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Research paper

Review on water evaporative cooling low-cost devices for tomato fruit preservation

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Abstract

In order to reduce post-harvest losses and ensure the availability of fresh tomatoes during the lean period to agro-industrial companies, farmers and those who market them, it is essential to find an inexpensive way to preserve them. Energy, environmental and economic issues lead us to seek solutions adapted to the context. Inexpensive means of conservation include water evaporative cooling systems. The aim of this article was to review the scientific, technical and legal aspects of existing evaporative preservation devices to ensure a continuous supply of this fruit. From our research and the field study, it appears that "pot-in-pot" technologies and evaporative cooling chambers (ECC) are deployed but still present several limitations, particularly in terms of storage time, adaptation to certain environments, device mass, mold growth; which justifies the fact that they are not yet adopted by many tomatoes' farmers. Perspectives have been proposed to overcome the limitations of these devices.

Keywords: *Evaporative Cooling; Low-Cost Devices; Post-Harvest Losses; Preservation; Tomato.*

1. Introduction

Tomato (Lycopersicon esculentum) is one of the most widely grown and consumed horticultural crops worldwide [1]. According to [2], tomato is botanically a fruit but classified as a vegetable commercially due to the way it is consumed. By weight, tomatoes rank second after potatoes in the universal production of all vegetable crops [3]. Due to the economic and nutritional importance of this crop, its production has increased in recent years to approximately 163 million tones [4], [1]. Unfortunately, a very large part of this production is lost, causing enormous economic losses of around 1.8 billion to 31.4 billion FCFA/year in Cameroon according to the FAO in 2018. They are spoiled mainly due to microorganisms [5], ripening and decomposition processes [6].The process of decomposition involves the emission of alcoholic gases (Ethylene) and Methane in traces [7 - 9]. This fruit and vegetable are very perishable and therefore have a short shelf life (2 to 5 days) due to its high-water content. A high rate of post-harvest loss of tomatoes has been observed throughout the world due to a lack of accessible and practical means of preservation for farmers. Although refrigeration and cold storage facilities are currently being developed to store horticultural products, they are not only energy-intensive but also require huge investments [10]. Water evaporative cooling systems are increasingly being developed to try to solve this problem that producers encounter. In this article, we will do a scientific review, a technical review and a legal-commercial review on inexpensive and energy-saving solutions, environmentally friendly and made from evaporative materials available locally at low cost. Subsequently we will identify the limits of these solutions and we will come up with perspectives.

2. Scientific review on evaporative cooling

2.1. Concept and principle

Evaporative cooling is a process by which the air temperature is lowered by the phenomenon of water evaporation. The conversion of sensible heat into latent heat cools the surrounding air as water evaporates [11]. Cooling becomes more effective when we regularly and continuously wet the surface and allow the water to evaporate. The particularity of this type of cooling is that it does not require additional energy, which is not the case with conventional refrigeration and air conditioning systems. The cooling obtained by the system results in an increase in relative humidity (RH) and a drop in air and environmental temperature inside a closed enclosure more suitable for the storage of horticultural products [12].
When dry air passes through a humid surface, water evaporates, which creates a drop in temperature. The effectiveness of an evaporative cooling system depends primarily on the relative humidity of the ambient air, its temperature and atmospheric pressure. The drier the air,

the more moisture it absorbs and a cooling effect can be observed [10]. Figure 1 illustrates the process of sensible and evaporative cooling and the rate of cooling achieved can be determined if the psychometric properties of the ambient air are known.

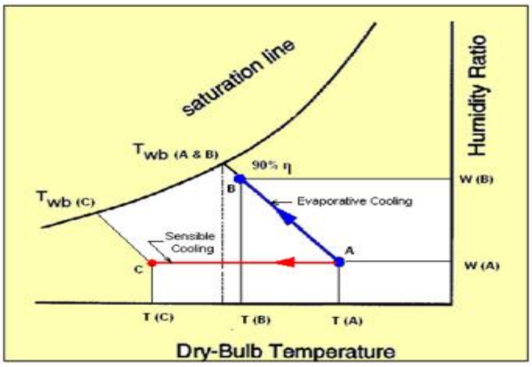

Fig. 1: Representation of Sensible and Evaporative Cooling on the Psychometric Diagram.

There are two types of evaporative cooling:

- Direct evaporative cooling (DEC)

Direct evaporative cooling (DEC) technologies use the latent heat of evaporation (conversion of liquid water to water vapor) to decrease the temperature and increase the relative humidity of the ambient air. It is an adiabatic process; warm, dry air is recirculated to cool humid air. The heat in the surrounding air causes the water to evaporate and the relative humidity reaches 70 to 90%. Humid air must be released into the atmosphere; otherwise, the air could become saturated and evaporation would cease [10]. This method is more effective if the ambient temperature is high. It facilitates the flow of warm air across a damp surface, where the water evaporates, resulting in a cooling effect. The cool dry air is then used to cool the environment within an enclosure, while the cool, moist air is exhausted outside to prevent saturation [13]. This phenomenon is illustrated in Figure 2.

- Indirect evaporative cooling (IEC)

In IEC technology, the primary air is cooled by direct contact between water and primary air. In the IEC system, primary air and secondary air follow distinct pathways located in separate conduits, namely the wet and dry channels. The heat transfer mechanism within the wet channel bears semblance to the process of direct evaporative cooling. Secondary air traverses the wet channel, contacts the water and is cooled due to evaporation [14]. [15] DEC produces high RH air, undesirable for certain specific applications. Indirect evaporative cooling (IEC) alleviates this problem by cooling dry air with cool moist air produced by evaporation. The resulting low-temperature air is then projected to cool the enclosure using a heat exchanger, which is shown in Figure 2 [16]. Therefore, the IEC needs a source of energy to operate the fan and the water pump, which is one of the major constraints, especially in rural production areas of developing countries. Although it is cheaper to build and run IEC compared to traditional air conditioning systems. However, this is not suitable for all environmental conditions because the temperature reduction is not as high as what can be achieved with conventional mechanics of cooling systems [15].

(A) (B)

Fig. 2: Evaporative Cooling. (A): Direct, (B): Indirect.

2.2. Factors influencing evaporative water-cooling systems

Temperature and relative humidity are the two most important environmental parameters. But there are still several other factors that influence the effectiveness of these systems, particularly for those intended for preservation [17].

The cooling efficiency is given by the following relationship:

$$\varepsilon = \frac{T_{out} - T_{int}}{T_{out} - T_{w}} \quad (1)$$

T_{out} : outside temperature

T_{int} : interior temperature

T_{w} : wet temperature

2.2.1. Temperature

- Ambient air temperature

Ambient conditions are unfavorable for the conservation of fruits and vegetables, particularly climacteric fruits such as tomatoes. Temperature is probably the most important factor limiting the shelf life of fruits and vegetables [18]; [19]. Evaporation occurs when water absorbs enough energy and changes from liquid to vapor. High temperature air with large humid depressions accelerates the evaporation process. Therefore, high air temperatures in arid regions increase evaporation as well as the cooling effect [20].

- The temperature of the cooled enclosure

When the storage temperature is low, the rate of decomposition and degradation by micro-organisms reduces, thus maintaining the quality and freshness of the fruits stored for longer. Generally, the storage temperature of tropical fruits and vegetables ranges from 5 to 13°C [21].

- The temperature of water

The lower the temperature of the water, the more heat it will absorb so that it can evaporate.

2.2.2. Relative humidity

- The relative humidity of the ambient air

The saturation deficit (difference between the saturated vapor pressure and the current vapor pressure) can also be expressed in another way using the notion of relative humidity. It is expressed by the following equation:

$$RH = \frac{e_a}{e_s} \times 100 \quad (2)$$

e_a= current or effective pressure of water vapour in the air
e_s= saturation vapour pressure
It is further emphasized that the saturation vapour pressure increases with temperature. It can be expressed as follows (in Pa and with the temperature in °C):

$$e_s = 611. Exp\left[\frac{17.27T}{237.3+T}\right] \quad (3)$$

T = Temperature (°C)

Low RH promotes water evaporation and increases cooling efficiency [22]. Conversely, very humid air is unfavourable for evaporation due to air saturation.

- The relative humidity of the cooled enclosure

Relative humidity is another crucial factor affecting the shelf life of horticultural products [23]. At low RH, the air can absorb more moisture, leading to an increase in the transpiration rate of the product [24].

2.2.3. Air speed

Natural or forced convection significantly affects evaporation. The evaporation rate will increase or remain constant if moist air near the water surface is continually displaced and replaced with dry air [25]. The relative humidity of the air closer to the water surface increases as water evaporates. The evaporation rate will begin to decrease if moist air remains in place.

2.2.4. The material of the cooling pad

Multiple studies have revealed that the material used plays an important role in cooling efficiency. Several organic and inorganic materials have been tested and evaluated for evaporative cooling in different climates by various researchers.
[26] evaluated the effectiveness of absorbent materials in evaporative cooling chambers for fruit and vegetable storage and reported that the average cooling efficiency of jute under no-load conditions was 86.2 %, compared to 76.3% for cotton waste and 61.7% for jute fiber cloth.
[27] assessed the feasibility of charcoal as an alternative to evaporative cooling pads in greenhouses and reported that the average saturation efficiency in charcoal was 70%, with an air speed of 1.38 m/s and water flow rates of 0.19/kg for each square meter of the slab.

2.2.5. Atmospheric pressure

The greater the total pressure above the wet buffer material, the greater the vapor pressure; but this effect remains negligible for total pressures below 106Pa (or 10 bars). On the other hand, some authors consider that the evaporation rate increases when atmospheric pressure decreases. This inverse relationship has not yet been clearly demonstrated, because the variation in barometric pressure is generally followed by other variations, such as those in temperature and wind conditions.

3. Technical review on water evaporative cooling low-cost devices for fruit preservation

Our research led us mainly to two low-cost water evaporation cooling technologies intended for the preservation of fruits and vegetables. These two technologies use the principle of direct evaporative cooling.

3.1. Pot-in-pot refrigerator or Zeer pot or desert fridge

This system was brought up to date in the 1990s by Mohammed Bah Abba, a teacher from a family of potters [28]. He noticed that girls often missed school because they had to deal with selling freshly harvested vegetables. The heat of these semi-desert regions does not allow them to be preserved for long. He therefore created “pots-in-pots” and won the Rolex Prize for his invention in 2001, which helped improve the standard of living of farmers in several countries. Even Doctors Without Borders were inspired by his idea to store certain medications. The pot-in-pot consists of a large terracotta pot, in which a smaller pot is placed. Then, the space between the pots is filled with sand and some water is poured on the sand; this water, as it evaporates, cools the air inside the small pot. Finally, the pot is covered with a damp cloth. Once the interior temperature has dropped, you can store your fruits and vegetables such as tomatoes. Figure 3 shows the technical drawing of the Zeer pot.

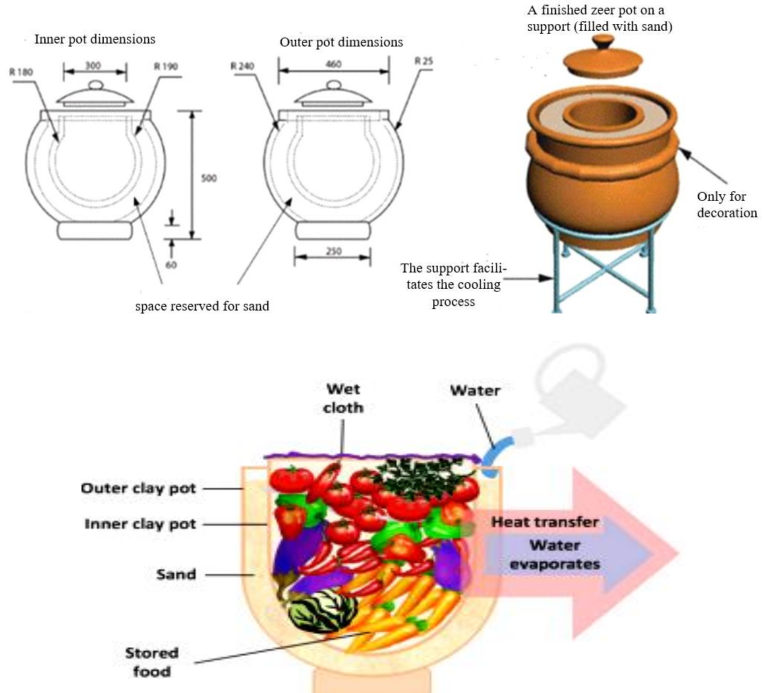

Fig. 3: Schematization of the Zeer Pot [29], [30].

According to a study carried out in Sudan with the support of the international NGO Practical Action, the desert fridge allows food to be preserved 10 times longer than usual. For example: the shelf life of a tomato in the open air is 2 days and, in the desert, fridge extends to 20 days. Several natural refrigerator models were developed in the following years. Figure 4 presents these different variants.

Fig. 4: Examples of 4 Models of Clay Pot Coolers Studied in Burkina Faso [30].

A) Small clay pot within a clay pot (approximately 5-liter capacity; 2,500 Fcfa; $4.28) with attached sensor data logger
B) Medium clay pot in a plastic dish (capacity ~ 20 liters; 3,300 CFA francs; $5.65)
C) Large clay pot in a metal dish (~ 60 liters capacity; 13,000 CFA francs; $22.27)
D) Plastic bucket in a clay pot (~ 10-liter capacity; 2,700 Fcfa; $4.63)

All clay pot coolers are covered with a damp cloth when in use. We can see in Figure 4 that these devices are equipped with temperature sensors to monitor the evolution of the temperature in the cooling chamber and compare with the outside temperature. Temperature and relative humidity measurements were made for several types of pot-in-pot. But in general, the different types present, apart from a few details, the same performances.

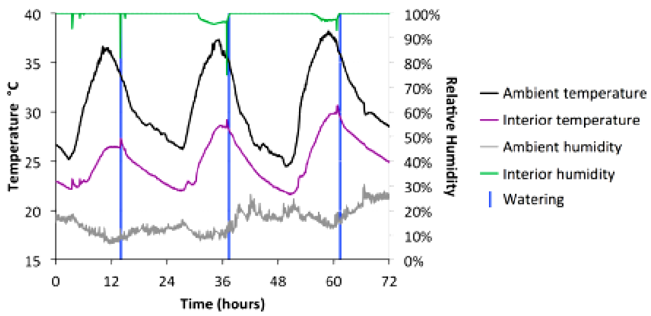

Fig. 5: Typical Daily Temperature and Relative Humidity Conditions when Watering a Clay Pot Cooler (Pot-in-Pot Configuration).

The data in Figure 5 shows that the average interior temperature of the clay pot cooler is reduced, with the cooling effect being most pronounced during the day when the temperature is at its highest and the relative humidity is at its lowest. This has the effect of decreasing maximum temperature, when the vegetables are most susceptible to spoilage/damage.

3.2. Evaporative cooling chamber (ECC) or zero energy cooling chamber (ZECC)

The Evaporative Cooling Chamber (ECC) is composed of a double mud brick wall structure, supported by a brick base layer, and covered with a straw mat. The space between the two brick walls is filled with sand, which holds water which is added. Inside the ECC, the fruits are placed in unsealed plastic containers, which keeps the vegetables off the floor of the ECC and allows them to breathe and be exposed to fresh, humid air inside the device, see Figure 6. The operating principle is the same as that of the Zeer; it is an innovation of the basic Zeer pot.

Fig. 6: Photo of a ZECC in Rwanda [29].

Over the years, work has been carried out to improve ECCs. From there, many other ECC models were born. The materials used can be raw or cooked earth bricks, sand, wood, straw, jute or burlap bags. The shelf life of tomatoes varies depending on the type of ECC material and the properties of the environment in which it was designed. Figures 6 and 7 show other types of ECC. Summary table 1 presents some work carried out on different types of ECCs and the associated number of days of preservation of tomatoes.

Fig. 7: Straw ECC.

Fig. 8: Sack ECC.

Table 1 shows the shelf life of tomatoes obtained by different types of Zeer pot and different types of ECC. For each type of ECC or Zeer pot, the temperature and relative humidity conditions are different. We notice in this table, the longest shelf life obtained is 32 days. This number of days is obtained by the Multi-Layer Cooling Pads. The shortest shelf life obtained is 8 days. This result is obtained by the Wood (Mahogany and Akwamari), jute bag, metal mesh wire.

Table 1: Shelf Life of Tomatoes Obtained by Different Types of ECC and Different Conditions

Materials/works	Tout (°C)	Tin (°C)	RHout (%)	RHin (%)	Shelf life (Days)	Refer-ences
ECC	14,5 -22	11,5-20,5	54–64	78-100	12	[31]
ECC Bricks and river sand	-	10-15	-	95	14	[32]
ECC	33	8,2	36,6	60,4	18	[33]
Multi-Layer Cooling Pads	28.3-36.3	14.0-19.0	39.0–58.0	82.0–96.0	32	[24]
Fired bricks and river bed sand	-	-	-	-	11	[34]
	38	28	35–45	75-85	12	[35]
Soft steel	26,1-31,8	20,4-30,23	59- 79	74- 95	15	[36]
Wood (Mahogany and Akwamari), jute bag, metal mesh wire	25-28	20 -23,5	47-58	51-93	8	[37]
Pot-in-pot (Clay-sand)	-	19.5	-	-	20	[38]
Pot-in-pot (Clay-charcoal)	33,8	-	40,8		16	[39]

Table 2: Buffer Materials and Their Effectiveness [10]

N°	Pad materials	Efficiency	Refer-ences
1	Jute, cotton waste and jute fiber	Cooling efficiency under no-load conditions: Jute 86.2%, Cotton waste 76.3%, and Hessian fiber 61.7% (good mold resistance)	[26]
2	Bulk charcoal	Saturation efficiency: 70%	[27]
3	Curtain and raw cotton fab-ric	Saturation efficiency: Curtain fabric 46.3%–61.3% Raw cotton fabric 29.7%–39.2%	[40]
4	Cellulose, aspen, and coco-nut coir	Cooling effectiveness: Cellulose 55.29%–64.55% Aspen 68.86%–80.99% Coconut coir 50.79%–68.15%	[41]

From this table it appears that the type of buffer significantly influences the efficiency of the equipment. The jute tampon offers better efficiency compared to other types of tampons.

The results of this study indicate that low-cost evaporative cooling devices, such as clay pot coolers and ECCs, have the potential to benefit both off-grid populations with limited access to electricity and on-grid populations with high electricity and/or equipment costs for refrigerators. Evaporative cooling can improve vegetable storage shelf life by providing:

- A stable storage environment with low temperature and high humidity, which reduces water loss and spoilage rate in most vegetables
- Protection from animals and insects that contaminate and eat the vegetables. The improved storage environment can have positive impacts including reduced post-harvest losses, less time spent traveling to the market, increased availability of vegetables for consumption and monetary savings. These devices can also have farther-reaching impacts, particularly for women who could benefit economically from producing and selling clay pots.

The costs of these water evaporative cooling devices essentially depend on the type of material used and its capacity. The following table presents some devices and their cost.

Table 3: Cost of some EEC and Pot-in-pot

Evaporative cooling device	Storage volume	Cost
ECC (straw)	250-4000 L	$50 - $250
ECC (sack)	250-4000 L	$50 - $250
ECC (brick)	500-5000 L	$70 - $350
Round pot-in-dish	10-150 L	$6 - $35

We find that ECCs can range from a capacity of 250L to 5000L, unlike the pot-in-pot which has a maximum capacity of 150L. Costs are relatively low.

As with Zeer pots, some researchers have equipped ECCs with temperature and relative humidity sensors for parameter monitoring. This can be observed in figure 9.

Fig. 9: ECCs equipped with data logger [30].

A) straw ECC interior sensor
B) straw ECC exterior sensor
C) sack ECC interior sensor
D) sack ECC exterior sensor
E) brick ECC interior sensor
F) brick ECC moisture sensor
G) brick ECC exterior sensor

On figure 10, typical internal daily temperature with watering for all three types of ECCs, and the ambient temperature measured by the independent sensor nearby to the ECCs is represented by the black line. A decrease in the temperature can be observed at the time of watering for each of the ECCs, indicated by the vertical blue lines.

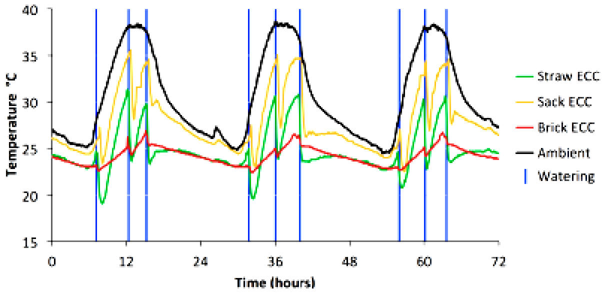

Fig. 10: Typical Internal Daily Temperature with Watering for All Three Types of Eccs.

For all types of ECCs, we observe that the ambient temperature is always much higher than that of the different ECCs. In addition, we observe a remarkable drop in temperature during watering, particularly for straw ECCs and sack ECCs. brick ECCs offer lower and more stable temperatures which is favorable for the preservation of fruits.
On figure 11, typical daily relative humidity with watering for all three types of ECCs, and the ambient humidity measured from the independent sensor nearby to the ECCs is represented by the black line. An increase in the humidity can be observed at the time of watering for each of the ECCs, indicated by the vertical blue lines.

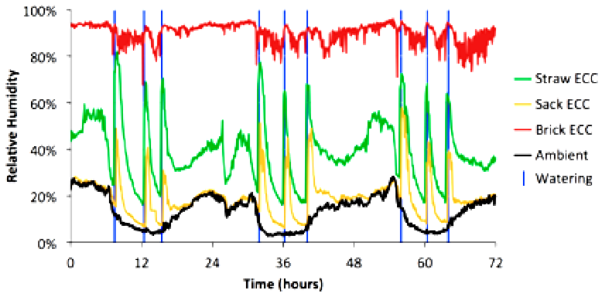

Fig. 11: Typical Daily Relative Humidity with Watering for All Three Types of Eccs.

When watered regularly the relative humidity inside the brick ECC remains consistently above 70% throughout the day. In contrast, the relative humidity inside the sack and straw ECCs decreases within a few hours, and sharply increases after each watering event. The ambient relative humidity has a significant effect on the performance of the ECCs. At higher relative humidity the evaporation rate of water is decreased, which reduces the cooling effect.

3.3. Limits and constraints for adoption of evaporative cooling technologies and proposed solution

We note that in ECCs the phenomenon of ethylene production is not taken into account; However, it is mainly this gas which is at the origin of the ripening of climacteric fruits. Despite many advantages (low initial and operational costs, environmentally friendly, no noise, no need for electricity, constructed from locally available materials, preservation of nutritional values, and extension of shelf life with less weight loss) of this technology [42], ECCs have not been adopted by farmers for the storage of horticultural commodities. ECCs must offer storage conditions that meet farmers' demands. Variations in the need to improve storage can arise due to seasonal growth and harvest cycles, production surpluses relative to local demand, and climatic variations [29]. If these criteria cannot be met, then ECCs may not provide sufficient benefits to justify their use. There are some challenges while constructing, operating and maintaining the structures for the prospective farmers and some of these challenges are as follows [10].

- Location
- Construction
- Availability of water
- Environment
- Cooling efficiency

We propose optimizing the use of ECCs to promote their adoption by several farmers and entrepreneurs. The work must focus on:

- Regulation of temperature and relative humidity on ECCs
- Automation of watering
- The design of ECCs for very large quantities of fruits and vegetables
- The durability of the construction material
- The mobility of ECCs
- Extraction of ethylene gas produced by fruits

4. Legal-commercial review

International standards relating to food safety, fruit and vegetable preservation, evaporative cooling equipment were consulted. These include the following standards:

- ISO 22000 Management and Food Safety
- ISO/ICS 27.200 Refrigeration equipment
- ISO 6949:1988(fr) Fruits and vegetables — Principles and techniques of the controlled atmosphere storage method
- ISO 2169:1981(fr) Fruits and vegetables — Physical conditions of refrigeration rooms — Definitions and measurement

It generally appears that:

- Tomato fruits can be stored in a temperature range of 10° to 25°C, because below that, the fruits are subjected to cold shock.

This is why the refrigerator is not suitable.

- Humidity should be between 85 and 90%
- Cooling water must be treated to prevent the proliferation of microbes and viruses
- The absorbent material must also be treated.
- Any ppm of ethylene value greater than 300 indicates that the fruit or vegetable is not edible [9].

5. Conclusion

Ambient air temperature and relative humidity conditions are unfavourable in certain countries, particularly those with dry tropical climates, for fruits and vegetables with a high-water content. Tomatoes are particularly affected; These unfavourable conditions lead to rapid deterioration of these perishable fruits. Additionally, even after harvest, they breathe. About 30% to 35% of these fruits suffer damage in the post-harvest storage, grading, transportation, packaging and distribution phase due to lack of proper facilities. The evaporative cooling chamber is a low-cost air conditioning system that uses induced heat and mass transfer processes with water and air as the working fluids. In hot, dry climates, these devices have proven useful for the short-term preservation of fruits and vegetables. Many researchers have developed ECCs in various locations and reported an increase in the shelf life of horticultural products. ECC has many benefits, but due to some constraints, such as problems associated with outdoor structures, unfavourable climatic conditions and weak infrastructures, this technique could not be well recognized and adopted. Challenges to its adoption can be minimized by adding a simple electronic control system, improving its robustness, adding extraction of ethylene gas produced by fruits, and improving efficiency to provide preservation facilities using green energy. The use of this technique will not only reduce post-harvest losses, but also improve the economic status of farmers in rural production areas and develop new avenues of entrepreneurship.

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