Direct Evaporative Cooling System for Tomatoes in India

BREE 495: Design 3

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ABSTRACT

As the world population increases, the demand for fruits and vegetables also rises. With postharvest losses remaining high for fresh produce, the availability of postharvest storage facilities becomes increasingly important to close existing food gaps. Karnataka, a province in India, is the second largest tomato producer in the country where postharvest losses represent 5-40% of the entire tomato production. An evaporative cooling system for tomatoes in India will decrease postharvest losses and increase farmers' profit while being a cost-effective alternative to traditional refrigeration systems. Different evaporative cooling systems were investigated and analyzed to fit this purpose, such as a non-passive evaporative cooling system and a passive evaporative cooling system. Both methods were analyzed to meet the selected criteria: cost-effective, easy to use, highly performant, and sustainable. Various locally sourced materials were considered to build the cooling system such as stainless steel, fly ash brick, and red clay brick. The red clay brick passive evaporative cooler was chosen due to its feasibility and low-cost. The prototype was built in Montreal, Quebec at McGill University. Prior to storage, the qualitative attributes of 10 ripe Roma tomatoes were ranked following a hedonic scale to determine the consumer acceptability. The initial moisture content was determined using the gravimetric method. The degree of ripeness was expressed using the CIE (1976) colour space. Total soluble solids of five tomatoes was tested to determine sugar content. The tomatoes were then stored in the evaporative cooler for a period of seven days. A control sample was used for comparative analysis. After the seven day period, the stored tomatoes were still considered store-grade in comparison to the control. After 12 days, the samples in the cooling system had white mold growing on the sepal/pedicel, due to poor temperature control. Due to the recent events with Covid-19, the experiment was terminated. Overall, results favoured the adoption of the red clay brick evaporative cooler, but further research remains.

Keywords: postharvest, storage, Karnataka, tomatoes, evaporative cooling, red clay brick

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ACRONYMS & ABBREVIATIONS

CAD	Canadian Dollar
CIE	Commission internationale de l'éclairage
CO_2	Carbon Dioxide
Ha	Hectares
H_2O	Water
IARI	Indian Agricultural Research Institute
IIHR	Indian Institute of Horticulture Research
LCA	Life Cycle Assessment
MT	Million Tons
NHM	National Horticulture Mission
NPV	Net Present Value
O_2	Oxygen
PP	Payback Period
RCB	Red Clay Brick(s)
ROI	Return on Investment
Rs	Indian Rupees
TSS	Total Soluble Solids
US	United States

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1 Introduction

1.1 The Challenge of Postharvest Losses in India

Food safety and security is a challenge for developing countries all over the world. These multidimensional and inter-related concepts are often used to represent food production and availability as well as its quality and quantity. In developing countries, such as India, the majority of food losses can be attributed to a lack of postharvest technologies. In India, 50% of horticulture production is lost after harvest due to insufficient storage, handling, and market facilities. Inaccessibility to proper storage practices is linked to a lack of financial capital and limited energy resources (Connolly-Boutin, 2007). Affordable on-farm storage facilities would help extend the shelf-life of horticulture produce and would avoid distress sales and economic losses (Liberty et al., 2013).

India is the second largest producer of fruits and vegetables in the world. In 2016, the country accounted for 10% of the world's fruit and vegetable production, producing 180 million tons (MT) of fresh produce (Fresh Plaza, 2018). Most of the amount produced is consumed internally (Connolly-Boutin, 2007). Due to India's growing population, the demands and pressures for greater food varieties and quality are only increasing.

Tomatoes are the world's most popular crop after potato and sweet potato (Indiaagronet, n.d.). Its popularity is attributed to its high nutritional content and its use in a variety of processed foods such as tomato paste, soup, and purees. Furthermore, tomatoes are a high-yield crop, produced year-round, making it an important horticultural commodity for farmers from an economic point of view (Indiaagronet, n.d.).

At harvest, the supply of tomatoes on the market exceeds the consumer demand, leading to a glut in the market (Dr. Raghavan, McGill University, personal communication, October 2019). This is common for other horticultural products such as onions and tomatoes. Due to a lack of accessible and appropriate storage options, the market glut causes a collapse in the selling price of tomatoes and the grower's remuneration falls below the cost of production. It is not uncommon to see a farmer plough over his crops if the selling price is below the production inputs (Connolly-Boutin, 2007). The bulk of these financial losses are borne by the farmers and their families. In fact, since the 1990s, there has been a high suicide rate amongst farmers, attributed mostly to their inability to repay loans and interests taken to support their operations. Proper storage facilities would help farmers hold onto their tomatoes until the crisis of low market prices are over. They could then sell them at a profit during the period of scarcity that follows harvest season (Connolly-Boutin, 2007).

1.2 Vision Statement

Cold storage system in developing countries to reduce post-harvest losses for low-income farmers.

1.3 Design Overview

The adoption of short-term cold storage facilities would allow farmers to maintain the physical quality parameters - like colour, texture, and freshness - that dictate the price of tomatoes. For this, temperature and relative humidity must be properly controlled in the storage area. Temperature control is the most important factor in the determination of the postharvest quality of tomatoes. Relative humidity is also a critical component of proper storage management. By increasing the relative humidity of the storage environment, the rate of water loss and other metabolic activities decreases. Proper temperature and relative humidity control will slow down the rate of respiration, reduce microbial growth, and ultimately, increase the shelf-life of tomatoes (Liberty et al., 2013).

Through the mentorship and guidance of Dr. Raghavan at McGill University, the team designed a short-term storage facility that considers the economic, social, and environmental landscape of India, while increasing or maintaining the quality parameters of tomatoes. The goal is for low-income farmers to see an increase in profit and a reasonable return on investment (ROI).

2 Literature Review

2.1 Tomatoes: An Indian Market Analysis

2.1.1 Postharvest Losses

India has some of the highest rates of postharvest losses amongst the developing tropical countries. In fact, 30-40% of the production of fruits and vegetables are lost due to a lack of postharvest technologies (Hegazy, 2016). Refrigeration and cold storage facilities along the cold chain could greatly reduce postharvest losses, especially for tomatoes whose postharvest losses are estimated around 5-40% (Connolly-Boutin, 2007).

2.1.2 Supply and Demand

Since the 1980s, the demand for vegetables has increased, mainly due to urbanization. Some vegetables, like cauliflower, are income elastic, meaning that they are mostly purchased by higher income households. In comparison, tomatoes are categorized as income inelastic crops because their purchase is seen across all income levels (Ali, 2000). This is especially true in rural areas, where an increase in income does not change consumer behavior towards the purchase of different vegetables.

2.1.3 Marketing Channels and Seasonality on Price Instability

Tomatoes are considered a *protective food* because of their high nutritional value and their versatility in Indian cuisine (Agritech, n.d.). The price instability of horticultural crops, such as tomatoes, is a common problem that threatens the financial, emotional, and general wellbeing of consumers and producers. Agriculture in India is very susceptible to climatic conditions. Unfavorable weather conditions lead to high yield variations which have negative effects on the price of produce. For tomatoes, the high price fluctuations mostly affect farmers. In India, the market channels are elaborate and could include up to four middlemen between the producer and the consumer (fig. 1) (Subramanian et al., 2000). In fact, a study performed by the Indian Institute of Horticulture Research (IIHR) in the 1980s indicated that 92% of farmers in Karnataka, a state in the south western region of India, used commission agents to sell their tomatoes (Subrahmanyam, 1989). Almost thirty years later, this has not changed. Over the years, the price of tomatoes has risen at the retail level but not at the wholesale level. Due to elaborate market channels, producers are not benefiting from these higher prices and must bear the economic hardships of agriculture (Connolly-Boutin, 2007).

Producer → Commission Agent → Shipper → Secondary Wholesale Trader → Retailer → Consumer

Figure 1. Example of a market channel for tomatoes in Karnataka, India
(Subramanian et al., 2000)

At a national level, the price of vegetables is heavily influenced by the seasons and the weather. During the rainy months of June to August, the weighted-average monthly market price index of all the vegetables is much higher than during the cooler months of January to March (Ali, 2000). Higher prices across the supply chain are attributed to the high temperatures, excessive humidity, frequent flooding, and poor field drainage experienced during the wet season. In these rainy months, the supply of vegetables is roughly 55% lower than that of the higher supply months. Furthermore, the price of horticultural commodities soar to roughly 120% of the low season price (Subramanian et al., 2000).

In India, the markets are poorly integrated; the price of tomatoes and other vegetables vary on a day to day basis (Subramian et al., 2000). Therefore, there is a need for short-term storage of tomatoes. Even though tomatoes are perishable crops, short-term storage facilities would avoid distress sales and economic losses.

2.2 Karnataka

The cold storage was built and designed for the farmers of Karnataka; a state located in the South Western region of India.

2.2.1 Geography

Karnataka is the eighth largest Indian state by population. Its largest city and capital is Bangalore, officially known as Bengaluru (Mudde, 2017). It is one of the country's most prosperous states with agriculture being one of the biggest drivers of its economy (Ramappa et al., 2016). Around 64% of the total geographical area of Karnataka is cultivated land (Bhende, 2013).

2.2.2 Weather and Climate

Favorable weather and climatic conditions drive agriculture. The state's climate depends on altitude, topography, and the distance from the Arabian Sea. However, it has three distinct types of climates: arid, semi-arid, and humid tropical, with only 25% of the geography witnessing the latter (Rotti, 2016). Karnataka experiences four seasons (Table 1).

Table 1. Karnataka's seasons and the effect on weather (Madur, 2015)

Season	Months	Weather
Summer	March-May	Hot; dry and humid
Monsoon	June-September	Heavy rainfall
Post-Monsoon	October-December	Low humidity
Winter	January-February	Low temperature and humidity

During the summer, monsoon, and winter the average daily temperatures are around 34°C, 29°C, and 32°C, respectively (Rotti, 2016). In Karnataka, agriculture depends heavily on the monsoon for water since only 26.5% of the land is irrigated (Ramappa et al., 2016).

2.2.3 Agriculture

Agriculture is the economic backbone of Karnataka. In a population census in 2011, the industry supported 13.74 million workers, which accounts for 55% of Karnataka's workforce (Bhende, 2013). Due to the large and rapidly growing population, exportation of agricultural commodities, such as grains, vegetables, and fruit is negligible (Mallapur, 2018). Vegetables, such as tomatoes, not only provide nutritional security, but they are also a source of income for small farmers. Since vegetables have a higher productivity and value than cereal crops, tomatoes provide economic security for producers (Ramappa et al., 2016).

Karnataka is the second largest tomato producer in India, with a tomato production area of 5780 hectares (ha) (Ramappa et al., 2016). From 2016-2017, tomato production in the state was at 25,488 MT (Jegede, 2019). Ramappa et al. (2016) performed a sample study with 150 tomato farmers from Karnataka in order to better understand their socioeconomic realities (Table 2). Based on these indicators, younger, more educated farmers are more likely to adopt new innovations and agricultural technologies (Ramappa et al., 2016).

Table 2. Socioeconomic indicators of 150 tomato farmers in Karnataka (Ramappa et al., 2016)

Indicators	Average
Age (years)	43
Education level (years)	6
Family size (individuals)	6
Experience (years)	15

The lack of postharvest technologies and cold storage facilities often leads to distress sales. During harvest season, tomato farmers rush to the markets with their produce, creating a glut in tomato production (supply is higher than the demand). In February 2018, farmers were selling their tomatoes for Rs 3/kg (CAD$0.056/kg). To reap a profit, a producer must sell his tomatoes at Rs 10/kg (CAD$0.19/kg) (The Hindu, 2018). If the supply remains higher than the demand, tomato prices will stay low. Farmers are more affected by the low prices when they do not have access to refrigeration and storage facilities.

2.2.4 Cold Storage

Karnataka is seen as a highly progressive state in regard to vegetable production and postharvest technologies (Bhende, 2013). In 2013, there were 68 operating cold storage units with a combined capacity of 210,000 MT. Four of these are run by the state's government, another four are operated by cooperatives, while the rest belong to the private sector. Out of the total combined capacity, only 70,000 MT is utilized. This is mainly because cold storage facilities often do not operate at different temperatures, making it difficult to store several commodities at once. Furthermore, most of the available cold storages are meant for chillies, potatoes, grapes, pomegranates, bananas, mangoes, and apples (Kulkarni, 2013). Storing tomatoes is especially difficult because they are susceptible to chilling injury.

To promote new or modernized cold storage facilities, the state's government proposed a 25% capital subsidy under the National Horticulture Mission (NHM). This initiative has not been popular due to the economic unviability of current cold facilities (Kulkarni, 2013). High operational costs and an infrequent and unreliable power supply make implementation of cold storage facilities difficult in Karnataka (Mallapur, 2018).

The design was implemented and built considering the socioeconomic realities of tomato farmers in Karnataka. The goal is to empower the farmers of Karnataka by making them less vulnerable to the price instability brought on by seasonality and the elaborate marketing channels.

2.3 Cold Storage

2.3.1 Goals of a Cold Storage Facility

The purpose of any cold storage facility is to slow the rate of decay or to extend the shelf-life of a food commodity in order to be consumed or utilized later (Gross et al., 2004). Not only do they provide and maintain favorable micro-environments, they also protect horticultural produce against weather and pests (Raghavan et al., 2019). Temperature control is the most important aspect of postharvest storage; produce should be kept at the lowest temperature possible without risk of chilling injury. By lowering the temperature, the product's respiration rate and sensitivity to ethylene gas decreases. At reduced temperatures, the commodity will experience less water loss, and ultimately, less shriveling and wilting (Kitinoja et al., 2004). In fact, a study conducted on the factors that influence postharvest losses of tomatoes in urban markets in Nigeria found that the vegetable's rate of spoilage depends on mechanical damage and loss of moisture (Ogbuagu et al., 2017).

Temperature is not the only factor that must be taken into consideration. Relative humidity of the ambient environment must also be optimized to reduce the rate of decay. Methods such as reducing temperature and the addition of moisture to the air surrounding the commodity are effective at increasing the relative humidity of the storage environment and slowing the rate of water loss (Kitinoja et al., 2004). Furthermore, tomatoes are susceptible to chilling injury. Chilling injuries could potentially lead to a ripening failure and the development of off-flavors (Gross et al., 2004).

The chosen design acknowledges the optimal storage conditions of tomatoes to reduce postharvest losses and lengthen the time of consumption.

2.3.2 Commercial Storage of Tomatoes

Tomatoes are a warm-season crop and are produced year-round in Karnataka, India. It is a climacteric fruit of moderate perishability that continues to ripen once harvested. Its price is dependent on the colour, texture, and freshness (Gross et al., 2004).

2.3.2.1 Respiration Rate

Respiration is a process seen in fruits and vegetables during which oxygen (O_2) combined with sugars produce energy, carbon dioxide (CO_2), and water (H_2O) (eq. 1) (Connolly-Boutin, 2007).

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + Energy\ (2667\ kJ) \tag{1}$$

In this reaction, 42% of the energy produced is utilized during the cell's metabolic processes. Unused energy is lost in the form of heat (Connolly-Boutin, 2007). Once harvested, tomatoes continue to respire, however since there is little cell development at this stage, the majority of the energy is released as heat. In the design of a cold storage facility, this released heat contributes to the refrigeration load (ASHRAE, 2003). To determine the rate of respiration of tomatoes, eq. 2 can be used (Connolly-Boutin, 2007):

$$W - \frac{10.7 \cdot f}{3600}\left(\frac{9 \cdot t}{5} + 32\right)^{g} \tag{2}$$

Where, w: rate of heat generation due to respiration (W/kg),

f: respiration coefficient (2.0074×10^{-4}),

g: respiration coefficient (2.8350),

t: Temperature (°C).

In lieu of calculations, Gross et al. (2004) published a table averaging the rates of respiration for different temperature ranges (Appendix A: Table 4).

2.3.2.2 Considerable Factors Affecting Respiration Rate

<u>Temperature</u>

Temperature is the biggest factor in the deterioration of tomatoes; low temperatures reduce the rate of respiration and the growth of food spoilage microorganisms (Liberty et al., 2013). Temperature in the cold room must be carefully monitored as to not ruin the quality and freshness of the tomatoes. At low temperatures, tomatoes are susceptible to chilling injuries. For both ripe and mature-green tomatoes, the storage temperature should never go below 7°C. In fact, 10°C was the lowest recorded temperature before the flavor and aroma started being affected (Gross et al., 2004).

Relative humidity

Relative humidity is also an important factor since it influences water loss in the produce. Water loss, also known as transpiration, occurs when water contained in the commodity is evaporated from the product's skin to its surroundings (Connolly-Boutin, 2007). The rate of transpiration has a direct impact on quality; rapid moisture loss will cause the tomatoes to shrivel. This will have negative consequences on the appearance, texture, and flavor (ASHRAE, 2003). Depending on the stage of development, the relative humidity should be between 85-90% (Gross et al., 2004).

Stage of development

After harvest, the respiration rate of tomatoes will increase unless it is stored at low temperatures. Storage temperatures vary depending on the stage of development. Ripe tomatoes should be stored at around 7-10°C while mature-green tomatoes are stored between 13-21°C. On average, ripe tomatoes can be stored up to one week while mature-green tomatoes can be stored for up to 5 weeks (Appendix A: Table 5) (Gross et al., 2013). It has been reported that a storage temperature over 27°C will reduce the intensity of the red skin (Liberty et al., 2013).

Physical stress

Physical stress, such as bruising, experienced during storage or handling will accelerate ripening by increasing the respiration rate and the production of ethylene. This will shorten the shelf-life of the tomatoes and make them more vulnerable to pathogens (Connolly-Boutin, 2007).

Atmospheric conditions

It is important to have a good balance of O_2 and CO_2 in the storage room. A lack of oxygen could make the produce go into anaerobic respiration and lead to spoilage and foul smells. However, higher CO_2 levels aid in decreasing the rate of respiration (Gross et al., 2004).

Ethylene

Climacteric vegetables and fruits such as tomatoes are often exposed to ethylene to kickstart the ripening process (Connolly-Boutin, 2007). Since the design will be mainly used as a short-term storage facility, it is not necessary to incorporate specific ripening rooms.

For the design of the cold storage, the team focused primarily on the temperature, relative humidity, physical stress, and the tomato development stage.

2.3.3 Principles of Cooling

Cooling is the removal of heat that usually results in a lower temperature and/or a phase change. Cooling a produce along the food supply chain removes heat from a product in order to decrease spoilage and pathogen growth to maintain quality and flavor (ASHRAE, 2003). Refrigeration systems do not create air; they remove thermal energy (heat) out of a low temperature reservoir and transfer it to a high temperature reservoir using energy (Fenton et al., 2019). The driving force of heat transfer is the temperature difference between the two media. Heat can be transferred through conduction, convection, radiation, and evaporation (Kitinoja et al., 2004). The efficiency of a cold storage system is an important economic and operational requirement. Suboptimal heat removal will increase energy inputs, spoilage, and decrease the quality of the product. Many natural and artificial refrigeration methods exist on the market. After preliminary research, the team concluded that mechanical refrigeration and evaporative cooling were the more desirable cooling mechanisms in the design of a cold storage for low-income tomato farmers in Karnataka, India.

2.3.3.1 Mechanical Refrigeration

Mechanical refrigeration is the principal method used in food refrigeration. It operates on the Rankine cycle. The fluid known as the refrigerant undergoes four steps: compression, condensation, expansion, and evaporation. Its main components are the compressor, the condenser, the expansion valve, and evaporator (Appendix A: Figure 5). The compressor is located outside of the cold room and compresses the refrigerant. The condenser is a heat exchanger designed to reject the condensing heat of the refrigerant. It is also located outside of the storage facility. The evaporator is located inside the room and absorbs heat by evaporating the refrigerant. It is located inside the room (Raghavan et al., 2019).

2.3.3.2 Evaporative Cooling

Evaporative cooling is a natural process by which air that is not overly humid passes over a wet surface. Water absorbs the heat from the air and reduces the temperature of a product, room, or substance through evaporation. Evaporative cooling converts sensible heat into latent heat which leads to a decrease in the ambient temperature of the cold storage (Liberty et al., 2013). As the temperature of the storage facility decreases and the relative humidity increases, the enthalpy of the air remains constant (Ogbuagu et al., 2017). The faster the rate of evaporation, the greater the cooling.

Evaporative cooling is an efficient and economical alternative to mechanical refrigeration. It also provides effective cooling without the use of external energy sources (Ogbuagu et al., 2017). If the system is not operating on an external source of energy, its efficiency is increased by the type of climate it operates in. Dry climates are ideal for evaporative cooling. Dry air absorbs moisture much faster than humid air; cooling is not possible if the air is already saturated with water (Liberty et al., 2013).

Methods of Evaporative Cooling

There are two main methods of evaporative cooling: direct and indirect.

Direct evaporative cooling occurs when dry, hot air passes through a wet media. As the hot air infiltrates the media, the adiabatic exchange of heat leads to water evaporation. As the water changes state, the air inside the storage room becomes saturated with water and the temperature decreases while the relative humidity increases. There are two forms of direct evaporative cooling: passive and non-passive. Passive evaporative cooling relies on natural air movements through a moist surface to initiate evaporation. Non-passive evaporation uses forced convection currents created by fans (ASHRAE, 2015).

Indirect evaporative cooling operates on the same principle as direct evaporative cooling; however the evaporative cooling cycle occurs in the heat exchanger; the water and the air inside the room never come into contact (ASHRAE, 2015). The main difference between direct and indirect evaporative cooling is that indirect coolers never change the moisture content of the air (Appendix A: Figure 6).

Factors affecting the Rate of Evaporative Cooling

Air temperature and movement, surface area, and relative humidity all interact with one another and influence the rate of evaporation (Liberty et al., 2013).

Evaporative coolers work more efficiently in hot and dry climates. Higher temperatures increase the rate of evaporation and cool the storage room more efficiently. Air can hold in more moisture at low humidity levels which also increases the rate of evaporation. The greater the difference between the wet-bulb and dry-bulb temperature of the air, the greater the rate of cooling. Evaporative cooling cannot take place if the dry-bulb temperature and the wet-bulb temperature are equal (ASHRAE, 2015).

Evaporative cooling is a natural process that can operate with natural convection. Fans are tools used to increase the rate of evaporation (ASHRAE, 2015). As water evaporates from the wet pad, the humidity of the surrounding air increases. Humid air tends to remain in place. Incorporating fans would create air flow by sucking in the humid air. This way, moist air is constantly being replaced with dry air (ASHRAE, 2015).

The surface area of the wet pad also plays an important role in the rate of evaporation. The greater the surface area, the more water can evaporate (Liberty et al., 2013).

3 Materials & Methods

3.1 Location of the Research Work

The Red Clay Brick (RCB) Evaporative Cooler was initially designed as a low-cost cold storage system for smallholder tomato farmers in the province of Karnataka, India. The prototype was built and tested in Dr. Mark Lefsrud laboratory, an Associate Professor at McGill University in the Faculty of Bioresource Engineering in Sainte-Anne-de-Bellevue (Montreal), Quebec, Canada.

3.2 Design Considerations

The following cooling storage methods were compared using a Pugh chart to rate each method independently: a passive evaporative cooling system, a non-passive evaporative cooling system, and a traditional refrigeration system (Appendix A: Table 6). Several social, environmental, and economic constraints were considered; however, the performance and capital cost were the most important factors. Based on the Pugh chart analysis, the cold storage systems that scored the highest were the non-passive and passive evaporative cooling systems.

The proposed system must not be difficult to operate, and the maintenance cost should be relatively low. Farmers would not need extensive technical knowledge to operate or maintain the evaporative cooling design. The capital cost of the system was of the utmost importance. While certain farmers might receive subsidies from the government for cold storage systems, they often use these subsidies to cover planting costs (Connolly-Boutin, 2007). Reducing the capital cost of the system through the use of locally sourced, recycled, and sustainable materials would benefit the farmers and would reduce the overall environmental footprint. The system performance was another crucial criterion since it directly impacts a farmer's profit.

A refrigeration system does not meet the criteria of an inexpensive cooling system, considering the costs of maintenance and power consumption (Appendix A: Table 6). On the other hand, the scores of both non-passive and passive evaporative cooling systems are significantly similar and both systems were considered as potential solutions. Three types of design alternatives are presented in this paper; yet, only one was considered for further development. The final decision was made based on the type of material used and the energy requirements for optimal efficiency.

When looking at the passive direct evaporative cooling system, the use of any technological items isn't required. Devices such as suction fans, an evaporative pad, and a water reservoir are replaced by a porous material that possesses the desired heat properties. In developing countries, many passive direct evaporative cooling systems made from bricks have already been built and are still in operation today (Liberty et al., 2013). For Karnataka's arid to semi-arid climate, it is necessary to select a material with a low thermal conductivity to lower the rate of heat transfer. A material with a low thermal conductivity would optimize efficiency as it will not be a good conductor of heat.

When dealing with a non-passive direct evaporative cooling system, the porosity of the material isn't as big of a concern. To make up for this, a wet pad made from hessian or cotton waste is implemented in the design. A water reservoir and pipes are used to properly distribute water over the wet pad. A suction fan is placed opposite from the wet pad to draw the humidity away from the wet surface and to increase the rate of evaporation (Liberty et al., 2013).

3.2.1 Non-Passive Direct Evaporative Cooling System

3.2.1.1 Material Considerations

A non-passive direct evaporative cooling system requires a material that does not rust in contact with water. Inspired by an existing non-passive evaporative cooling system built by Zakari et al. (2016), the first design proposal was made of aluminum sheets. However, aluminum has a high thermal conductivity and would increase the rate of heat transfer making cooling inside the system very difficult. To overcome this, stainless steel was considered as an alternative. In the food industry, stainless steel is often used for its reliability and versatility in food handling and preparation.

Dewangan et al. (2015) reviewed its use in the dairy industry and provided a non-exhaustive list of characteristics that make stainless steel a suitable alternative. In the context of this project, the most relevant stainless steel properties include its resistance to oxidation and corrosion, toughness, low thermal conductivity (when compared to other metals), and its total life cost. Stainless steel is the generic name given to the different variations of steels; however, they all possess the same chemical elements: iron, nickel, and chromium (Dewangan et al., 2015). A study conducted by Mills et al. (2004) to determine the thermo-physical properties of stainless steel showed that austenitic stainless steel has a thermal conductivity of 14.2 $W.m^{-1}.K^{-1}$ at a temperature equal to 298.2K (25°C). The research also showed that the thermal conductivity of steel seems to decrease with temperature.

Austenitic stainless steel is a specific type of stainless steel that possesses high nickel and chromium content, allowing it to be stable, even at low temperatures. It is also easily cleanable and will not contaminate the products it encounters (Team Stainless, n.d.). As a food contact surface material, grade 304 austenitic stainless steel is most commonly used in food equipment for its high corrosion resistance as explained by Schmidt et al. (2012). The average life expectancy of most stainless steel products is between 15 and 25 years (Team Stainless, n.d.).

In this system, a water reservoir is required to store the water. Pipes are implemented to direct the water from the reservoir to the desired part of the system. In addition to a water resource and the various pipes, an evaporative pad is needed. The role of this pad is to retain water and to enhance the evaporative process. Water can then be sprinkled on the evaporative pad allowing incoming air to come in contact with a larger amount of water. The flow of air will be regulated by suction fans that will be placed on the opposite side of the evaporative pad. The use of a water pump could be avoided if the water reservoir is placed above the design since the flow of water is initiated by gravity. Finally, powering suction fans will require energy input which can be accomplished by using a solar panel.

3.2.1.2 Prototype

The non-passive evaporative cooling prototype was designed and drafted using AutoCAD (Appendix A: Figure 7). The model is made of stainless steel sheets whose dimensions are 600mm x 1000mm and 500mm x 1000mm with a thickness of 0.381mm. The system has a height of 1m, a width of 0.5m, and a depth of 0.6m; for a total volume of 0.3m^3. The front and rear sides, the left- and right-hand sides, and the top and bottom sections have an area of 0.5m^2, 0.6m^2, and 0.3m^2 respectively. The sheets covered all the faces except the front which was made of jute material. The specific heat of jute was considered as 1.36x10^3 J.kg^{-1}.K^{-1}.

COMSOL simulation software was used to model the temperature distribution of the stainless steel evaporative cooler. The material properties of stainless steel were already incorporated into the COMSOL software; however, jute was not a material in the built-in library. Its material properties such as its thermal conductivity, equal to 0.4273 W.m^{-1}.K^{-1}, and its density, considered to be 1450 kg.m^{-3}, were user-defined (Bandyopadhyay et al., 1987). The ambient temperature was assumed to be 29°C.

The geometry of the COMSOL model respected the original volume of the evaporative cooler: 0.3 m^3 (Appendix A: Figure 8). Components such as the water reservoir, suction fans, and pipes were excluded in the simulation. A time-dependent study was conducted to model heat transfer through solids for stainless steel and jute using COMSOL.

From the results obtained, stainless steel has a higher surface temperature (302K) than the jute pad (288K). Since the thermal conductivity of stainless steel is higher than jute, the rate of heat transfer by conduction should also be greater for stainless steel. The results also show that the thermal conductivity of jute will allow a cooling effect through the edges that connect the wet pad to the stainless steel (Appendix A: Figure 9). This design requires the use of suction fans that can mitigate the thermal conductivity effect of stainless steel. Further simulation is required to analyze the convection of air, the rate of evaporation, and the relative humidity inside the cooler.

3.2.1.3 Health and Safety Considerations

Stainless steel was first invented and used to overcome recurring corrosion problems that would lead to food deterioration. Most of the concerns linked with the use of stainless steel as a food contact surface material occur during cooking where it could potentially leach chemicals (Kamerud et al., 2015). Studies performed on canned tomato sauce have shown that trace amounts of nickel and chromium could leach into the product. This possibility also increases with the shelf-life of the product. By simulating a food and stainless steel interaction through the use of citric acid, the results of a report prepared by Mazinanian et al. (2014) showed that although stainless steel did release small amounts of chemical contaminants, these levels were far below the specific release limits determined by the Council of Europe.

3.2.2 Passive Direct Evaporative Cooling System

3.2.2.1 Material Considerations

Evaporative coolers made of bricks are used in India as inexpensive storage systems. Red clay is a commonly used material in developing countries as it is relatively inexpensive, easy to use, and readily available. Clay has been used in numerous passive evaporative cooling systems, such as pot, bamboo, and static cooling designs (Practical, n.d.). In recent years, a new alternative to RCBs known as fly ash has emerged. Fly ash or coal fly ash is an industrial byproduct of coal combustion thermal power plants (Civil Engineering Discoveries, n.d.).

Fly ash bricks are cast in molds in comparison to clay bricks which are handmade. This makes them easier to use and size since they are uniform. Fly ash bricks are made from waste materials which makes them lighter and less costly than clay bricks that are made of fertile land and topsoil. Furthermore, they can be locally sourced in India and are environmentally friendly (Civil Engineering Discoveries, n.d.).

As discussed previously, porosity is a material property that affects the overall efficiency of the design. An experiment conducted by Hasan et al. (2015) showed that a higher amount of fly ash in the base mixture resulted in a higher water absorption. Lingling et al. (2005) carried out research to study the properties of bricks depending on their content of fly ash. The content of fly ash ranged from 50% to 80%. This study helped confirm that apparent porosity and water absorption increased proportionally to the volume of fly ash. The brick with 80% fly ash content presented an apparent porosity of 42.12% and a water absorption of 31.26%.

The thermal conductivity of fly ash brick must also be considered. In a report conducted by Lingbawan (2009) the thermal properties of fly ash bricks were observed. The experiments showed that their thermal conductivity was around 0.35 $W.m^{-1}.K^{-1}$ lower than that of regular RCBs, which could vary from 0.59 to 0.72 $W.m^{-1}.K^{-1}$ depending on the density of the clay. In addition to better material properties, fly ash bricks could also help reduce the overuse of clay, helping reduce land degradation and pollution (Gadling et al., 2015).

The Indian Agricultural Research Institute (IARI) developed a cooling system that can be built from bricks and river sand. Its construction involves a layer of bricks and a cavity brick wall at the outer edge which allows the sand filling to be in between the brick layers. The sand must always be saturated with water to maintain moisture and temperature within the chamber (lal Basediya et al., 2013). These structures are known as zero-energy cooling chambers designed for on-farm use and operate using evaporative cooling. The chambers were shown to be suitable for short-term storage of fruits and vegetables, such as tomatoes (lal Basediya et al., 2013). Brick evaporative cooling systems can be built from locally available resources in most parts of the world since no heavy machinery is required.

3.2.2.2 Prototype

The prototype was designed following the guidelines of the IARI's *Static Cooling Chamber* and Dr. Gyan Shrestha's, a member of the Green Energy Mission, *Naya Cellar Storage* (Practical Action, n.d.) (Appendix A: Figure 10).

The size of the cellar storage can vary to suit the user. Since this prototype is a proof-of-concept, it was designed to fit one plastic crate of tomatoes. By using the dimensions of a standard brick to be 240mm x 112mm x 70mm, the total volume of the brick evaporative cooler is $0.71m^3$ (ConstructionOr, n.d.) (Appendix A: Figures 11, 12, 13; Appendix B, 7.2.1.1). The inner brick cavity, where evaporative cooling takes place, has a volume of $0.25m^3$. Assuming a standard plastic crate size of 52.1cm x 36.5cm x 30.5cm and a packaging density of 65% (the maximum possible packing density when the tomatoes are randomly placed in the crate), the storage system can hold up to 162 tomatoes (Jain, 2014; Rapusas et al., 2009) (Appendix B: 7.2.1.2).

Clean sand is placed between the two cavities of the double-walled chamber. The sand and porous bricks must be watered continuously to ensure proper evaporation. This can be done by installing a drip-watering system with a high-density polyethene hose with pinholes; water released from the reservoir can spread through the hose and keep the sand and bricks moist. Ideally, the flow of water is regulated following any changes to outdoor temperatures. Natural air currents from the outdoors would help circulate air around and through the chamber, evaporating the water from the porous bricks and sand to raise the relative humidity and decrease the temperature of the inner cavity. To prevent damage to the tomatoes, such as bruising, they should be stored in a plastic crate. The storage system should also be built in an area with minimal sun exposure with a roof or cover made from plant material, sacks, cloth, bamboo, or wood (Practical Action, n.d.).

3.2.2.3 Health and Safety Considerations

Fly ash is a byproduct of coal and can potentially contain heavy metals and toxins. This poses a safety risk since the fly ash bricks will be filled with water. As the water evaporates in the inner cavity, these heavy metals and toxins could leach on to the tomatoes and pose significant health hazards.

Research conducted by Liu et al. (2009) showed that wet fly ash bricks emitted four times more radon gas than dry fly ash bricks. Since the system relies on bricks absorbing a large amount of water, there is a potential risk of contaminating the produce. Luckily, rainfall caused negligible amounts of heavy metals to be released from the bricks. The study also showed that the amount of heavy metals present in the brick wasn’t high enough for the fly ash bricks to be considered hazardous for construction purposes. Gupta et al. (2017) compared the leaching of heavy metals between clay bricks and fly ash bricks. Two types of fly ash bricks were presented with both types being sourced from two different thermal power stations. Even if the leaching results weren’t conclusive, the physico-chemical characteristics of fly ash bricks depend on the coal source and quality. Fly ash brick is an inexpensive and highly available material; however, it represents a major health hazard in the food industry due to its toxicity. Its use as a replacement to RCBs needs further research.

The river sand between the two walls of the evaporative cooler must be free from soil. Soil can contain organic impurities that would come in direct contact with the tomatoes, making the product unsafe for consumption (Practical Action, n.d.).

3.3 Selection of a Design

After careful analysis, the stainless steel design was selected as the optimal solution to decrease postharvest losses of tomatoes in Karnataka, India. The stainless steel prototype includes a fan, a solar panel, a wet pad, and a water reservoir. Although the prototype is more expensive, stainless steel is durable and is widely used in the food processing industry. Furthermore, adding an off-grid source of electricity, such as a solar panel, to power a fan would help increase the efficiency of the system.

The original goal of the experiment was to build both the non-passive and passive direct evaporative coolers made of stainless steel and RCB, simultaneously. Due to low funding availability, it was a major challenge to find financial resources to solely start building and testing the stainless steel design, yet alone both prototypes. After further discussion with the team's mentor and client, the RCB storage system would be constructed before the stainless steel prototype given the strict timeline and available funding. Moreover, the RCB unit was a less expensive solution with a higher payback period (PP) and ROI (Appendix C: Table 12).

3.4 Construction of the RCB Evaporative Cooler

3.4.1 Materials

The materials needed to build the RCB Evaporative Cooler include RCBs, sand, a thermometer and humidity meter, an overhead water tank/bucket, a drip-watering system with pipes, bamboo or plastic mesh trays/baskets. The prototype is intended for smallholder tomato farmers in Karnataka, India, however the experiment was conducted in the northern climate of Montreal, Canada. The list of materials provided below (Table 3) is a list of necessary equipment required to build the RCB evaporative cooler in Canada. Local India alternatives are also offered. The amount of each material can vary since the size of the system can be adapted to suit the needs of the user.

Table 3. Basic materials required to construct the RCP evaporative cooler

Material	Amount	Supplier	Indian alternative
Red clay bricks	200 units (400 lbs.)	Montréal Brique et Pierre Inc.	Any clay brick
Dry sand	180 kg (396 lbs.)	Patrick Morin Rona	River sand (soil free)
Plastic tarp	1 unit (6' x 8')	Patrick Morin	Omitted when design is built outdoors
Water valve	1 valve	Laboratory	Overhead water tank/bucket
30m Micro Drip Irrigation System Sprinkler Plant Watering Irrigation System	1 polythene hose 12 nozzles	Amazon	Omit nozzles and make holes in the polythene hose
Masonite	Two planks, 48"x48", 1/8" thick	Rona	Cane or other plant material, sacks, or cloth mounted to a bamboo frame

ThermoPro TP50 Digital Hydrometer Indoor Thermometer Humidity Monitor with Temperature Humidity Gauge	1	Amazon	Any trusted relative humidity and temperature sensor, if necessary
Plastic crate	2 units	Aramark Inc.	Bamboo or plastic mesh trays/baskets

Given the winter Canadian climate, Roma tomatoes were purchased from a local grocery store in Montreal, Canada. The produce is imported from the United States (US) and supplied by *Sunset*, the leading greenhouse vegetable company in North America (Sunset, n.d.)

3.4.2 Design Calculations

The evaporative cooler was designed considering the size of both the tomatoes and the plastic crate. Following the dimensions and the design of the structure (Appendix A: Figures 11, 12, 13), the total heat load of the system is calculated. The material characteristics, such as thermal conductivity, of the equipment used were investigated to determine the thermal heat transfer. Ideally, the flow rate of the water emitted from the reservoir should also be calculated. It is important to note that the temperature and relative humidity are based on the optimal conditions in Karnataka, India, and the ideal storage conditions for tomatoes.

3.4.2.1 Total Heat Load

Warm, dry air that enters the system is cooled and humidified as it moves across the porous sand and the inner brick cavity. This change in air conditions is necessary to remove the heat load from the storage of tomatoes. The various sources of heat loads supplied to the RCB Evaporative Cooler are the heat gain by conduction of the walls, floor, and roof of the cooler, the respiration rate of the tomatoes, the field heat of the produce, and the infiltration of air (Obbuagu et al., 2017).

Any assumptions made in the following calculations are based on ideal weather and climate conditions of Karnataka, India.

Heat gain by conduction through the walls, roof, and floor of the system

Heat transfer by conduction through the roof, walls, and floor of the structure is calculated using the thickness of the outer and inner brick walls and the layer of sand. Using the dimensions of the standard RCB, the outer and inner walls are 112mm thick (ConstructionOr, n.d.). The sand, tightly packed between the two walls, has a thickness of 127mm. The thermal conductivities for the RCBs and the sand, reciprocal to the material thickness, are 0.59 $W.m^{-1}.K^{-1}$ and 2.9 $W.m^{-1}.K^{-1}$ respectively (Lingbawan, 2009). According to Smith et al. (2009), the thermal conductivity of $2.9 W.m^{-1}.K^{-1}$ is obtained assuming that the sand is tightly packed with a porosity of 0.322. Heat transfer by conduction is calculated using the thermal resistance of the outer and inner brick walls and the sand layer (eq. 3) as well the temperature difference between the outdoor ambient air and the inside cavity of the cooler (eq. 4). The ambient outdoor and inner cavity air is assumed to be 29°C and 8°C respectively.

$$R = \frac{x}{k \cdot A} \tag{3}$$

Where, R: thermal resistance of the material (K/W),

k: thermal conductivity of the material (W/m.K),

A: area of the material (m^2).

$$Q_c = \frac{\Delta T}{\sum R} \tag{4}$$

Where, Q_c: total heat transfer by conduction (W),

ΔT: change in temperature (°C),

$\sum$R: sum of the thermal resistance of the materials (K/W).

Based on the calculations, the total heat transfer by conduction of the walls and the sand cavity is 20W (Appendix B: 7.2.2.1). Similar calculations are done for the masonite cover and the floor. The thickness of the masonite cover is 0.003175m (⅛ inch) and its thermal conductivity is taken as $0.0476 W.m^{-1}.K^{-1}$ (Western University, n.d.). Furthermore, the brick flooring of the evaporative cooler should be installed on a layer of sand approximately 25mm thick. Underneath the flooring and the layer of sand, the evaporative cooler will sit on soil. The soil temperature regime in Karnataka is classified as isohyperthermic, meaning its temperature is 22℃ or higher (Badrinath, et al., 1997; Plant and Soil Sciences, 2020). For the calculations, the soil temperature is assumed to be 22℃. The heat transfer by conduction of the masonite cover and flooring are 530W and 74W respectively (Appendix B: 7.2.2.1).

<u>Respiration heat load of the tomatoes</u>

Respiration is a process seen in fruits and vegetables. The byproducts of this chemical reaction are CO_2, water, and energy (Connolly-Boutin, 2007). This energy is released in the form of heat. Respiration rate is proportional to the temperature; as the temperature increases, so does the respiration rate. The heat of respiration is calculated by multiplying the mass of produce by the rate of respiration (eq. 5).

$$Q_r = M \cdot RR \tag{5}$$

Where, Q_r: Heat of respiration (W),

M: mass of tomatoes (kg),

RR: Respiration rate (W/kg.hr).

The mass of one tomato is roughly 182g (Hannaone, 2020). Assuming the plastic crate is at maximum capacity, it can hold 162 tomatoes. The USDA does not have a record for the respiration rate of tomatoes below 10℃, thus 15 $mg.CO._2kg^{-1}.h^{-1}$ is assumed for 8℃ (Gross et al., 2004). Using these values, the respiration heat load of the produce is 1.3W (Appendix B: 7.2.2.1).

<u>Field heat of the tomatoes</u>

Field heat is energy released in the form of heat after fruits and vegetables are harvested. Excess field heat can lead to increased metabolic activity, respiration rate, and ethylene production. Storing tomatoes in a cold storage facility, like the RCB Evaporative Cooler, can drastically minimize the effects of field heat (Arah et al., 2016). The field heat is calculated by multiplying the total mass of tomatoes by the specific heat capacity of tomatoes (4.0 $kJ.kg^{-1}.K^{-1}$) and the temperature differential (Sprenger Instituut, 1986). To obtain a rate, all of this is divided by the cooling time (eq. 6)

$$Q_f = \frac{m \cdot c_p \cdot \Delta T}{t} \tag{6}$$

Where, Q_f: field heat of the tomatoes (W),

m: mass of the produce (kg),

c_p: specific heat capacity of a tomato (kJ/kg.℃)

t: cooling time (s).

If the RCB Evaporative Cooler is implemented in India, it is possible to expect a field heat load of 4.095×10^{-3}W if the tomatoes are stored for seven days at maximum capacity (Appendix B: 7.2.2.1). However, since the experiment was conducted in a laboratory in Montreal, the produce will be purchased from a local grocery store; field heat would not be applicable.

Infiltration of air

Proper air flow is essential in reducing the temperature and increasing the relative humidity in the inner cavity of the cooler. According to Olosunde et al. (2009), the heat from air infiltration is estimated to be around 10-20% of the total heat load from conduction, respiration, and field heat (eq. 7). Assuming the heat gain from air infiltration is minimal due to the presence of natural air currents, the heat transfer of air through the porous bricks is estimated to be 10% of the total heat load.

$$Q_a = \left(Q_c + Q_r + Q_f \right) \cdot 0.10 \tag{7}$$

Where, Q_a: heat transfer of air through the bricks (W),

Q_c: heat transfer by conduction (W),

Q_r: heat transfer by the respiration rate (W),

Q_f: heat transfer by field heat (W).

The heat transfer of air through the bricks is estimated at 63W (Appendix B: 7.2.2.1).

3.4.3 Construction of the Prototype

The RCB Evaporative Cooler is a modification of the *Static Cooling System* designed by the IARI and the *Naya Cellar Storage* designed by Dr. Gyan Shrestha from the Green Energy Mission (Practical Action, n.d.). The RCB Evaporative Cooler is intended for smallholder farmers in Karnataka, India. The prototype was built and adapted to the Northern climate of Canada; certain materials and modifications reflect this.

The basic structure of the RCB Evaporative Cooler is made from RCBs and dry sand. Two masonite blanks cover the system to protect the produce from the sun. In India, it is possible to use non-uniform clay bricks and river sand. The masonite planks can be replaced by locally available materials such as cane or other plant materials mounted on a bamboo frame. The cooling chamber must be near a source of water.

Before the construction, the user should choose a small piece of land, roughly 2m^2. The plot of land should have minimal sun exposure. If this is not possible, the structure should be protected from the sun by a roof. Ideally, the ground should slope slightly to drain groundwater and ensure that it does not seep into the chamber (Practical Action, n.d.). Since the prototype was built indoors, sun exposure and groundwater were not concerns.

The RCB Evaporative Cooler has a rectangular shape, 1.184m x 1.424m, and should be around 0.42m high, which is equivalent to roughly six layers of bricks. The size of the storage facility can be varied to suit the user. A plastic tarp was placed on the concrete floor of the lab to keep the environment clean. A layer of sand, roughly 25mm (1in.) thick is spread on the tarp. This represents one bag (30kg) of dry sand. In India, the tarp can be omitted, and the sand spread directly on the ground over the plot of land where the chamber is to be built. A layer of RCBs is placed over the sand. An outer wall is constructed around the edge of the floor, leaving a gap of 125mm (5in.) between the outer wall and inner cavity. To build the double-walled chamber, including the flooring, the user will need roughly 200 bricks. Five bags of dry sand (150kg) are placed between the two walls. River sand can also be used; however, it must not contain soil to avoid organic impurities coming in contact with the tomatoes, rendering them unsafe for consumption. The system can hold 162 tomatoes (29kg). Finally, two masonite planks, 3.175m (⅛in.) thick, are used to cover the chamber. A farmer from Karnataka can construct a cover made with canes covered in sacking, mounted on a bamboo frame (Practical Action, n.d.).

Once construction is completed, the entirety of the RCB evaporative cooling system should be saturated with water. The lab is equipped with a water valve and a hose to facilitate this task. In India, the water valve would be replaced by a water reservoir. A twice-daily automated drip-watering system should be implemented to maintain the moisture and temperature inside the chamber.

A plastic or bamboo mesh basket/crate that can hold the tomatoes is placed inside the inner cavity of the chamber. A temperature and relative humidity sensor can also be placed inside to monitor atmospheric conditions (fig. 2).

Figure 2. Construction process of the RCB Evaporative Cooler

3.4.4 Cost Analysis

A full cost-benefit breakdown was conducted to calculate the PP, the net present value (NPV), and the ROI of implementing a RCB Evaporative Cooler. The cost analysis concluded that an RCB unit can significantly increase farmers' profits as shown in Appendix C: 7.3.1. The RCB Evaporative Cooler design targets farmers that produce around one ton of tomatoes per season and considers tomato price fluctuations throughout the year. An assumption is also made that farmers can sell their tomatoes at a high price and store all of their tomatoes in the system at a constant rate of harvest and storage Farmers can sell their tomatoes at a profit at all times due to the convenience of having an evaporative cooling system to store the produce.

The analysis concluded a PP of 0.70 years and a ROI of 144%. A comparison between an RCB and a stainless steel evaporative cooling system shows that an RCB unit is a less expensive solution with a higher PP (Appendix C: Table 12).

The RCB Evaporative Cooler costs CAD $277.85 to build in Montreal, with the materials listed in Table 3. Since the tomatoes had to be purchased, the total cost of the experiment was CAD $342.65 (Appendix A: Table 7).

3.4.5 Social, Economic, and Environmental Impacts

The system will have a positive economic impact as it would result in an increased profit for the farmers. At harvest, the supply of tomatoes on the market exceeds the consumer demand, leading to a glut in the market (Dr. Raghavan, McGill University, personal communication, October 2019). Due to a lack of accessible and appropriate storage options, the market glut causes a collapse in the selling price of tomatoes and the grower's remuneration falls below the cost of production (Connolly-Boutin, 2007). The cold storage facility would allow farmers to hold onto their produce until the market price stabilizes. Even though there is a high capital investment, the system has a reasonable PP of 0.70 years and a ROI up to 144% (Appendix C: 7.3.3). The cold storage facility would help alleviate the financial pressure of the harvest season in Karnataka.

An environmental assessment was done to evaluate the potential environmental effects of the storage facility. An RCB Evaporative Cooler does not require electricity. A cold storage system that relies on this mechanism is ideal for a location with little to no access to power. In certain areas of the world where conventional refrigerating systems have been replaced by evaporative systems, there have been energy savings up to 75%. There are roughly 20 million residential evaporative cooling systems in the world, to date. These systems save around 60 million petroleum drums and 27 billion pounds of CO_2 per year (Basediya, 2013).

The RCB can be repurposed after the device's life cycle and the sand can be taken from a river if available. Furthermore, as the evaporative cooler will be made from locally sourced materials there will be a reduction in greenhouse gas emissions related to the imports of materials (Basediya, 2013). CO_2 emissions can be produced from material transport, but the device will not produce emissions once installed. These emissions can be mitigated using locally available bricks and river sand.

Water use is one of the few drawbacks of an evaporative cooling system. A lot of water is required to generate the wet pads in order to increase the relative humidity in the room. Furthermore, the cold storage working sub-optimally could lead to food loss and an overuse of resources (Basediya, 2013). Water quality is also an important concern. Since the water will be evaporated into saturated air, it must be free of dangerous contaminants.

3.4.6 Life Cycle Assessment

The purpose of the life cycle assessment (LCA) is to study the environmental impact of the cold storage solution for tomatoes. Therefore, it is important to use recycled and locally sourced materials when possible. The design follows a cradle-to-cradle type of life cycle; most of the components of the storage facility could be repurposed or reused (Appendix A: Figure 14).

The bricks, river sand, and crates should be recycled or repurposed, if possible. However, many of the materials used to construct the prototype in Montreal were purchased from specialty stores since they weren't readily available. The only equipment that was not purchased were the plastic crates, gifted by *Aramark Inc.*, and the water valve, already available in the laboratory. Water is the only raw material needed for the operation of the design. It is important to note that the evaporative cooler requires a lot of water to work efficiently. The product is relatively easy to assemble, use, and adjust. The greenhouse gas emissions such as CO_2 involved in retailer distribution would be an environmental concern. In terms of consumer use, the evaporative cooler requires a lot of water. In general, the system does not require major repairs or maintenance and all materials can be reused if the RCB Evaporative Cooler is no longer useful.

3.5 Experimental Procedure

The RCB Evaporative Cooler was built on March 3rd, 2020, on McGill University's MacDonald Campus in Dr. Mark Lefsrud's laboratory, an Associate Professor. The unit took roughly two hours to build and set up. On March 6th, 64 *Sunset* Roma tomatoes, grown in a greenhouse and imported from the US, were purchased from a local grocery store in Montreal, Quebec. A sample of 10 tomatoes were randomly chosen to undergo quality assessment tests before storing them in the cooling system. The quality assessment tests were performed on the same day the tomatoes were purchased in Dr. Vijaya Raghavan's laboratory, in Montreal, Quebec. The laboratory tests were supervised by Mr. Yvan Gariépy. The tests were to be conducted again after seven days of storage, on March 13, to determine any quality differences between the stored tomatoes and the control sample (Appendix D).

The 10 tomatoes were ranked using a hedonic scale based on their visual appearance such as their colour, firmness, and presence of disease of defects. A hedonic test describes the degree of consumer acceptability of a product based on key attributes. The product is rated individually on a scale of extreme dislike to extreme likeability (Attestia, 2005; Peryam et al., 1957). Their overall market quality was determined by classifying the tomatoes on a scale of one to five; a ranking of one means that the tomato is field fresh quality while a tomato with a ranking of five has no commercial value. This test was to be conducted on both the stored tomatoes and the control prior and after storage.

Fresh tomatoes have a high moisture content of around 93-95% (Correia et al., 2015). As tomatoes ripen and lose water, they will start to wilt. This negatively impacts consumer acceptability; nutritive value, color, consistency, and flavor are the major quality attributes of tomatoes (Thaku et al., 2009). To determine the quality difference between the stored tomatoes and the control, the moisture content loss was determined using the gravimetric method. Gravimetric analysis assumes that weight loss is solely caused by the removal of water. It ignores other variables and the loss of other volatiles. The mass loss is determined by taking the initial and final mass of the product (eq. 8) (Appendix A: Figure 15) (Zambrano et al., 2019).

$$Mass\ loss\ (\%) = \frac{(Initial\ Mass - Final\ Mass)}{Initial\ Mass} \cdot 100 \qquad (8)$$

Colour is one of the most important quality attributes of fruit and vegetables and largely influences consumer acceptability. Colour measurements, such as color space coordinates, are an indirect and fast way of estimating colour change of foods (Antal et al., 2015). The CIELAB or CIE (1976) is the most complete color space defined by the *Commission internationale de l'éclairage* (CIE). The CIE uses the color space coordinates (L*, a*, b*) to describe colour differences, not visible to the human eye. In this system, L* is the degree of lightness and a* and b* are the chromaticity coordinates that describe the degree of redness (+) and greenness (-) and the degree of yellowness (+) and blueness (-), respectively. The colour of the raw tomato samples were measured using the Minolta Chromameter. Using this instrument, it is possible to get the exact colour coordinates of the tomato samples. Prior to this test, the chromameter was calibrated using a white ceramic plate (Antal et al., 2015). Out of the 10 tomatoes, three tomatoes were randomly selected to undergo colour testing. These tomatoes were scanned three times each to determine a mean value. Colour testing should be done prior and after storage to determine the differences between the colour after one week of storage and any colour differences with the stored tomatoes and the control (eq. 9).

$$\Delta E^*{}_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{9}$$

Where, ΔE^*_{ab}: total colour difference,

ΔL^*: difference in brightness,

$\Delta a^*/\Delta b^*$: difference in chromaticity.

Sensory attributes, such as flavor profile, is also important to consumers. With fruits, sugar content heavily determines the flavor profile. Half of the tomatoes were cut and squeezed to measure their total soluble solids (TSS) which is associated with sugar content. Following this test, five of the tomatoes were composted (Appendix A: Figure 16).

With the initial quality attributes tests completed, the tomatoes were placed in the storage system for a period of seven days. Out of the 64 tomatoes, 49 were placed in the RCB unit while 10 were placed in a secondary plastic crate beside the cooler in the laboratory. The laboratory had a constant relative humidity of 30%. The ambient temperature could fluctuate between 7℃ to 21℃ throughout the day. Initially, a twice-daily automated drip-watering system was supposed to supply water to the RCB Evaporative Cooler, however it was of poor quality. To make up for this, the team decided to visit the lab once every two days to manually water the system. Although this was suboptimal, it was the only way to perform the first round of the experiment; the majority of the team's members live more than one hour away from where the experiment took place. The intention was to run the first round of the experiment, then rework the RCB unit with the necessary improvements, such as a better watering system with new tomato samples.

On March 13, 2020, the experiment was terminated due to the recent events with Covid-19. The team was unable to complete all the quality assessment tests on the stored tomatoes and the control. Only qualitative tests were performed.

4 Results and Discussion

4.1 Performance Evaluation of the RCB Evaporative Cooler

The performance evaluation of the RCB Evaporative Cooler was tested by conducting total heat load calculations using the ambient conditions and variables present during the experiment in Montreal.

Heat gain by conduction through the walls, roof, and floor of the system

Heat transfer by conduction through the roof, walls, and floor of the structure was calculated using eq. 4 with the same material properties and system dimensions as done with ideal conditions in Karnataka, India. The ambient indoor laboratory temperature was taken as 19.7℃, the daytime average. From the TP50 Thermometer and Relative Humidity Monitor, the average temperature inside the cooler was 19.2℃. The heat transfer by conduction of the walls and the masonite cover were $4.85x10^{-1}$W and 12.6W respectively. In this case, the heat gain by conduction through the floor was null since the flooring in the lab was made of concrete. (Appendix E: 7.5.1).

Respiration heat load of tomatoes

Respiration rate of tomatoes is directly proportional to temperature. As the temperature inside the cooler was averaged at 19.2℃, it is estimated that the respiration rate of the tomatoes is 35 $mg.CO_2.kg^{-1}.h^{-1}$ (Appendix A: Table 4) Furthermore, the storage system was not at full capacity; only 49 tomatoes were placed in the unit. From this, the respiration heat load of the tomatoes was 1.27W (Appendix E: 7.5.1).

<u>Field heat of tomatoes</u>

Field heat is energy released in the form of heat after fruits and vegetables are harvested. Since the tomatoes were purchased from a local grocery store, the field heat of the tomatoes was already removed and not considered for the total heat load.

<u>Infiltration of air</u>

Proper air flow is essential in reducing the temperature and increasing the relative humidity in the inner cavity of the cooler. The heat from air infiltration is deemed minimal due to the experiment being conducted indoors. Using eq. 7, the heat transfer of air through the bricks was estimated at 1.4W (Appendix E: 7.5.1).

The total heat load of the RCB Evaporative Cooler was 15.80W in comparison to the total heat load calculated of 678W using ideal conditions in Karnataka. This drastic difference is attributed to the different ambient conditions and climates of an indoor laboratory in Montreal in contract to Karnataka, India. Since the RCB unit does not operate on an external source of energy, its efficiency is increased by the type of climate it operates in. Evidently, the winter and indoor climate of Montreal offers suboptimal conditions for proper system performance; an evaporative cooling system works best in hot and dry climates.

The relative humidity inside the RCB Evaporative Cooler was 99%. This is extremely high and beneficial in preventing water loss in the tomatoes. However, the temperature inside the cooler never reached the ideal storage temperature of 8°C. Lack of proper air flow had a negative impact on heat transfer through the bricks. To achieve temperature reductions in the system, air flow is essential (Ogbuagu et al., 2017). Since the experiment was conducted indoors, there was an obvious absence of natural air currents, already present outdoors. To mimic ideal conditions and accelerate heat transfer, numerous fans could have been installed in the room near the cooling system. A heater could also have been placed to increase ambient temperature in the laboratory room to create a temperature differential.

The performance of the RCB Evaporative Cooler could have been evaluated prior to storing the tomatoes by conducting a no-load test. The no-load test would have allowed the team to see the effect of evaporation, whether the process is taking place, to determine the efficiency of the cooling system. A DHT-22 sensor equipped to an Arduino UNO and Raspberry Pi could have recorded the temperature and relative humidity during different times of the day. Adjustments and improvements could then be made to the evaporative cooling structure or the environment to better the results prior to loading the system with the tomatoes.

4.2.1 Equipment Improvements

Some of the equipment purchased for the RCB Evaporative Cooler were of poor quality. The drip-watering system initially purchased came with nozzles to allow water to be sprayed over the sand and brick continuously. Upon installation, the hose would move, or the nozzles would come apart, creating large puddles of water on the sand. To continue running the experiment, the team decided instead to water the system manually once every other day. Allocating more funds to a better watering system could have ensured that the cooling system would have been watered twice daily, as is the norm (Ogbuagu et al., 2017). The TP50 Digital Thermometer and Humidity Monitor was also unreliable. To perform the no-load and load tests, a DHT-22 sensor equipped with an Arduino UNO and Raspberry Pi would have produced more accurate results since it would have been possible to have continuous recordings instead of one-time readings.

In India, crop theft is a growing concern amongst farmers. Theft is most common at night, when no one is available to guard the produce (Loiwal, 2020). An added security measure, such as a lock on the cover of the RCB Evaporative Cooler, could bring the grower piece of mind and ensure that the harvested product remains safe.

4.2 Tomato Quality Analysis

The quality assessment tests were completed on March 6th, 2020 in Dr. Raghavan's laboratory under the supervision of Mr. Yvan Gariépy (Appendix D). The intent was to store 49 tomatoes for a period of seven days in the RCB Evaporative Cooler. A control of ten tomatoes was used to compare the changes in the various quality attributes such as colour, firmness, and sugar content. The storage unit was supplied with water once every two days until March 13, 2020. During this time, the state of the tomatoes was compared qualitatively. On March 13, the goal was to complete the quality assessments tests once more to quantify any changes and to see if the RCB unit had any significant impact on the quality of the tomatoes. The tomatoes would then be placed once again in the evaporative cooler to observe how spores would attack the stored tomatoes in comparison to the control. However, on this day, due to the recent developments with Covid-19, the experiment was terminated and very few results were collected. The stored tomatoes stayed in the evaporative cooler for an extended period of five days. During this time, the cooler was not supplied with water. Although the implementation of the RCB Evaporative Cooler in Karnataka, India seems promising, further research is needed.

4.2.1 Qualitative Assessment of Tomatoes

The hedonic scale describes the degree of consumer acceptability of a product based on key attributes such as colour, firmness, sugar content, and any visible presence of disease or defects. Fruit firmness is also an important characteristic to test the maturity of tomatoes. Firmness is also a primary textural attribute; it is a combination of cell structure and tissue turgor (Antal et al., 2015). Similarly, to visual observations, the firmness is tested by squeezing the tomatoes lightly. If this motion causes bruising of any sort, the tomato will most likely not meet consumer acceptability. The hedonic test was performed before and after storage on both the stored tomatoes and the control; the pedicel, sepal, and crown of the tomatoes were carefully examined (fig. 3). As the tomatoes were purchased from a local grocery store, they were already red and ripe for consumption.

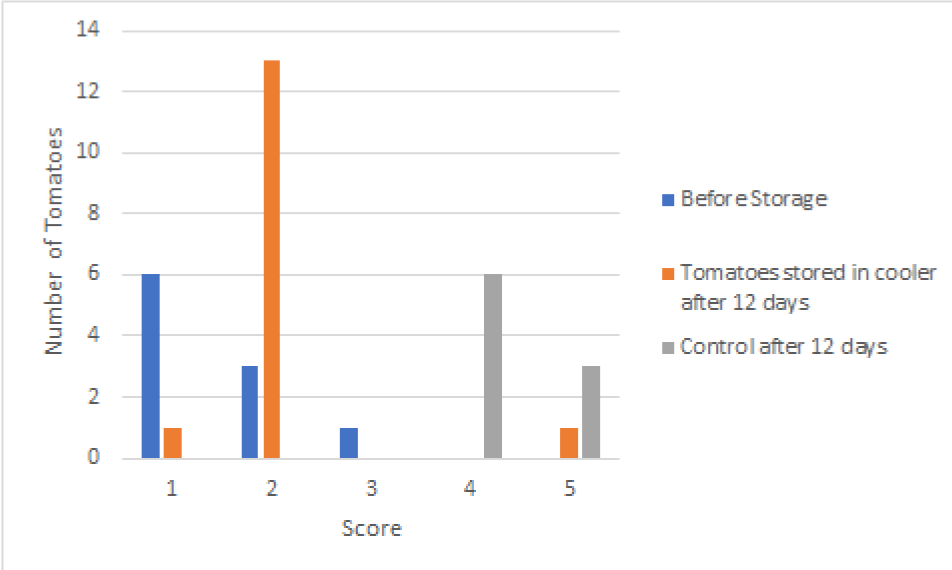

Figure 3. Quality comparison of the tomatoes stored inside and outside of the RCB unit after 12 days

As previously mentioned, 49 tomatoes were stored in the evaporative cooler while 10 tomatoes were placed outside of the cooler in the lab. Out of the tomatoes stored inside of the RCB unit, 15 were evaluated using the hedonic scale. Nine tomatoes of the control were tested. When the quality tests were initially performed, 60% of the tomatoes were given a score of one, meaning they were field quality fresh. After 12 days, 93% of the tomatoes stored in the RCB Evaporative Cooler were still considered *store grade*. In contrast, the tomatoes placed outside of the cooler were of poor quality after the experimental period; 100% of them were not suitable for consumption. In order to understand the performance of the experiment, a chi-squared statistical analysis was conducted. Since the hedonic scale gives discrete values, the chi-squared test was chosen. It was conducted twice: once to compare the quality of the tomatoes stored outside and inside of the cooler, and a second time to compare the quality of tomatoes before and after the 12 storage days. In both tests, the degree of freedom was computed to be four and the probability level was set to 0.05. The first test was conducted to determine whether storing the tomatoes inside the storage system would have a positive impact on their quality - with the following null hypothesis: there is no difference in terms of quality between tomatoes stored inside and tomatoes stored outside of the storage system. The critical chi-squared value obtained was of 9.488 but the computed one was of 3.46×10^{-4} (Appendix E: Table 20). Thus, since the computed chi-squared value was smaller than the critical chi-squared one, the null hypothesis was rejected, and it was concluded that tomatoes stored inside of the storage system were of higher quality; proving the efficiency of the storage system. Overall, the tomatoes outside of the system were very soft, seen by the skin blemishes and wrinkles, and were much easier to bruise than the tomatoes stored in the cooler.

After 12 days of storage, white mold on the sepal and pedicel of the stored tomatoes was present. The growth of spores was not anticipated. After cutting open a few of these tomatoes, very few had major mold infiltration in the fruit. White mold was not present on the sepal and pedicel of the tomatoes placed outside of the RCB unit. The presence of white mold on the stored tomatoes was attributed to the high relative humidity and elevated storage temperature inside the system. Mold growth is favored in warm and humid conditions. Spores are airborne and can spread easily from one fruit to another, especially in closed environments. Although mold can grow at refrigerated temperatures, its growth is reduced at lower temperatures (USDA, 2013). If the temperature of the inner cavity of the chamber was reduced from 19.2℃ to 8℃, mold growth would have been limited. Once the mold was discovered, Dr. Raghavan encouraged the team to store the tomatoes for an extended period to observe how the spores attacked the tomatoes in the cooler in comparison to the control. To prevent the mold from appearing or to limit its spread, the pedicel and sepal could be removed prior to storage. However, this could negatively impact consumer acceptability and this solution is not favored. Furthermore, a small portion of the stored tomatoes had skin blemishes. Physical stress accelerates bruising, respiration rate, and ethylene production which increases fruit ripening rendering the fruit more vulnerable to spore and pathogen attacks. Connolly et al. (2007) found that traditional plastic baskets or crates resulted in larger losses caused by bruising and compression. In lieu of the plastic crate, racks could be installed in the evaporative cooler to encourage air circulation and prevent bruising of the fruit.

4.2.2 Moisture Content Loss of Tomatoes

Fruit and vegetables, such as tomatoes, have a high moisture content. As tomatoes ripen and lose water, they start to wilt. Wilting, skin blemishes, and wrinkles present on fruit impacts consumer acceptability as it affects the organoleptic properties of tomatoes. To determine the quality difference between the stored tomatoes and the controls, before and after storage, the moisture content loss is evaluated using the gravimetric method. Prior to storage, the 10 tomatoes that underwent quality assessment tests weighed on average 251.21g (Appendix D: Table 13).

Since the experiment was terminated, the final weight of both the control and the stored samples is unknown. However, the tomatoes in the storage system were much firmer, leading the team to believe that these tomatoes retained more moisture than the tomatoes outside the cooler.

4.2.3 Colour Change of Tomatoes

Colour is one of the most important quality attributes of fruit and vegetables and largely influences consumer acceptability. The CIE uses the color space coordinates (L*, a*, b*) to describe colour differences, not visible to the human eye. At the start of the experiment, colour measurements were performed on three tomatoes to obtain their L* (lightness value), a* (red-green component), and b* (blue-yellow component) values, which are used to determine color - all three components of the CIELAB color space. Camelo et al. (2004) stated that the ratio a*/b*, and to an extent $(a^*/b^*)^2$, were the best indicators of tomato colour changes. They showed that an increasing amount of the a*/b* ratio was related to a higher percentage of red colour. The results obtained showed the a*/b* ratios ranging from 0.660 to 0.929; results higher than the 0.59 a*/b* ratio obtained by Camelo et al. (2004). This may be caused by differences in maturity levels. The purpose was to perform similar colour measurements at the end of the experiment to determine the changes in tomato colours in order to relate them to the quality of the fruit during storage. As this was not possible, color comparisons were done through visual observations. After the 12 days, the tomatoes left outside of the RCB unit had an orange hue (fig. 4).

Figure 4. Tomato left outside of the storage (left) has an orange hue in comparison to the tomato stored in the RCB unit (right) (Vincent Desaulniers Brousseau, McGill University, personal communication, 18 March 2020)

Lycopene and carotene are two plant pigments responsible for giving tomatoes their red and yellow-orange colours respectively. As ripening occurs, the green pigment known as chlorophyll present in mature-green tomatoes breaks down while the lycopene and carotene pigments increase. The process of ripening is dependent on temperature. The ideal temperature range for tomato ripening is 18℃ to 24℃. Temperatures below or above this range inhibit proper development of carotene and lycopene. Since the controls and the stored tomatoes were subjected to similar ambient temperatures, 19.7℃ and 19.2℃ respectively, it was important to determine why the pigment expressions differed. A possible conclusion is that the tomatoes inside of the RCB Evaporative Cooler were placed in a closed environment which would initiate ethylene production, giving them a redder hue (Albert, n.d.).

4.2.4 Sugar Content of Tomatoes

The sugar content of the sample pool - composed of five different tomatoes - was measured at the beginning of the first week of the experiment. The results were obtained in °Brix. A brix represents the ratio of total soluble solids in a liquid and is often used to measure sweetness of fruits and vegetables. In general, 1°Brix represents 1g of sugar per 100g of solution, such as water. According to the Agriculture Research Service of the US Department of Agriculture, on average, a Roma tomato contains 2.7g of sugar, which represents 2.7°Brix (USDA, 2019). The tomatoes that were used in this experiment, Roma tomatoes from the company *Sunset*, contain around 3g of sugar per 107g of tomato which represents roughly a 3°Brix (Sunset, n.d.). The average sugar content of the tomatoes tested in the laboratory was 3.6°Brix. Although the sugar content was not tested after the storage period, it is assumed that the evaporative cooler helped in preserving the TSS content as the stored tomatoes were much firmer than the controls. Deoraj et al. (2015) showed that tomatoes stored in an evaporative cooler had a lower pH and TSS than tomatoes exhibited to ambient conditions and was even better than refrigeration at preserving key organoleptic attributes, such as acidity and TSS.

5 Conclusion

The non-passive RCB Evaporative Cooler designed for tomatoes in India meets the design criteria and satisfies all safety requirements. Building a non-passive evaporative cooling system made of stainless steel requires a higher budget and experienced assembling skills. An RCB unit uses the principle of evaporative cooling which is a natural process that does not demand excessive energy inputs and only requires locally sourced materials. The experimental data collected shows that the quality of the tomatoes stored in the evaporative cooler was superior. Due to a worldwide pandemic, the experiment was suspended causing major changes to the team's timeline. The experimental data and the design process conclude that the RCB evaporative cooler is a cost-effective and sustainable approach to reduce postharvest losses of tomatoes in Karnataka, India.

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7 Appendix

7.1 Appendix A: Tables and Figures

Table 4. Rates of respiration of tomatoes at different temperatures (Gross et al., 2004)

Commodity	Respiration (mg $kg^{-1}h^{-1}$)					
	0°C	5°C	10°C	15°C	20°C	25°C
Tomato	Nd	Nd	15	22	35	43

Table 5. Storage conditions of tomatoes depending on maturity (Gross et al., 2004)

Maturity	Temperature Range (°C)	Relative Humidity (%)	Storage Life (weeks)
Mature-green	13-21	85-90	5
Ripe	7-10	90	1

Table 6. Pugh Chart

Criteria	Weight Factor	Non-Passive Direct Evaporative Cooling System Powered by Solar Energy		Refrigeration System		Passive Direct Evaporative Cooling	
		Rating	Weighted	Rating	Weighted	Rating	Weighted
Ease of Use	2	1	2	1	2	1	2
Ease of Maintenance	2	1	2	-1	-2	1	2
Capital Cost	3	1	3	-1	-3	1	3
Environmental Impact	1	1	1	-1	-1	1	1
Performance	3	0	0	1	3	-1	-3
Power Consumption	2	1	2	0	0	1	2
Score			10		-1		7

Weight Factor	
1	Normal
2	Very Important
3	Extremely Important

Table 7. Total Experimental Cost

Material	Cost ($)
Dry Sand	28.14
Plastic Tarp	2.99
Red Clay Bricks	199.60
Drip-Watering System with Nozzles	15.99
Masonite + C	14.94
Relative Humidity & Thermometer Sensor	16.99
Sunset Roma Tomatoes	64.00
Total	342.65

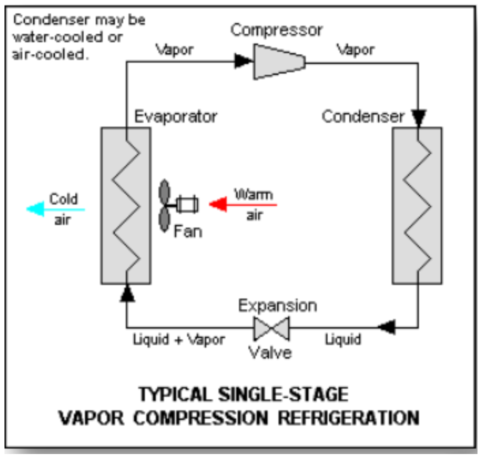

Figure 5. The main components of mechanical refrigeration and their mode of operation

(Raghavan et al., 2019)

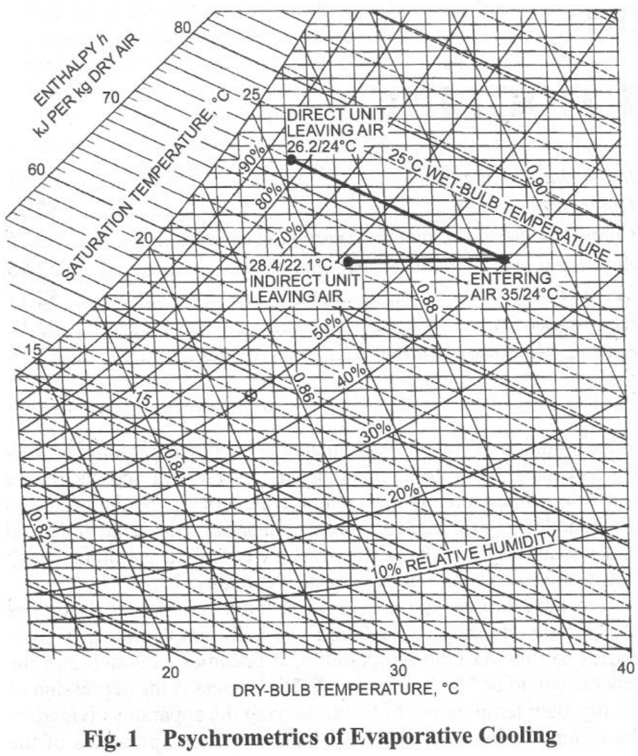

Figure 6. Difference between direct and indirect evaporative cooling (ASHRAE, 2015)

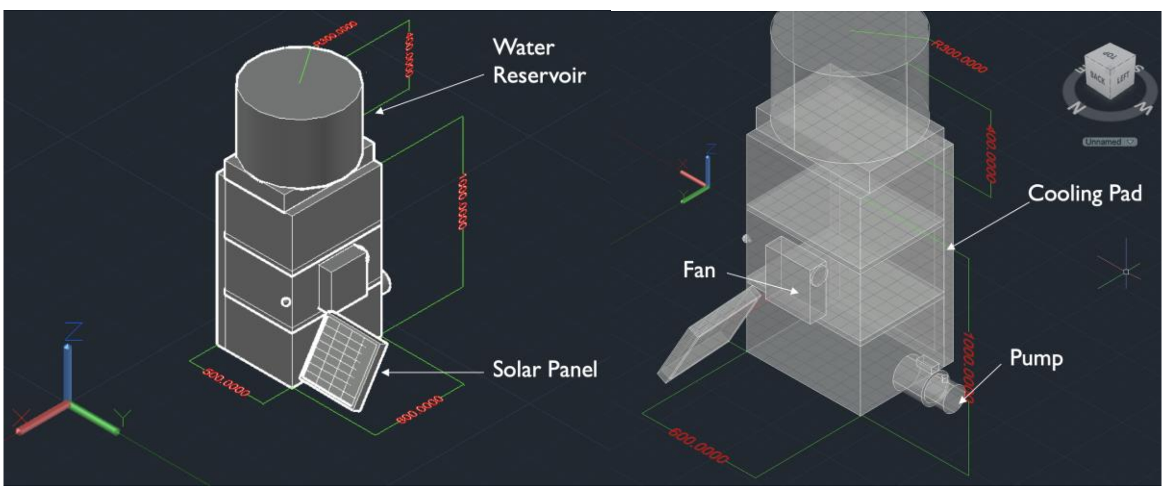

Figure 7. Front and right view of AutoCAD stainless steel prototype using shades of grey view

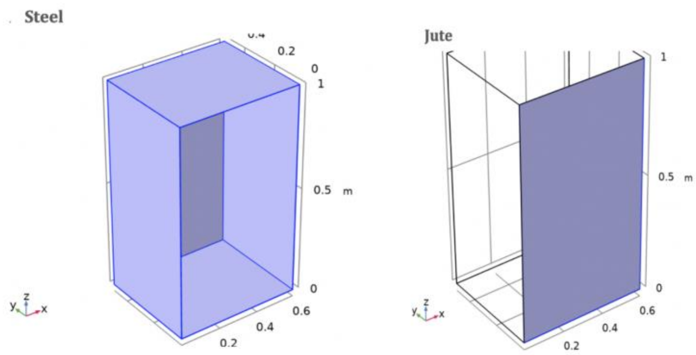

Figure 8. COMSOL geometry used to run stainless steel and jute simulation

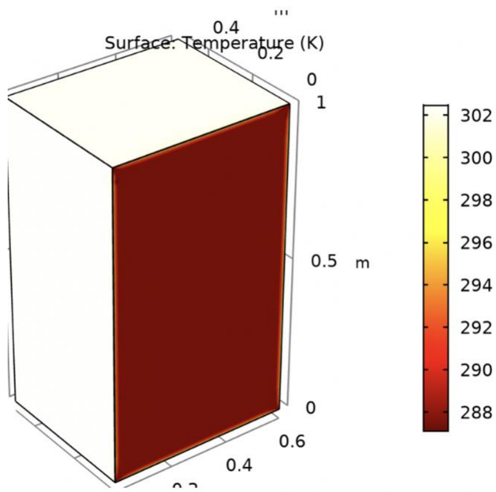

Figure 9. Temperature modelled through jute pad front stainless steel design

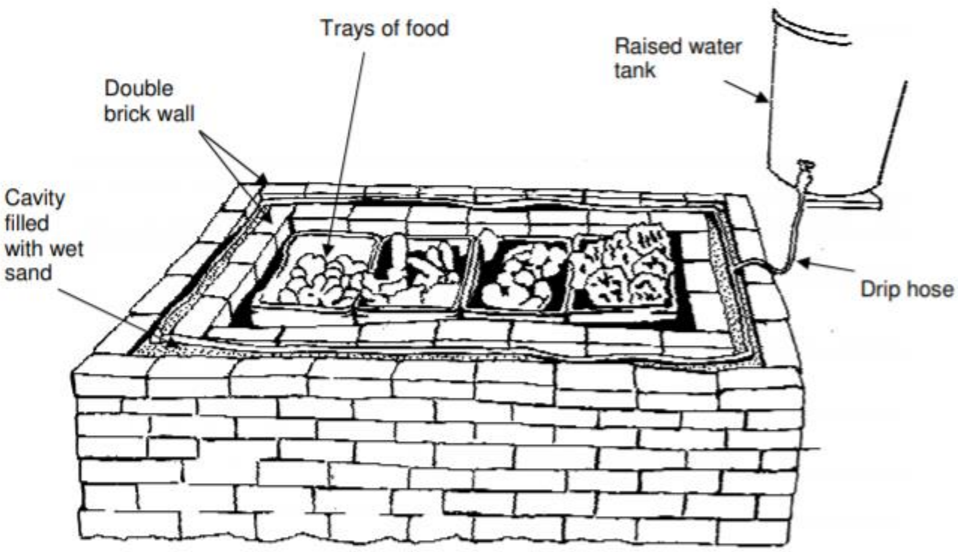

Figure 10. A static cooling chamber by the IARI (Practical Action, n.d.)

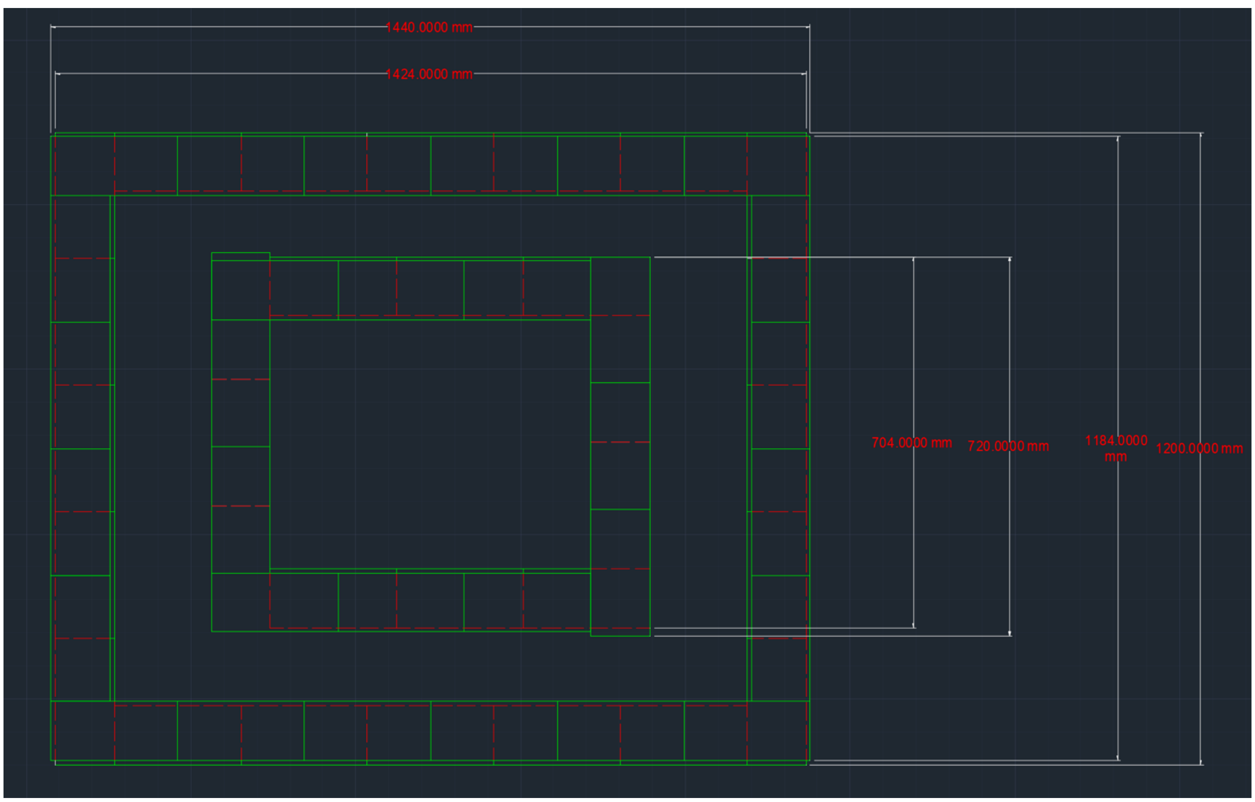

Figure 11. Top view of RCB Evaporative Cooler

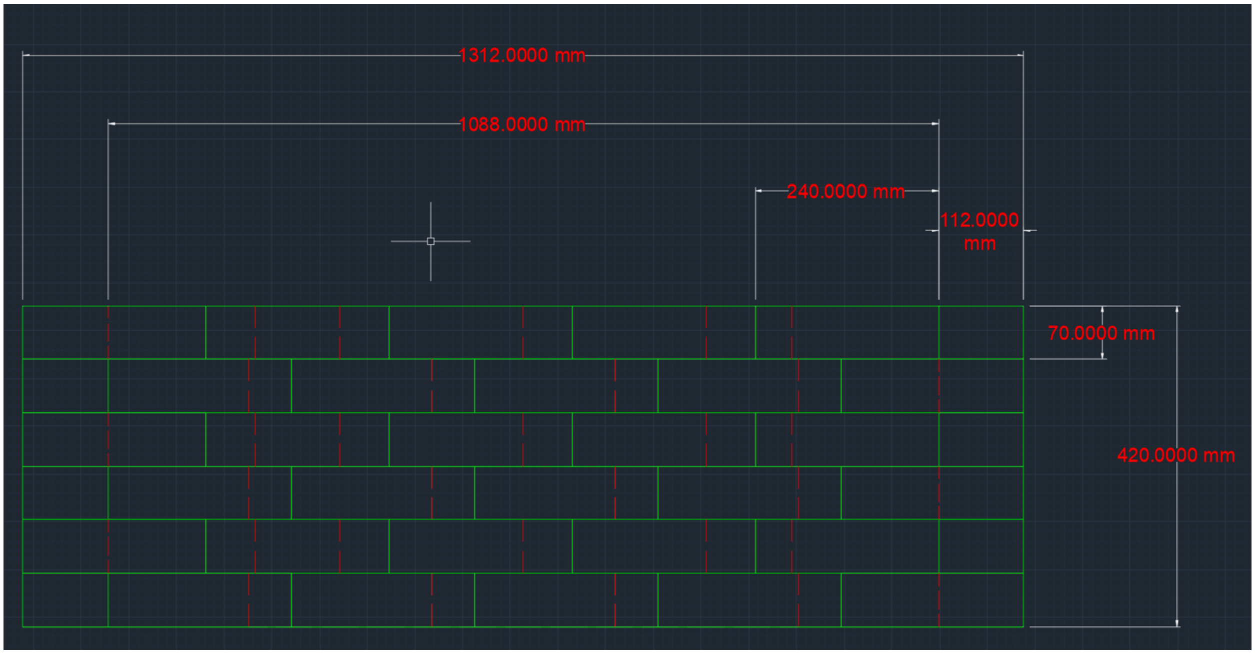

Figure 12. Side view of the RCB Evaporative Cooler

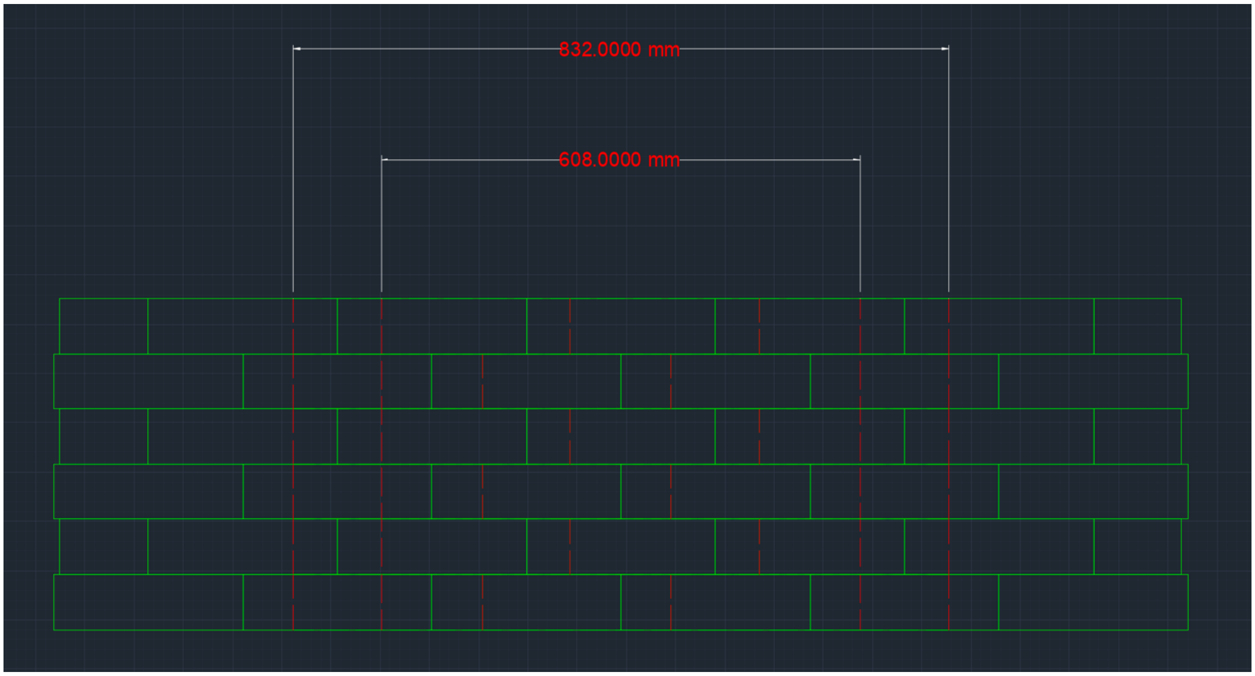

Figure 13. Front view of the RCB Evaporative Cooler

Figure 14. Life Cycle Analysis of the RCB Evaporative Cooler

Figure 15. Initial mass of a Roma tomato

Figure 16. One of the team's members measuring TSS

7.2 Appendix B: Design Prototype Calculations

7.2.1 Passive Direct Evaporative Cooler

7.2.1.1 Area and Volume

- Assumptions:
    - Standard size of brick: 240 mm x 112 mm x 70 mm (ConstructionOr, n.d.)
- Area of the front and rear sides of the storage system (outer brick):

$$A_f = H_f \cdot L_f$$
$$A_f = 0.42m \cdot 1.424m$$
$$A_f = 0.60m^2$$

- Area of the top and bottom sides of the storage system (outer brick):

$$A_t = L_t \cdot W_t$$
$$A_t = 1.424m \cdot 1.184m$$
$$A_t = 1.686\ m^2$$

- Area of the left and right sides of the storage system (outer brick):

$$A_L = H_l \cdot W_l$$
$$A_L = 0.42m \cdot 1.184m$$
$$A_L = 0.50\ m^2$$

- Volume of the storage system (outer brick):

$$V_c = L_c \cdot B_c \cdot H_c$$
$$V_c = 1.424m \cdot 1.184 \cdot 0.42$$
$$V_c = 0.71m^3$$

- Area of the front and rear sides of the storage system (inner cavity):

$$A_f = H_f \cdot L_f$$
$$A_f = 0.42m \cdot 0.832m$$
$$A_f = 0.35\ m^2$$

- Area of the top and bottom sides of the storage system (inner cavity):

$$A_t = L_t \cdot W_t$$
$$A_t = 0.72m \cdot 0.72m$$
$$A_t = 0.52m^2$$

- Area of the left and right sides of the storage system (inner cavity):

$$A_L = H_l \cdot W_l$$
$$A_L = 0.42m \cdot 0.72m$$
$$A_L = 0.30\ m^2$$

- Volume of the storage system (inner cavity):

$$V_c = L_c \cdot B_c \cdot H_c$$
$$V_c = 0.832m \cdot 0.72m \cdot 0.42m$$
$$V_c = 0.25m^3$$

7.2.1.2 Storage Capacity

- Assumptions:
  - Standard plastic crate size: 52.1 cm x 36.5 cm x 30.5 cm (Rapusas et al., 2009)
  - Maximum packing density if the tomatoes are randomly stacked: 65% (Jain, 2014)
  - Tomato diameter: 0.0762 m (Traditional Oven, 2019)
  - Tomato is spherical
- Storage Capacity:

$$Storage\ capacity = \frac{Box\ volume}{Tomato\ volume} \cdot Packing\ density$$

$$Storage\ capacity\ = \frac{l \cdot w \cdot h}{\frac{4}{3} \cdot \pi \cdot r^3} \cdot 0.65\%$$

$$Storage\ capacity\ = 162\ tomatoes$$

7.2.2 Design Calculations for the RCB Evaporative Cooler

7.2.2.1 Total Heat Load

<u>Heat gain by conduction through the walls, roof, and floor of the cooler</u>

- Assumptions:
  - The surface of the outer brick wall has a temperature of 29℃.
  - The surface of the inner brick wall of the inner cavity of the cooler has a temperature of 8℃.
  - The soil temperature of Karnataka is 22℃.
  - To calculate the heat conduction through the floor, only the floor space of the inner cavity of the system is considered for the area.
- Material properties and surface areas:
  - Walls:

Table 8. Thermal resistance of the walls

	k (W/m.K)	A (m^2)
RCB_o	0.59	0.50
Sand	2.9	0.40
RCB_i	0.59	0.35

  - Roof/cover:

Table 9. Thermal resistance of the cover

	k (W/m.K)	A (m^2)
Masonite	0.0476	1.686

  - Floor:

Table 10. Thermal resistance of the flooring

	k (W/m.K)	A (m^2)
Sand	2.9	0.67
RCBi	0.59	0.67

- Thermal resistance:
    - Walls:

$$R_o = \frac{x}{k \cdot A} = \frac{0.112}{0.59 \cdot 0.50} = 0.38 \frac{K}{W}$$

$$R_s = \frac{x}{k \cdot A} = \frac{0.127}{2.9 \cdot 0.40} = 0.11 \frac{K}{W}$$

$$R_i = \frac{x}{k \cdot A} = \frac{0.112}{0.59 \cdot 0.35} = 0.54 \frac{K}{W}$$

    - Roof/cover:

$$R = \frac{x}{k \cdot A} = \frac{0.003175}{0.0476 \cdot 1.686} = 0.0396 \frac{K}{W}$$

    - Floor:

$$R_s = \frac{x}{k \cdot A} = \frac{0.025}{2.9 \cdot 0.67} = 0.013 \frac{K}{W}$$

$$R_i = \frac{x}{k \cdot A} = \frac{0.07}{0.59 \cdot 0.67} = 0.177 \frac{K}{W}$$

- Heat conduction:
    - Walls:

$$Q_{tot} = \frac{\Delta T}{\sum R}$$

$$Q_{tot} = \frac{29 - 8}{0.38 + 0.11 + 0.54}$$

$$Q_{tot} = 20W$$

    - Roof/cover:

$$Q_{tot} = \frac{\Delta T}{R}$$

$$Q_{tot} = \frac{29 - 8}{0.0396}$$

$$Q_{tot} = 530\ W$$

    - Floor:

$$Q_{tot} = \frac{\Delta T}{\sum R}$$

$$Q_{tot} = \frac{22 - 8}{0.013 + 0.177}$$

$$Q_{tot} = 74W$$

Heat of respiration

- Assumptions:
  - Weight of a tomato: 182 g (Hannaone, 2020)
  - The respiration rate of the tomatoes at 8°C is 15 mg CO_2/kg.h (Appendix A: Table 4)
  - Maximum capacity of the plastic crate: 162 tomatoes
- Respiration heat:

$$Q_r = M \cdot RR$$

$$Q_r = 0.182\, kg \cdot 162 \cdot 15 \frac{mg \cdot CO_2}{kg \cdot h} \cdot 10.639 \frac{J}{mg \cdot CO_2}$$

$$Q_r = 4705.2 \frac{J}{h}$$

$$Q_r = 1.3\ W$$

Field heat of the tomatoes

- Assumptions:
  - The tomatoes are stored for a period of 7 days.
  - The plastic crate is filled to maximum capacity.
- Field heat of tomatoes:

$$Q_f = \frac{m \cdot c_p \cdot \Delta T}{t}$$

$$Q_f = \frac{0.182 \cdot 162 \cdot (29 - 8)}{604800}$$

$$Q_f = 4.095 \cdot 10^{-3} W$$

Infiltration of air

- Assumptions:
  - The heat transferred from air infiltration corresponds to 10% of the heat gain from conduction, respiration, and field heat.
- Heat transfer of air through the brick:

$$Q_a = \left(Q_c + Q_r + Q_f \right) \cdot 0.10$$
$$Q_a = \left(530 + 74 + 20 + 1.3 + 4.095 \cdot 10^{-3} \right) \cdot 0.10$$
$$Q_a = 63\ W$$

7.3 Appendix C: Cost Analysis of the RCB Evaporative Cooler

7.3.1 Indian Market Cost-Benefit Breakdown

- Assumptions:
  - The evaporative cooling design targets farmers that produce around one ton of tomatoes per season.
  - Farmers can sell their produce as low as Rs. 3/kg which leaves no profit (Madaan, 2018)
  - According to Indiamart (2019), the potential high cost of tomatoes is Rs. 15/kg
  - According to AgriFarming (2019), the cost of planting one ton of tomatoes is around Rs. 3000 per season
  - Farmers can sell their tomatoes at a profit all the time due to the convenience of having an evaporative cooling system to store the produce
- Cash Inflow at Rs. 3/kg of tomatoes:

$$Tomato\ Value\ per\ season \left(\frac{Rs.3}{kg} \right) = Price \times Kg\ sold\ =\ 3 \times 1,000\ =\ Rs.3,000$$

$$Tomato\ Value\ per\ year = \ Rs.3,000\ \times 3\ =\ Rs.9,000$$

- Cash Inflow at Rs. 15/kg of tomatoes:

$$Tomato\ Profit\ per\ season \left(\frac{Rs.15}{kg} \right) Price \times Kg\ sold\ =\ 15 \times 1,000\ =\ Rs.15,000$$

$$Tomato\ Profit\ per\ year\ Rs.15,000\ \times 3\ =\ Rs.45,000$$

- Cash Inflow Difference:

$$System\ Surplus\ =\ Amount\ gained\ with\ system\ -\ Amount\ gained\ without\ system\ =$$
$$Rs.\ 45,000\ -\ 9,000\ =\ Rs.\ 36,000$$

7.3.2 Cost Analysis of the Stainless Steel Prototype

- Assumptions:
  - The cost of the evaporative cooling system in India made of stainless steel is Rs. 41,000
  - Life span of seven years
- Cost Estimate of the Stainless Steel prototype:

Table 11. Cost Estimate of the Stainless Steel system

Item	Description	Price	Quantity
Fan	Small suction fan 12 volts 0.5 A 118 CFM 120 x 120 x 38 mm	21 CAD	1
Stainless Steel Sheets	4 x 4 feet each New sheets	544 CAD	4
Wet Pad [Hessian]	0.5x1m	14CAD	1
Water Reservoir	Plastic water tank, 120L with faucet	146 CAD	1
Solar Panel	12V Depends on the voltage of the fans	10 CAD	1
PVC Pipe	0.5 inches x 10 ft	9.48 CAD	1
Total		744.48 CAD	

- Payback Period:

$$PP = \frac{Investment}{Annual\ Cash\ Inflow}$$

$$PP = \frac{41,000}{36,000}$$

$$PP = 1.14\ years$$

- Net Present Value:

$$NPV = \sum \frac{Cash\ Flow}{(1+t)^{t}} - Initial\ Investment$$

$$NPV = \frac{36,000}{(1+0.0515)^{1}} + \frac{36,000}{(1+0.0515)^{2}} + \ldots + \frac{36,000}{(1+0.0515)^{7}} - 41,000$$

$$NPV = Rs\ 166,181.78$$

- Return on Investment:

$$ROI = \frac{Net\ Profit}{Total\ Investment} \cdot 100\%$$

$$ROI = \frac{36,000}{41,000} \cdot 100\%$$

$$ROI = 87.8\%$$

7.3.3 Cost Analysis of the RCB Evaporative Cooler

- Assumptions:
  - If the farmer cannot install the system himself, the brick design could be assembled on site. The two and a half hours of labour which is CAD $125. Material costs would be Rs. 25,000
  - The life span of the system is seven years.
- Payback Period:

$$PP = \frac{Investment}{Annual\ Cash\ Inflow}$$

$$PP = \frac{25,000}{36,000}$$

$$PP = 0.70\ years$$

- Net Present Value:

$$NPV = \sum \frac{Cash\ Flow}{(1+t)^{t}} - Initial\ Investment$$

$$NPV = \frac{36,000}{(1+0.0515)^{1}} + \frac{36,000}{(1+0.0515)^{2}} + \ldots + \frac{36,000}{(1+0.0515)^{7}} - 25,000$$

$$NPV = Rs\ 182,181.78$$

- Return on Investment:

$$ROI = \frac{Net\ Profit}{Total\ Investment} \cdot 100\%$$

$$ROI = \frac{36,000}{25,000} \cdot 100\%$$

$$ROI = 144\%$$

7.3.4 Cost Analysis Comparison between the Stainless Steel & RCB Unit

Table 12. Cost Analysis between the two designs

	Stainless Steel	Brick
Payback Period (years)	1.14	0.70
Net Present Value (Rs.)	166,181.78	182,181.78
Return on Investment (%)	87.8	144

7.4 Appendix D: Laboratory Worksheet

Table 13. Weight of Samples

Weight of samples	
Sample 1 (grams)	**Sample 2 (grams)**
252.82	247.37
258.61	251.67
251.65	250.9
246.64	253.58
240.34	258.52
Average=**250.012**	Average=**252.408**

Table 14. Initial Quality Test

Quality Test (score 1 to 5)	
Units	Score (1 to 5)
6	1
3	2
1	3

Table 15. Initial Sugar Content

Sugar Content (°Brix)
3.6
3.2
3.9
3.7
3.6

Table 16. Initial Colour Tests of Multiple Samples

Colour		
Sample 1		
L*	**a***	**B***
41.8	17.54	20.27
39.22	17.02	18.33
41.41	19.31	22.07
Sample 2		
L*	**a***	**b***
41.84	16.88	19.99
43.17	10.55	20.6
42.82	14.16	21.47
Sample 3		
L*	**a***	**b***
40.94	15.55	18.48
42.39	19.27	22.26
39.64	16.41	22.2

7.5 Appendix E: Results

7.5.1 Heat Load

Heat gain by conduction through the walls, roof, and floor of the cooler

- Assumptions:
  - Ambient room laboratory temperature is 19.7℃.
  - The temperature in the inner cavity of the system is 19.2℃.
  - Heat conduction through the floor is null.
- Heat conduction:
  - Walls:

$$Q_{tot} = \frac{\Delta T}{\sum R}$$

$$Q_{tot} = \frac{19.7 - 19.2}{0.38 + 0.11 + 0.54}$$

$$Q_{tot} = 4.85 \times 10^{-1} W$$

  - Roof/cover:

$$Q_{tot} = \frac{\Delta T}{R}$$

$$Q_{tot} = \frac{19.7 - 19.2}{0.0396}$$

$$Q_{tot} = 12.6\ W$$

<u>Heat of respiration</u>

- Assumptions:
  - Weight of a tomato: 251.21 g
  - The respiration rate of the tomatoes at 19℃ is 35 mg CO_2/kg.h (Appendix A: Table 4)
  - 49 tomatoes were stored
- Respiration heat:

$$Q_r = M \cdot RR$$

$$Q_r = 0.25121\ kg \cdot 49 \cdot 35 \frac{mg \cdot CO_2}{kg \cdot h} \cdot 10.639 \frac{J}{mg \cdot CO_2}$$

$$Q_r = 4583.55 \frac{J}{h}$$

$$Q_r = 1.27\ W$$

<u>Infiltration of air</u>

- Assumptions:
  - The heat transferred from air infiltration corresponds to 10% of the heat gain from conduction, respiration, and field heat.
- Heat transfer of air through the brick:

$$Q_a = \left(Q_c + Q_r + Q_f\right) \cdot 0.10$$

$$Q_a = \left(4.85 \times 10^{-1} + 12.6 + 1.27\right) \cdot 0.10$$

$$Q_a = 1.44\ W$$

7.5.2 Statistical Analysis (Chi-Squared Test) on Quality Difference

Table 17. Observed values

Observed Units	1	2	3	4	5	Total
Outside	1	13	0	0	1	15
Inside	0	0	0	6	3	9
Totals	1	13	0	6	4	24

Table 18. Expected value

Expected Units	1	2	3	4	5	Total
Outside	0.625	8.125	N/A	3.75	2.5	15
Inside	0.375	4.875	N/A	2.25	1.5	9
Totals	1	13	N/A	6	4	24

Table 19. Chi-Square points

Chi-Square Points	1	2	3	4	5
Outside	0.225	2.925	N/A	3.75	0.9
Inside	0.375	4.875	N/A	6.25	1.5

Table 20. Obtained results

Chi-square	20.8
Critical value of chi-square	9.487729037
Tabulated Chi-squared value	0.00034693