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Sustainable cooling solutions: Designing a zero-energy chamber with local materials in Eritrea

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Abstract

Tomatoes are one of the most widely consumed vegetables globally, yet they are also among the most perishable agricultural products, resulting in significant losses. In Eritrea, a low-income country, tomatoes hold great importance as a vital vegetable crop. To prolong the shelf life of tomatoes and other vegetables, controlled storage conditions, including temperature and humidity management, are essential. However, many small-scale farmers in Eritrea cannot afford expensive storage equipment for their harvested crops. This research aims to address this challenge by exploring the use of a zero-energy cooling chamber to extend the shelf life of raw tomatoes. The cooling achieved by this chamber also results in getting high relative humidity of the air in the cooling chamber from which the evaporation takes place relative to ambient air. A four side rectangular storage with total 0.175 cubic meter capacity, made of bricks; fine bed river sand, jute pad, PVC pipe having 16mm nominal diameter and it is reshaped in to square shape the edges connected by elbow connector placed at the upper center of cavity for keeping wet the sand with dimension of 78 x 78cm, a water tank with capacity of 20 litres connected to perforated PVC pipe for supplying water to the system. Results of the transient performance tests revealed that the zero energy cooling chamber storage temperature varied from ambient temperature by 17-20 ^{o}C. The environmental temperature at the period of test ranged over 25-32 ^{o}C. After construction of the structure, two stages (red and green mature) of sanmarzano variety tomato were tested. Data at 1, 5, 8,11,23,28 days was recorded and evaluated for firmness, color, general observation, and weight loss. As a result, those stored outside the chamber in ambient environment was in poor state and stayed only for 8 days in case of red tomatoes and 11 days in case of green mature tomato respectively, whereas tomato stored inside ZECC remained fresh at 23 and 28 days red ripe and green mature respectively.

Keywords: Tomato; Evaporative cooler; Highly perishable; Firmness

1. Introduction

Energy is integral to almost every aspect of modern life. It is used for transportation, communication, industrial and domestic purposes like heating, cooling, cooking, and lighting as well as other appliances for both economic growth and technological advancements of a country. For example, energy in the agricultural sector maintains the freshness of fruits and vegetables during storage; moreover, in irrigation and machinery aspect it plays an important role. There are different types of cooling systems available such as Conventional Vapor Compression Cooling Systems that use Chlorofluorocarbons (CFCs), Hydro chlorofluorocarbons (HCFCs), and Hydrofluorocarbons (HFCs) which contribute to ozone depletion and global warming. The International Institute of Refrigeration in Paris (IIF/IIR) has estimated that approximately 15% of all the electricity produced in the world is employed for refrigeration of various kinds, and the

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energy consumption for air conditioning systems has recently been estimated at 45% for all households and commercial buildings [1].Therefore, an eco-friendly cooling system is required to reduce the emissions of harmful gases. Spoilage of fresh fruits and vegetables is a serious problem in tropical countries. Cool storage can prolong the life of fresh produce, but refrigeration equipment is expensive to buy, run, and maintain. Eritrea is a low income country and most of the farmers are not able to afford the cost of purchasing high-tech storage equipment's for their harvested crops. Minimizing deteriorative reactions in vegetables enhances their shelf lives, implying that the produce will be available for longer periods; this would reduce fluctuation in market supply and prices. Evaporative cooler works on the principle of cooling resulting from evaporation of water from the surface of the structure. The cooling achieved by this device also results in high relative humidity of the air in the cooling chamber from which the evaporation takes place relative to ambient air [2, 3]. The atmosphere in the chamber thus becomes more conducive for storage of vegetables. The zero energy cooling systems have prospect for use for short term preservation of vegetables after harvesting. In order to overcome the problem of on-farm storage, low cost environment friendly Zero Energy Cooling Chambers have been developed. The importance of this low cost cooling technology lies on the fact that it does not require any electricity or power to operate and all the materials required to construct the cool chamber are easily available at cheaper cost. Even an unskilled person can install it at any site, as it does not involve any specialized skill. Most of the raw materials used in cool chamber are also reusable [1].

Zero Energy Cooling Chamber (ZECC) is a cooling chamber in which the temperature inside the chamber is 10-15 degree Celsius lower than the outside ambient temperature. And also it can maintain 90% of relative humidity [4]. Zero Energy Cooling Chamber can retain the freshness of the fruits and vegetables for a short period. Small farmers can easily construct these chambers near their houses or fields to store their harvested produce [5]. In this way, the farmers can store their produce for few days and send the bulk of the commodity to the whole sale market so that they will not be forced to make any distress sale in the local market. The cool chamber can reduce the temperature by few degrees and maintain a high relative humidity compared to the ambient condition, thereby helping in enhancing the freshness of the produce. The chamber is an above-ground double-walled structure made up of bricks. The cavity of the double wall is filled with riverbed sand. The rise in relative humidity (90% or more) and fall in temperature (10-15 ^{o}C) from the ambient condition can be achieved by watering the chamber twice a day. Spoilage of fresh fruits and vegetables is a serious problem in tropical countries. Cool storage can prolong the life of produce. The study deals with the construction of ZECC with modification in its design, construction and temperature measuring tests are being conducted on it to determine the capacity of structure to lower the temperature. The concept of application of evaporative cooling principle for building wall to create natural cooling is also discussed.

Tomato is one of the most popular and widely grown vegetables in the world. It is grown throughout the world, either outdoors or indoors, because of its wide adaptability and versatility. The estimated world production of tomato is about 89.8 million Mg from an area of about 3,170,000 ha; the leading producers are China (with 25.3% of the total production), USA, Mexico and Egypt. Tomato production is widely distributed in Asia, Europe, North and South America, and in North Africa. Demand for tomato products has, in recent years, risen on the international market. In 2003 the main importers were United States of America (26.5%), Germany (19.3%), United Kingdom (12.4%) and France (8.7%), which accounted together for more than 66% of the total world imports. The top ten exporters of tomato in the world in 2003 were the Netherlands (23.9%), Spain (20.5%), Mexico (20.5%), Belgium (6.5%) and Canada(5.5%), accounting together for 77% of the world exports. There is a long history of horticulture production in Eritrea, starting from the first days of Italian colonization and peaking in the 1970s when Eritrea annually exported horticultural goods valued at about 4.5 million US dollars. Domestic horticultural production in 1993 was estimated at a total of 56,000 metric tons, with a total value of around 10.8 million US dollars. Domestic annual consumption was estimated at 14 kg per capita for fruit and 13 kg per capita for vegetables. Tomato is placed as one of the four priority vegetable crops along with onion, potato, and pepper in Eritrea. It stands second both in terms of acreage, 1074 ha, and production, 5912.6 mg per year. Moreover, the production seems to be well distributed in all administrative zones. In Eritrea, tomato is grown almost all over the country, mostly under irrigation (furrow, drip or spate irrigation) and sometimes under rain fed conditions. It is the most popular vegetable, used daily, mixed with sauce, soup, and salad, making the staple food more palatable. Tomato production has a long tradition among farmers in Eritrea. Farmers like growing tomato because the crop grows fast, covers large area with little investment has a high demand in the market, has a reasonably good yield and a good return. However, the average yield of tomato in Eritrea has remained low, 15 Mg/ha compared with 19.1 mg/ha in Africa, 23 mg/ha in Asia and 27.2 mg/ha averaged over the world [6].

2. Materials and methods

2.1. Bricks

A brick is a type of block used to construct the wall and surface of the structure. Properly, the term brick denotes a block composed of dried clay, but is now also used informally to denote other chemically cured construction blocks. Brick can be joined using mortar, adhesives or by interlocking them.

2.2. Sand

Sand is one component of the storage which fills the cavity between the inner and outer walls. River sand has a clean and smooth type of grain with sizes between 0.06 mm - 2 mm. After the storage starts operation the sand will be in wet condition. And it will receive hot air from outer wall and cool down, and then will send it to the inner wall.

2.3. Watering Can

The level of water (20 liters per day) was added to drip irrigation system to moisten the sand in the cooling chamber. Water is distributed from a water supply to low-pressure drip nozzles through a programmable flow valve for wetting the layer of sand.

2.4. Pipes

Pipes are conduit that is used to convey water from the source to the structure, which are perforated allowing the water to drop to the sand between the bricks. Roughly half of the world's polyvinyl chloride resin manufactured annually is used for producing pipes for various municipal and industrial applications.

2.5. Storage Container

Three perforated crates made from high density polyethylene were used to store vegetables. Vegetables were placed inside the perforated plastic and stored inside zero energy cooling chamber, freeze in room condition for evaluation of its quality.

2.6. Shed

Shed is made over the chamber in order to protect it from direct sun or rain. The storage should be covered by the thatched shed against sun rise and set properly. The dimensions of the shed are 250cmx300cm and 1.80m height.

2.7. Design Criteria of the Storage System

Zero Energy Cooling Chamber consists basically of three layers which is inner and outer layer bricks and middle cavity [7]. This storage system is rectangular in shape, and the design specification for the system was done as follows:

$$\text{Design of inner storage; } A_i = L_i * W_i$$

Where; A_i=area of inner space,L_i=length of inner bricks, W_i=width of inner bricks
Area of sides; $A_s = Hs*Ws$, Where; As=area of the sides, Hs=height of the sides, Ws=width of the sides
Cross sectional area of the lateral pipe; $A=\pi D^2/4$, Where; A=cross section area of lateral pipe
D=diameter of the lateral pipe

2.8. Heat Transfer Mechanisms

The heat gain through the system could be estimated using Fourier's law of heat conduction

$$Q_{hg} = -KA\Delta T/dx;$$

Where;
Q_{hg}=quantity of heat gained by the material
(W),A=Area of the material
(m),K=Thermal conductivity of the material
(W/mK),ΔT=Temperature difference
(k),dx=Thickness of the material (m).

2.9. Field heat load of tomato (Q)

$$Q = (MC_P \Delta T)/t,$$

M=mass of tomato (kg),
C_P=specific heat capacity of tomato (3.98KJ/kg ^{0}C),
t=cooling time for tomato equals 12hr

2.10. Respiration heat load

Respiratory activity of tomato=mass of tomato * rate of evaluation of tomato

2.11. Physiological Weight Loss (PWL)

Physiological loss in weight measures the degree of spoilage and can be calculated using the formula;

$$PLW = \frac{W1 - W2}{W1} X 100\% \;;$$

Where;
PWL= Physiological weight loss,
W1=initial weight of the product,
W2=final weight of the product.

3. Result and discussion

Zero Energy Cooling Chamber is designed for the storage of tomato. In this study sanmarzano species of tomato was tested at two different environmental conditions, one is low cost storage which is zero energy cooling chamber (ZECC), and the other is ambient storage. The tomatoes were harvested at two stages: a) green mature tomato, and b) red ripe tomato.

3.1. Designing of the capacity of zero energy cooling chamber

A surface zero energy cooling chamber was designed and constructed by utilizing locally sourced materials. The chamber's exterior dimensions are 116 cm x 116 cm x 65 cm, with interior dimensions of 50 cm x 50 cm x 70 cm. The materials used include perforated PVC pipes, bricks, pillars, dry-grass, gunny, and water tanks. The structure features a thatched shed and two standing shelves to hold the water tanks, which have a capacity of 20 liters each. The water tanks are designed to store water for future use. The capacity of the system is calculated to be 0.175m^3 (3).

3.2. Heat transfer calculation

The amount of heat transfer can be calculated,

$$Q = \frac{\Delta T}{Kt}$$

$$Kt = \frac{\Delta xb}{KbA} + \frac{\Delta xs}{KsA} + \frac{\Delta xb}{kbA}$$

$$Kt = \left(\frac{0.1m}{\frac{0.711w}{mk} * 3.016 sq.m}\right) + \left(\frac{0.08}{\frac{0.25w}{mk} * 2.366 sqm}\right) + \left(\frac{0.1}{\frac{0.711w}{mk} * 2.1 sq.m}\right) = 0.248 \text{k/w}$$

$$Q = \frac{303 - 292}{0.248 k/w} = 44 \text{watt}$$

3.3. Field Heat Load of Tomato

3.3.1. Ripe tomato

M=mass of ripe tomato (30kg), C_p=specific heat capacity of red tomato (3.98kJ/kg ^{0}c)

t=cooling time for tomato 12hr

$$Q = \frac{MCp\Delta T}{t} = 30\text{kg}*3.98\text{kJ/kg}\,^0\text{C}*(30\text{-}19)/12hr = 109.45\text{kJ/hr} = 30.4\text{watt}$$

3.3.2. Green tomato

M=mass of green tomato (30kg), Cp=specific heat capacity of green tomato (4.02kJ/kg ^{0}C)

Q=30kg*4.02kJ/kg^{0}C*(30-19)/12hr=30.7watt

3.4. Respiration Heat Load

$$Q = Mass\ of\ tomato\ stored\ x\ rate\ of\ evaluation\ of\ tomato$$

Q=0.06tonne x 1890kcal/tone/day

Q=5.486watt

Total heat in ZECC=field heat load + respiration heat load + heat due temperature difference

=61.1 + 5.486 + 44

=110.586watt

3.5. Water to be Applied

$$Q = \frac{T - t}{\frac{1}{hA} + \frac{L}{KA}}$$

$$Q = \frac{30 - 15}{\frac{1}{23*0.754} + \frac{0.1}{0.71*0.754}}$$

Q=61.36watt*4=245.44watt

Q= $m * hfg$

m= $\frac{\text{Q}}{\text{Hfg}}$

m=245.44/2466= 9.953*10^{-5}kg/sec

m=8.6 kg/day **(1Kg=1 liter for pure water)**

3.6. Heat load entered through the jute pad(cover)

Q=$\frac{\boldsymbol{KA\Delta T}}{\boldsymbol{\Delta X}}$**=**$\frac{0.0765*0.25*(30-19)}{\mathbf{0.01}}$**=**21watt

3.7. Respiration heat load from the above calculation

Q=5.486watt

Q total= heat load entered through the jute pad + Respiration heat load from the above calculation

Q $_{\textbf{total}}$=21watt + 5.486watt=26.486 watt

Mass= $\frac{Q}{hfg}$=$\frac{26.486}{2445}$=0.0000108kg/sec=0.936Kg/day

Total water applied per day=8.6+0.936=9.536kg/day

3.8. Data analysis

3.8.1. Temperature

Temperature and relative humidity are the main parameters should be measured for the system to work efficiently and properly. The efficiency of the storage increased with decreasing the temperature and increasing the relative humidity. Temperature is measured using digital thermometer for both outside and inside the ZECC storage. The reading is taken at every six hours' interval for 28 days. The result is listed in table 1. By maintaining an average storage temperature of approximately 19 °C, we were able to significantly extend the shelf life of tomatoes in two stages of maturity: red ripe tomatoes for up to 23 days and green mature tomatoes for up to 28 days.

Table 1 Temperature at 6 hrs interval

Time at 6 hrs interval	**Temperature (^{0}C)**	
	Temperature inside ZECC(^{0}C)	**Temperature outside the chamber (^{0}C)**
7 am	18.7	22.7
1 pm	19.2	32.3
7 pm	19.3	23

3.9. Qualitative evaluation

3.9.1. Appearance of Tomato

Figure 1 illustrates the comparative effects of storage conditions on tomatoes. Specifically, it shows:

- Green tomatoes stored in the chamber for 28 days (Fig. 1A) versus those stored in ambient conditions for 11 days (Fig. 1B).
- Ripe tomatoes stored in the chamber for 23 days (Fig. 1C) versus those stored in ambient conditions for 8 days (Fig. 1D). Numerous studies have shown that perishable agricultural products, such as fruits and vegetables, exhibit improved storage performance when kept in controlled environments [8-9]. The ideal storage temperature for these products is between 18 °C and 20 °C [8]. Consistent with these findings, our experiment revealed that tomatoes can be stored for an extended period at an average temperature of 19°C, with ripe tomatoes lasting 23 days and green tomatoes lasting 28 days.

Figure 1 A. Green tomato stored in ZECC(28 days)

Figure 1 B. Green tomato stored outside chamber (11 days)

Figure 1 C. Ripe tomato stored in ZECC in 23 days

Figure 1 D. Ripe tomato stored outside chamber for 8 days

3.10. Firmness of the Tomato

To assess the firmness of tomatoes, a penetrometer would have been the ideal instrument, but due to its unavailability, we relied on tactile evaluation and visual observation. A noticeable change in firmness was observed over time. Tomatoes stored in the cooler maintained their firmness, whereas those stored in ambient conditions began to lose firmness after the third day, and by the eleventh day, most had become completely rotten.

3.11. Physiological Loss in Weight (PLW)

Table 2 provides details of the Physical Loss in Weight (PLW) of tomatoes stored in a zero-energy cooling chamber and an uncontrolled environment. The experiment, conducted from April 29 to May 26, 2023, revealed that the chamber storage extended the shelf life of green and ripe tomatoes by 28 and 23 days, respectively (Figure 2). In contrast, tomatoes stored in the ambient environment deteriorated completely within 11 and 8 days for green and ripe tomatoes, respectively (Figure 3 and 4). The calculated PLW percentage showed a minimal loss of 5.33% for ripe tomatoes and 5.6% for green tomatoes [10].

Table 2 Physiological weight loss (g)

Day	Weight of tomato in ZECC(gram)		Weight of tomato in room (gram)	
	RED	GREEN	RED	GREEN
1	500	500	500	500
5	490.1	496.1	373.6	386.4
8	487.2	493.8	-	364.2
11	483	490.7	-	-
23	473.35	481.2	-	-
28	-	472	-	

Physiological loss in weight can be calculated as:PWL$(ripe) = \frac{weight1 - weight2}{weight1}$*100%

$$= \frac{500 - 473.35}{500} x100\% = 5.33\%$$

$$PWL(green) = \frac{500 - 472}{500} \text{x } 100\% = 5.6\%$$

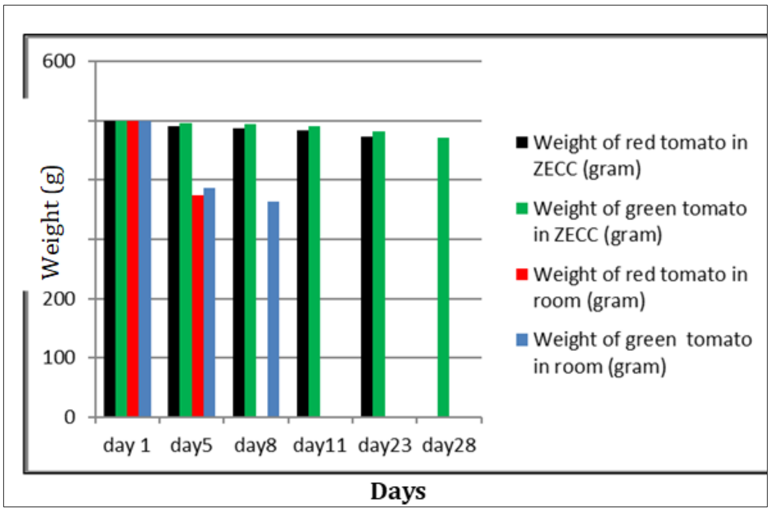

Figure 2 Effects of storage types on weight loss in gram of tomato with storage days

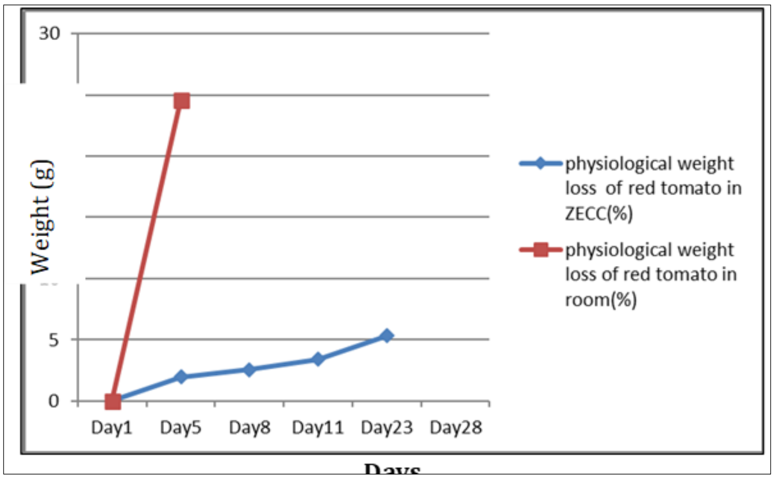

Figure 3 Effect of storage types on physiological weight loss in (%) of red tomato with storage days

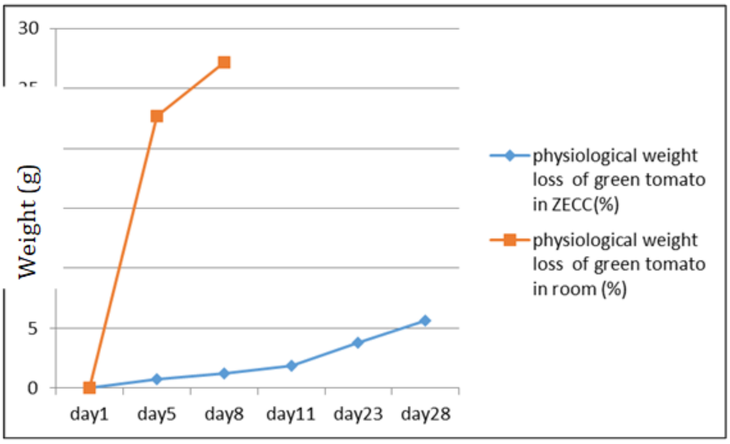

Figure 4 Effect of storage types on physiological weight loss in (%) of green tomato with storage days

4. Conclusion

This study investigated the potential of a zero-energy cooling chamber (ZECC) for storing agricultural products, specifically tomatoes. The ZECC was constructed using locally available materials and demonstrated the potential for short-term storage of agricultural products at the farm level, enhancing their post-harvest storage life. The ZECC system generated a temperature gradient that remained lower than ambient conditions throughout the testing period. Results showed that the ZECC decreased the temperature by 10-15 °C compared to ambient temperature. The lower temperature and higher relative humidity (85-90%) of the ZECC slowed down physiological weight loss and controlled chemical parameters for qualitative and nutritive storage of tomatoes.

Marginal and small-scale vegetable farmers face significant challenges due to the perishable nature of their produce. This forces them to sell their products at low prices in local markets, as transporting small quantities to distant markets is not economically viable. Conversely, consumers pay high prices for low-quality produce due to the lack of cold chain facilities in many areas of Eritrea, North East Africa. To address these challenges, farmers cultivating multiple vegetables on small plots require alternative storage technologies that can preserve their produce for shorter periods. This would enable them to accumulate daily harvests and transport larger volumes to market at economical intervals, benefiting both farmers and consumers with fresh, nutritious produce.

The ZECC offers an alternative technology for storing produce, allowing farmers to accumulate daily harvests and transport larger volumes to market, benefiting both farmers and consumers. The ZECC is an environmentally friendly, low-cost solution that can be constructed using locally available materials, making it a viable option for on-farm and household storage of horticultural produce.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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