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Research Article

Principles and Application of Evaporative Cooling Systems for Fruits and Vegetables Preservation

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Abstract

In order to extend the shelf life of fruits and vegetables, they need to be properly stored. Proper storage means controlling both the temperature and relative humidity of the storage area. The essence of storage is of great importance because not all the harvested vegetables or crops in general will be used immediately after harvest so, measures of preserving the vegetables before it exceeds its shelf life is of great importance. Most of the peasant farmers are not able to afford the cost of purchasing high tech storage equipments for their harvested crops. Evaporative cooling has been found to be an efficient and economical means of reducing temperatures and increasing humidity in an enclosure where the humidity is comparatively low. Minimizing deteriorative reactions in fruit and 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. The atmosphere in the chamber therefore becomes more conducive for fruit and vegetable storage. Therefore, this paper reviews the concept, principle, method and types of evaporative cooling. The evaporative cooling systems has prospect for use for short term preservation of fruits and vegetables after harvested. It reduces the storage temperature and also increases the relative humidity within the optimum level of the storage thereby helps in keeping the fruits and vegetables fresh. Potential improvements for evaporative cooling devices include improvements in materials used, mainly in absorbent pads and ceramic pots. Experimentation needs to be performed to identify more locally available materials that can successfully be used as absorbents.

***Keywords**: Applicability; Cooling; Evaporative; Systems; Preservation*

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1. Introduction

Fruits and Vegetables are vital agricultural products for human consumption worldwide. They are rich in vitamins and minerals such as carotene (provitamin A), ascorbic acid, riboflavin, iron, iodine, calcium etc (Ihekoronye and Ngoddy, 1985). Deficiency of these nutrients can lead to widespread of diseases and on the long run, lead to death. Vegetables are also rich in fibres which are essential for good digestion. Results from the Global Burden of Disease project for year 2000 show that up to 2.7 million deaths worldwide and 1.8 percent of the total global disease burden may be attributed to inadequate consumption of fruits and vegetables (Lock *et al*., 2004).

However, these produce are not only seasonal but highly perishable. The essence of storage is of great importance because not all the harvested vegetables or crops in general will be used immediately after harvest so, measures of preserving the vegetables before it exceeds its shelf life is of great importance. Some methods of preservation of raw and processed fruits and vegetables include: storage in ventilated shed, storage at low temperatures, use of evaporative coolant system, waxing and chemical treatment (Olosunde, 2006).

Most of the peasant farmers are not able to afford the cost of purchasing high tech storage equipments for their harvested crops. Evaporative cooling has been found to be an efficient and economical means of reducing temperatures and increasing humidity in an enclosure where the humidity is comparatively low (Sushmita *et al*., 2008). Minimising deteriorative reactions in fruit and vegetables enhances their shelf lives, implying that the produce will be available for longer periods; this would reduce fluctuation in market supply and prices (Dzivama, 2000).

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2. Concept of evaporative cooling

Evaporative cooling is the process by which the temperature of a substance is reduced due to the cooling effect from the evaporation of water. The conversion of sensible heat to latent heat causes a decrease in the ambient temperature as water is evaporated providing useful cooling. This cooling effect has been used on various scales from small space cooling to large industrial applications.

Evaporative cooling differs from common air conditioning and refrigeration technologies in that it can provide effective cooling without the need for an external energy source. Effective cooling can be accomplished by simply wetting a surface and allowing the water to evaporative. Humans can most notably feel this effect as the body is cooled by evaporating sweat from the skin during physical exertion. This simple form of evaporative cooling is the basis for more mechanized and complex evaporative cooling systems.

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. The atmosphere in the chamber therefore becomes more conducive for fruit and vegetable storage.

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. Generally, an evaporative cooling structure 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 (FAO, 1995).

In developing countries like Nigeria, agriculture constitutes the bulk of the informal sector of the economy. It is reported that among the various types of activities that can be termed as agriculturally based, fruit and vegetable processing are among the most important (FAO 1995). However farmers are not getting enough value for their product due to weak infrastructure, poor transportation, and perishable nature of the crops, which result in substantial economic losses. During the post-harvest glut, the loss is considerable and often some of the produce has to be fed to animals or allowed to rot. According to Ndirika and Asota, (1994), the damage that occurs in some bio products is primarily by loss of moisture, change in composition and pathological attack.

An aspect to consider when handling fruits and vegetables is the temperature and relative humidity of the storage environment. For fresh harvested produce, any method aimed at increasing the relative humidity of the storage environment (or decreasing the vapour pressure deficit (VPD) between the commodity and its environment) will slow the rate of water loss and other metabolic activities (Katsoulas *et al*., 2001). This will slow both the respiratory processes and activities of micro-organisms (pathogens) which are the most destructive activity during storage of fruits and vegetables (Barre *et al*, 1988).

Although, refrigeration is very popular but it has been observed that several fruits and vegetables, for example banana, plantain, tomato etc. cannot be stored in the domestic refrigerator for a long period as they are susceptible to chilling injury (Shewfelt, 1994; Olusunde *et al*. 2009). Apart from this, the epileptic power supply and low income of farmers in the rural communities' makes refrigeration expensive.

FAO (1983) advocated a low cost storage system based on the principle of evaporative cooling for storage of fruits and vegetables, which is simple, and relatively efficient. The basic principle relies on cooling by evaporation. However sometimes when evaporative cooling system is used in preservation, it is used with shade on top (Kittas *et al* 2003).

The fundamental governing process of evaporative cooling is heat and mass transfer due to the evaporation of water. This process is based on the conversion of sensible heat into latent heat. Sensible heat is heat associated with a change in temperature. While changes in sensible heat affect temperature, it does not change the physical state of water. Conversely, latent heat transfer only changes the physical state of a substance by evaporation or condensation (Watt and Brown, 1997).

As water evaporates, it changes from liquid to vapor. This change of phase requires latent heat to be absorbed from the surrounding air and the remaining liquid water. As a result, the air temperature decreases and the relative humidity of the air increases. The maximum cooling that can be achieved is a reduction in air temperature to the wet-bulb temperature (WBT) at which point the air would be completely saturated (La Roche, 2012).

A. Conditions Affecting Cooling

The cooling effect of an evaporative cooler depends on the rate of evaporation and on conditions within the cooler. Environmentally, temperature and humidity have the most significant impact on evaporation. The temperature must be high enough to allow for evaporation and the relative humidity must be low enough to allow for more water vapor to enter the air. Water quality also has an important role in both evaporation and keeping the system well maintained (Fouda and Melikan, 2011). Evaporative coolers can only provide cooling down to 10C under optimal conditions. Lower temperatures require different cooling technologies (Holand, 2010).

B. Evaporation vs. Boiling

Evaporation differs from boiling and can be accomplished at a temperature lower than the boiling temperature of water because it occurs at the liquid-vapor interface. Evaporation occurs when the vapor pressure of water is lower than the saturation pressure of water. Conversely, boiling occurs when a liquid contacts a surface at a temperature at or above the saturation temperature. This solid-liquid interaction causes vapor bubbles to form and rise to the free service of the water (Cengel and Boles, 2008).

3. Brief history of evaporative coolers

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. 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. There have been various designs over the years. In early Ancient Egyptian times, paintings depicting slaves fanning large, porous clay jars filled with water which is essentially is a very, very early form of evaporative cooling. The first man made coolers consisted of towers that trapped wind and funnelled it past water at the base and into a building. This in turn kept the building cool at the time. (dualheating.com).

In 1800 B.C the new England textiles factory began to use the evaporative cooling systems to cool their mills (www.evaprocool.com). In the 1930's the Beardmore tornado airship engine used to reduce and completely remove the effect of using a radiator which reduces the effect of lag.(coco.cooler.com) Bamboo coolers were constructed with bricks with hessian cloth which were used to wrap the bricks. Also, charcoal coolers were also produced together with the Almirah coolers. Rusten, (1985) described some types of evaporative cooling that was been used in New Delhi, India in which a wetted mat with fan was used to cool a local restaurant. The concept of water-cooling a roof has a long history but it is estimated that less than 60 million square feet of roof have ever been water cooled (Tiwari *et al.*, 1992). It was also reported that if only a small amount of water is placed on the roof, the evaporation is highly accelerated as compared to what would be if the roof surface was flooded (Carrasco, 1987).

4. Usage and performance of evaporative cooling systems

One study of an evaporative cooling system in Ethiopia used an evaporative cooler to successfully increase the storage life of mangoes. The storage cooler was able to reduce the ambient temperature throughout the day from a range of 23-43C to 14.3-19.2C with an increase in relative humidity from 16-79% to 70-82.4%. On average, the temperature and relative humidity differences were 10.7C and 36.7% respectively. This caused the storage life of mangoes to double from 14 to 28 days with a 55% increase in the number of marketable mangoes. Another study in Ethiopia showed that a multi-pad evaporative cooler resulted in a 5C temperature drop and 18% relative humidity increase compared to a single pad cooler (Getinet *et al.*, 2008). Multiple studies have been conducted regarding vegetable storage in Nigeria. One study used a cooler with coconut fiber as the absorbent in a cabinet shaped cooler. During a no-load test, the cooler was able to achieve cooling of 0.1C-8.3C. When the relative humidity was 80%, it was found that no cooling occurred. Using the cooler, pumpkins were stored 60 hours instead of 12 hours without cooling and tomatoes lasted for 93 hours compared to 32 hours (Anyanwu, 2004).

A different study in Nigeria constructed an evaporative cooler out of clay with one cooling pad and a reflective surface on the roof. The cooler reduced ambient temperatures from 32-40C to 24-29C throughout the day. This cooler was found to have a cooling capacity from 870-1207 W and was able to store tomatoes for 19 days (Chinenye, 2011). Similar studies have shown increases in storage life of 14 days over ambient storage conditions Mogaji and Fapetu, 2011).

The study of a pot-in-pot cooler also had successful cooling results. During the hottest part of the day, the cooler was 15C cooler than the ambient temperature. The cooler also had smaller temperature fluctuations throughout the day compared to the ambient temperature. In this study, carrots were preserved for 40 days and bell peppers were kept for 25 days compared to 18 days without cooling (Aimiuwu, 2008).

5. Types of evaporative coolers

Evaporative cooler designs vary based on absorbent medium, storage chamber construction, method of evaporation. Many different evaporative cooler designs exist in both unpowered and externally powered forms. Evaporative coolers that need no external power are designed to allow for natural airflow to provide the convection needed for adequate cooling. Various designs within this group allow for heat transfer in slightly different ways. While all coolers rely on converting sensible heat to latent heat, the mechanism for this conversion can be different.

Some evaporative cooler designs are created using porous materials to allow water to seep from an inside container to an outer surface where evaporation occurs. For these designs, evaporation is aided by drawing heat from the inner cooling chamber. As warmer water molecules evaporate and leave the outer surface, the surface cools and a heat gradient causes heat to diffuse from the inner chamber out to the surface (Animiuwu, 2008). As a result, the temperature within the inner chamber decreases causing a cooling effect on whatever is stored in the cooler.

A second type of evaporative cooler operation relies on airflow through a wetted pad to provide cooling. In this design, an absorbent pad forms part of the wall of a cooling chamber and air, either through natural airflow or forced flow from a powered fan, passes through the wetted pad. Water is evaporated from the pad into the air and causes a drop in the air temperature. This air then flows through the cooling chamber to provide cooling.

A. *Unpowered*

One of the most notable evaporative coolers is the pot-in pot cooler due to its simplicity and effectiveness. The pot-in-pot evaporative cooler design is a simple passive cooler designed by Mohammed Bah Abba who received a Rolex Award for his innovation (www.rolexaward.com). The cooler consists of two concentric clay pots, one placed inside the other with a buffer layer of sand between them. The sand acts as a wetted medium that holds water needed for cooling. A wet cloth is placed over the top of the pots to aid cooling. Also called a Zeer pot due to the name of the pots used in some parts of Africa, the pot-in-pot system has been tested for food preservation by the organization Practical Action and has shown to significantly increase produce storage life, in some cases up to five times as long as for certain vegetable (Nobel, 2003). The pot-in-pot cooler has an approximate capacity of 12kg of vegetables (www.scidev.net). While very effective, the pot-in-pot cooler is limited in storage volume by the size of the pots used.

Many other passive cooler designs exist in addition to the pot-in-pot design. Developed by the Food and Nutrition Board of India, the Janata cooler is similar to the pot-in-pot cooler in that it uses ceramic pots. The Janata uses a storage pot placed in a large bowl of water with a cloth placed over the pot and dipped into the bowl to soak up water which is then evaporated to provide cooling. A charcoal cooler consists of a wooden frame holding two layers of wire mesh with a gap between them that encloses charcoal pieces which act as the absorbent. An Almirah cooler is made from a wooden frame with cloth enclosing the frame to create a storage chamber. The cloth is dipped into a tray of water to absorb water to provide a cooling surface for evaporation (Nobel, 2003).

Unpowered static cooling systems provide a larger chamber for increased storage. These systems are generally designed with a double wall chamber made of bricks. The gap between the walls varies with multiple designs using a gap between 3-5 inches. The gap is filled with sand like the pot-in-pot cooler. The sand is either kept moist by manually wetting it or through the use of a drip hose connected to a water reservoir. In the cooling chamber, food is stored, usually separated into different tray (Davis, 2002).

B. Externally Powered

Evaporative coolers can be designed using an externally powered fan to provide airflow and a pump to provide continuous wetting. These systems are constructed differently than unpowered systems in that they use a cooling pad in place of an absorbent medium and do not rely on water flowing through a porous structure for evaporation. Instead, a fan forces air through a wetted absorbent pad from which water is evaporated thus cooling the air. The cooled air then travels through the cooling chamber to reduce the storage temperature.

In these systems, the absorbent pad plays a major role in the cooling process. Many factors affect pad performance including pad material, pad thickness, and size of perforations (Malli, 2011). Current commercial pads are often made of cellulose, plastic, or fiberglass which can be expensive and are not made of locally available materials (Gunhan, 2006; Elmetenani, 2011). Investigation has been done into using local materials to make effective cooling pads for evaporative cooling systems. One criterion for cooling pad evaluation is cooling efficiency calculated by:
(Al-Sulaiman, 2002)

$$\eta_{cooling} = \frac{\Delta T}{T_d - T_w}$$

where ΔT is the change in actual temperature, T_d and T_w are the dry bulb and wet bulb temperatures respectively. Experiments with palash and coconut fibers show comparable performance with aspen and khus pads with improved effectiveness in some situations(Jain and Hindoliya, 2011). Luffa fibers were determined to be a suitable material for evaporative pads based on performance and slower degradation than other materials (Al-Sulaiman, 2002). Volcanic tuff and pumic were compared to commercial cellulose pads with volcanic tuff pads found to be a suitable alternative to the commercial pad at a specific air velocity (Gunhan, 2006). Straw and sliced wood pads have also been investigated for greenhouse use with sliced wood providing the best performance (Ahmed, 2011).

C. Other Types

Other alternative evaporative cooling methods include fog or misting systems, which spray small diameter water droplets into the air for evaporation, and roof top evaporation systems which involve a thin water layer on the top of a building resulting in evaporation and cooling (Sethi and Sharma, 2007).

6. Principles of evaporative cooling

A. Evaporative Cooling with Psychrometric Chart

According to Rusten, (1985) cooling through the evaporation of water is an ancient and effective way of cooling water. He further disclosed that this was the method been used by plant and animal to reduce their temperature. He gave the conditions at which evaporative cooling would take place which are stated below:

(1) Temperatures are high
(2) Humidity is Low
(3) Water can be spared for its use
(4) Air movement is available (from wind to electric fan)

Also he disclosed that the change of liquid stage to vapour requires the addition of energy or heat. The energy that is added to water to change it to vapour comes from the environment, thus making the environment cooler.

Therefore, the use of the psychrometric chart is of great importance in order to discover whether evaporative cooling has taken place. Air conditions can be quickly characterized by using a special graph called a psychrometric chart. Properties on the chart include dry-bulb and wet-bulb temperatures, relative humidity, humidity ratio, specific volume, dew point temperature, and enthalpy Beiler, (2009).

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. When the temperatures are the same, no net evaporation of water in air occurs, thus there is no cooling effect (Wikipedia.com).

Therefore for optimum cooling efficiency using the evaporative cooling technique temperature and the relative humidity measurement is needed to be taken and the psychrometric chart defines these variables at various stages.

B. Factors Affecting Rate of Evaporation

Evaporative cooling results in reduction of temperature an increase in relative humidity (Olosunde, 2006).It is necessary to understand the factors that can limit the efficiency of the system from producing the intended results. There are four major factors that affect the rate of evaporation which was analysed by (Rusten, 1985). He later added that though they are discussed separately but it is important to keep in mind that they all interact with each other to influence the overall rate of evaporation, and therefore the rate of cooling. The factors discussed by (Rusten, 1985) include:

(1) Air Temperatures:

Evaporation occurs when water is absorbs sufficient energy to change from liquid to gas. Air with a relatively high temperature will be able to stimulate the evaporative process and also be capable of holding a great quantity of water vapour. Therefore, areas with high temperatures will have a high rate of evaporation and more cooling will occur. With lower temperature, less water vapour can be held and less evaporation and cooling will take place.

(2) Air Movement (Velocity)

Air movement either natural (wind) or artificial (fan) is an important factor that influences the rate of evaporation. As water evaporates from wet surface, it raises the humidity of the air that is closest to the water surface (moist area) .If the humid air remains in place, the rate of evaporation will start to slow down as the humidity rises. On the other hand if the humid air near the water surface is constantly being moved away and replaced with drier air, the rate of evaporation will either increase or remain constant.

(3) Surface Area

The area of the evaporating surface is another important factor that affects the rate of evaporation. The greater the surface area from which the water evaporates, the greater the rate of evaporation.

(4) Relative Humidity of the Air

This is the measurement of the amount of water vapour in the air as a percentage of the maximum quantity that the air is capable of holding at a specific temperature. When the relative humidity of the air is low, this means that only a portion of the total quantity of water which the air is capable of holding is being held. Under this condition, the air is capable of taking additional moisture, hence with all other conditions favourable, the rate of evaporation will be higher, and thus the efficiency of the evaporative cooling system is expected to be higher.

7. Methods of evaporative cooling

Rusten, 1985 specified that there are two main methods of evaporative cooling namely:

(1) Direct evaporative cooling (2) Indirect evaporative cooling

(1) Direct Evaporative Cooling

This is a method by which air is passed through a media that is flooded with water .The latent heat associated with the vaporizing of the water cools and humidifies the air streams which now allows the moist and cool air to move to its intended direction. (Sellers, 2004) Sanjeev, (2008) disclosed that direct evaporative cooling has the following major limitations:
1) The increase in humidity of air may be undesirable.
2) The lowest temperature obtainable is the wet-bulb temperature of the outside air,
3) The high concentration and precipitation of salts in water deposit on the pads and the other parts, which causes blockage, and corrosion, and requires frequent cleaning, replacement, and servicing.

(2) Indirect Evaporative cooling:

A heat exchanger is combined with an evaporative cooler and the common approach used is the passes return/exhaust air through an evaporative cooling process and then to an air-to air heat exchanger which in turn cools the air, another approach is the use of a cooling tower to evaporatively cool a water circuit through a coil to a cool air stream (Sellers, 2004).

Sanjeev, (2008) also said indirect cooling differs from direct cooling in the sense that in indirect cooling the process air cools by the evaporation of water. But there is no direct contact of water and process air. Instead a secondary airstream is used for evaporation of water. So the moisture content of process air remains the same.

8. Forms of direct evaporative cooling

Dzivama, (2000) did a study on the forms of evaporative cooling process and discovered that there are two forms in which the evaporative cooling principle can be applied. The difference is based on the means of providing the air movement across/through the moist materials .These is the passive and non-passive forms. The passive form of evaporative cooling relies on the natural wind velocity, to provide the means of air movement across/through the moist surface to effect evaporation. This form can be constructed on the farm, for short term on farm storage while the non- passive form uses a fan to provide air movement.

A. Passive-direct evaporative cooling system

Construction and design varies but the general principles are the same. The main components include:
i) The cabinets where the produce is stored.
ii) The absorbent material used to expose the water to the moving air
iii) An overhead tank/through through which the water seeps down on to and wet the absorbent material. The absorbent material covering the cabinet absorbs water from the tank on top of the cabinets, the entire cloth that was used as cabinet is soaked in water and the air moves past the wet cloth and evaporation occurs. As long as evaporation takes place, the contents of the cabinet will kept at a temperature lower than that of the environment and the temperature reduction obtained in this type of cooler ranged from 5°C to 10°C. Different researches have been done by researches names like Rusten, (1985), Susanta and Khurdiya, (1986), Olosunde, (2007), Sushmita *et al*.,(2008) have designed various forms of coolers.

B. Non- passive direct evaporative cooling system

This uses a small fan, a water pump which is powered by electricity. The products are kept in storage cabins inside the coolers, Absorbent material which receives the water and expose it to evaporation with the help of the fan which draws air through the pad and a overhead tank which is constantly supplying water to the absorbent material. Materials used as the absorbent materials are hessian materials, cotton waste and celdek and the body frame is made of wood. The pad and the fan are directly opposite to each other.

9. Cooling pad material

There is transfer of heat from the pad material during evaporation and during this
process water is been evaporated. The cooling capacity of a system is independent on the amount of air flow and its saturation which in turn depends on the characteristics of the pad, air velocity through the pad and the water flow rate (Thakur and Dhimgra, 1983).

Evaporation from the wetted pad affected by some factors which are wind, temperature, surface area , humidity, air velocity ,water flow rate and thickness. The amount of water that the air can evaporate from the pad depends on the rate of saturation and the temperature of the air(Olosunde ,2006).The lower the relative humidity the higher the rate of evaporation and thus the more the cooling takes place(Dvizama, 2000).

Various materials have been used as pad ranging from, palm tree leaves, hessian cloths, ,aspen wood, jute, cotton materials, perforated clay blocks mad some other materials based on the functionality , costing and availability. Dvizama (2000) tested luffa (aegyptica), stem variety sponge and jute material for the use of pads in an evaporative cooler. During the experiment it was discovered that jute pad had the highest efficiency with thickness of 60mm compared the other used pad materials. Olosunde (2006) tested three materials namely jute, hessian and cotton waste and after series of experiment, jute pad also had the highest efficiency.

Conclusion

Vegetable and fresh produce storage has proven to be a good application for evaporative cooling. High temperature is an important factor in produce preservation that can be combated by evaporative cooling. To lengthen storage life, fresh produce needs to be stored in conditions of high humidity to reduce water loss which evaporative cooling can also achieve. Potential improvements for evaporative cooling devices include improvements in materials used, mainly in absorbent pads and ceramic pots. Experimentation needs to be performed to identify more locally available materials that can successfully be used as absorbents.

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