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ORIGINAL ARTICLE

Evaporative cooling system for storage of fruits and vegetables - a review

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Abstract Horticultural produce are stored at lower temperature because of their highly perishable nature. There are many methods to cool the environment. Hence, preserving these types of foods in their fresh form demands that the chemical, bio-chemical and physiological changes are restricted to a minimum by close control of space temperature and humidity. The high cost involved in developing cold storage or controlled atmosphere storage is a pressing problem in several developing countries. Evaporative cooling is a well-known system to be an efficient and economical means for reducing the temperature and increasing the relative humidity in an enclosure and this effect has been extensively tried for increasing the shelf life of horticultural produce in some tropical and subtropical countries. In this review paper, basic concept and principle, methods of evaporative cooling and their application for the preservation of fruits and vegetables and economy are also reported. Thus, the evaporative cooler has prospect for use for short term preservation of vegetables and fruits soon after harvest. Zero energy cooling system could be used effectively for short-duration storage of fruits and vegetables even in hilly region. It not only reduces the storage temperature but also increases the relative humidity of the storage which is essential for maintaining the freshness of the commodities.

Keywords Evaporative cooling system · Storage conditions · Factors affecting · Design consideration · Economy · Merits & demerits

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Introduction

India is the second largest producer of fruits and vegetables in the world after Brazil and China respectively. Production of fruits and vegetables account for 209.72 million tonnes (MT) of which 73.53 MT & 136.19 MT are fruits & vegetables respectively (Anon 2010). Storage of fresh horticultural produce after harvest is one of the most pressing problems of a tropical country like India. Due to their high moisture content, fruits and vegetables have very short life and are liable to spoil. Moreover, they are living entities and carry out transpiration, respiration and ripening even after harvest. Metabolism in fresh horticultural produce continues even after harvest and the deterioration rate increases due to ripening, senescence and unfavourable environmental factors. Hence, preserving these types of foods in their fresh form demands that the chemical, bio-chemical and physiological changes are restricted to a minimum by close control of space temperature and humidity (Chandra et al. 1999).

Due to the short shelf life of these crops, it is estimated that about 30 to 35% of India's total fruits and vegetables production is lost during harvest, storage, grading, transport, packaging and distribution in a year which reduces the growers share. Only 2% of these crops are processed into value added products. Hence, there is a need for maximum commercial utilisation of fruits and vegetables. If the nutritive value of the processed food products could be maintained, this sector will emerge as a major value-added food industry. At present, the grower is getting hardly 25–35 paisa of out of a rupee of the consumer. Therefore, there is a need to evolve a marketing system where benefit is prevailed to both growers and consumers. The fruits and vegetables, being perishable, need immediate post harvest attention to reduce the microbial load and increase their shelf life, which can be achieved by storing them at low temperature and high relative humidity conditions. These conditions are usually achieved in cold storages.

Farmers and traders still practice their age-old storage methods leading to large-scale wastage during storage and transportation. Traditionally, after harvest, most of the fruits and vegetables are kept in temporary wooden/bamboo huts constructed near the residential buildings or production catchment. In the warm plains of India, fruits and vegetables are stored in pits or cool dry rooms with proper ventilation on the floor or on bamboo racks. Inside the hut, fruits and vegetables are kept on floor or over racks and covered are with straw or plant leaves to avoid exposure to the atmosphere. By this method fruits and vegetables can be stored for few days without much damage and farmers sell it in local village weekly market according to their financial needs

Several simple practices are useful for cooling and enhancing storage system efficiency wherever they are used, and especially in developing countries, where energy savings may be critical. Mechanical refrigeration is, however, energy intensive and expensive, involves considerable initial capital investment, and requires uninterrupted supplies of electricity which are not always readily available, and cannot be quickly and easily installed. Available cold storage in India is used primarily for the storage of potatoes. Appropriate cool storage technologies are therefore required in India for on farm storage of fresh horticultural produce in remote and inaccessible areas, to reduce losses. Low-cost, low-energy, environmentally friendly cool chambers made from locally available materials, and which utilize the principles of evaporative cooling, were therefore developed in response to this problem. These cool chambers are able to maintain temperatures at 10–15 °C below ambient, as well as at a relative humidity of 90%, depending on the season.

The evaporative cooled storage structure has proved to be useful for short term, on-farm storage of fruits and vegetables in hot and dry regions (Jha and Chopra 2006). Evaporative cooling is an efficient and economical means for reducing temperature and increasing the relative humidity of an enclosure, and has been extensively tried for enhancing the shelf life of horticultural produce (Jha and Chopra 2006; Dadhich et al. 2008; Odesola and Onyebuchi 2009) which is essential for maintaining the freshness of the commodities (Dadhich et al. 2008). Evaporative cooling is an environmental friendly air conditioning system that operates using induced processes of heat and mass transfer where water and air are working fluids (Camargo 2007).

Such a system provides an inexpensive, energy efficient, environmentally benign (not requiring ozone-damaging gas as in active systems) and potentially attractive cooling system (Zahra and John 1996).

In this paper, an attempt is made to review the basic concepts and principle, types of evaporative cooling system with their application in storage of fruits & vegetables and comparison of economics of storage in evaporative cooled room with that in cold storage also reported. The current status of research in this area is summarized with some notes on recent developments.

Theory and basic principle of evaporative cooling system

Evaporative cooling is a physical phenomenon in which evaporation of a liquid, typically into surrounding air, cools an object or a liquid in contact with it. When considering water evaporating into air, the wet-bulb temperature, as compared to the air's dry-bulb temperature, is a measure of the potential for evaporative cooling. The greater the difference between the two temperatures, the greater the evaporative cooling effect. Evaporation of water produces a considerable cooling effect and the faster the evaporation the greater is the cooling. When the temperatures are the same, no net evaporation of water in air occurs, thus there is no cooling effect. The principle of working of this system is 'when a particular space is conditioned and maintained at a temperature lower than the ambient temperature surrounding the space, there should be release of some moisture from outside the body'. This maintains low temperature and elevated humidity in the space compared to the surrounding. This evaporative cool chamber fulfills all these requirements and is helpful to small farmers in rural areas (Dadhich et al. 2008).

Evaporative coolers provide cool air by forcing hot dry air over a wetted pad. The water in the pad evaporates, removing heat from the air while adding moisture. When water evaporates it draws energy from its surroundings which produces a considerable cooling effect. Evaporative cooling occurs when air, that is not too humid, passes over a wet surface; the faster the rate of evaporation the greater the cooling. The efficiency of an evaporative cooler depends on the humidity of the surrounding air. Very dry air can absorb a lot of moisture so greater cooling occurs. In the extreme case of air that is totally saturated with water, no evaporation can take place and no cooling occurs. The evaporatively cooled storage structures work on the principle of adiabatic cooling caused by evaporation of water, made to drip over the bricks or cooler pads. Generally, an evaporative cooler is made of a porous material that is fed with water. Hot dry air is drawn over the material. The water evaporates into the air raising its humidity and at the same time reducing the temperature of the air.

Cooling is provided by the evaporative heat exchange which takes advantage of the principles of the latent heat of evaporation where tremendous heat is exchanged when water evaporates. It makes use of the free latent energy in the atmosphere. The relationship between air and water is shown in the psychometric chart (Fig. 1). Air acts like a sponge to water. The key difference is that as the air increases in temperature it can hold more water. As air takes up water it moves along the line of constant energy D. If the ambient conditions of the air are known then the amount of cooling can be determined using this chart.

For an ideal evaporative cooler, which means, 100% efficient, the dry bulb temperature and dew point should be equal to the wet bulb temperature (Camargo 2007). The psychometric chart in Figs. 1 and 2 illustrates that which happens when the air runs through an evaporative unit. Assuming the condition that the inlet dry bulb temperature is 30 °C and the wet bulb temperature is 18 °C, the initial difference is 12 °C, the process A–B represents a direct evaporative unit. If the efficiency of the direct unit is 90%, the depression will be 10.80 °C and the dry bulb temperature of air leaving this unit will be $30 - 0.9 \times 12 = 19.20$°C (point B).

Methods of evaporative cooling

There are many methods to cool the environment. Evaporative cooling is well-known system amongst them. In this system of cooling, temperature drops considerably and humidity increases to the suitable level for short-term on-farm storage of perishables (Jha and Kudas Aleksha 2006). It also used for pre-cooling of fruits and vegetables before transit and storage in cold store (Maini and Anand 1992). The different methods are:

Direct cooling system

The process where water evaporates into the air to be cooled, simultaneously humidifying, it is direct evaporative cooling (DEC) and the thermal process is the adiabatic saturation. The main characteristics of this process is the fact that it is more efficient when the temperature is higher, that means, when more cooling is necessary for thermal comfort. Direct evaporative cooling commonly used with residential systems, cools the air by evaporating water to increase the moisture content of the air. It involves the movement of air past or through a moist material where evaporation, and therefore cooling, occurs. This cooled moist air is then allowed to move directly to where it is needed. In contrast to this process, indirect cooling uses some form of heat exchangers that use the cool moist air produced through evaporative cooling, to lower the temperature of the dry air. This cool dry air is then used to cool the environment, and the cool moist air is expelled.

A direct evaporative cooling is a line of constant wet bulb temperatures. In the course of direct cooling operation, wet bulb temperature and enthalpy remains unchanged, dry bulb temperature reduces while relative humidity and specific humidity increases. These systems have an effectiveness of 55 to 70%. Effectiveness is a measure of how closely the supply air temperature leaving the evaporative cooler approaches the outdoor wet-bulb temperature. Direct evaporative cooling systems are suitable for hot and dry climates where the design wet-bulb temperature is 68 °F or lower. In other climates, outdoor humidity levels are too high that allow sufficient cooling. However, there are some limitations of this system. The drop in temperature will generally be only a small fraction of the total evaporative reduction that is possible. This is primarily due to the large volume of water that needs to be cooled by a relatively small evaporating surface area. Only a small number of items can be placed in large water containers (Odesola and Onyebuchi 2009). This system usually uses either a porous clay container or a water tight canvas bag in which water is

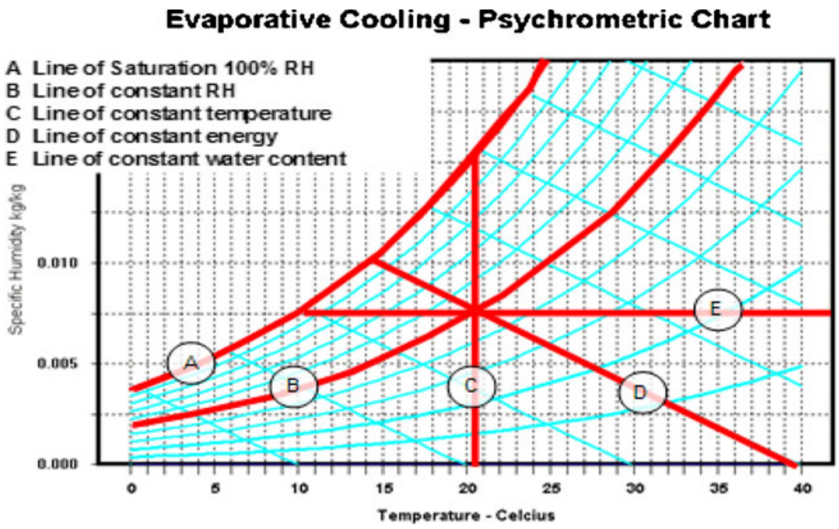

Fig. 1 The principle of evaporative cooling

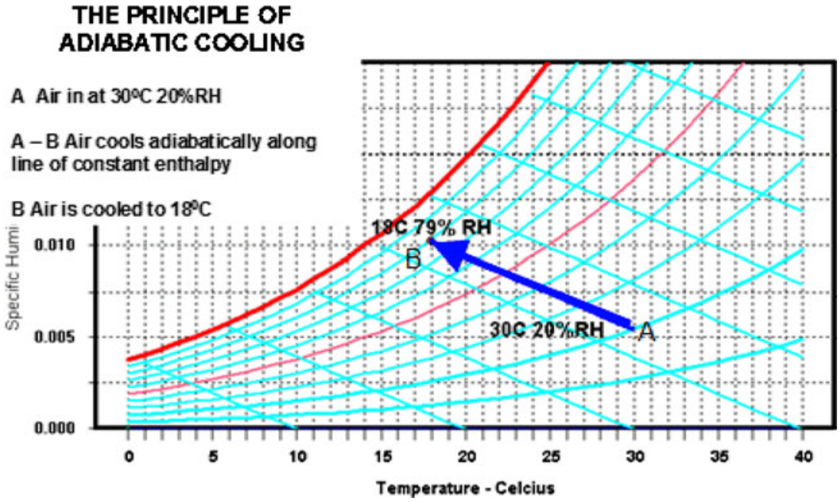

Fig. 2 The principle of adiabatic cooling

stored. These containers are then either hung or placed so that the wind will blow past them. The water in the container slowly leaks through the clay or canvas material and evaporates from the surface as warm dry air flow past. This process of evaporation slowly cools the water.

Indirect evaporative cooling system

Indirect evaporative cooling uses an air to air heat exchanger to remove heat from the primary air stream without adding moisture. In one configuration, hot dry outside air is passed through a series of horizontal tubes that are wetted on the outside. A secondary air stream blows over the outside of the coils and exhausts the warm, moist air to the outdoors. The outside air is cooled without adding moisture as it passes through the tubes. Indirect evaporative cooling typically has an effectiveness of 75%. The high level of humidity that is produced by direct evaporative cooling may be undesirable for some applications. Indirect evaporative cooling attempts to solve this problem by using the cool moist air produced through evaporation to cool drier air. The resulting cool air is then used to cool the desired environment. This transfer of coolness is accomplished with the help of a heat exchanger (Singh and Naranyahgkeda 1999).

All methods of indirect evaporative cooling require power to run both water pump and fans. For this reason, indirect evaporative cooling have limited applications. It is primarily used to cool dwellings and rooms. In such situations these cooling system are generally less expensive to buy or build and operate than conventional air conditioning systems. On the other hand, indirect evaporative cooling cannot be used in all environments and the reduction in temperature that can be achieved with this system is not as great as the reduction that can be achieved with conventional mechanical cooling systems.

Two stage systems

Indirect cooling is often paired with a second direct evaporative cooling stage to cool the supply air further while adding some moisture to the supply air. Such two-stage systems also referred to as indirect-direct evaporative (IDEC) cooling systems that can meet the entire cooling load for many buildings in arid to semi-arid climates. Indirect-direct evaporative systems provide the cooler supply air at a lower relative humidity than direct evaporative coolers. The first indirect stage cools the supply air without increasing humidity. Since, the air is cooled it has a reduced capacity to hold moisture. The air is then passed through a direct stage, which cools the air further while adding moisture. IDEC systems typically have an effectiveness of 100% to 115%, cooling the air to a temperature slightly below the outdoor air wet-bulb temperature. Since the systems use 100% outside air for cooling, they can also be paired with heat recovery to capture some of the energy that is lost in the exhaust air stream and reduce the ventilation cooling load. IDEC systems used in arid climates (with a design wet bulb temperature of 66 °F or lower) can have power consumption as low as 0.22 kw/ton, much lower than compressor-based cooling which can have power consumption on the order of 1 kw/ton. However, in more humid climates indirect-direct systems have less power reduction and energy savings.

Storage conditions and factors affecting fresh fruit and vegetables

The desirable effects on fruits and vegetables are ripening, color development, sprout induction and undesirable effects including accelerates ripening, accelerates yellowing, induces leaf loss, bitter taste in carrots, induces sprouting in potatoes. In general, proper storage practices include temperature control, relative humidity control, air circulation and maintenance of space between containers for adequate ventilation, and avoiding incompatible product mixes. Storage losses are mainly caused by the processes like respiration, sprouting, evaporation of water from the tubers, spread of diseases, changes in the chemical composition and physical properties of the tuber and damage by extreme temperatures. All the losses mentioned above depend on the storage conditions and therefore can be limited by maintaining favourable conditions in the store. The storage life of a product varies with species, variety and pre harvest conditions particularly quality and maturity. In general, there are three groups of products: (1) foods those are alive at the time of storage, distribution and sale e.g. fruits and vegetables, (2) foods that are no longer alive and have been processed in some form e.g. meat and fish products, and (3) commodities that benefit from storage at controlled temperature e.g. beer, tobacco, khandsari, etc. Preservation of non-living foods is more difficult since they are susceptible to spoilage.

Shelf life of a commodity is governed by several factors e.g. variety, stage of maturity, rate of cooling, storage temperature, relative humidity, packaging system, etc. It is important to keep in mind that they usually interact with each other to influence the overall rate of evaporation, and therefore, the rate and event of cooling. Storage temperatures and relative humidity affect the storage losses to a great extent. Proper control of temperature and relative humidity is the key to prolong the storage life and marketable quality. The shelf life of the fruit and vegetables maintained in the cool chamber was reported to be increased from 3 days at room temperature, to 90 days (Choudhury 2005). Tables 1, 2, 3, 4 and 5 present some reported storage conditions for fruit and vegetables. The storage temperatures, relative humidity and storage lives listed are those that have been suggested in various publications. For some commodities a general temperature for short term storage has also been suggested. Where it is necessary to achieve a long storage life for a particular crop, expert advice should be sought because factors such as variety and pre-harvest conditions determine the physiological response to the storage environment. There are four major factors that impact the rate of evaporation. Most important factors are briefly described here:

Table 1 Change as Shelf-life (in days) of vegetables with and without using Zeer (pots)

Produce	Shelf-life produce without using the Zeer (pots)	Shelf-life of produce using the Zeer (pots)
Tomatoes	2	20
Guavas	2	20
Rocket	1	5
Okra	4	17
Carrots	4	20

Longmone 2003

Temperature Tropical fruits and vegetables are harvested under ambient temperatures from 25 to 35 °C. Under this temperature, the respiration rate is higher and the storage life is short. Deterioration of fruits and vegetables during storage depends largely on temperature. Throughout the period between harvest and consumption, temperature control has been found to be the most important factor in maintaining product quality. Respiration and metabolic rates are directly related to room/air temperatures within a given range. The higher the rate of respiration, the faster the produce deteriorates. One way to slow down this change and to increase the length of time of storage for fruits and vegetables can be achieved by lowering the temperature to an appropriate level. Reduced the rate of water loss slows the rate of shrivelling and wilting, causing of serious postharvest losses. Therefore, areas with high temperatures will have higher rates of evaporation and more cooling will occur. With lower air temperature, less water vapour can be held, and slow respiration rates and the ripening and senescence processes, and cooling will take place, which prolongs the storage life of fruits and vegetables. By lowering produce temperature as soon as possible after harvest, generally within 4 h, the following effects are achieved: (1) Respiration rate is decreased, (2.) water loss is reduced, (3) ethylene production is suppressed, (4) sensitivity to ethylene is reduced, and (5) microbial development is slowed.

Most leafy vegetables and temperate fruit including citrus fruits are not chill-sensitive and can be stored between 0 °C and 2 °C for long periods without significant loss of visual quality. Meanwhile, 'tropical and sub-tropical' fruit and some root vegetables are chill sensitive and may be damaged at low temperatures. Hence they are generally stored at temperatures of 13 °C or above, although some may be stored safely as low as 5 °C if cooled soon after harvest. Low temperature does not destroy those spoilage agents as does high temperature, but greatly reduces their activities, providing a practical way of preserving perishable foods in their natural state which otherwise is not possible through heating. Storage of fruits and vegetables at low temperature, immediately after harvesting reduces the rate of respiration resulting in reduction of respiration heat, thermal decomposition, microbial spoilage and also it helps in retention of quality and freshness of the stored material for a longer period (Chopra et al. 2003).

Relative humidity (RH) Another important aspect to be considered during handling of fruits and vegetables is the relative humidity of the storage environment. The Transpiration rates that means water loss from produce, are

Table 2 Relative perishability and storage life of fresh horticultural crops

Relative Perishability	Potential storage life (weeks)	Commodities
Very high	<2	Apricot, blackberry, blueberry, cherry, fig, raspberry, strawberry; asparagus, bean sprouts, broccoli, cauliflower, green onion, leaf lettuce, mushroom, muskmelon, pea, spinach, sweet corn, tomato (ripe); most cut flowers and foliage; minimally processed fruits and vegetables
High	2–4	Avocado, banana, grape (without SO_2 treatment), guava, loquat, mandarin, mango, melons (honeydew, crenshaw, Persian), nectarine, papaya, peach, plum; artichoke, green beans, Brussels sprouts, cabbage, celery, eggplant, head lettuce, okra, pepper, summer squash, tomato (partially ripe).
Moderate	4–8	Apple and pear (some cultivars), grape (SO_2-treated), orange, grapefruit, lime, kiwifruit, persimmon, pomegranate; table beet, carrot, radish, potato (immature).
Low	8–16	Apple and pear (some cultivars), lemon; potato (mature), dry onion, garlic, pumpkin, winter squash, sweet potato, taro, yam; bulbs and other propagules of ornamental plants.
Very low	>16	Tree nuts, dried fruits and vegetables

Kader 1993

determined by the moisture content of the air, which is usually expressed as relative humidity. At high relative humidity, produce maintains its saleable weight, appearance, nutritional quality and flavor, while wilting, softening and juiciness are reduced. When the relative humidity is low, only a small portion of the total possible quantity of water vapour that the air is capable of holding is being held, and also the air is capable of taking additional moisture. Low relative humidity increase transpiration rates. On the other hand, when the relative humidity is high, the rate of water evaporation is low, and therefore cooling is also low (Odesola and Onyebuchi 2009). Maintaining high humidity around harvested produce reduces water loss, which would result in decreased returns through poor quality (wilting, shrivelling) and loss of saleable weight. High humidity should be used with low temperature storage because humidity and warmth or high temperate in combination favours the growth of fungi and bacteria.

Air movement and surface area The movement of air and surface area are an important factor that influences the rate of evaporation. As water evaporates from a surface it tends to raise the humidity of the air that is closet to the water surface. If this humid air remains in place, the rate of evaporation will start to slow down as humidity rises. On the other hand, if the humid air and the water surface is constantly been moved away and replaced with drier air, the rate of evaporation will either remain constant or increase. Cooling surface is the heart of the evaporative cooling system, which influences the efficiency of the evaporative cooling structure (Jha and Kudas Aleksha 2006). Various types of cooling surfaces such as bare bricks, silicon pads prepared from wood shavings (Roy and Khurdiya 1986) are used. The greater the surface area from which water can evaporate, the greater the rate of evaporation (Odesola and Onyebuchi 2009).

Table 3 Recommended temperature, relative humidity and storage life of fruits

Fruit	Temperature (°C)	Relative humidity (%)	Approx. storage live (weeks)
Custard apple	7–10	85–90	1–2
Guava	5–10	90	2–3
Jackfruit	11–12.8	85–90	3–5
Mango	13	95–90	2–3
Pineapple	7–13	85–90	2–4
Pomegranate	0–5	90–95	2–3 months

http://www.fao.org

Maximum cooling potential

The extent to which evaporation can lower the temperature of a container depends on the difference between the wet bulb and dry bulb temperatures. Theoretically, it is possible to bring about a change in temperature equal to the difference in these two temperatures. For example, if the dry and wet bulb temperatures were 35 °C and 15 °C, respectively, the maximum drop in temperature due to evaporative cooling would theoretically be 20 °C. In reality, though, while is not possible to achieve 100% of the theoretical maximum temperature drop, a substantial reduction in temperature is possible (Odesola and Onyebuchi 2009).

Status of cold storage and its potential in India

The estimated annual production of fruits and vegetables in India is about 209 MT. Due to diverse agro climatic conditions and better availability of package of practices, the production is gradually rising. Although, there is a vast scope for increasing the production, the lack of cold storage

Table 4 The critical relative humidity and temperatures for various fruits and vegetables

Products	Temperature °C	Relative humidity %	Maximum storage time Recommended (ASHRAE handbook 1998)	Storage time in cold stores for vegetables in tropical countries
Apple	0–4	90–95	2–6 m	–
Beetroot	0	95–99	–	–
Cabbage	0	95–99	5–6 m	2 m
Carrots	0	98–99	5–9 m	2 m
Cauliflower	0	95	2–4 w	1 w
Cucumber	10–13	90–95		
Eggplant	8–10	90–95		
Lettuce	1	95–99		
Leeks	0	95	1–3 m	1 m
Oranges	0–4	85–90	3–4 m	
Pears	0	90–95	2–5 m	
Pumpkin	10–13	70–75		
Spinach	0	95	1–2 w	1 w
Tomatoes	13–21	85–90		

http://www.fao.org

Table 5 Optimal storage conditions recommended for extended shelf life and maximum eating quality of various produce

Commodity	Temperature (°F)	Relative Humidity (%)	Storage Life
Apples, late season	30–38	95	2–6 months
Beet, bunched	32	98–100	10–14 days
Beet, topped	32	98–100	4–6 months
Broccoli	32	95–100	10–14 days
Brussels Sprouts	32	95–100	3–5 weeks
Cabbage	32	98–100	3–6 weeks
Carrot, bunched	32	95–100	2 weeks
Carrot, mature	32	98–100	7–9 months
Cauliflower	32	95–98	3–4 weeks
Celeriac	32	97–99	6–8 months
Celery	32	98–100	2–3 months
Garlic	32	65–70	6–7 months
Horseradish	30–32	98–100	10–12 months
Kale	32	95–100	2–3 weeks
Kohlrabi	32	98–100	2–3 months
Onion, dry	32	65–70	1–8 months
Parsnip	32	98–100	4–6 months
Pears	34–36	95	2–4 months
Pepper, sweet	45–55	90–95	2–3 weeks
Potato, late	50–60	90–95	5–10 months
Radish, winter	32	95–100	2–4 months
Rutabaga	32	98–100	4–6 months
Squash, winter	50	50–70	Variable
Tomato, ripe	46–50	90–95	4–7 days
Turnip	32	95	4–5 months

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and cold chain facilities are becoming major bottlenecks in tapping the potential. The cold storage facilities now available are mostly for a single commodity like potato, orange, apple, grapes, pomegranates, flowers, etc. which results in poor capacity utilization.

Design consideration/choosing the right technology

It is important to review carefully the cooling needs, weighing them against a range of other factors before making a decision (Odesola and Onyebuchi 2009). The following checklist may be useful in choosing the right design:

1. Cooling needs. Cooling of different foods require different temperatures.
2. Average relative humidity of the area where cooling is needed. If the relative humidity is consistently high, evaporative cooling will not be a viable option, and therefore another system needs be considered. If the relative humidity is low, then evaporative cooling may be effective.
3. Windy area, where the cooling is needed. If there is little wind evaporative cooling may not be the way to go.
4. A good supply of water where the cooling system will be used. If this is readily available, evaporative cooling may be feasible.
5. The materials and skills needed to build the cooler available.
6. If commercial systems are not too costly available, then may be a better choice of thistechnology.

Heat load factors in a cold storage design Heat load factors normally considered in a cold storage design are:(1) wall, floor and ceiling heat gains due to conduction, (2) wall and ceiling heat gains from solar radiation, (3) load due to ingression of air by frequent door openings and during fresh air charge, (4) product load from incoming goods,(5) heat of respiration from stored product, (6) heat from workers working in the room, (7) cooler fan load, (8) light load, (9) aging of equipment, and (10) miscellaneous loads, if any

Evaporative cooling system (scientific storage systems)

Refrigerated cold storage is considered to be the best for storage of fruits and vegetables. But this method is not only energy intensive, but also involves large initial capital investment. Besides, it is not suitable for on-farm storage in the rural areas. Considering, the acute energy shortage in rural areas, there is better scope for adoption of small capacity, low cost, on-farm scientific storage structure like Zero Energy Cool Chamber (ZECC) developed at IARI, New Delhi by Roy and Khurdiya (1986) based on the principle of evaporative cooling. The process of evaporative cooling is an adiabatic exchange of heat when ambient air passes through a saturated surface to obtain low temperature and high humidity, which is desirable to extend the storage life of fruits and vegetables (Das and Chandra 2001). Storage of horticultural products inside the cool chamber has showed reduction in physiological loss in weight, optimum colour, better firmness and extended shelf life by 1–2 weeks in other parts of the country. Cool chambers are effective in maintaining the fruit acceptability for a longer period and minimizing the weight loss during storage (Bhatnagar et al. 1990). Relatively lower weight loss of fruits and vegetables under evaporative cooler than that of ambient has been reported by many researchers. Sandooja et al. (1987) reported least deterioration in quality parameters of tomato such as TSS, acidity and ascorbic acid content when stored in zero energy cool chamber. Wasker et al. (1999) reported slower rate of change of physico-chemical constituents in fruits stored in cool chamber. Weight loss of fresh tomato has been reported to be primarily due to transportation and respiration, and limited shelf-life and losses in quality have been identified as the major problems faced in the marketing of fresh tomatoes (Bhowmic and Pan 1992). Zero energy cool chambers along with packaging materials, ventilation and anti fungal treatments can help in minimizing the losses of ascorbic acid in the stored lemon fruits to some extent compared to the storage under ambient conditions of storage (Prabha et al. 2006). Different types of evaporative cooler have been reported in the literature, some of which are included in this review.

Evaporative cooling (EC) occurs when air that is not already saturated with water vapour is blown across any wet surface. Thus evaporative coolers consist of a wet porous bed through which air is drawn and cooled and humidified by evaporation of the water (Khader 1999). One adaptation on the basic pot design is the janata cooler, developed by the food and nutrition board of India (Anonymous 1985).These are simple designs of evaporative coolers that can be used at home. The basic design consists of a storage pot placed inside a bigger pot that holds water. The inner pot stores food that is kept cool. A storage pot is placed in an earthenware bowl containing water. The pot is then covered with a damp cloth that is dipped into the reservoir of water. Water drawn up the cloth evaporates keeping the storage pot cool. The bowl is also placed on wet sand, to isolate the pot from the ground. Mohammed Abbah, a teacher in Nigeria, developed a small scale storage pot-in-pot system that uses two pots of slightly different size (Longmone 2003). The smaller pot is placed inside the large pot and the space between is filled with sand.

The India Agricultural Research Institute develops a cooling system that can be built in any part of the country using locally available materials (Anonymous 1985). The basic structure of the chamber can be built from bricks and river sand, with a cover made from cane or other plant materials and sacks or cloth. There must be a nearby source of water. Construction is fairly simple, first the floor is built from a single layer of bricks, and then a cavity wall is constructed of bricks around the outer edge of the floor with a gap of 75 mm between the inner wall and the outer wall. This cavity is then filled with sand. About 400 bricks are needed to build a chamber of the size. A covering for the chamber is made with canes covered in sacking all mounted in a bamboo frame. The whole structure should be protected from sunlight by making a roof to provide shade. After construction of the walls and floor, the sand in the cavity is thoroughly saturated with water. Once the chamber is completely wet, twice a daily sprinkling of water is done, which enough to maintain the moisture and temperature of the chamber.

A zero-energy cool chamber was developed using locally available materials in New Delhi, India (Roy and Pal 1994). The chamber is designed for on-farm use, operates by evaporative cooling, and is constructed from double brick with sand-filled cavity walls. The shelf life of tropical fruits held in the chamber was increased by 2 to 14 days (15–27% increase) as compared to storage at room temperature, and the physiological loss in weight was lower. The chambers were shown to be suitable for short-term storage of fruits and vegetables.

Roy and Khurdiya (1982) constructed 4 types of evaporatively cooled chambers for storage of vegetables.

The first chamber was made of cheap quality porous bricks and riverbed sand, which was latter known as Zero energy cool chamber. The other three chambers were ordinary earthen pots placed in three tanks: the first one made of bricks, the second one an ordinary wooden box and the last, an ordinary fruit basket. The gap in all the cases was filled with sand. The sand and the gunny bags covering the top of the chambers were kept saturated with water. The cool chambers maintained a temperature between 23 and 26.5 °C and relative humidity (RH) between 94 and 97% as against the ambient temperature between 24.2 and 39.1 °C and RH 9–36% during the months of May–June. Chamber 1, i.e. the Zero energy cool chamber, performed best with the enclosed air temperature remaining between 23 and 25.2 °C.

Roy (1984) reported that a 6 tonne cool chamber was constructed, where the side wall was constructed with two layers of bricks leaving approx. 7.5 cm gap in between them. This gap was filled with riverbed sand. The floor was made of wooden planks. Below the floor, a 33 cm deep tank was constructed with 4 air ducts made of bricks opening at the centre and submerged under wet sand. The sand in the wall and surrounding the ducts were saturated with a drip system. The top of the chamber was insulated and incorporated with an exhaust fan. The air while passing through saturated duct and walls cooled sufficiently and took away heat from the produce.

Chouksey (1985) reported the design aspects of a solar-cum-wind aspirator ventilated evaporative cooling structure of 20-ton capacity for potatoes and other semi perishables, which was constructed at the Central Potato Research Station (CPRS), Jalandhar. The structure maintained a temperature of 21–25 °C with 80–90% RH at ventilation rate of 24m^3/min when the outside temperature and RH were 40–42 °C and 30–35%, respectively.

Anonymous (1985) and Roy and Khurdiya (1986) reported the detailed method of construction of a Zero energy cool chamber. A chamber for storage of about 100 kg horticultural produce was constructed with two layers of bricks as side walls leaving approx. 7.5 cm gap in between them. This gap was filled with riverbed sand. The top of the storage space was covered with khaskhas/gunny cloth in a bamboo-framed structure. There was no provision for mechanical ventilation. The sidewall and top cover were kept completely wet during the period of storage. It was observed that the cool chamber had a temperature of less than 28 °C during summer, when the maximum outside temperature was 44 °C. The average minimum temperature of the cool chamber was either less than or near the outside average minimum temperature, excepting in winter, when it maintained a few degrees centigrade more than the outside average minimum temperature.

Habibunnisa et al. (1988) fabricated a metallic EC chamber measuring 45×45×45 cm (approx. 0.1 m^3) with a 2 mm GI sheet with the top side open. The four sides of metallic chamber were covered with a cloth, the top ends of which were immersed in water placed in the top tray. For allowing evaporation, the cloth surrounding the metallic chamber was made to remain wet continuously by downward gravitational flow of water. A wire mesh basket of size 30×30×30 cm filled with fruits was kept inside the chamber, leaving adequate space all around the basket for circulation of the air. The EC storage increased the shelf life of apple by 6 times and mandarins by 4 times.

Rama et al. (1990) studied the relative performance of two models of EC storage structures with regard to their efficiency in maintaining the temperature close to the ambient wet bulb temperature and high RH. The first structure was the same as that used by Habibunnisa et al. (1988). The second one resembled the first one except that the outer metallic wall was replaced by a weld wire mesh (2.5×2.5 cm) with evaporative sides covered with wet gunny cloth to help in free movement of evaporatively cooled air. The top tray used in this system (to serve as the water reservoir to wet the gunny cloth) was devoid of vents. The inside temperature for both the systems were almost similar and close to the ambient wet bulb temperature and the relative humidities were 90±5%, respectively. The lower RH of the system 2 was attributed to the free air circulation through the structure.

Sharma and Kachru (1990) used evaporatively cooled sand stores, where a 5 cm thick potato layer was placed on floor in between two sand layers each of 20 cm thick. In order to allow evaporative cooling, 2.1 m^3 of water was sprinkled daily to wet the sand. It was observed that under low atmospheric RH conditions, wet sand was suitable for storing potatoes for up to 90 days as compared to 60 days in jute bags and still less in other storage methods like bamboo baskets and heaps.

Roy and Pal (1991) developed a low cost zero energy cool chamber—an on-farm rural oriented storage structure at IARI, New Delhi, using locally available raw materials such as bricks, sand, bamboo, dry grass, jute cloth etc., which operates on the principle of evaporative cooling. 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 lid was made by using dry grass/straw on a bamboo frame. The rise in relative humidity (90% or more) and fall in temperature (10–15 °C) from the ambient condition could be achieved by watering the chamber twice a day. Performance evaluation of cool chambers at different locations of the country was found to be satisfactory for short term storage of mangoes. Eventually, 3 to 4 days more shelf life of mature green mangoes could be obtained in cool chamber storage as compared to ambient condition storage. However, ripe mangoes when stored in cool chamber had 9 days shelf life as compared to 6 days under ambient condition and also scored high organoleptic values. It is most effective during the dry season.

Umbarkar et al. (1998) constructed an EC structure of 2 tonne capacity based on the results of their previous studies (Umbarkar et al. 1991). The walls of the structure were constructed with 10 cm thick brick batt pad sandwiched between two 10 cm thickness brick perforated walls. To add to the structural strength, 8 mm diameter mild steel reinforcement anchored the latter with each other. Holes of 50×40 mm were provided between two successive brick layers for air circulation throughout the height of the structure. A thatched roof with bamboo mat and dry grass was provided as cover at the top. At the bottom of storage stacks, a free board of 10 cm was left for bleed off water from walls. The temperature in the chamber varied between 23 and 26.5 °C as against ambient temperature variations between 25 and 44 °C on a test day. The relative humidity in the structure was 85–97%. The water requirement was 325 litres per day.

The potential energy savings envisaged by replacing conventional refrigerated systems by evaporative systems is ≈75% (Datta et al. 1987). Indirect systems can achieve comfort conditions similar to refrigerated systems in climatic zones where the wet bulb temperature is usually <25 °C. The comfort afforded by indirect evaporative systems is superior to that achieved by direct evaporative systems. An 8.5 ton indirect-direct evaporative cooling system has been fabricated and tested and its performance compared with a computer prediction.

An evaporative cooling system having an efficiency of 50%, has significant effect on room temperature of non-air-conditioned as well as shaded rooms (Lawrence and Tiwari 1989). Taha et al. (1994) designed and tested a special type of evaporative cooler for its performance under different conditions and concluded that the ambient temperature was reduced by 10–13 °C.

Physiological losses in tubers of three potato cultivars remained less than 10% until 12 weeks of storage under evaporatively cooled storage (Mehta and Kaul 1997). Reducing sugar contents increased by only 52.4–242.1% in tubers stored in evaporatively cooled storage as compared to 90.5–484.2% increase in tubers stored in refrigerated storage until 14 weeks. Potatoes stored in evaporatively cooled store were more suitable for processing into chips and french fries due to lower physiological losses and lower reducing sugar content of tubers.

Krishan Kant et al. (2001) examined the possibility of space conditioning the interiors of a multi-storey office building in Delhi using evaporative cooling in the summer months of April, May and June. The temperature and humidity conditions obtained in a room of the building with direct evaporative cooling are studied by simulation. In this case study, the room is assumed to have a south-facing wall with a window and all other walls, ceiling and floor are interior partitions. The effect of number of air-changes per hour (ACH) from 1 to 40 and fresh-air bypass factor (BPF) 0% to 100% on performance is studied by simulation. The aim is to find whether some combination of ACH and BPF succeeds in keeping room conditions below 80% RH and temperatures between 27 °C and 31 °C, depending on RH. It is found that the desired results are achieved by keeping the ACH and the BPF within certain limits depending on weather conditions. If the temperature and relative humidity of the ambient air are too high then a direct evaporative cooler cannot achieve comfort in the room. Appropriate combinations of ACH and BPF have to be selected to obtain the best results.

Bhardwaj and Sen (2003) treated fresh mandarin fruits ‘Nagpur Santra’ with 0, 10 and 20% neem leaf extract and kept at ambient condition (14.7–31.2 °C, 19.4–55.1% RH) and in zero energy cool-chamber (11.1–22.0 °C, 89.9–95.0% RH). The results showed that zero energy cool-chamber with 20% neem leaf extract significantly reduced the physiological loss in weight (PLW, 17.88%), rotting (18.07%), loss in juice content (11.08%), organoleptic taste score (6.08) and reduction in diameter (11.54%). The TSS (11.61° Brix) and total sugar (7.15%) were increased gradually though the rate of change was less under same treatment. The maximum retention of acidity (0.400%) and ascorbic acid (27.17 mg/100 ml juice) on 42nd day of storage was recorded in zero energy cool-chamber with 20% neem leaf extract. The fresh fruits could be kept upto 42 days in the same treatment as compared to 20 days in ambient condition, without any treatment (control).

Mordi and Olorunda (2003) built an evaporative cooler structure for fresh tomatoes storage with an average temperature drop of 8.2 °C from ambient condition of 33 °C while the RH increase was 36.6% over an ambient 60.4%. The evaporative cooler samples were rated higher for visual quality attributes and marketability than those stored under ambient conditions. The storage life of fresh tomatoes without packaging in evaporative cooler was 11 days from the 4 days storage life under ambient conditions. In combination with sealed but perforated polyethylene bags the fresh tomatoes were kept for over 18 days in the evaporative cooler and 13 days under ambient conditions. For the completely sealed samples however, the storage life of the tomatoes under ambient and evaporative cooler conditions were 6 and 8 days, respectively.

Anyanwu (2004) carried out the design, construction and measured performance of a porous evaporative cooler for preservation of fruits and vegetables. The experimental cooler, with a total storage space of 0.014 m^3, consists of a cuboid shaped porous clay container located inside another clay container. The gap between them is filled with coconut fibre. A water reservoir linked to the cooler at the top through a flexible pipe supplied water to fill the gap, thus keeping the coconut fibre continuously wet. Results of the transient performance tests revealed that the cooler storage chamber temperature depression from ambient air temperature varied over 0.1–12 °C. Ambient air temperatures during the test periods ranged over 22–38 °C. The results also illustrate superior performance of the cooler over open air preservation of vegetables soon after harvest during the diurnal operations. Thus, the evaporative cooler has prospects for use for short term preservation of vegetables and fruits soon after harvest.

Ganesan et al. (2004) studied the application of different levels of water on Zero energy cool chamber with reference to the shelf-life of brinjal and concluded that the shelf-life at room temperature which was hardly 3 days enhanced to 9 days with the addition of 100 litres of water per day. Jha and Kudas Aleksha (2006) worked on physical properties of pads for maximizing cooling in evaporative cooled store and concluded that partal wood savings was found to be best among the safeda, partal and root pad for maximum cooling effect in evaporatively cooled storage system. A thickness of 7 mm of partal wood savings cooling was found to give maximum surface evaporation of 14.87 g of water per minute. Singh and Satapathy (2006) evaluated the performance of IARI design Zero Energy Cool Chamber (ZECC) at ICAR Research Complex, Umiam, Meghalaya. The ZECC was evaluated for two consecutive years and shelf life of various fruits and vegetables like bitter gourd, capsicum, tomato, cauliflower, pineapple and peach was evaluated under cool chamber and ordinary room condition. It was observed that the mean maximum temperature inside the cool chamber was about 5 °C and 6 °C lower than the ambient during summer and winter season, respectively. Throughout the year, relative humidity (RH) inside the cool chamber was between 80 and 94%, whereas under the ambient it varies between 70 and 83%. The RH inside the cool chamber was nearly 13.34% and 12.34% higher during summer and winter months, respectively. It was observed that the shelf life of bitter gourd, capsicum, and cauliflower could be increased for 5 days whereas; the shelf life of tomato and peach and pineapple can be increased for about 6 and 9 days respectively, when it is kept inside the cool chamber as compared to ordinary room condition. Since it costs only about Rs.2500/- and can be easily constructed in the rural areas even by a layman, the fruits and vegetables growers can use it for short duration storage of horticultural produce.

Jain (2007)developed a modified evaporative cooler named two-stage evaporative cooler (TSEC) to improve the efficiency of evaporative cooling for high humidity and low temperature air conditioning. Two-stage evaporative cooler consists of the heat exchanger and two evaporative cooling chambers. The performance of cooler has been evaluated in terms of temperature drop, efficiency of the evaporative cooling and effectiveness of TSEC over single evaporation. The temperature drop through TSEC ranged from 8 to 16 °C. It was observed that TSEC could drop the temperature up to wet bulb depression of ambient air and provided the 90% relative humidity. Efficiency of single evaporation was 85–90%. Effectiveness of the two-stage evaporative cooling was found to be 1.1–1.2 over single evaporation. The two-stage evaporative cooler provided the room conditions as 17–25 °C temperature and 50–75% relative humidity, which can enable to enhance the shelf-life of wide range of fruit and vegetables of moderate respiration rates.

Thiagu et al. (2007) compared the tomatoes ripened in evaporative cooling (EC) storage conditions (20 °C–25 °C, 92–95% RH) with control fruits stored under room conditions (28 °C–33 °C, 45–65% RH) during summer in Mysore. EC ripened tomatoes on the 15th day reached 100% ripening index (RI) with a value of 2.48 for the ratio of redness to yellowishness (a/b) and hue angle (θ) of 22.1° whereas the control tomatoes on the same day reached a maximum 83.3% RI with a/b ratio of 1.59 and a hue angle of 32.9°. The lycopene content of EC ripened fruits double that of the control. EC stored fruits showed lower values for rupture and shear stresses. The rate of moisture loss for control fruits was 6.5 times as great as for EC stored tomatoes.

Dadhich et al. (2008) constructed an evaporative cool chamber with the help of baked bricks and riverbed sand. Maximum and Minimum temperature and relative humidity were recorded inside and outside the chamber for about 1 month. It was found that inside temperature was about 10–15 °C lower than outside temperature and inside humidity was about 30–40% higher than outside. It has been recorded that weight loss of fruits and vegetables kept inside the chamber was lower than those stored outside the chamber. The storage of fruits and vegetables as fresh was up to 3 to 5 days more inside than outside of the chamber.

Jha (2008) developed and tested a 5-tonne capacity evaporative cooled storage structure (ECSS) at pilot scale for fruits and vegetables grown in hot and dry regions. Performance of ECSS was evaluated in terms of temperature drop in ECSS and loss in weight of stored materials by preserving potatoes (4.5 tonnes), Kinnow (4.5 tonnes) and tomatoes (0.5 tonne) during 2005 and 2006 at CIPHET, Ludhiana. Temperature drops at center of ECSS as compared to outside conditions were about 20 °C (very near to wet bulb depression of 23.5 °C for prevailing outside conditions in corresponding day) and 17 °C and rise in relative humidity from 10 to 65%.

Several types of materials, namely metals, fibres, ceramics, zeolite and carbon, has potential to be used as heat and mass transfer medium in the indirect evaporative cooling systems (Zhao et al. 2008). A comparative analysis into different types of material for indirect evaporative cooling systems was carried out, and concluded that the wick (sintered, meshes, groves and whiskers) attained metals (cooper or aluminium) are the most adequate structure/material over the others. Wick-attained aluminium sheet is much cheaper than cooper with the same structure and therefore more suitable for this application.Pad evaporative cooling systems for the Mediterranean region of Turkey may provide a solution for controlling the high temperatures that can negatively affect poultry houses (Metin et al. 2009). Average evaporative cooling efficiency was determined as 69.2% on July 18, 70.1% on July 19, 69.4% on July 25, 70.8% on July 29 and 72.0% on August 3. The temperature decrease in pad exit during the experiment was determined as 6.1 °C, 7.3 °C, 4.4 °C, 5.0 °C and 5.9 °C, respectively.

Economics

The economics of using evaporative cooling are surprising to most people. An 85% reduction in energy used compared to a conventional air conditioning unit seems too good to be true. Compared to air-conditioning which uses mechanical refrigeration, the operating cost of heat evaporative exchanging are 90% less than air conditioning. There are, now a days in operation, more than 20 millions of residential evaporative cooling in all world, saving approximately 60 millions of petroleum's drum and avoiding the emission of 27 billions of CO_2 pound yearly (Camargo 2007). In the USA, only the fair of residential evaporative cooling moves US$ 180 millions in the year, with more than 4 millions of units installed. The cost per unit of equipment is between US$ 35 for simple direct system and US$ 2,000 for completely systems with ducts, and the average cost between US$ 300 and US$ 700. The direct settling reduce the operation costs between 25% and 40% when it is compared with costs of mechanical refrigeration only (ASHRAE 1995), to produce the same cooling effects. A direct/indirect system accounts for saving between 40% and 50% energy in moderately wet areas. On farm evaporative cool storage was found to be technically feasible at reducing potato storage losses by as much as 50% over farmer's methods (Fuglie et al. 1997). However, the additional cost of ECS may be too high to encourage widespread adaptation.

Advantage of evaporative cooled storage

1. Avoid distress sale of fresh fruits, vegetables and flowers. It requires no special skill to operate and therefore is most suitable for rural application.
2. It can be made from locally available materials.
3. Its size can be fitted to the house hold need.
4. Better marketability of fresh horticultural produce than ambient.
5. Retain nutritive value.
6. Environment friendly storage system with no pollution.
7. Highly efficient evaporative cooling systems that can reduce energy use by 70%.
8. Evaporation not only lowers the air temperature surrounding the produce, it also increases the moisture content of the air. This helps to prevent the drying out of the produce, and therefore extends its shelf life.
9. Less expensive to install and operate.
10. It can be easily made and maintained.
11. The evaporative cool chamber does not require mechanical or electrical energy input and can be constructed with locally available material with unskilled labour.
12. It is economical and can store the fruits and vegetables for 3 to 5 days without any significant loss

Disadvantage

1. Evaporative cooling system requires a constant water supply to wet the pads. Therefore, need to be watered daily.
2. Space is required at outside the home.
3. Water high in mineral content leave mineral deposits on the pads and interior of the cooler gets damaged.
4. High dew point (humidity) condition decreases the cooling capability of the evaporative cooler.
5. No dehumidification. Traditional air conditioners remove moisture from the air, except in very dry location. Evaporative cooling adds moisture and in dry climates, dryness may improve thermal comfort at higher temperatures.

Conclusion

India is the fruit and vegetable basket of the world. Approximately 23–35% of the horticulture produce goes waste due to improper post harvest operations and due to lack of enough storage facilities. Evaporative cooling system have a very large potential to propitiate thermal comfort. Nowadays, evaporatively cooled storage system is increasingly being used for on-farm storage of fruits and vegetables. Evaporative cooling system not only lowers the air temperature surrounding the produce, it also increases the moisture content of the air. This helps prevent the drying amount of the produce, therefore extends the shelf life of horticultural produce. Evaporative cooling system is well suited where; temperatures are high, humidity is low, water can be spared for this use, and air movement is available. There are many different styles of evaporative coolers. The design depends on the materials available and the users requirements. It is most suitable for the short term storage of vegetables and fruits soon after harvest. Zero Energy Cool Chamber could be used effectively for short-duration storage of fruits and vegetables even in hilly region. It not only reduces the storage temperature but also increases the relative humidity of the storage which is essential for maintaining the freshness of the commodities.

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