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Design, Fabrication and Evaluation of Evaporative Cooling System for the Storage of Fruits and Vegetables

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Abstract:** Due to inadequate post-harvest storage facilities, post-harvest losses of horticultural crops (fruits, vegetables, and flowers) are quite high in Ethiopia. The loss has a detrimental effect on societal welfare, economic growth, and food security. A prototype of an evaporative cooling system was designed, built, and evaluated for its efficacy in the short-term storage of tomatoes in order to overcome these issues and decrease the perishability of the most economically viable crops. Technical advancements and reorganizations were made to the evaporative cooling system's architecture to make maintenance, operation, and handling easier. The design combines an indirect and direct evaporative cooling system to store horticulture products in a variety of locations with different environmental conditions. The cooler is portable and can hold 260 kg, which is the ideal amount of food for Ethiopia's majority of small-scale horticulture distributors. Temperatures dropped 9.6°C and 10.3°C, respectively, at a cabinet relative humidity of 85%, compared to traditional cooling systems. Tomatoes were the subject of a storage trial to compare its efficacy to the conventional method of merchant display in the open market for six days. The cooler used half as much energy as a normal vapour compression refrigerator with roughly the same amount of storage. It is found that integrated evaporative cooling systems may perform better in the majority of climatic situations.

***Keywords:** Post-Harvest, Horticultural Crops, Ethiopia, System, Cooling.*

1. INTRODUCTION

Ethiopia's economy is based largely on agriculture. Small-scale agriculture is the primary source of income for more than 85% of the population. Ethiopia's horticultural sector has been growing recently. The growing horticulture industry produces a lot of jobs and can help the rural economy become more commercialized. However, poor post-harvest technology, such as storage facilities, result in 50% of horticulture crops being lost after harvest[1] .

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The chain of distribution for food must include the cold storage. Perishable goods are kept from spoiling and are made available during the off-season and in areas where the crops are not yet harvested. It is crucial for maintaining produce quality, increasing the shelf-life of perishable goods, ensuring a consistent supply to the market, preventing surpluses, post-harvest losses, and minimizing traffic jams during periods of peak output. Therefore, it is essential that cold storage facilities be built in significant production and consuming hubs. Perishable goods are produced and consumed in direct relation to cold storage. In this sense, the development of cold storage in Ethiopia plays a significant role in lowering the amount of fruits and vegetables that are wasted, paying the growers fairly, and making farm products accessible to consumers at a reasonable cost.[2]

A variety of technologies are used in modern cold storage units to control the temperature and humidity. A typical refrigeration unit utilizing chemicals as coolant is what is used in conventional refrigeration technology. A compressor, condenser, expansion valve, and an evaporator filled with refrigerant make up this entire industrial refrigeration equipment[3]. Although more expensive, this is more effective at regulating humidity and temperature in storage units. Using evaporative cooling technology, it is still possible to keep the environment cool without a secondary refrigeration system.

The heat from a hot fluid can be successfully removed using an evaporative cooling system. Products that are sensitive to chilling are best suited for such a cooling system. It is economically feasible for Ethiopia's small- scale farmers and sellers because to its low initial cost and capacity to be constructed using materials found locally.

Because water is used as the refrigerant, it is pollution-free and environmentally benign. It is also advantageous to employ small solar panels in locations without access to electricity.

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2. MATERIALS AND METHODS

Illustration of the Research Activities Using Engineering Model

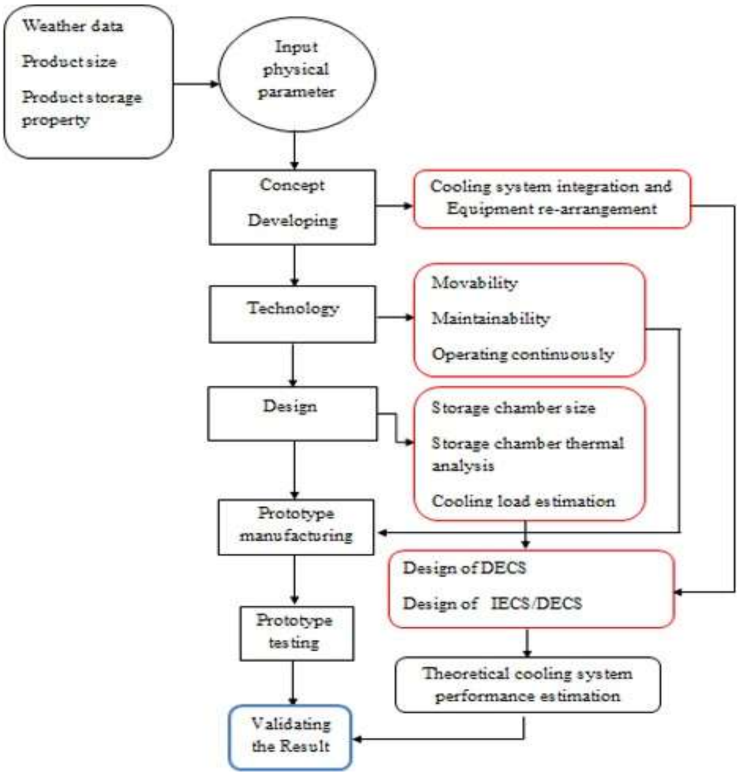

Figure 1.

Experiment Setup for product Load test

To assess the effectiveness of the evaporative cooler in comparison to the traditional practice of storing tomatoes outdoors, a storage experiment was conducted. The fresh tomatoes were purchased at the neighbourhood market in Addisabeba. Total tomatoes weighing 16 kg were purchased, and they were then randomly divided into 8 groups (figure 2). Then, four of the groups were placed on the evaporative cooler's shelves. There could be changes in the temperature and relative humidity among the four cabinet shelves. The tomatoes were doubled up on each of the four shelves of the cabinet to lessen the possibility of an uncontrolled error (figure 3). The four tomato groups were arranged on a basket for a control group (figure 5) to resemble the conventional method of keeping tomatoes that merchants use to show tomatoes for sale (figure 4).

They were compared with the control group in terms of the duration of storage, the tomatoes' shelf life within the cooler, and their weight loss. At the time of storage, the weight and quantity of tomatoes were noted. After that, a two-day interval was used to measure the weight decrease. Additionally, the quantity of spoiled and damaged tomatoes was counted.

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Figure 2. Tomatoes randomly assigned in to 8 groups

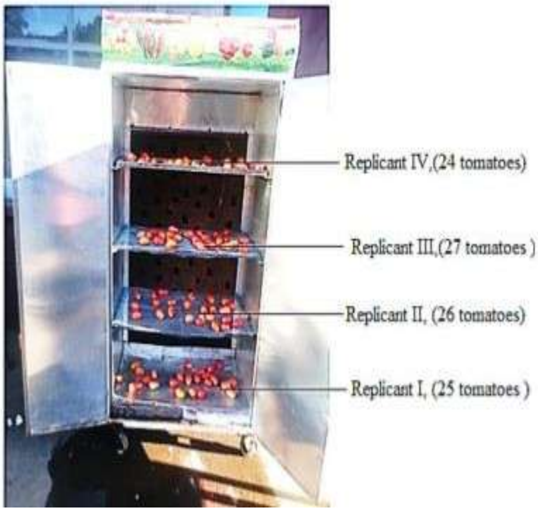

Figure 3. Experimental group of tomatoes stored inside the Shelves of evaporative cooler

Figure 4. Traditional practice of tomatoes displaying on the market

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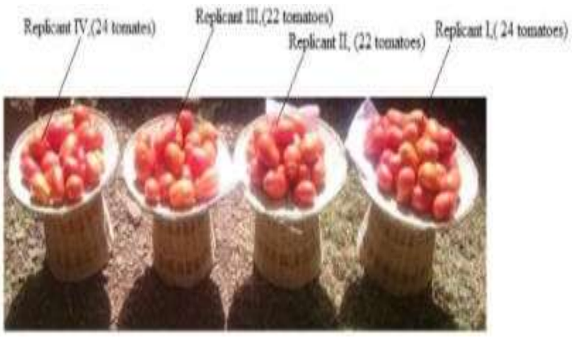


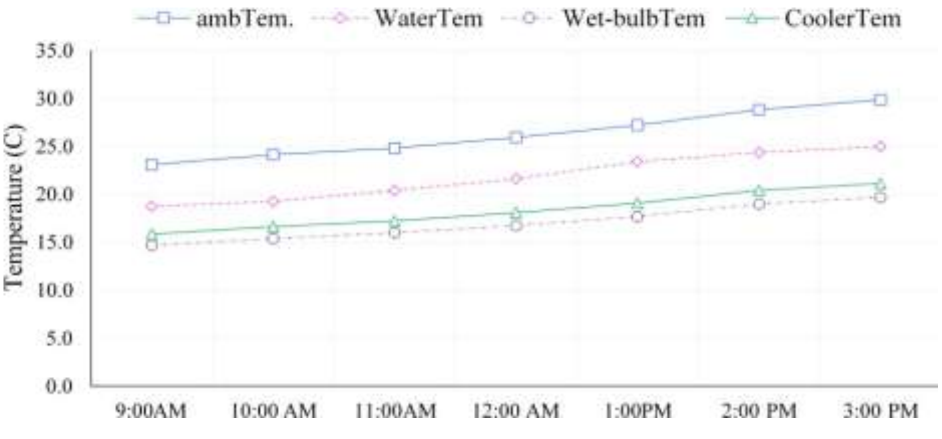
Figure 5. Control group of tomatoes displayed in a traditional way

3. RESULTS AND DISCUSSION

Evaluating the performance of the evaporative cooler without loading products

For five days, from August 1 to August 5, 2021, the evaporative cooling system's effectiveness was assessed without loading the product inside the storage chamber. Data was gathered at 1-hour intervals while the equipment and performance evaluation were read from 9:00am to 3:00pm.

The weather station equipment was predicting that the ambient temperature and relative humidity would continue to rise over time as the evaporative cooler started up at the same time the cooling system's effectiveness was being assessed. While the equipment on the cabinet side was forecasting that the relative humidity inside the cabinet was rising and the temperature inside the cabinet was expected to drop for a few minutes before reaching its attainable low temperature.



Time of the day (hr)

Figure 6. Variation of cabinet temperature with ambient, water from the tank and wet bulb temperature

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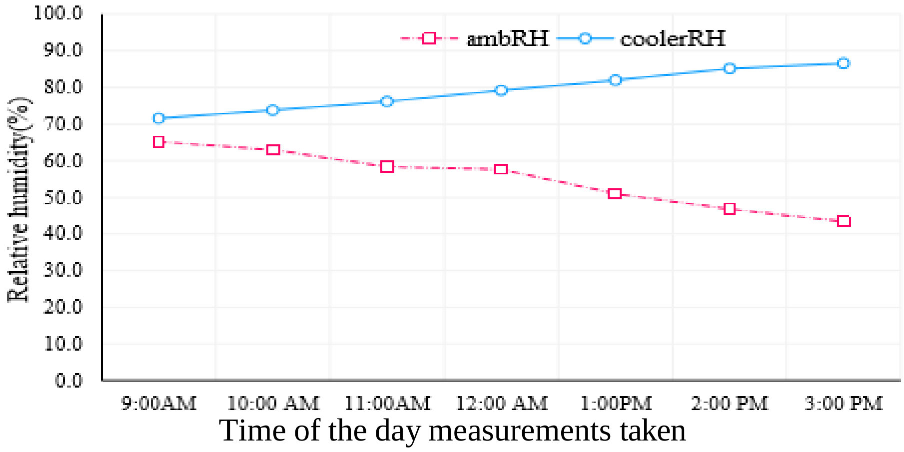

Figure 7. Variation of ambient and storage cabinet relative humidity

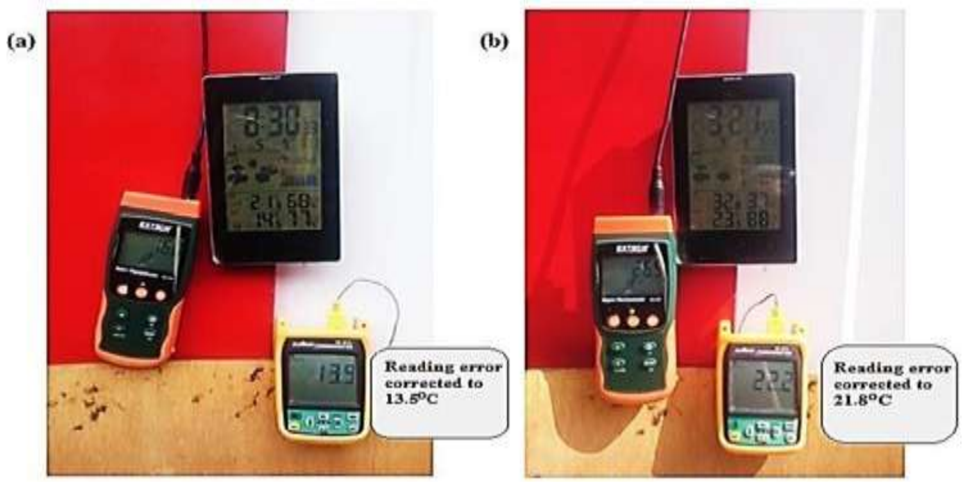

Figure 8. The maximum and minimum temperature drop reading in two different days

The tests were run for five days, and the results are displayed on the graph in (figures 6 and 9). Ambient circumstances were used as a reference to compare the first three data points with the cabinet conditions. Every time interval showed an increase in the ambient temperature, and every interval also showed an increase in the cabinet temperature relative to the ambient temperature with a minor increase in temperature drop. The rate of evaporation will be assisted by the moist surface. Therefore, it was assumed that the temperature decrease on the cabinet side would grow as the ambient temperature rises. The fact that the wet- bulb temperature and cabinet temperature were near to one another shows that the insulation of the cabinet wall was preventing heat gain from the surrounding environment and that the storage cabinet was under control (figure 6). Due to the ambient temperature's warmth facilitating the rate of evaporation from the soaked jute pad, the relative humidity increased with time (figure 7) and ambient temperature (figure 6).
Calculating from equation, the real evaporative cooling system's cooling capacity, coefficient

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of performance (COP), and effectiveness of the evaporative cooler were assessed (6, 7 and 8).

$QC = \dot{m}_a \times Cp \times (T_{db1} - T_{db2})$ 1

COP= $\frac{cooling\ capacity}{}$

…………………………………………………….2

$(fan\ power + pump\ power)$

$\eta = ^{Tdb1 - Tdb2}$…………………………………………………………………………….3
$Tdb1 - Twb2$

The evaporative cooler's main cooling capacity for five days was between 1572.74 and 1866.32 watts (figure 9), and the highest cooling capacity ever recorded was 1887.2W. The main performance coefficient ranged from 3.76 to 4.46 (figure 9), with the highest coefficient of performance at a specific period of 32°C being

1. 51. (figure 8).

As the time was shifting and the ambient temperature rose, the cooler's saturation efficiency decreased. Due to the fact that the water flow rate over the jute surface remained constant throughout the day, the rate of evaporation from the jute surface will be aided when the ambient temperature rises, and the moistening water size was insufficient to cover the full jute surface. The main cause of the lower saturation efficiency is the low water flow rate per m^3 of cooled air [33]. Figure 10 clearly demonstrates that the rate of evaporation was accelerated by the ambient temperature difference as cooling capacity increased, going from 86.2 to 86.5 to 85.5 at the same time that saturation efficiency increased.

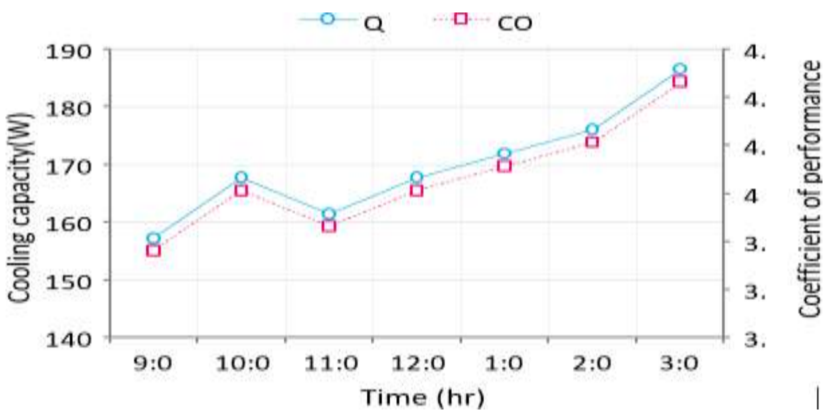

Figure 9: Timely variation of the cooling capacity and coefficient of performance of the cooler

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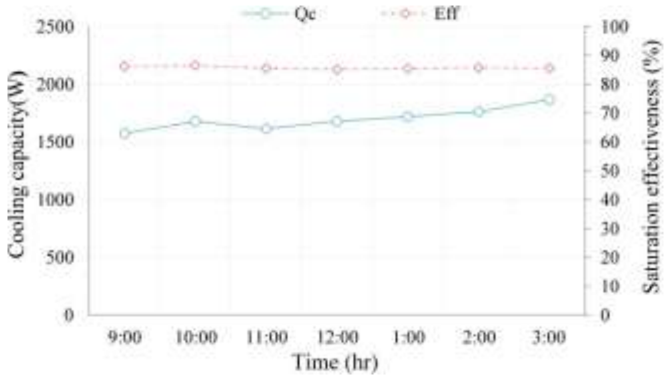

Figure 10: Timely variation of cooling capacity of the cooler Vs the cooling effectiveness of the evaporative cooler

Validation of analytical results with actual test results

The theoretical result of the evaporative cooling system related with phychromrtric analysis was compared and validated with the actual prototype test of the evaporative cooler at the same environmental conditions.

Table 1. Validation of theoretical results with the actual prototype test result

Physical quantities and performance parameters	Theoretical design results	Actual test results	Error(%)
	Two stage/DECS	Two stage/DECS	
Ambient temperature(Tdb1)	Specified 32°C	Measured 32°C	--
Ambient relative humidity (Ø1)	Specified 34%	Measured 37%	--
Wet bulb temperature (Tdb2)	Calculated 20.23	Measured 21.5	+6.27
Storage cabinet relative humidity(Ø2)	Specified 85%	Measured 88%	+3.52
Storage cabinet temperature (Twb2)	Specified 21.7	Measured 23	+5.99
Saturation effectiveness (η)	Specified 87%	Calculated 85%	−2.29
Cooling capacity (Qc)	2016 W	1887.2W	−6.42
COP	4.82	4.51	−6.42

There are some situations that were affecting the performance of the actual prototype result from the theoretical conditions. The cleanness of the water and the dust from the jute materials affects the rate of evaporation from the jute surface. The overlapping of the jute

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layer may prevent the cold air passing to the cabinet. Ambient temperature may get in to the storage chamber constantly through some spaces of the side cover and in between jute pad holder and storage cabinet.

Evaluating the effectiveness of the evaporative cooler by product load test
Tomatoes were loaded to test the effectiveness of the evaporative cooler for short-term storage of vegetables and fruits. The cooler significantly extend the shelf life of tomatoes and preserve the quality compared to tomatoes stored in a traditional way in ambient condition. The percentage of tomatoes spoiled over the storage period increased rapidly and reach about 80% after six days of storage in the ambient condition, whereas the spoilage on tomatoes stored in the cooler. Were about 5% after six days of storage (figure 11). In other words, the percentage of fresh tomatoes that can be marketable after six days of storage in the cooler was 95% and that of the ambient condition was only 20% (figure 12). The weight of tomatoes reduced from on average from 2010g to 1510 that is 500g in six days' storage time, whereas tomatoes stored in the cooler reduced in weight from 2002g to 1903g that is about 100g only after six days of storage (figure 13).
The main causes of spoilage were related to exposure to improper temperature and relative humidity, which resulted in shrivelling, moisture loss (dehydration), excessive softening, increased rate of respiration and susceptibility to decay (figure 14 photos C and D). Tomatoes that show shriving and sign of decay have a very serious defect, which render it unmarketable. Evaporative cooler offers adequate protection from unfavourable climatic conditions and extends the shelf life of tomatoes, whereas the traditional method of storing tomatoes did not protect tomatoes from the adverse conditions and cause significant post-harvest losses.

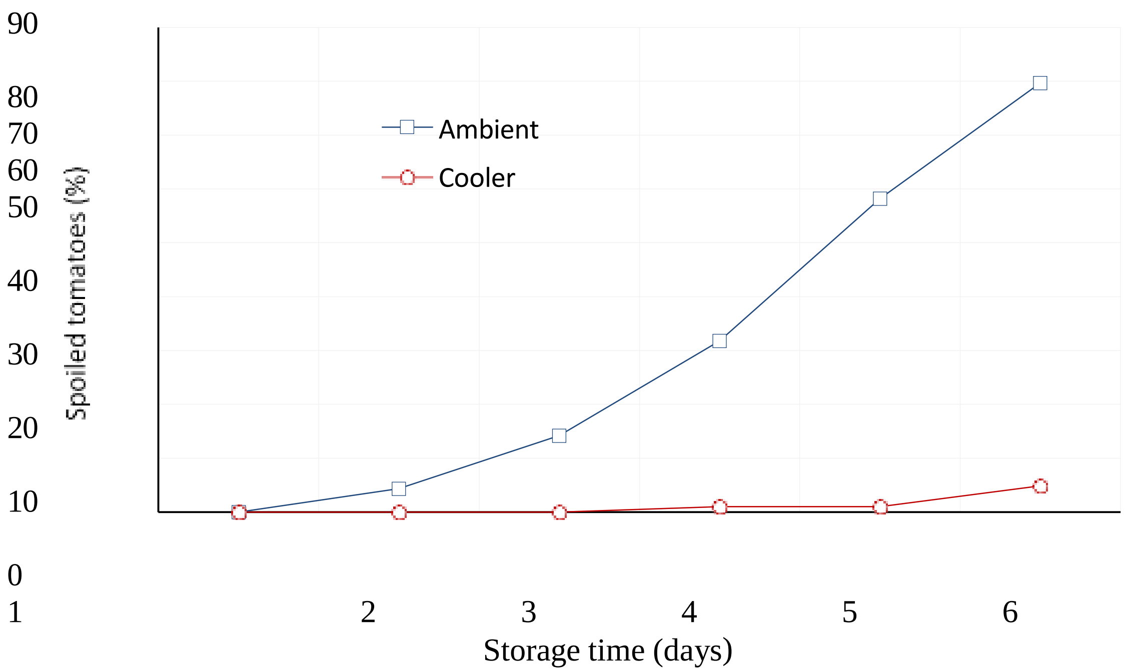

Figure 11: Percentage of spoiled tomatoes over six days of storage in the cooler and ambient conditions

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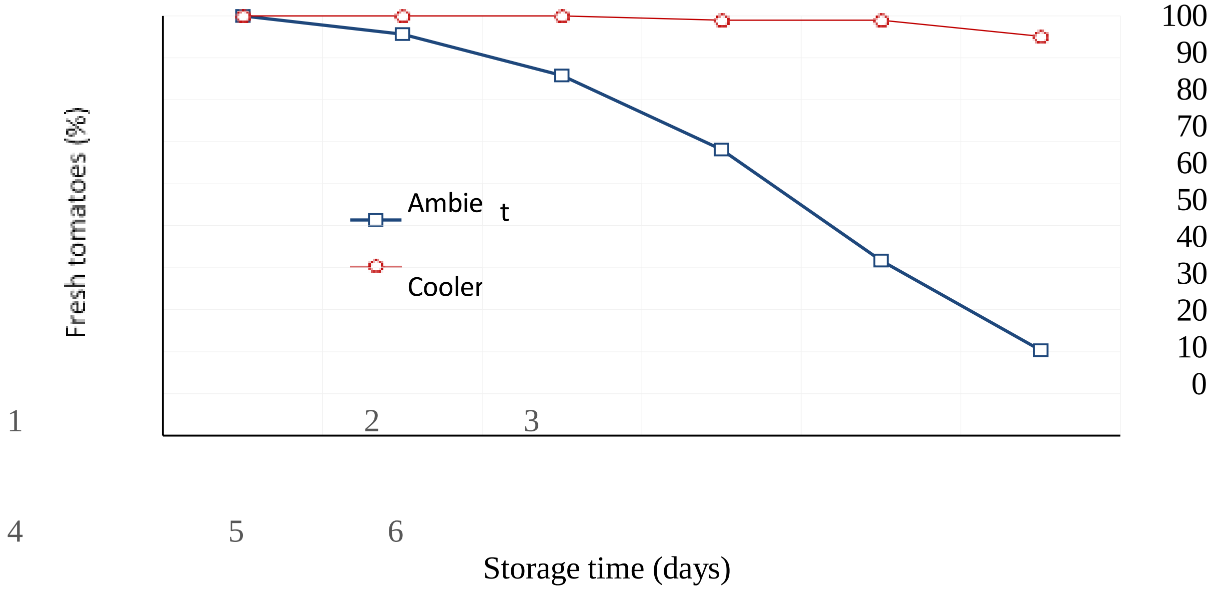

Figure 12: A reduction in fresh tomatoes over six days of storage in the cooler and ambient condition

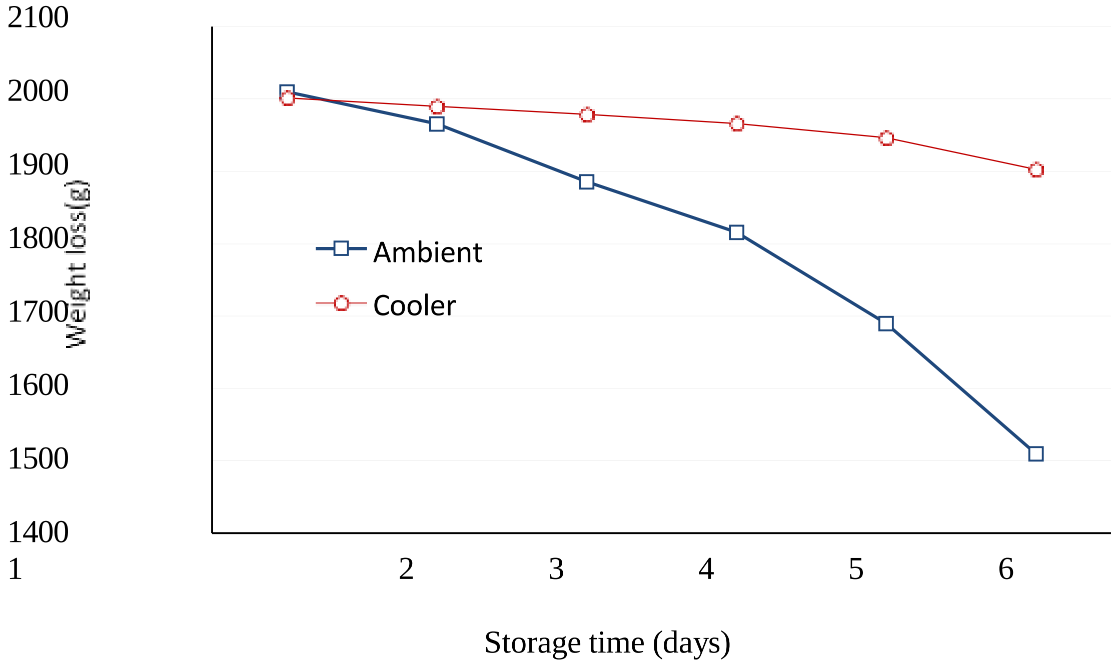

Figure 13: Weight loss of tomatoes over six days of storage in the cooler and ambient conditions

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Tomato quality component includes colour, size, freedom from defects and decay, firmness, which can be change and affected by post-harvest handling. The quality of the tomatoes stored in the ambient condition was seriously affected (figure 14 Photo C and D). In addition, there is loss in nutritional value, market opportunity and possible adverse effect on health of consumers due to consumption of poor quality tomatoes. Tomatoes subjected to bruising and decay has less tomato like flavour and more off-flavour than those without decay. Tomatoes stored in the traditional way become softer (less firm) day after day.

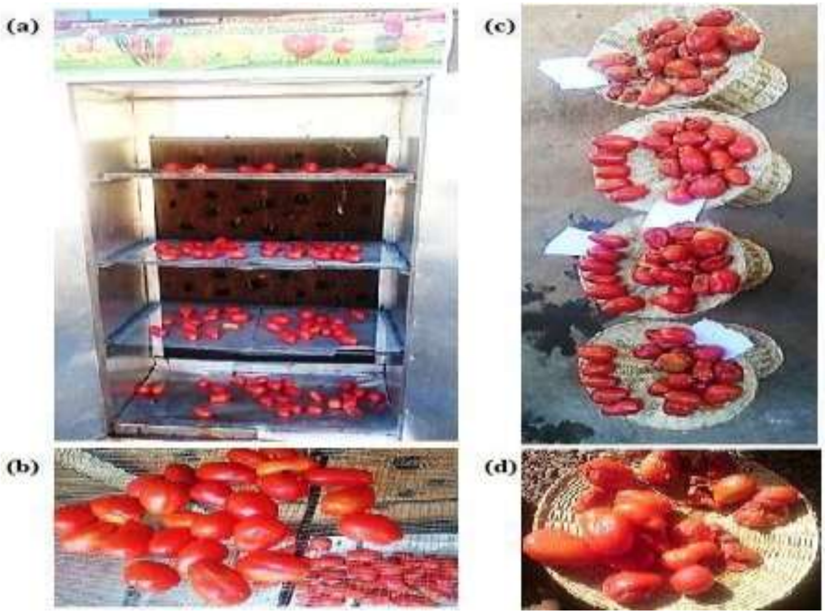

Figure 14: Tomatoes stored in the cooler (a, and b) and tomatoes stored in the ambient condition (c, and d)

Comparison of the current work with some existing evaporative coolers

After the optimal condition of the cooling system was investigated, the current work was compared with some existing evaporative cooler in overall advantages and to the (VPR) of commercial restaurant refrigerator of same size.

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Table4. 2: List of some existing evaporative cooler with the comparators to the current work

Comparator	An evaporative cooler for vegetable crops [4]	Evaporative cooler (Dilijohn,2010)	Development of Evaporative cooling system [5]	An evaporative cooler for the storage of fruits and vegetables (current work 2021)
Power conception (K w)	1.620	0.06	0.436	0.418
Speed of Fan(m^3/s)	0.19-0.28	0.00273	Three identical fans $0.5m^3/s$	Two fans (0.09)
Storage capacity	272 kg produce can be stored in the storage chamber in 1 to 2 hrs.	3Kg of produce can be stored in the chamber	$0.24m^3$	260 Kg (bulk density) of produce can Be stored in 50% of the storage volume
Type of cooling pad	Aspen fiber	-Cedar -Teak	Palm fruit fiber	Jute
Area of Cooling pad(m^2)	0.743	0.0103	Not specified	$1.5m^2$
Weight(kg)	Not specified	Not specified	Not specified	124.8Kg
Dimension (W×D×H)m	Not specified	0.508×0.483 ×0.854	Not specified	1×0.6×1.7
Operational assessment of the device	The device verified the effectiveness of the evaporative cooler by testing various produces by varying	The maximum efficiency was determined at an average temperature drop of 6.1°C, relative	Provides storage conditions of 23.2°C with 96.8% relative humidity at the ambient	Provides a temperature drop of 6.8 -9.3°C from the ambient of 21.8 32.8°C. With cabinet RH of 77%-88%. COP=4.5, it is better
	several parameters.	humidity as 24.3% and	condition of 37°C.	in its movability and maintainability.

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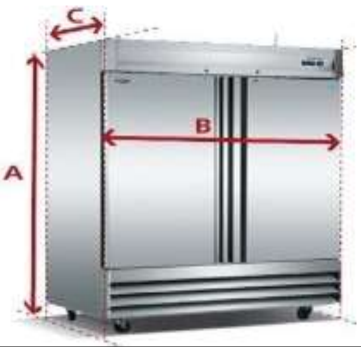
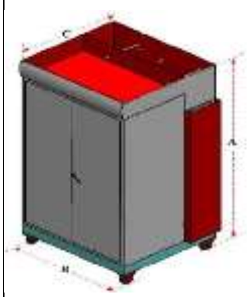
Table3: Comparison of equivalent storage size commercial vapour compression refrigerator with evaporative cooler

Commercial supermarket refrigerator (VCR)	Evaporative cooler for fruits and vegetable preservation
	
Size :A=2095mm, B= 1391mm, C=818mm	Size: A=2010mm,B=1000mm,C=905mm
Gross storage capacity =1321L=1.32m^3	Gross storage capacity =1020L = 1.02m^3
Gross weight =247kg	Gross weight = 124.8Kg
Refrigrant type R134 a	No refrigeration effect, and no refrigerants used, water used for moistening the pad.
Compressor power =835W	Fan and pump power=418W
Cooling temperature range from 1°C to 6°C	Lowers the ambient temperature range 32°C-22°C to the cabinet temperature range 23°C to 14.5°C respectively
Expensive purchasing cost to the local small scale distributers and farmers	Small initial cost of construction to the local small scale distributers and farmers

4. CONCLUSION

In general, evaporative cooling system can be used as a storage system with a significant slowdown of the deterioration process of some vegetables and fruits, thus making possible gain in terms of shelf life and marketing periods with a small initial coast of construction and negligible power consumption rate to the most developing countries like Ethiopia. Direct evaporative cooling systems and integrated evaporative cooling system was designed with some re-arrangement of equipment's and adding extra technical improvements from the previous related works on this area. The analytical and experimental result was Evaluated to both direct evaporative cooling system and integrated evaporative cooling system. The analytical result of integrated evaporative cooling system has a negligible difference from direct evaporative cooling system to the desired current optimum ambient

Conditions. However, integrated evaporative cooling system might have a chance to pre-cool the air and enhances the performance of the cooling system in hottest and arid low land areas of Ethiopian regions, more specifically in afar and south east of Ethiopian regions with the ambient conditions from 35℃ to 42℃. The current type of integrated evaporative cooling system might also be used with a better performance, if there is a possibility and interest of customer to supply chilled water to the lowest water tanker continuously. Direct evaporative cooling system is also feasible to use in most moderate temperature regions with a reduced cost from the previous type by removing the indirect evaporative cooling system.

Although the evaporative cooler showed significant effect in extending the shelf life of tomatoes and maintaining the quality for short term, additional research and effort is needed to develop a long-term storage system to reduce the post-harvest loss and waste of vegetables and fruits in Ethiopia. Proper temperature and humidity control is critical to quality and shelf life of fruits and vegetables. Further work is needed to improve the performance of the evaporative cooler. Including some additional futures and improvements which is suggested and recommended in the current research paper, the cooling system might give a wide range application to the distributers, retailers and small scale farmers.

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