also look for commercialization partners in suitable markets, including the African Sahel, East Africa, the Middle East, and South Asia. Some key factors to look for when determining the suitability of this technology include:

- A hot and dry climate for a majority of the year is required, particularly during the time when improved storage is most needed.
- An unmet need for fruit and vegetable storage at the farm gate, during transportation, at aggregation points, and retail locations.
- While this technology is well-suited for short and medium-term storage, this technology is particularly advantageous in contexts where rapid pre-cooling would be especially beneficial.
- While this technology can be used in many settings, this technology is particularly advantageous in contexts where there is a need for low-cost off-grid storage.

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Appendix

The appendix provides design documentation, including:

- Diagrams of the chambers with elevation, plan, and cross-section views with measurements of specific dimensions.
- 3D renderings using the computer-aided design (CAD) software Rhinoceros (Rhino3D) showing the chambers from various angles and cross-sections, with multiple configurations of the chamber doors being opened or closed.

Dimensional diagrams and 3D renderings were created for the following forced-air evaporative cooling chamber versions:

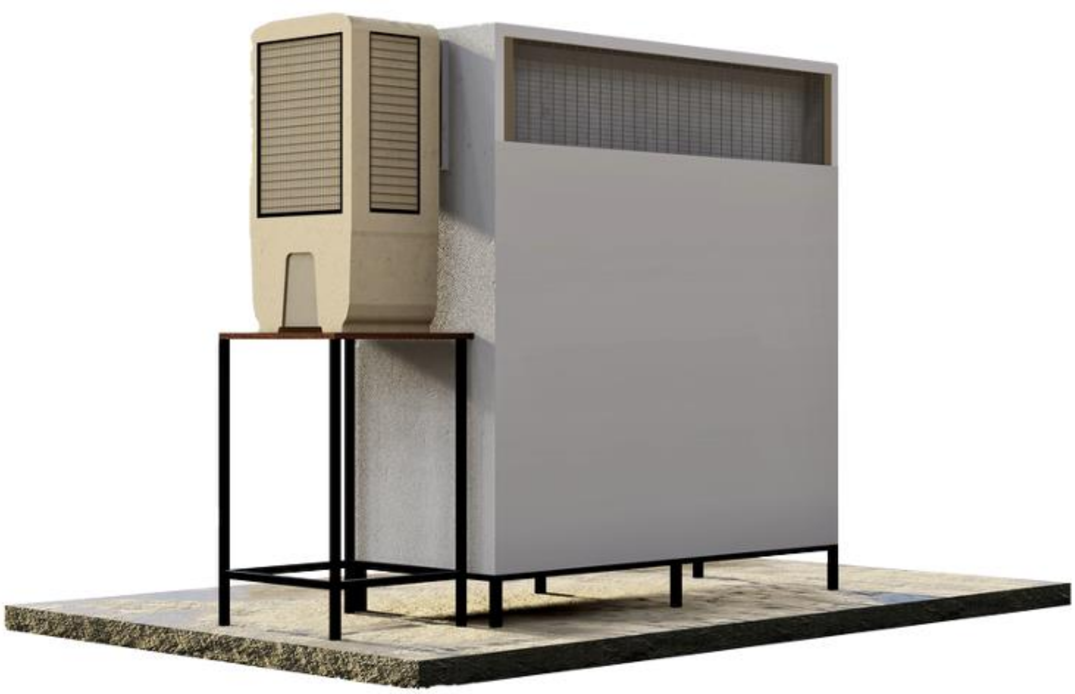
- Design Documentation for the 25-Crate Portable Chamber in Nigeria
- Design Documentation for the Mobile Chamber in Nigeria
- Design Documentation for Portable Chambers in India (dimensional diagrams only)
    - 25 -crate capacity
    - 20-crate capacity
    - 15-crate capacity (includes an alternative air exhaust design that directs cool air toward the front of the chamber)

Front (doors closed)

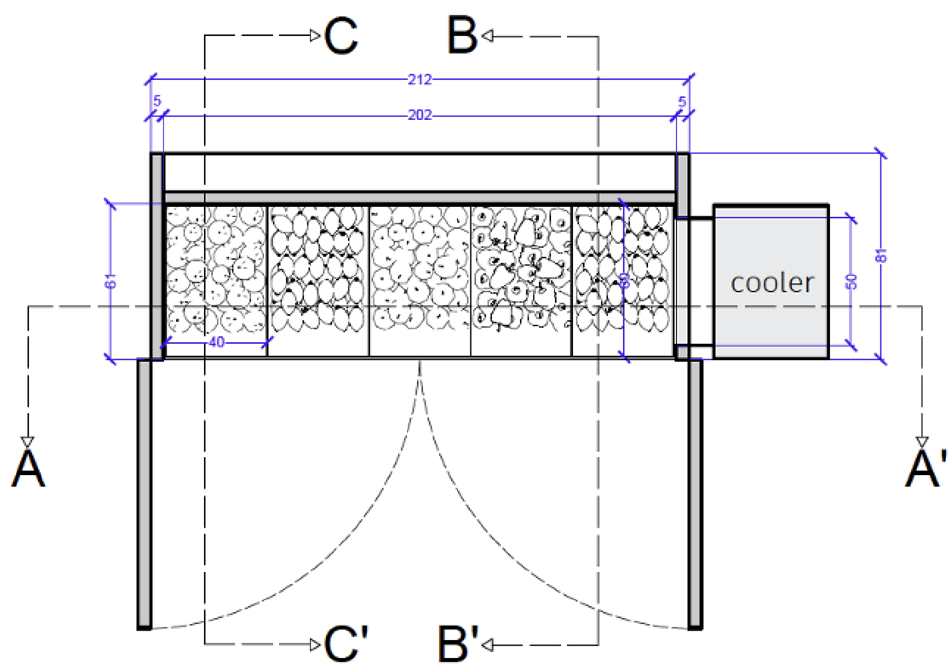
Front–right

Rear

Rear–right

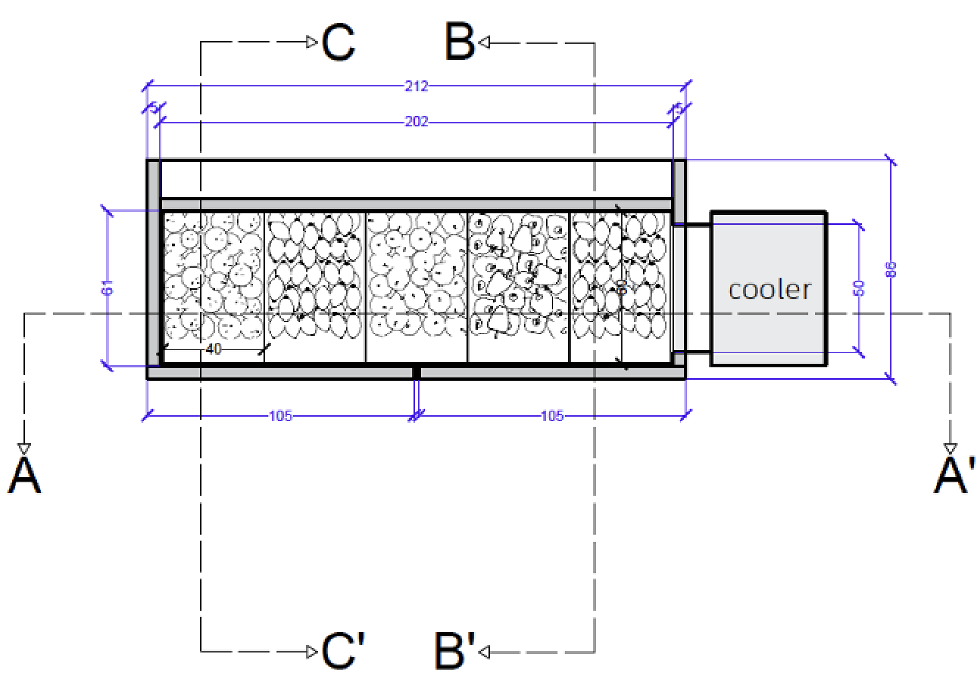


Top view (doors closed)

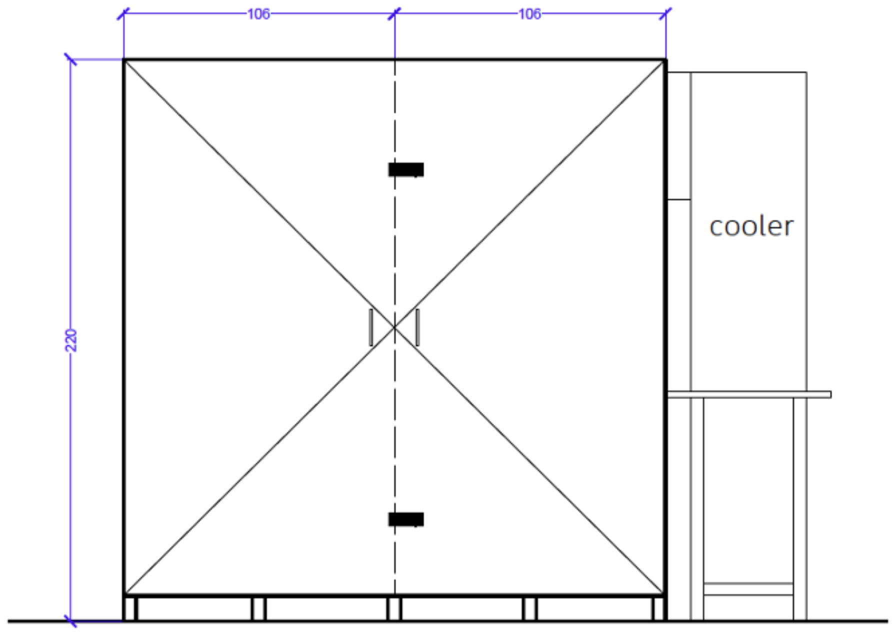


Top view (doors open)

All dimensions are in centimeters (cm)

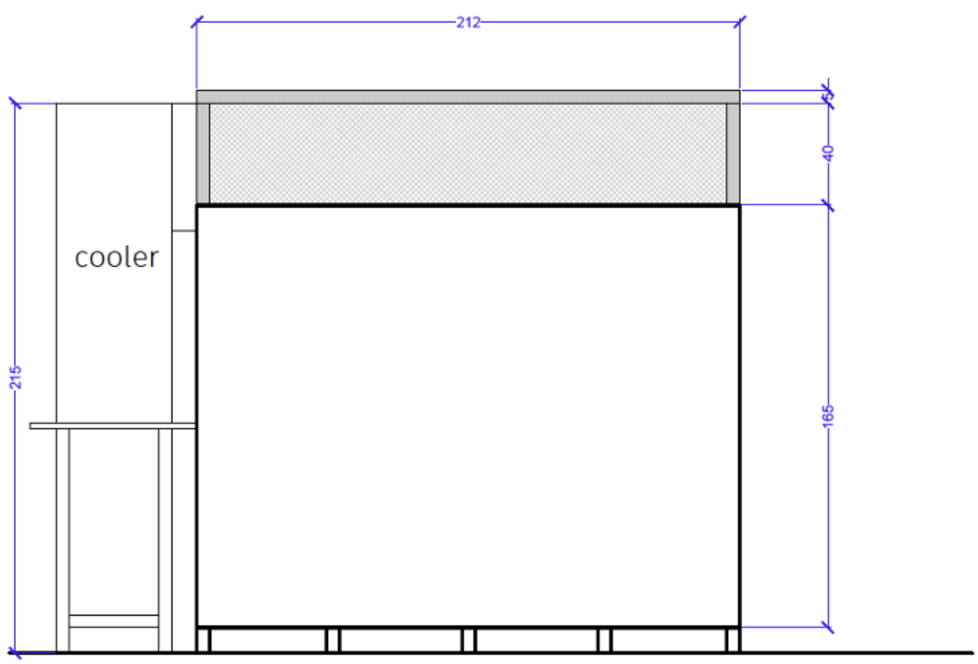


Design Documentation for the 25-Crate Portable Chamber in Nigeria

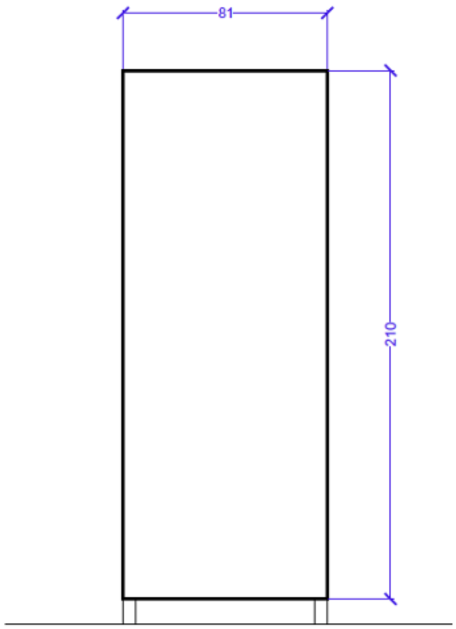


Front Elevation

All dimensions are in centimeters (cm)

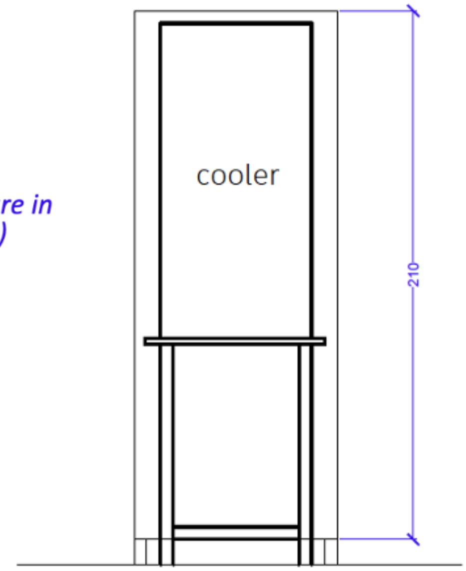


Rear Elevation

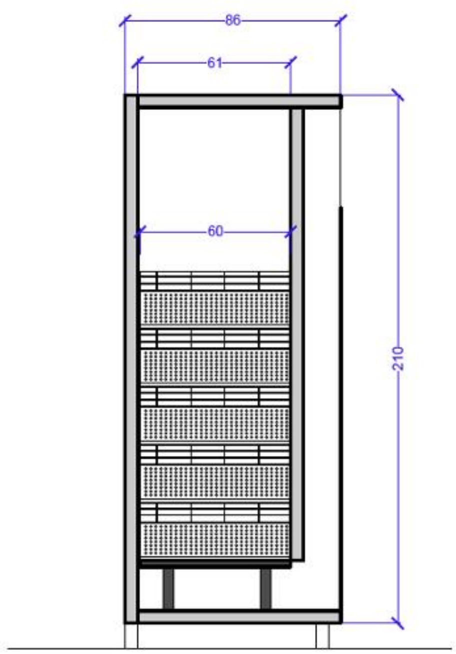


Left side elevation

All dimensions are in centimeters (cm)

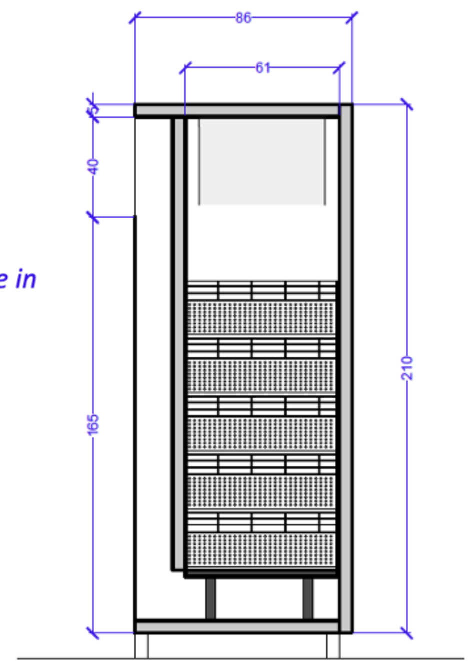


Right side elevation



Section BB'

All dimensions are in centimeters (cm)

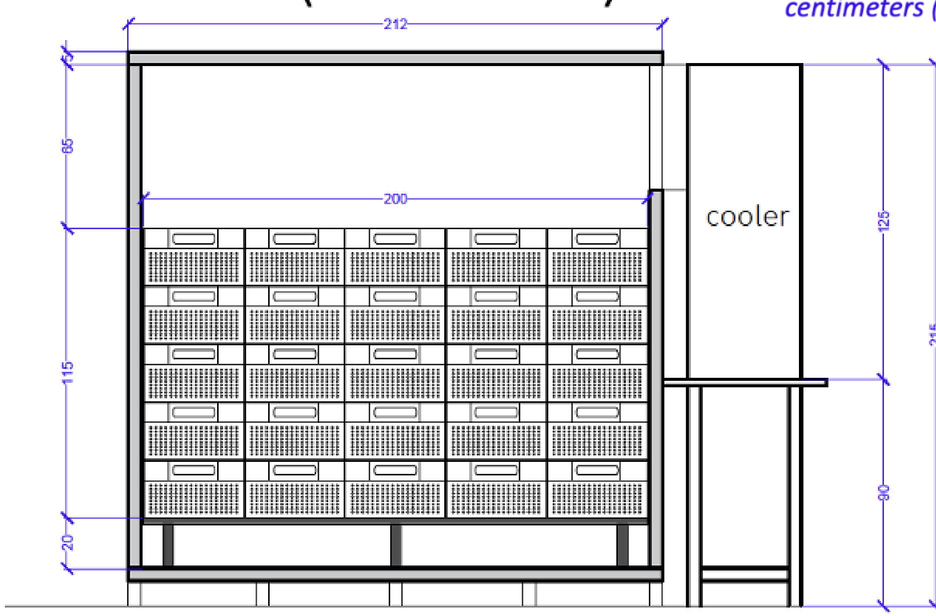


Section CC'

Front (doors open)

Front (cross-section)

All dimensions are in centimeters (cm)



Section AA'

Insulation Panel Sizes for the 25-Crate Portable Chamber in Nigeria

Below is a table showing the dimensions of the insulated sandwich panels that are needed to construct the portable chamber designed for crates measuring 60 cm x 40 cm x 23 cm (length, width, and height).

The sandwich panels can be made from several types of insulation, including: Polyurethane Foam (PUF), Extruded Polystyrene (XPS), or Expanded Polystyrene (EPS). The metal cladding should be made of either aluminum or galvanized steel to prevent rusting. The metal sheet that forms the exhaust channel can be made from either aluminum or galvanized steel to prevent rusting. A hole in one of the side panels (left or right) will need to be cut to allow air from the evaporative coolers to enter the chamber.

Panel	Material	Width (cm)	Height/Length (cm)	Thickness (cm)
Bottom	PUF sandwich panel	81	212	5
Top	PUF sandwich panel	81	212	5
Rear	PUF sandwich panel	202	180	5
Left door	PUF sandwich panel	106	210	5
Right door	PUF sandwich panel	106	210	5
Left side	PUF sandwich panel	81	200	5
Right side	PUF sandwich panel	81	200	5
Rear - channel	Metal sheet	212	160	0.08

Design Documentation for the Mobile Chamber in Nigeria

Front (doors closed)

Front (doors open)

Rear

Rear (cut-away cross section)

Front – Right

Front – Left

Rear – Right

Above (All doors open)

Left side (exterior doors open)

Left side (one exterior door open)

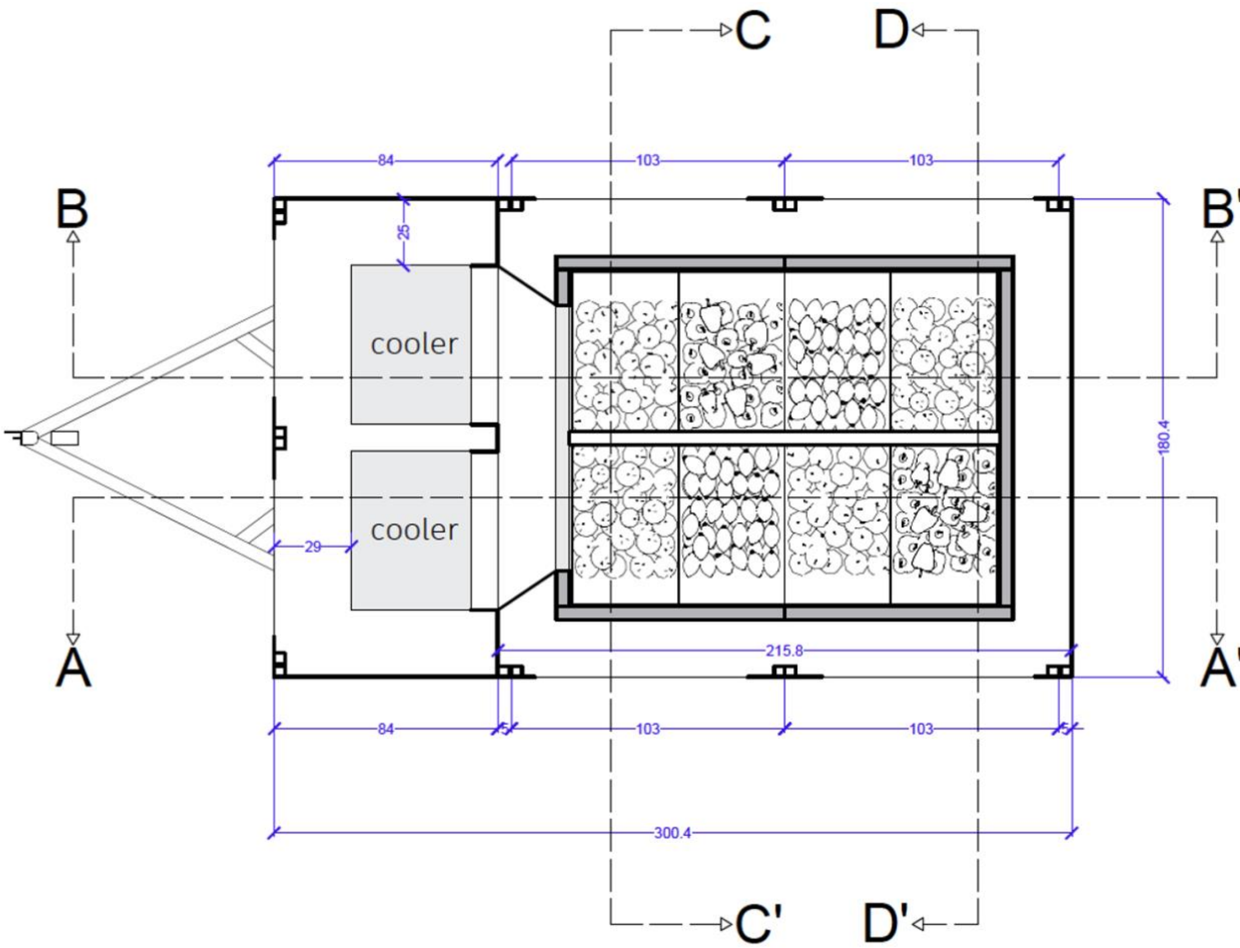
Left side (one exterior and interior door open)

Left side (two exterior doors and one interior door open)

Left side (exterior and interior doors open)

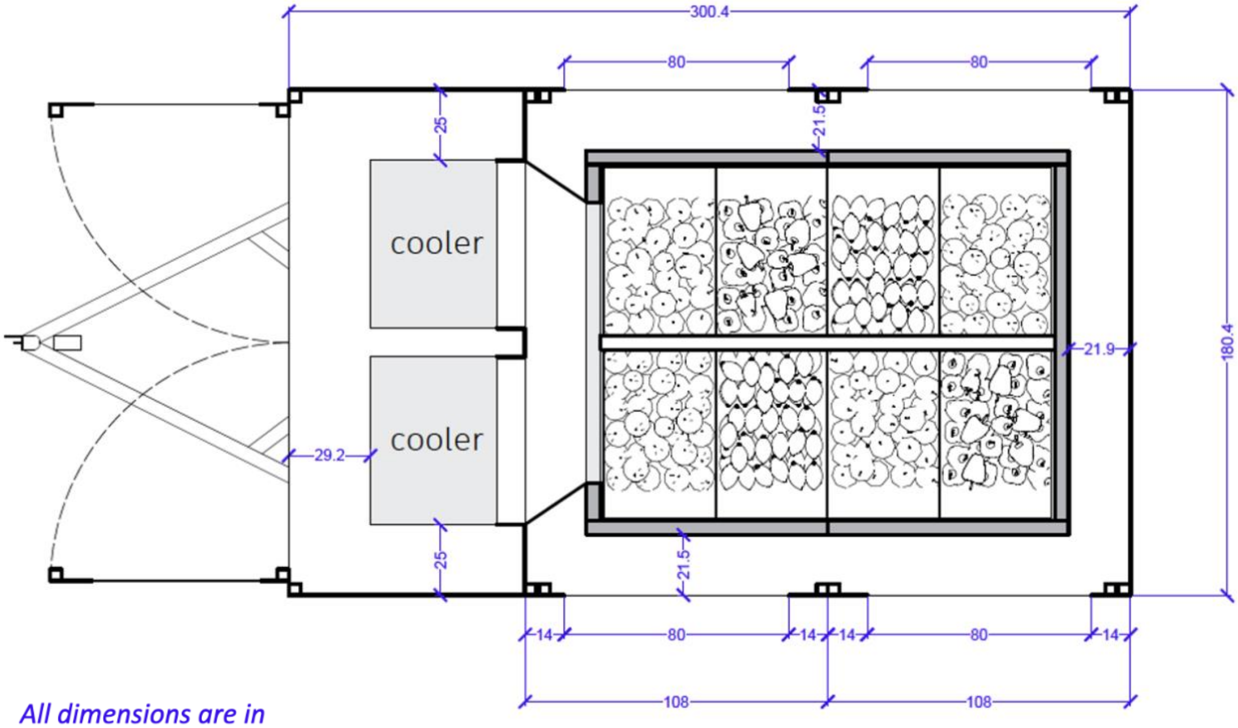
Rear – Left (exterior and interior doors open)

Front – Left (exterior and interior doors open)



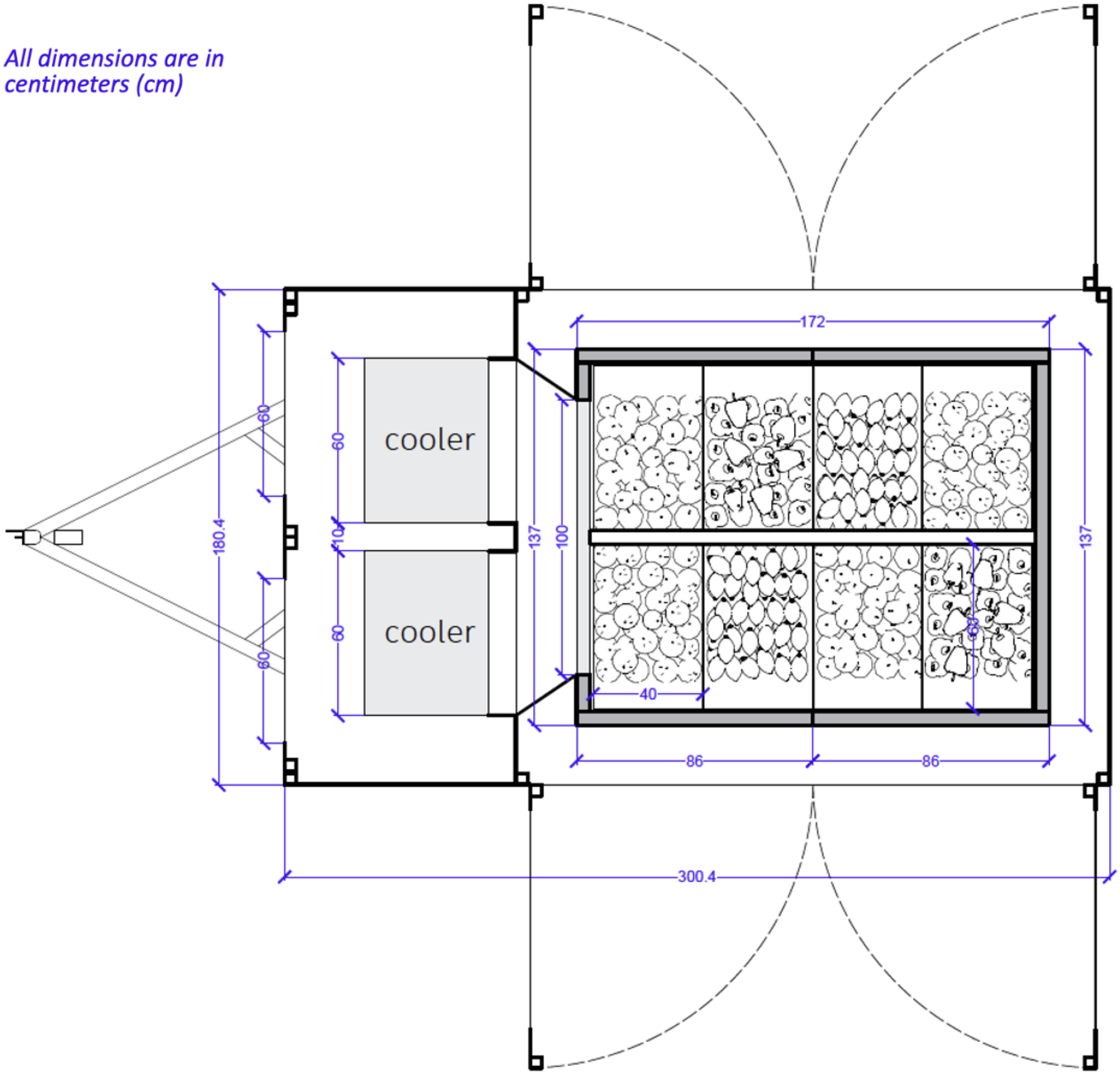
All dimensions are in centimeters (cm)

Plan (doors closed)

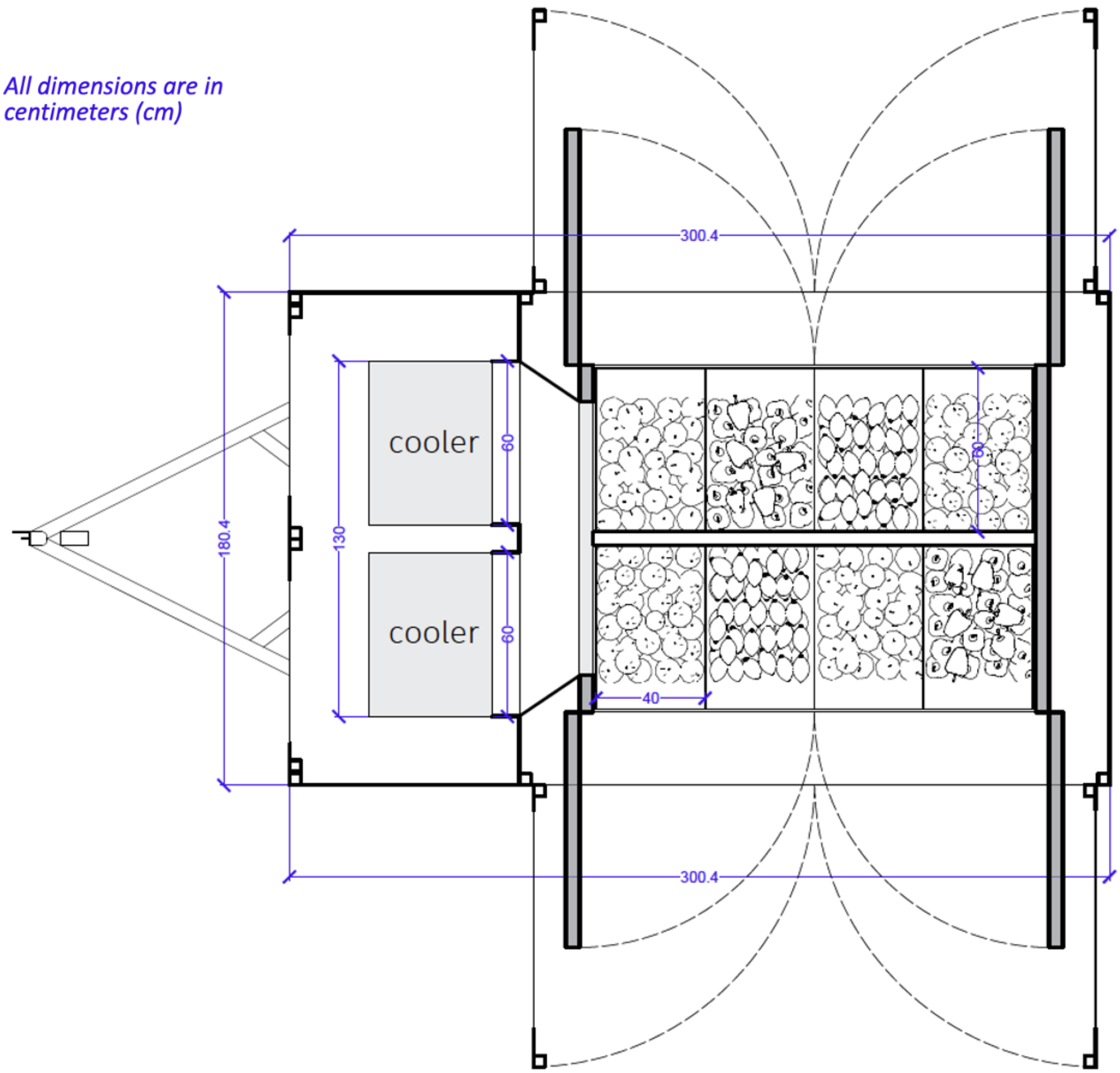


All dimensions are in centimeters (cm)

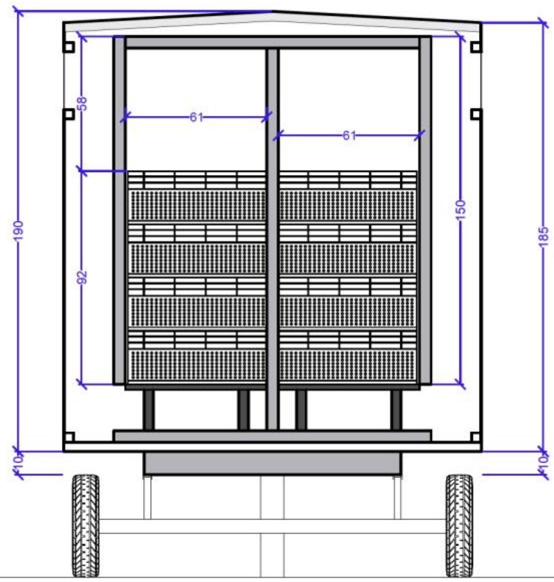
Plan (front doors opened)



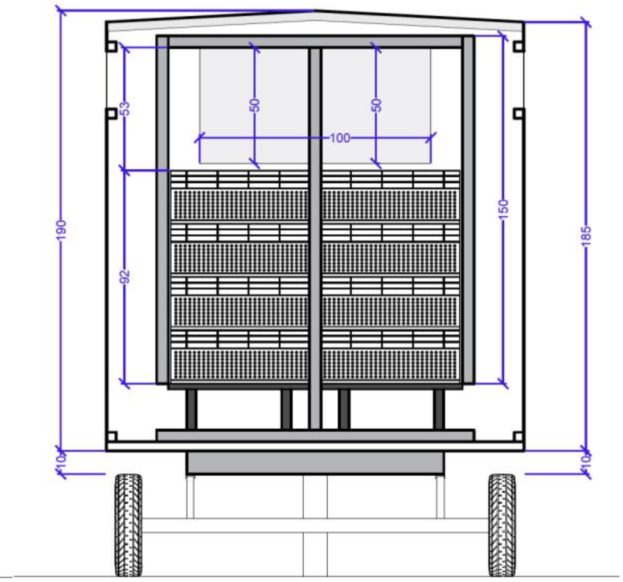
Plan (side doors opened)



Plan (inner doors opened)

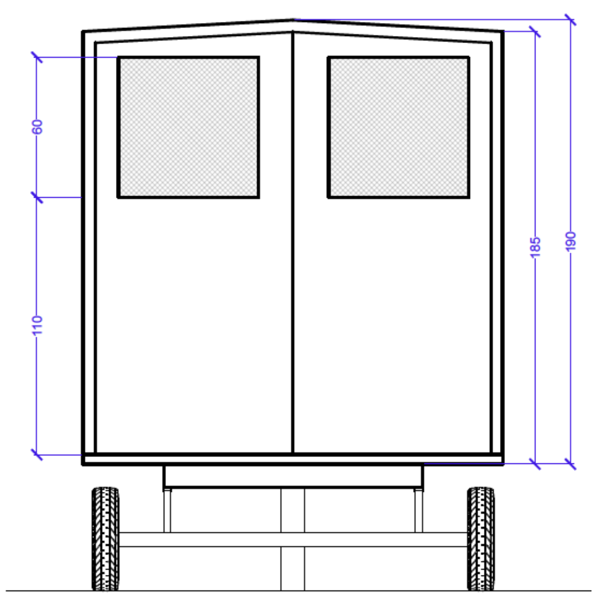


Section CC'



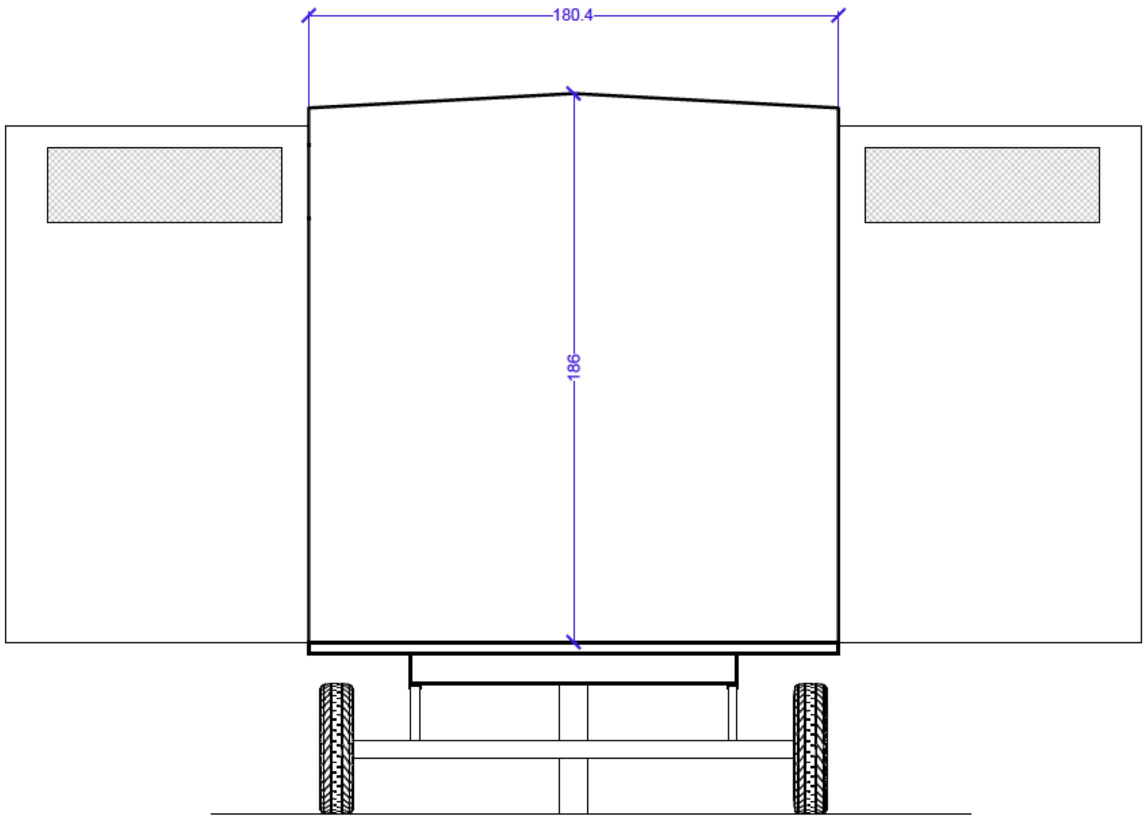
Section DD'

All dimensions are in centimeters (cm)



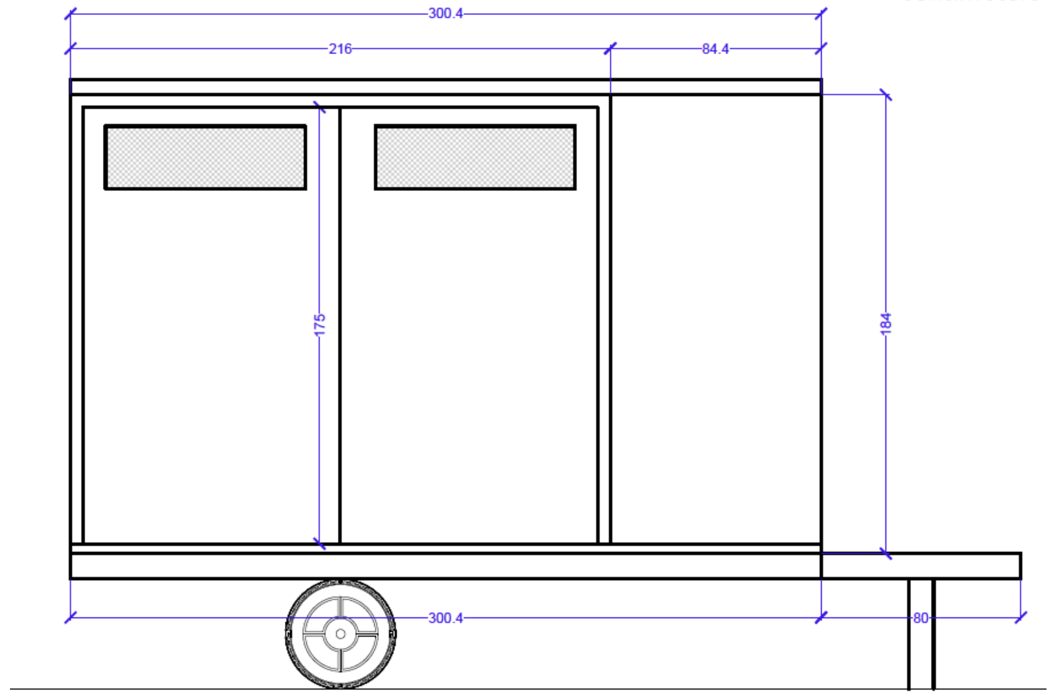
Front elevation

All dimensions are in centimeters (cm)

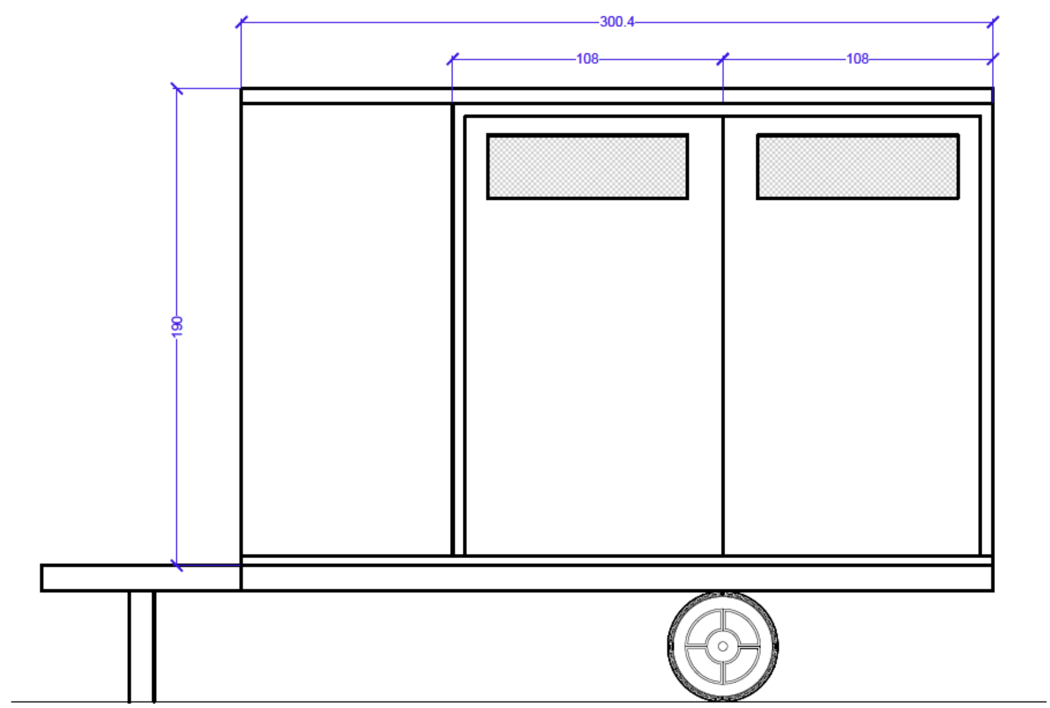


Rear elevation

All dimensions are in centimeters (cm)

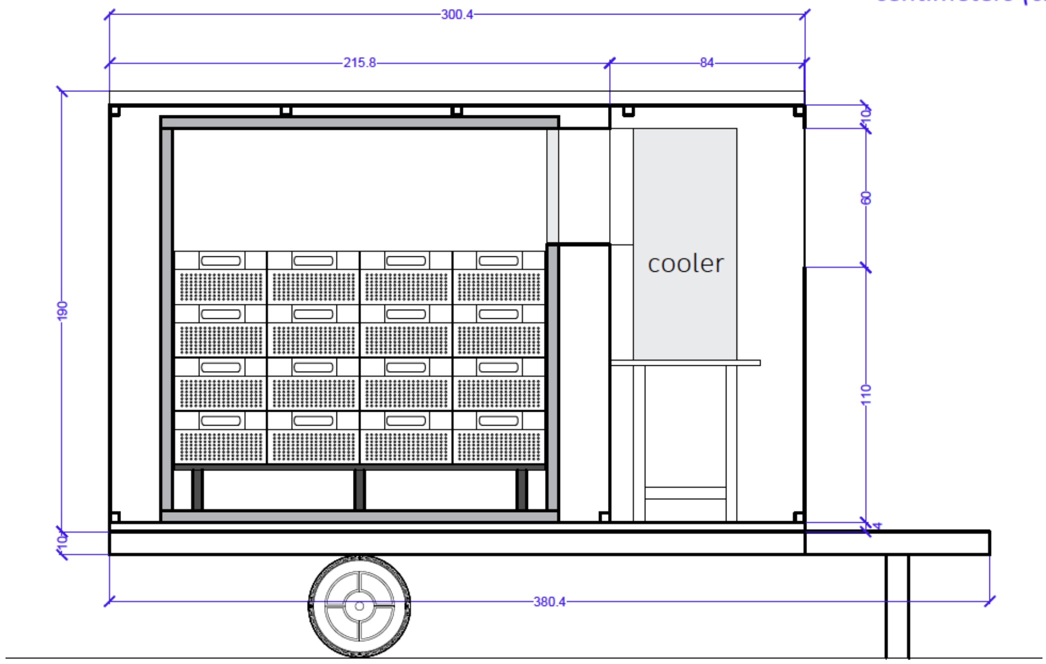


Left side Elevation

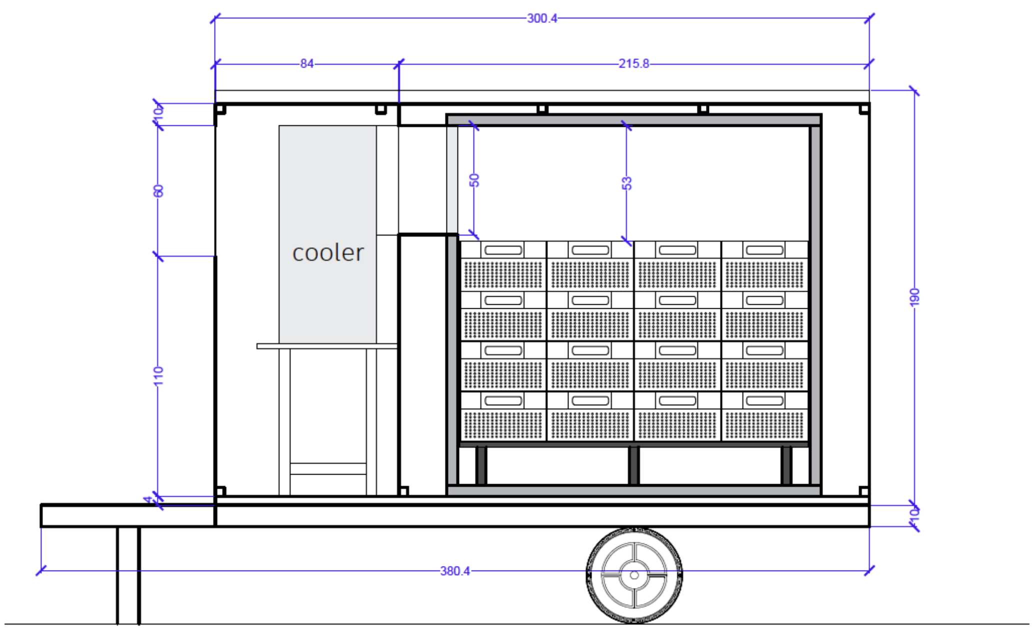


Right side Elevation

All dimensions are in centimeters (cm)



Section AA'



Section BB'

Insulation Panel Sizes for Mobile Chambers in Nigeria

Below is a table showing the dimensions of the insulated sandwich panels that are needed to construct the mobile chamber designed for crates measuring 60 cm x 40 cm x 23 cm (length, width, and height).

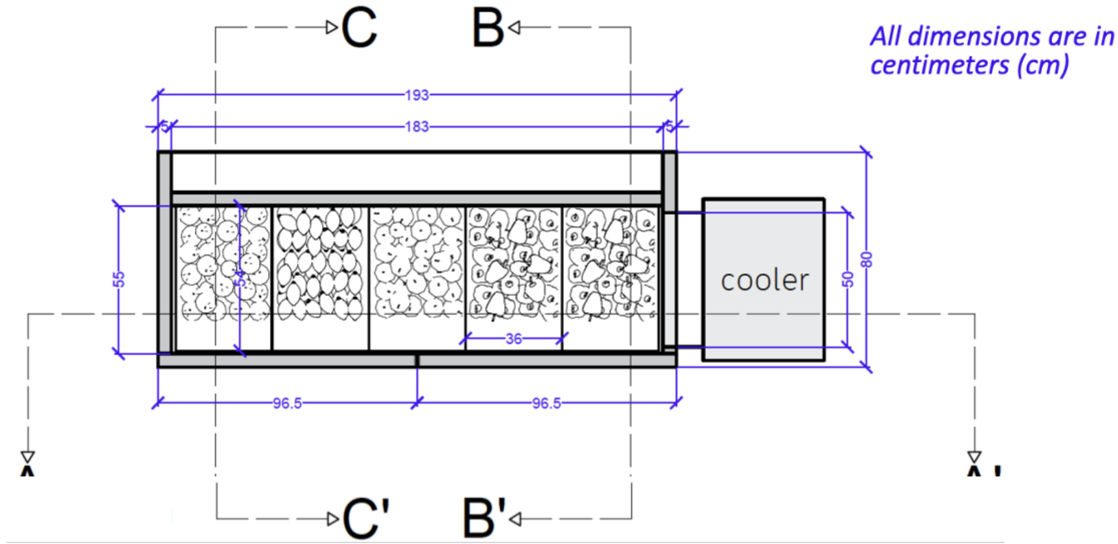
The sandwich panels can be made from several types of insulation, including: Polyurethane Foam (PUF), Extruded Polystyrene (XPS), or Expanded Polystyrene (EPS). The metal cladding should be made of either aluminum or galvanized steel to prevent rusting. A hole in the front panel will need to be cut to allow air from the evaporative coolers to enter the chamber.

Panel	Material	Width (cm)	Height/Length (cm)	Thickness (cm)
Bottom	PUF sandwich panel	127	165	5
Top	PUF sandwich panel	127	172	5
Front	PUF sandwich panel	127	172	5
Rear	PUF sandwich panel	127	165	5
Left-front door	PUF sandwich panel	86	155	5
Left-rear door	PUF sandwich panel	86	155	5
Right-front door	PUF sandwich panel	86	155	5
Right-rear door	PUF sandwich panel	86	155	5
Center partition	PUF sandwich panel	162	165	5

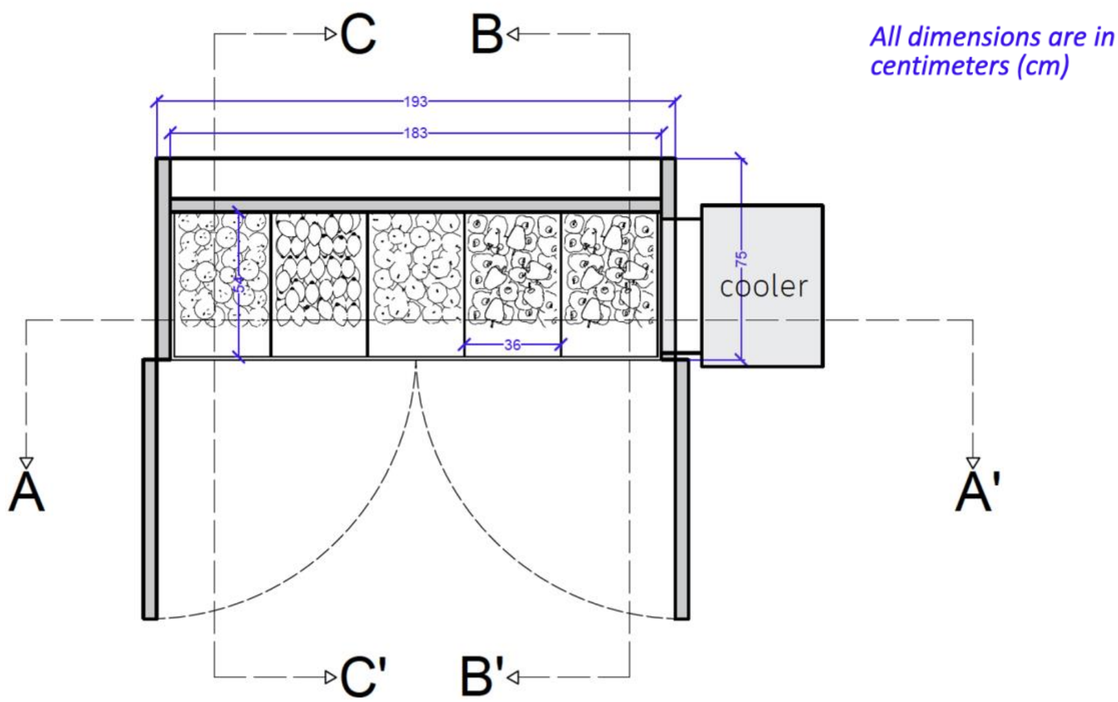
Design Documentation for Portable Chambers in India

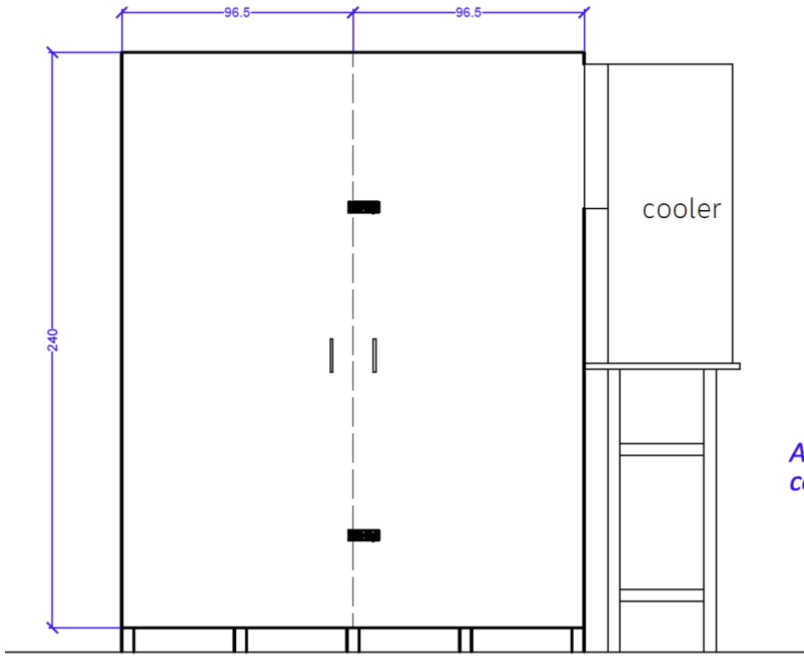
Design Documentation for the 25-Crate Portable Chamber in India

Top view (doors closed)



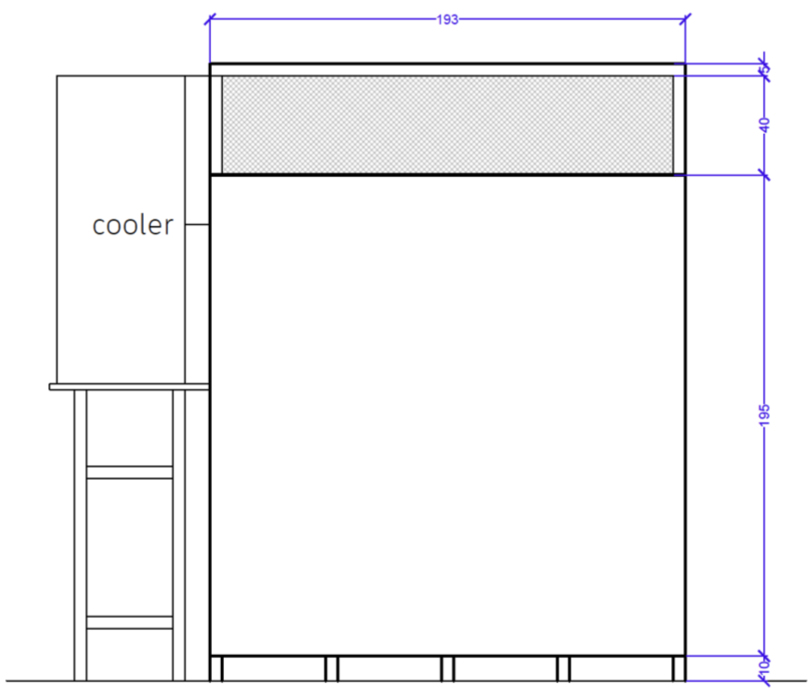
Top view (doors open)





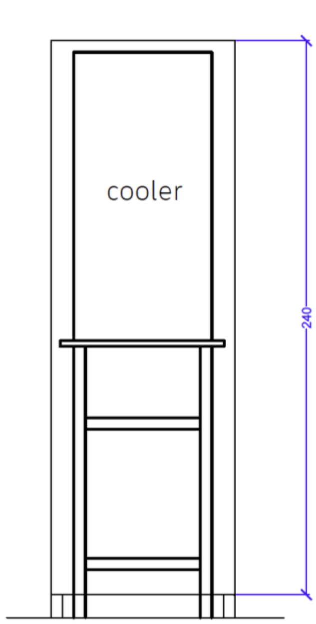
Front Elevation

All dimensions are in centimeters (cm)



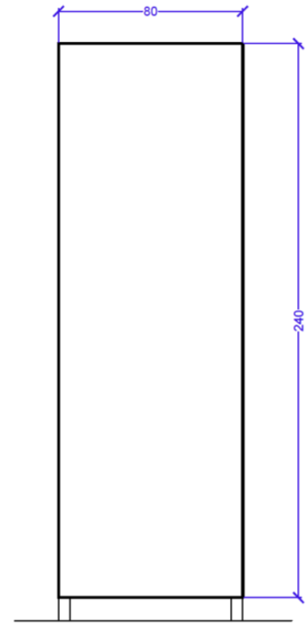
Rear Elevation

Design Documentation for the 25-Crate Portable Chamber in India

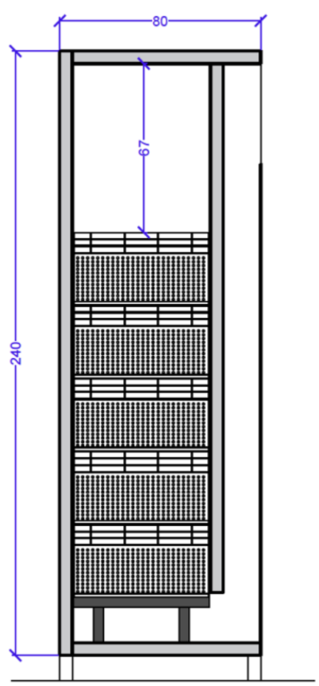


Right side elevation

All dimensions are in centimeters (cm)

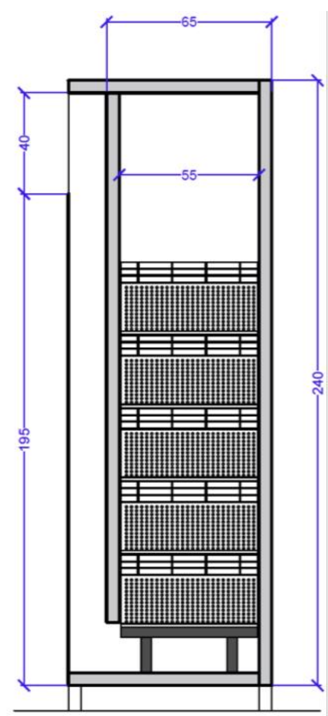


Left side elevation



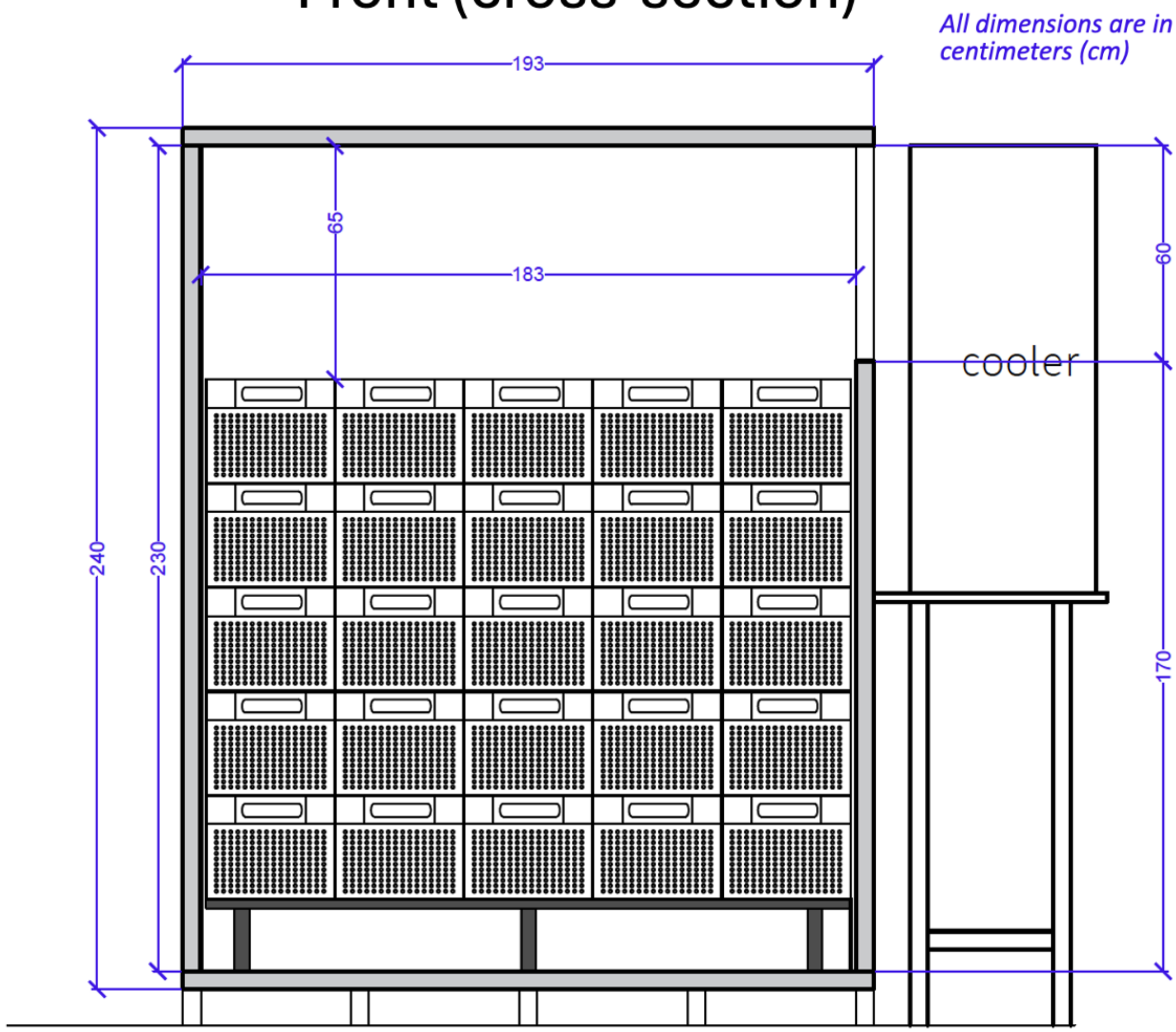
Section BB'

All dimensions are in centimeters (cm)



Section CC'

Front (cross-section)



Section AA'

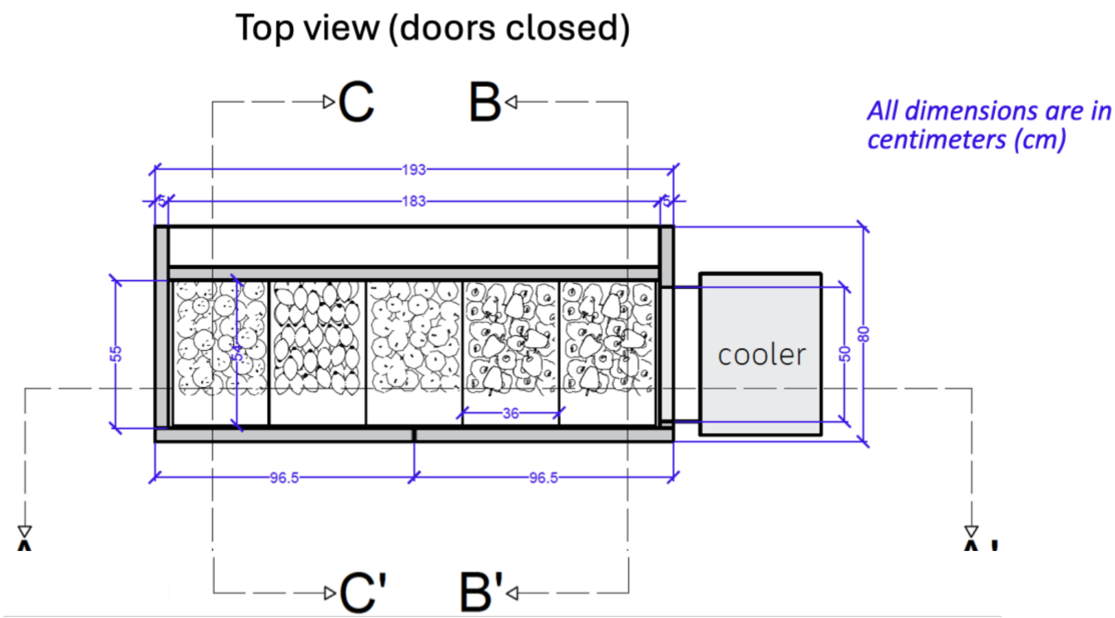
Insulation Panel Sizes for the 25-crate Portable Chamber in India

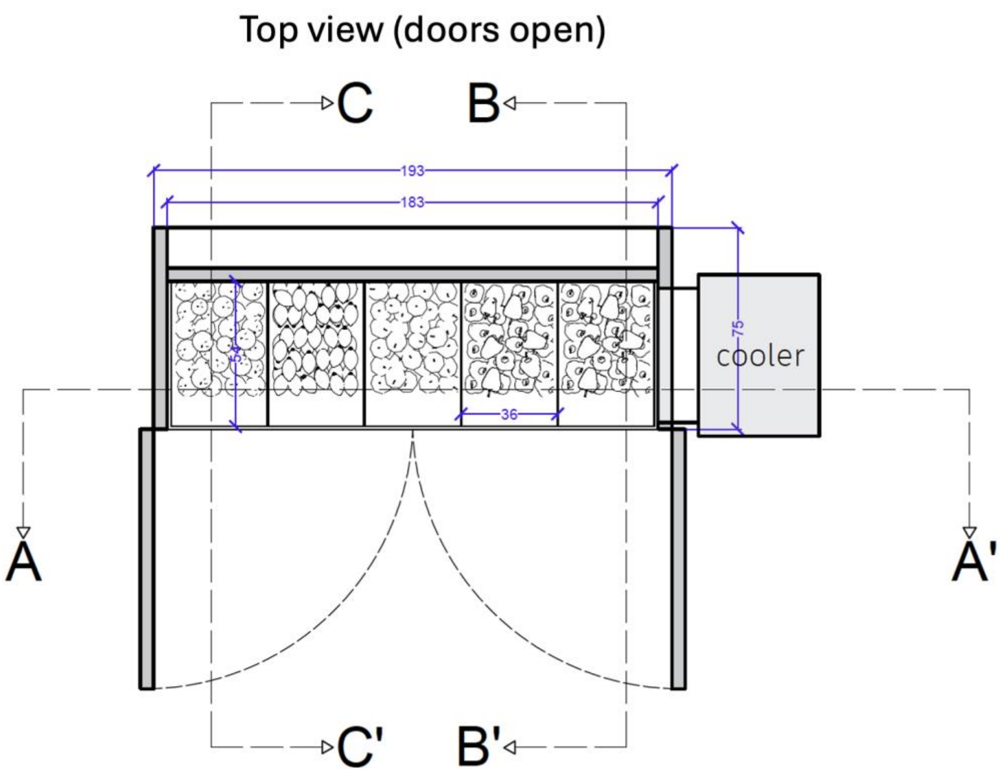
Below is a table showing the dimensions of the insulated sandwich panels that are needed to construct the portable chamber designed for crates measuring 54 cm x 36 cm x 29 cm (length, width, and height).

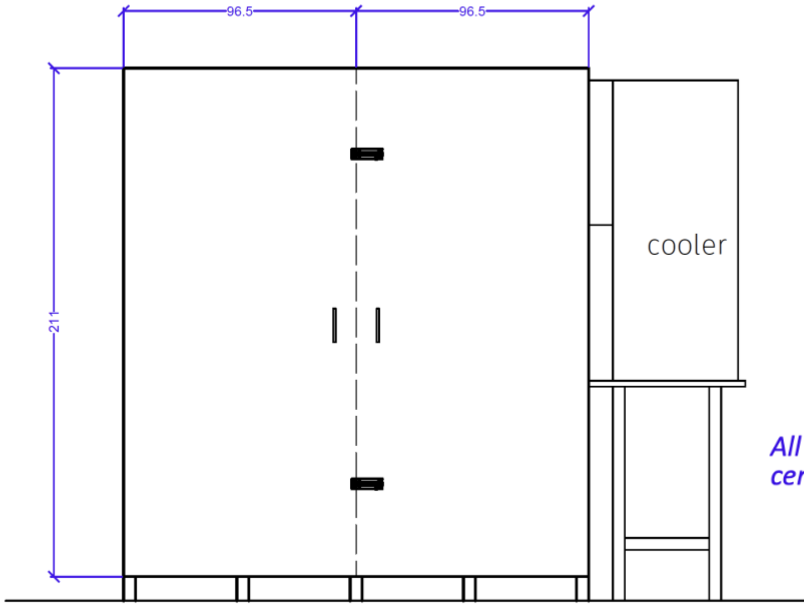
The sandwich panels can be made from several types of insulation, including: Polyurethane Foam (PUF), Extruded Polystyrene (XPS), or Expanded Polystyrene (EPS). The metal cladding should be made of either aluminum or galvanized steel to prevent rusting. The metal sheet that forms the exhaust channel can be made from either aluminum or galvanized steel to prevent rusting. A hole in one of the side panels (left or right) will need to be cut to allow air from the evaporative coolers to enter the chamber.

Panel	Material	Width (cm)	Height/Length (cm)	Thickness (cm)
Bottom	PUF sandwich panel	75	193	5
Top	PUF sandwich panel	75	193	5
Rear	PUF sandwich panel	183	210	5
Left door	PUF sandwich panel	96.5	240	5
Right door	PUF sandwich panel	96.5	240	5
Left side	PUF sandwich panel	75	230	5
Right side	PUF sandwich panel	75	230	5
Rear - channel	Metal sheet	193	190	0.08

Design Documentation for the 20-Crate Portable Chamber in India
This chamber is a shorter version of the 25 crate portable chamber described above.

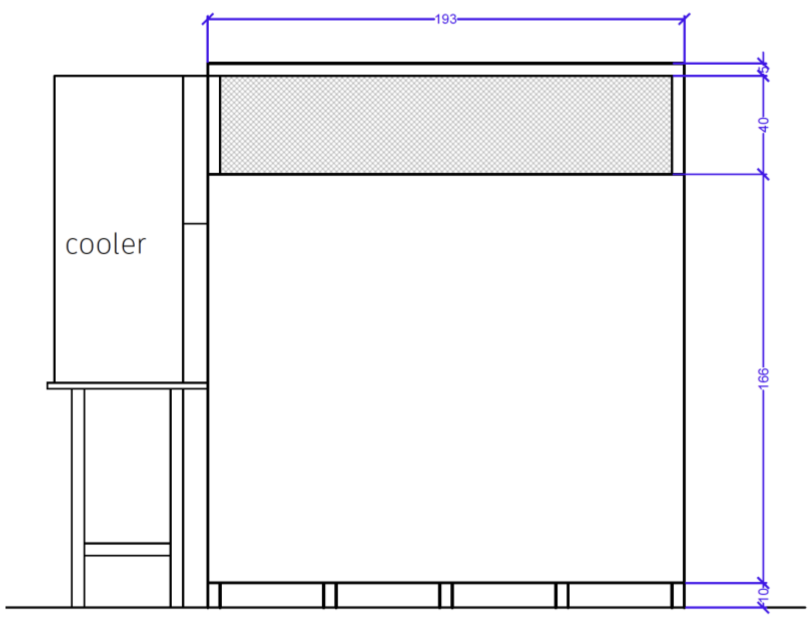




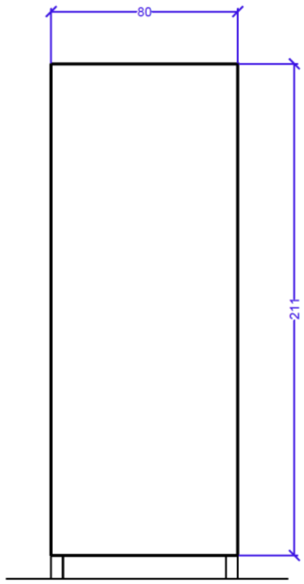


Front Elevation

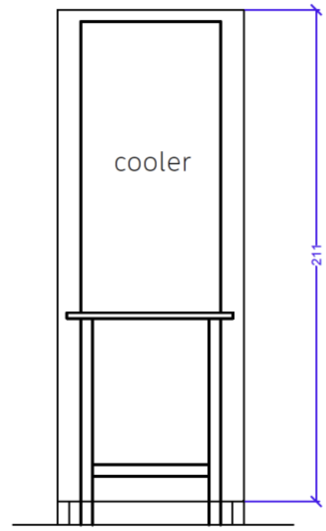
All dimensions are in centimeters (cm)



Rear Elevation

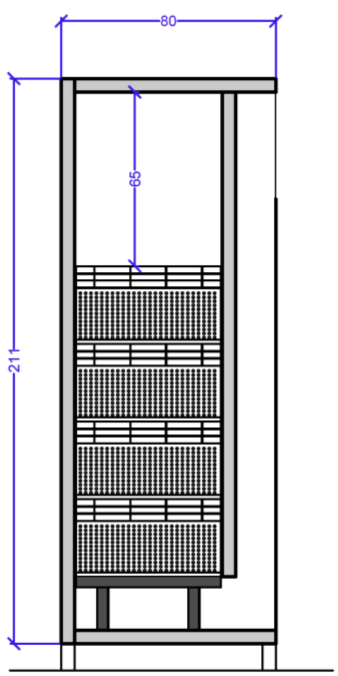


Left side elevation

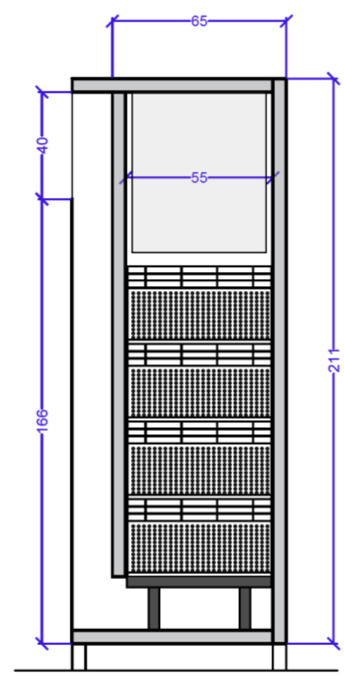


Right side elevation

All dimensions are in centimeters (cm)



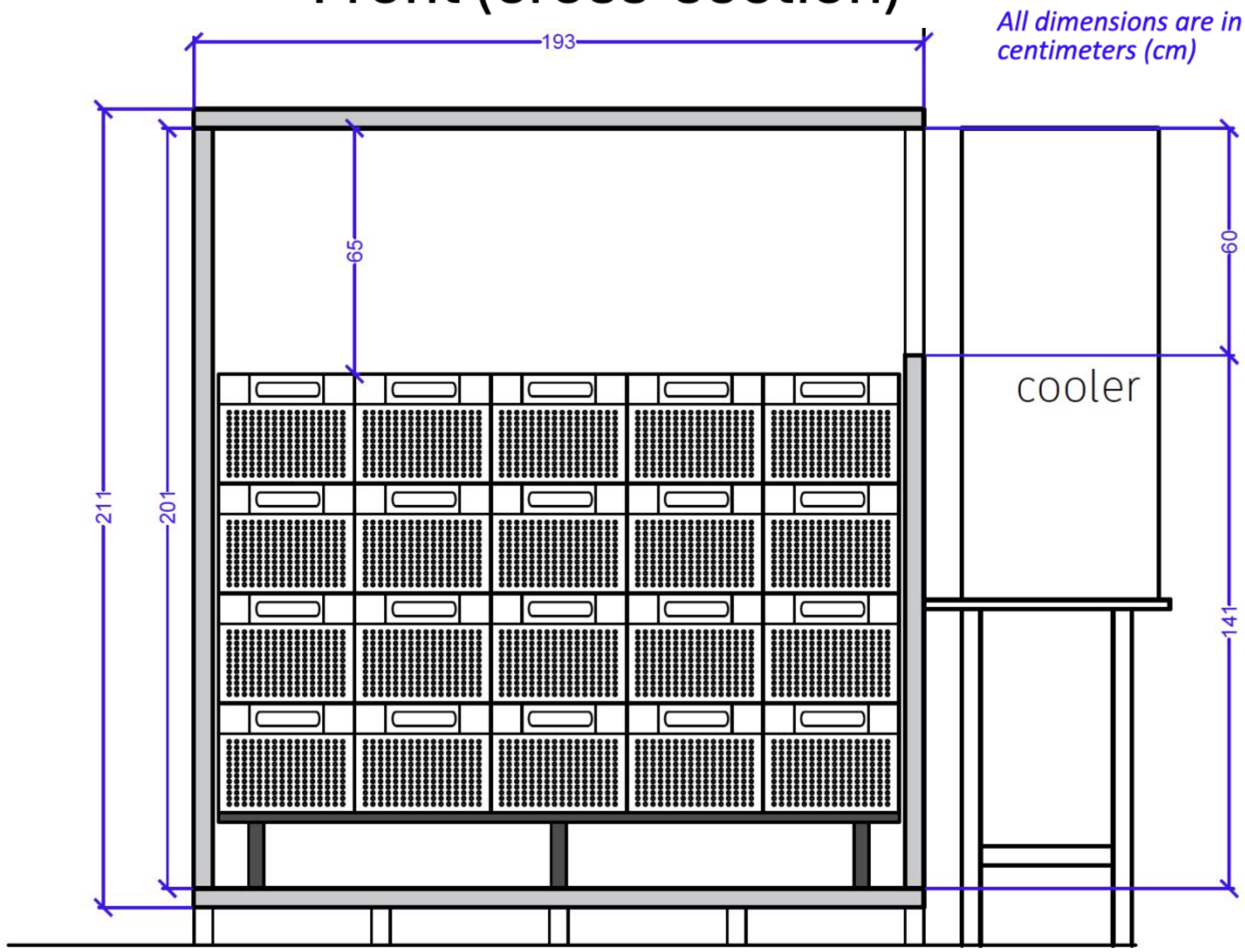
Section BB'



Section CC'

All dimensions are in centimeters (cm)

Front (cross-section)



Section AA'

Insulation Panel Sizes for the 20-crate Portable Chamber in India

Below is a table showing the dimensions of the insulated sandwich panels that are needed to construct the portable chamber designed for crates measuring 54 cm x 36 cm x 29 cm (length, width, and height).

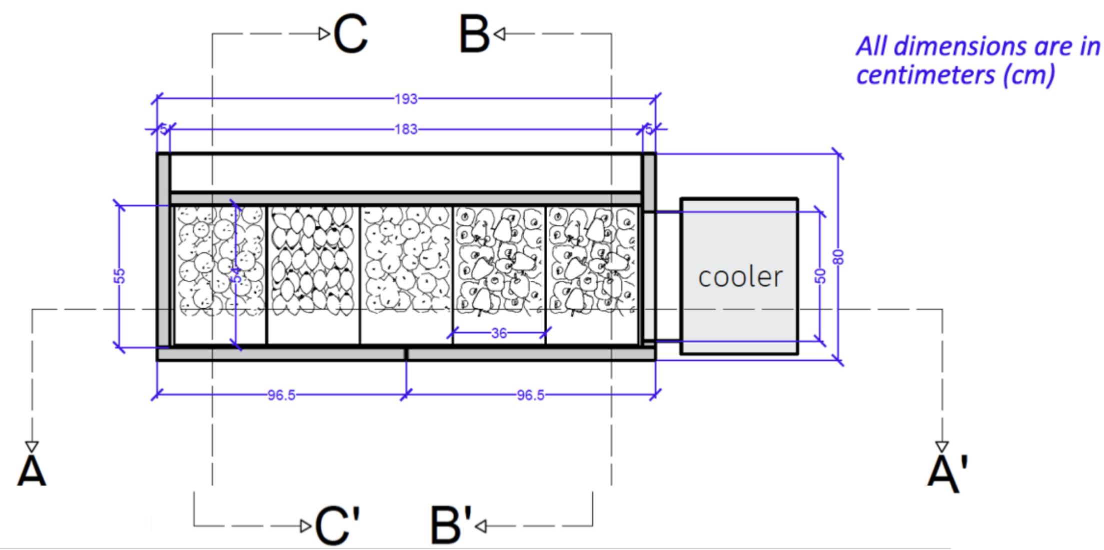
The sandwich panels can be made from several types of insulation, including: Polyurethane Foam (PUF), Extruded Polystyrene (XPS), or Expanded Polystyrene (EPS). The metal cladding should be made of either aluminum or galvanized steel to prevent rusting. The metal sheet that forms the exhaust channel can be made from either aluminum or galvanized steel to prevent rusting. A hole in one of the side panels (left or right) will need to be cut to allow air from the evaporative coolers to enter the chamber.

Panel	Material	Width (cm)	Height/Length (cm)	Thickness (cm)
Bottom	PUF sandwich panel	75	193	5
Top	PUF sandwich panel	75	193	5
Rear	PUF sandwich panel	183	181	5
Left door	PUF sandwich panel	96.5	211	5
Right door	PUF sandwich panel	96.5	211	5
Left side	PUF sandwich panel	75	201	5
Right side	PUF sandwich panel	75	201	5
Rear - channel	Metal sheet	193	161	0.08

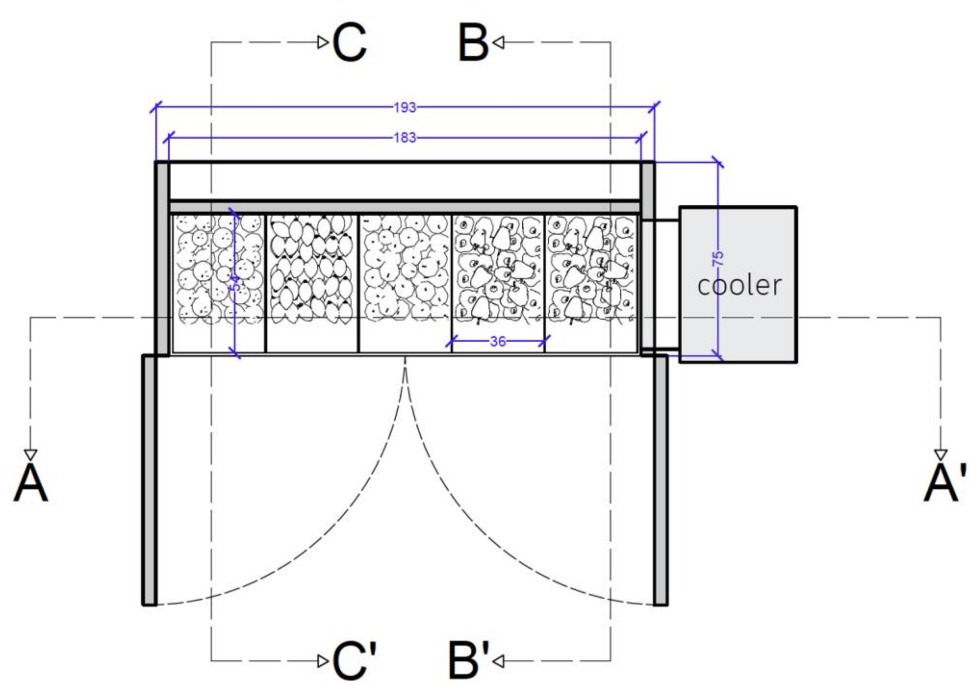
Design Documentation for the 15-Crate Portable Chamber in India

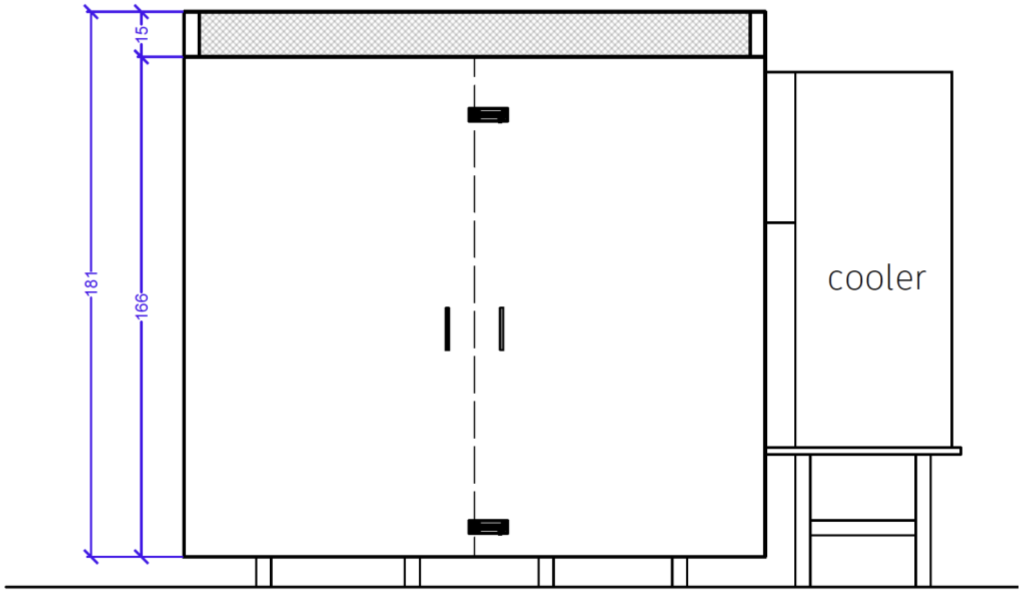
This chamber is a shorter version of the 20 and 25 crate portable chambers described above. A feature to have the exhaust air directed towards the front of the chamber instead out of the rear of the chamber was integrated in order to provide cooler air in the area in front of the chamber. This feature was included based on user research with vendors who would benefit from having cooler air for the customers and staff of their fruit and vegetable shop.

Top view (doors closed)



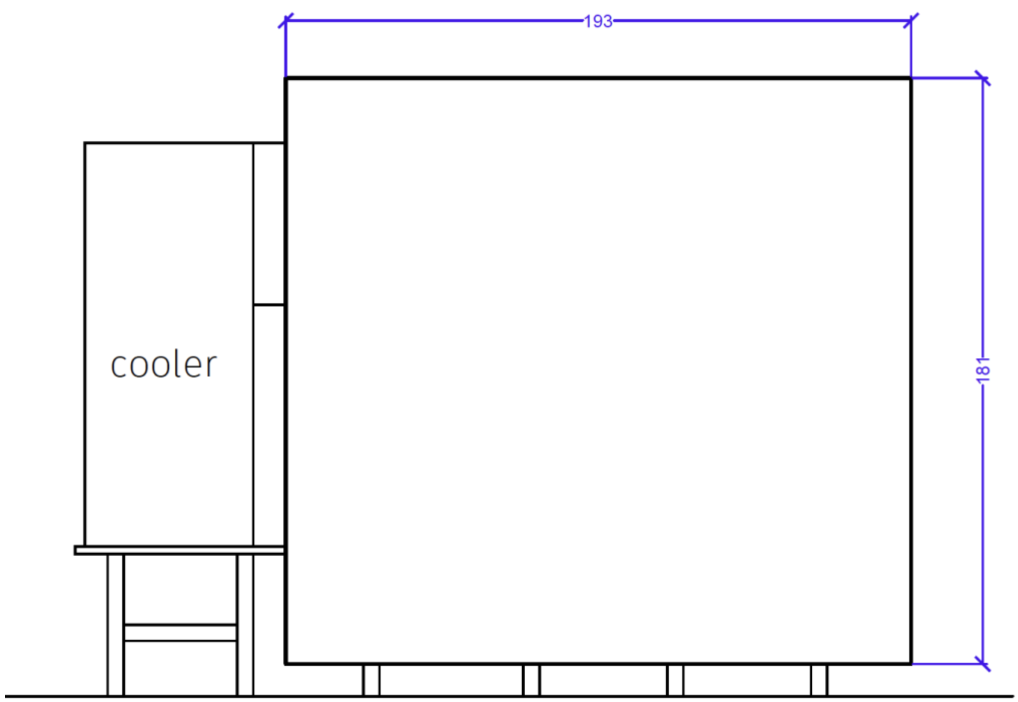
Top view (doors open)



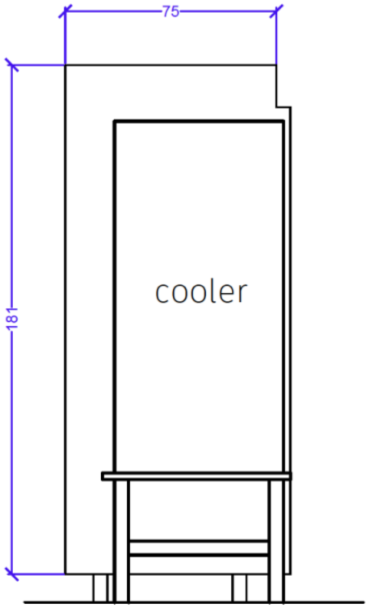


Front Elevation

All dimensions are in centimeters (cm)

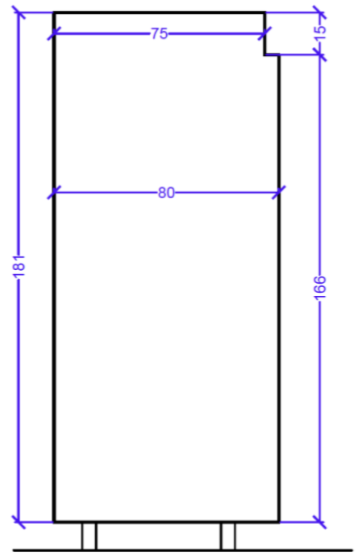


Rear Elevation

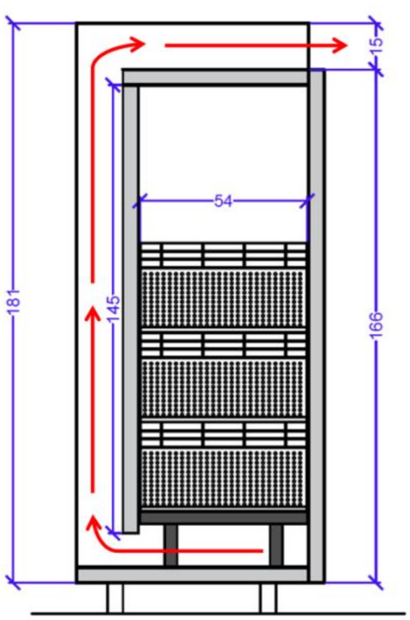


Right side elevation

All dimensions are in centimeters (cm)

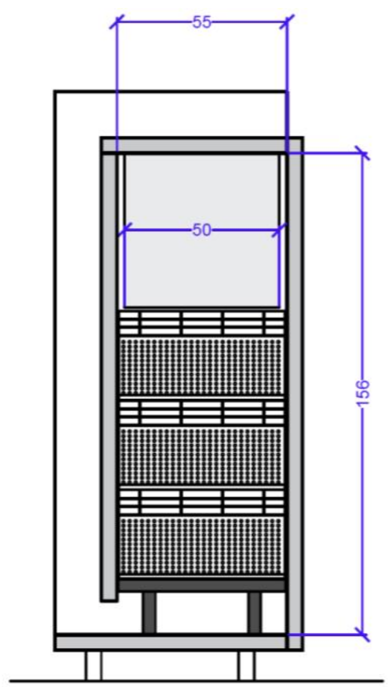


Left side elevation

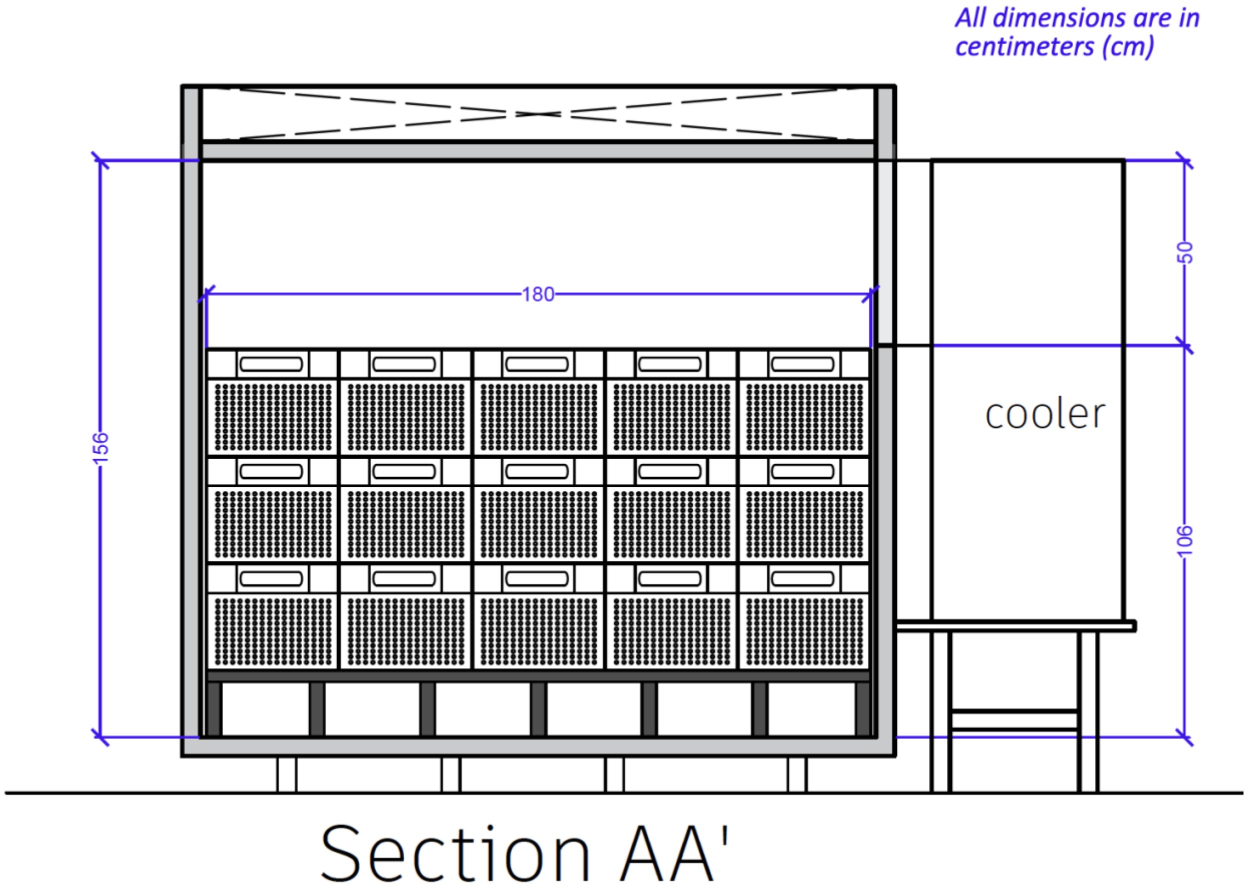


Section CC'

All dimensions are in centimeters (cm)



Section BB'


All dimensions are in centimeters (cm)
180
156
50
106
cooler
Section AA'

Insulation Panel Sizes for the 15-crate Portable Chamber in India

Below is a table showing the dimensions of the insulated sandwich panels that are needed to construct the portable chamber designed for crates measuring 54 cm x 36 cm x 29 cm (length, width, and height).

The sandwich panels can be made from several types of insulation, including: Polyurethane Foam (PUF), Extruded Polystyrene (XPS), or Expanded Polystyrene (EPS). The metal cladding should be made of either aluminum or galvanized steel to prevent rusting. The metal sheet that forms the exhaust channel can be made from either aluminum or galvanized steel to prevent rusting. A hole in one of the side panels (left or right) will need to be cut to allow air from the evaporative coolers to enter the chamber.

Panel	Material	Width (cm)	Height/Length (cm)	Thickness (cm)
Bottom	PUF sandwich panel	75	193	5
Top	PUF sandwich panel	60	183	5
Rear	PUF sandwich panel	183	145	5
Left door	PUF sandwich panel	96.5	170	5
Right door	PUF sandwich panel	96.5	170	5
Left side	PUF sandwich panel	75	180	5
Right side	PUF sandwich panel	75	180	5
Rear - channel	Metal sheet	193	181	0.08
Top - channel	Metal sheet	193	75	0.08