Review of research and application of evaporative cooling in preservation of fresh agricultural produce

M. C. Ndukwu[1,2], S. I. Manuwa[2]

(1. *Department of Agricultural and Bio-resources Engineering, Michael Okpara University of Agriculture, Umudike Umuahia Abia State, Nigeria*;
2. *Department of Agricultural Engineering, Federal University of Technology Akure, P.M.B. 704 Akure, Ondo State, Nigeria*)

Abstract: Extensive review of evaporative coolers for the preservation of fresh agricultural produce in some countries was presented. Most of the designs employ mainly direct evaporative cooling methods which are simple but with lower thermal performance, and can only be used for short term storage of agricultural produce with moderate respiratory rates. Researches into novel technologies in evaporative cooling systems which can improve the cooling performances, such as membrane air treatments, dew point type and heat pipe type heat exchanger in indirect/direct evaporative cooling application, and their feasibilities in agricultural storage are either absent or scarce. Some kinds of materials especially agricultural residues have been used for air water contact in evaporative cooling in different climates, but most of the analyses focused on effect of air flow rate and pad thickness on the cooling effectiveness, and the energy efficiency and evaporation loss of these materials in most cases were not evaluated or presented. The paper highlights the prospects and constraints of commercialization and marketing of evaporative coolers in some developing countries, and the general weakness in researches and the ways forward in new area of research and development are concluded.

Keywords: agricultural products, evaporative cooling, passive coolers, active coolers, pad materials
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1 Introduction

The world population has continuously increased over the years, and consequently the energy demand for many countries has also increased. The global population is predicted to hit around 8 billion by the year 2025[1]. The major concern is the economic rise of highly populous countries such as China, Brazil, India and even Nigeria, which leads to rise in the overall living standard in these countries. However from an agriculture perspective, this translates into a real increase in the food demand[2]. Agricultural engineers are challenged with the technology that will aid the farmers in meeting the food demand of the ever increasing world population, and also to lower the price of food and its products. According to Kael[2], the basic economics principles in stabilizing the cost of a product, undergoing an increase in its demand requires either an increase in its supply or a decrease in its cost of production. One of the areas to tackle is the reduction in

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Biographies: Manuwa S I, PhD, professor. Majoring in equipment engineering for plant production, soil dynamics in tillage and traction, conservation agriculture mechanization, and postharvest technology. Tel. + 2348034152976, Email: manuwaseth@rocketmail.com. Member of the ASABE, member of Nigerian Institution of Agricultural Engineer (NIAE) and Registered Agricultural Engineer by the Council for the Regulation of Engineering Practice in Nigeria (COREN).

***Corresponding author: Ndukwu Macmanus Chinenye**, PhD student, lecturer of Department of Agricultural and Bioresources Engineering, Michael Okpara University of Agriculture, Umudike. P.M.B. 7267 Umuahia, Abia state, Nigeria. Majoring in equipment engineering for plant production and postharvest technology. Tel. +2348032132924, Email: ndukwumcu@gmail. com or ndukwumcb@yahoo.com. Member of the ASABE and NIAE and Registered Agricultural Engineer by theCOREN.

the post harvest losses in order to achieve the above objective. The major post harvest losses in the developing countries are those that are related to temperature and humidity, due to lack of proper or adequate storage facility. Post harvest losses in South East Asia can range from 10%-50% depending on a particular country[3]. However in Africa, post harvest losses are not properly documented but experts have projected the losses to be up to 80%. This is because, during the period of glut in the market, unsold agricultural products especially fresh produce are allowed to rot away and some eating or fed to animal. Most of the farmers in developing countries cannot afford the high cost of storage facility available in the market. Also in these countries, power outage is very regular due to the rising cost of energy for power generation. This has greatly affected their income generation sincemost products produced cannot be properly preserved, resulting in huge waste especially of fruits and vegetables.

The Food and Agriculture Organization (FAO) of the United Nation has envisaged this crisis and its impact in the global food production since 1983[4]. Therefore the FAO advocated for a low cost and energy saving storage system based on the principle of evaporative cooling for the storage of fresh agricultural produce during the favourable weather conditions. The World Bank also in 1999[5] recognized the benefits of evaporative cooling which includes reduction in the energy cost, low carbon emission if any, no usage of hydrocarbon gases, improving indoor air quality and humidity and regional energy independence. In the beginning, evaporative coolers are mostly the passive design type and they are called swamp, desert or wet air coolers[6-8]. They are called desert coolers because they are well suited for climates where the air is hot and humidity is low like in Iran and Kuwait of the Persian Gulf countries. Evaporative air-cooling is also popular and well suited to the temperate area like southern Australia. According to Gutenberg[9], in the United States, the use of the term swamp cooler may be due to the odor of algae produced by early units. The use of evaporative cooling techniques in reducing the temperature of a system is very old, but it grew in the importance at the turn of the twentieth century, when it became a subject of flurry of patents in the U.S.A[10-12]. With the ever increasing cost of power consumption and competition from many appliances, gradual shift to the use of efficient equipment that can utilize less power becomes necessary. The installation and the operating cost of an evaporative cooler can be much lower than that of refrigerator or air conditioner, often by 50% or so[13]. Subsequent research has shown that using an evaporative cooler to preserve fresh agricultural products like fruits and vegetables, prevent chilling injury and color changes unlike compression refrigerators[14].

Most of the research in evaporative cooling especially in the developed countries has focused on its utilization in building for comfort cooling. This is different in most tropical region which a lot of the developing countries of the world fall into. In many tropical countries, research in evaporative cooling has been on the utilization for short term preservation of fresh agricultural products. Several kinds of materials have been used as the cooling pad for air water contact in the evaporative cooling designs. The aim of this paper was to collectively highlight and review some researches on evaporative cooling preservation of agricultural produce as much as possible. This paper takes cognizance of other literature published in different languages but will limit itself to review of literature published in English language because of language barrier. The authors acknowledge that they cannot lay their hands in all the works in evaporative cooling of fresh produce but those highlighted, will serve as a reference guide for future developments.

2 Principle of evaporative cooling and applications

2.1 Principle of evaporative cooling

Evaporative cooling is a physical phenomenon in which the evaporation of liquid into surrounding air cools a body in contact with it. The surface of the body becomes much cooler when water evaporates from it because it requires heat to change the liquid into vapor[15]. The wet bulb temperature, as compared to the air dry bulb temperature is the measure of the potential for evaporative cooling when considering water evaporating into air. The greater the difference, between the two temperatures, the greater the evaporative cooling effect[16]. Therefore, evaporative cooling works by utilizing the natural process of water evaporation, along with an air moving system, to create an effective cooling environment. The fresh and warm outside air moves through the wet porous pad that cooling the air through water evaporation (see Figure 1).

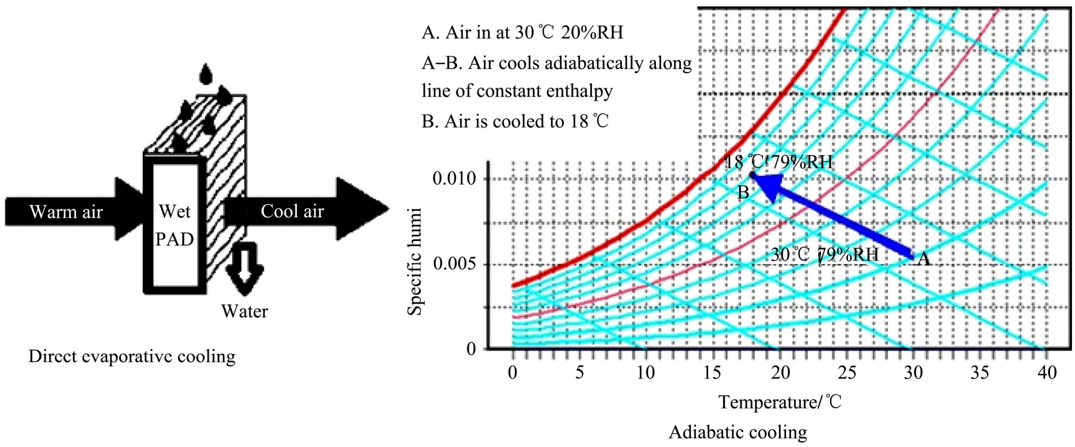

Figure 1 Schematic of direct evaporative cooling (Source: www.ecocooling.co.uk/psychr.html)

The major components of this system are pad media, water supply, distribution pipe, gutter, sump, and bleed-off line. Some of the moisture evaporates into the air stream as air flows past the moist pad surfaces. Heat is withdrawn from the air during this process and the air leaves the pad at a lower temperature with higher moisture content.

2.2 Water absorbent materials (cooling pads) for evaporative cooling systems

Water is the working fluid in the evaporative cooling systems and several kinds of materials have been used to provide the wet surface for air water contact in the evaporative cooling designs. The major characteristic of these materials is the ability to hold water and allow air to pass through. Several organic and inorganic materials have been tested for the evaporative cooling purpose under different climates. These include the metal pads, cellulose pad, hessian pads, Aspen, PVC pad, porous ceramic pad, wood shaven, jute, rice straw; excelsior of pine, fir, cotton wool, charcoal and latex foam. Others are luffa , cedar, red wood, spruce, plain and etched glass fibers, copper, bronze, galvanized screening , vermiculite, perlite, palm leaf, palm fruit fiber, expanded paper, woven plastic etc[5,14,17-22]. Some of these materials are shown in Figures 2-4.

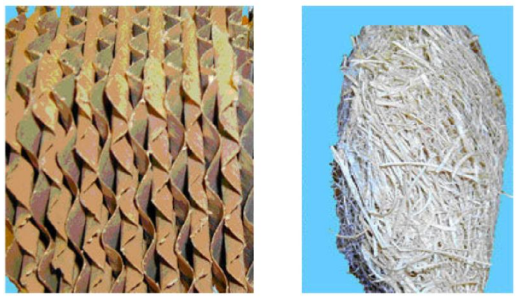

Figure 2 Aspen pad

Figure 3 Porous ceramic pad

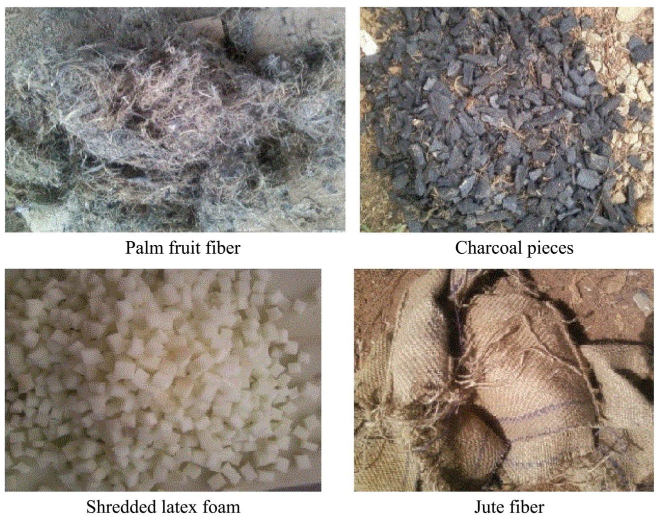

Figure 4 Pad materials

The few pads used in the tropical environment especially Nigeria are mainly agricultural residues and were evaluated using passive coolers which limits its performance to areas with constant natural moving air[12,23-25]. This pad media is packaged in the range of 2, 6, 8, 12 and 18 inches (1 inch=2.54 cm) thickness. A typical 12 inches pad can provide 123 square inches of surface area of cooling per cubic foot of media[26]. They have a higher effectiveness because of a large evaporation area but this will come at the cost of higher fan capacity and construction materials. Commercial available pads from companies like Munters, Kuul, and Glacier-Cor, who offer various paper thicknesses, high resin content in the binder glue and different curing methods that improve the tensile strength and crush strength[26], are scarce in most developing countries.

The performances of these absorbent materials have also been presented with graphs, tables and schematics. These include the thermodynamic properties, the cooling efficiencies, evaporative effectiveness, cooling capacity, saturation densities and water holding capacities.

2.3 Common types of evaporative cooling methods

There are two basic types of evaporative cooling systems which include direct and indirect evaporative cooling systems[15]. The air passes straight across the humidifier into the cooling chamber in direct evaporative cooling system, while the air is first pre-cooled with mostly heat exchangers before passing through the cooling pad or vice versa depending on the purpose in an indirect evaporative cooling system[21]. The process is adiabatic in direct evaporative cooling and 100% cooling cannot be achieved because total saturation of the air is not possible[5]. This has limited the performance and application of direct evaporative cooling systems. The two basic types of direct evaporative cooling system are active and passive evaporative cooling systems. Active evaporative cooling systems use a system of fans or blowers to drive the ambient air through the wet pad into the system[28]. This system can function against high static pressure and sometimes combined with a heat exchanger (indirect evaporative cooling). Passive evaporative cooling systems use natural circulation of air to drive cold air into the system (direct evaporative cooling). Passive systems are mostly applicable in the windy environment with large amount of air moving around and low pressure head. This is the oldest method of evaporative cooling and sometimes referred to as zero energy cooling.

2.4 Utilization of evaporative cooling in fruits and vegetable preservation

The principal function of evaporative cooling is to lower the temperature and increase the relative humidity of the ambient air especially in direct evaporative cooling systems. It has been reported that in fruit and vegetable preservation, low temperature and high humidity is required, which slows pathological activity[14,29] and prolongs its shelf life. Any method that lowers the temperature and increases the relative humidity of the storage environment relative to the ambient, will suppress enzymatic degradation and respiratory activity (softening) for fresh agricultural produce especially fruits and vegetables. It will also slow or inhibit water loss (wilting), slow or inhibit the growth of decay-producing microorganisms (molds and bacteria), reduce production of ethylene (a ripening agent) or minimize the product’s reaction to ethylene and other metabolic activities[30,31]. Therefore evaporative cooling systems have been developed to achieve this purpose.

3 Feasibility studies of evaporative cooling for preservation of agricultural produce

Several works have been presented on the use of evaporative cooling in fresh storage. The design is based on any of the two methods of evaporative cooling. Therefore the feasibility study will be grouped into these methods.

3.1 Direct evaporative cooling for preservation of agricultural produce (passive types)

Direct evaporative cooling is a very old method of cooling which has been adopted even in the ancient days. This method is simply passing the inlet air through a wet porous humidifier. Two things are achieved here (i) lowering of the inlet temperature (ii) increasing the humidity of the inlet air. These two conditions are required for the cold preservation of agricultural produce. The process of heat transfer in direct evaporative cooling is assumed adiabatic and therefore follows the constant enthalpy line in the psychometric chart. Lowering the inlet temperature is more difficult than increasing the relative humidity of incoming air in this case. However 100% efficiency is not possible because the contact time might be inadequate and complete wetting of the pad might not be achieved. This limits its performance and its application is restricted to geographical regions with favourable ambient conditions. In many countries, researchers are faced with the problem of durable construction material for the construction of evaporative cooling and also the high cost of fan or blowers. As a result, review of literature showed that most direct evaporative coolers are of the passive type. Traditionally, many households in the tropics employ evaporative cooling in preservation before scientific research in the area began. However it was in the early eighty's that researchers began to take interest on it especially in Africa. Generally most design of direct evaporative coolers in developing countries especially Africa are prototypes and are limited to cooling a small quantity of produce. The feasibility studies therefore focuses on what has been presented in literature and their description and performances.

FAO reported[32] the straw packinghouse used for the cooling of produce. The packinghouse is made from natural material that can be moistened with water. The wetting of the roof and wall regularly creates the condition for the evaporative cooling to occur. These cooler are best suited to lower humidity regions, since the degree of cooling is limited to 1 to 2℃ (2 to 4℉) above the wet bulb temperature. Redulla et al[33] reported drip evaporative cooler that was constructed from a simple material such as burlap and bamboo. The drip cooler operates solely through the process of evaporation without the use of fan. Water drips onto the burlap sack through the perforated bamboo pipe. Cooling can be improved by keeping the cooler under a shade and in a well-ventilated area. Literature [34] presented two simple evaporative coolers, which were developed in the Philippines for cooling and storage of vegetables. Figure 5 is standing on a galvanized iron pan of water, and has another pan of water on top. The sides and top are covered with jute sack kept wet by dipping their top and the bottom edged into the pans of water. The inner sidewalls are constructed from plane galvanized sheet with fine holes (spaced 5 cm ×5 cm) while the outer walls are made of fine mesh (0.32 cm) wire in Figure 6.

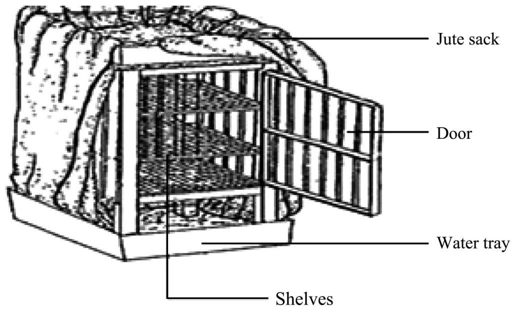

Figure 5 Evaporative cooler with jute bag as cooling pad

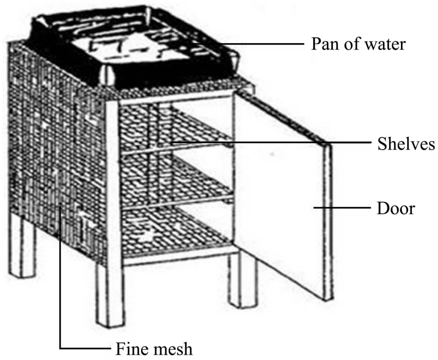

Figure 6 Evaporative cooler with rice husk as cooling pad

The 1.5 cm space between the inner and outer wall is filled with rice husk kept wet by contact with a cloth that is dripping into the pan of water placed on top of the cooler. The produce stored in these coolers has a shelf life of up to 3 weeks. Decay can be prevented by washing in chlorinated water before cooling. Literature [35] reported an evaporative cooler located at the peak of storage structure which can cool an entire room of stored produce especially those chilling sensitive crops. The vents for outside – was located at the base of the building so that cool air is circulated throughout the room before it can exit. Literature [36] presented a low cost cooling chamber made from bricks and shown in Figure 7. The cavity between the walls is filled with sand saturated with water. Fruits and vegetables are loaded inside, and the entire chamber is covered with a rush mat which is also kept moist. Since a relatively large amount of materials is required to construct this cold storage chamber, it may be useful only when handling high value products. During the hot summer months in India, this chamber is reported to maintain an inside temperature between 15-18℃ (59-65℉) and a relative humidity of about 95%.

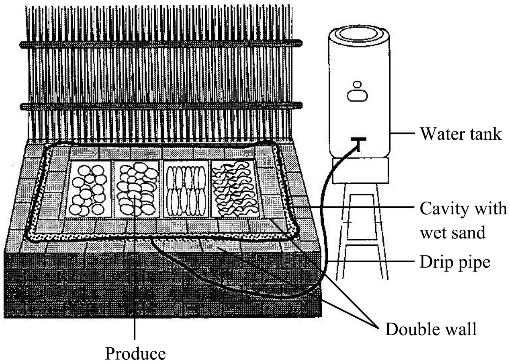

Figure 7 Evaporative cooler made from bricks

There are so many simple passive evaporative coolers which are available for local farmers for preservation of agricultural produce, though they may be given different names depending on the location or country involved. Literature [37] described some of these coolers. According to him, the design and capacity will depend on the material available, the user requirement and financial ability. Some of these coolers identified are; (i) Janata cooler: The cooler consist of a storage pot placed inside a bigger pot that holds water (pot in pot). The inner pot stores produce or water that is kept cool. The porous earthenware bowl is then covered with a damp cloth that is dipped into the reservoir of water. Water is drawn up the cloth by capillary action and evaporates keeping the storage pot cool. The bowl is also placed on wet sand, to isolate the pot from the hot ground. (ii) Zeer pot cooler: This cooler (Figure 8) is based on the design presented by Mohammed Bah[38] while he called it pot in pot system that uses two pots of slightly different size. The smaller pot is placed inside the larger pot and the gap between the two pots is filled with sand. This design was adopted in the practical action for the women of Sudan. The test shows an increase in the storage life of some crops.

Figure 8 Zeer pot

(iii) Bamboo cooler: The base of the cooler is made from a large diameter tray that contains water. Bricks are placed within this tray and an open weave cylinder of bamboo or similar material is placed on top of the bricks. Hessian cloth is wrapped around the bamboo frame, ensuring that the cloth is dipping into the water to allow water to be drawn up the cylinder wall. Food is kept in the cylinder with a lid placed on the top. (iv) Almirah cooler: This is more sophisticated cooler that has a wooden frame covered in jute cloth. There is a water tray at the base and on top of the frame, into which the cloth dips, thus keeping it wet; a hinged door and internal shelves allow easy access to the stored produce. (v) Charcoal cooler: This cooler, is made from an open timber frame of approximately 50 mm×25 mm, in section. The door is made by simply hinging one side of the frame. The wooden frame is covered in mesh, inside and out leaving a 25 mm cavity which is filled with pieces of charcoal. The charcoal is sprayed with water and when wet provides evaporative cooling. Air flows can be artificially created through the use of a chimney by employing a mini, electric fan or oil lamp. The resulting draft draws coolers air into the cabinet situated below the chimney. (vi) Neya celler storage: This is similar to the cooler presented by Literature [36]. It was adopted and designed in practical action for Naples. This cooler was originally designed for green energy mission. The construction material is basically dependent on the size of the cooler. However it consists of bricks, sand, polyethene hose, water tank, bamboo or wood, straw and sacks. This cooler is a permanent structure always situated on a sloppy ground for easy drainage of water. A layer of sand about 25 mm thick is spread on the ground over the area where the chamber is to be built and a layer of bricks or stones is laid onto the sand. A double wall chamber is created from the bricks. The cavity between these two walls is filled with clean sand. A high-density polyethene hose with pinholes made along its length is laid on the sand within the cavity. The hose is blocked at the end so that water released from a tank spreads through these holes and keeps the sand moist. A thatched roof supported by four bamboo poles is placed above the cool chamber. To prevent damage to the fruits and vegetable, they should be carefully stored in bamboo or plastic mesh trays/baskets. The trays/baskets have four legs so that their contents are raised off the floor of the chamber. The flow of water through the hose needs to be regulated in response to changes in the outside temperature to allow conditions within the chamber to remain constant.

The feasibility of passive evaporative pad cooling system in the storage of tomatoes has been investigated[39]. It showed that the moisture loss in tomatoes is 6.5 times as great in ambient conditions (28–33°C, 45%-65% RH) as in evaporative cooling conditions (20–25°C, 92%-95%RH). They also demonstrated that lycopene development is significantly higher (double in this case) in evaporative cooling storage conditions than the ambient conditions. Literature [40] studied the benefits of evaporative cooling for storage of tomato in a tropical environment. The obtained average temperatures drop of 8.2°C between the draft air and the cold storage chamber. Also they recorded an increase in relative humidity of 36% RH. The storage life of the tomatoes within the evaporative cooling unit was 11 days in comparison to 4 days of ambient conditions storage. Literature [23] presented a cabinet porous evaporative cooling system and was evaluated under Nigerian climate for tomatoes. The cabinet is made of clay, reinforced with 3 mm thick steel wire mesh and provided with a side door for accessing the storage chamber. The overall inside dimensions of the cooler were 240 mm long, 240 mm wide, 240 mm high with a wall of 20 mm thickness. This was housed in an outer cuboid of inside dimensions 380 mm × 380 mm × 380 mm with 20 mm thick wall, such that a uniform gap of thickness 50 mm between the vertical, top and bottom side walls was filled with coconut fiber to enhance the water retention capacity of the walls. Results of the transient performance tests revealed that the cooler storage chamber temperature depression from ambient air temperature varied over 0.1–12°C. He achieved a storage life of about four days for tomatoes. Literature [24] presented a direct evaporative cooler for storage of tomatoes in northern Nigeria. They used jute as cooling pad wrapped round a square frame. The pad was allowed to drop inside a sump filled with water. The fiber absorbs the water and the water rises through the pad by capillarity. Air circulation and passage into the storage chamber is by wind action. They achieved a storage life of more than three weeks for tomato. However, they harvested the tomato at maturity when ripening is about to start. Literature [25] developed a clay evaporative cooler for preservation of tomatoes in southern Nigeria. The evaporative cooler made up of double jacket walls were evaluated during the winter period in Nigeria. The inside wall is a cuboids (60 cm long × 52 cm wide × 85 cm deep) shaped clay (mud) storage with partitions for storage of fruits and vegetables. The outside wall is also a cuboid (75 cm long × 67 cm wide × 100 cm deep) with a 15 cm gap separating it from the inside wall. At the front is a cooling pad (42 cm long × 8 cm thick and 85 cm deep) made of wood shaven stacked in between perforated (pin hole) bamboo stick of 42 cm long and 0.4 cm thick to prevent sagging. The walls of the cooler were double jacketed to reduce the heat transfer by conduction. The top of the structure is covered with an aluminum foil (75 cm long × 67 cm × 85 wide) because of its high heat reflectivity. The foil contains pin holes (2.5 mm in diameter) for the exhaust air. Through a natural convection by the help of buoyancy, the air passes through the wet cooling pad into the storage chamber. The results showed that the evaporative cooler can reduce the daily maximum ambient temperature from 32–40℃ to 24–29℃ i.e. a temperature reduction of up to 10℃ and increase the relative humidity of the air from 40.3% of the ambient to 92% of the storage chamber.

Researchers have reported passive evaporative coolers for the storage of other agricultural produce. Literature [41] presented a porous evaporative cooler for preservation of carrot, spinach and radish. The cooler was made up of 0.7 m^3 brick structure which improved storage life for a number of different produce. After 7 days, produce within the evaporative cooler retained much more of its moisture as compared to the control. The percent weight (%) loss of produce after 7 days is shown in Table 1.

Table 1 Percent weight (%) loss of produce after 7 days

Product	Inside cooler	Outside cooler
Carrots	5%	50%
Spinach	8%	49%
Radish	12%	55%

Literature [22] reported two coolers of equal capacity of 2.21×10^5 cm^3 for fruits and vegetable preservation. However, they neither stated what agricultural product it is used for its storage nor showed the detailed drawing and the cooling pad and material used but they stated that the hexagonal section cooler was 29.5 cm wide while the height was 98.0 cm. However, the square cross-section cooler has each side measured 47.5 cm and 98.0 height like the hexagonal cross-section cooler. The frame was made of wood, while mild steel sheet was used for the containers and perforated galvanized pipes for supplying water on the cooling pads. The coolers were painted white to minimize the effect of solar radiation on the coolers' surfaces. They achieved a temperature reduction range of 3.6 to 6.4°C with jute, latex foam and charcoal as cooling pad. Literature [42] studied the effect of passive evaporative cooling on the barn for storage of potato in Ghana. The barn was constructed and tested using two varieties of sweet potato. The mean dry bulb temperature and relative humidity of the inside and outside air stream were 25°C and 90% and 31.5°C and 67.5%, respectively. The systems cooling efficiency was determined to be 127%. A test on the evaporative cooling barn using 18 mini sacks, each containing 14 tuberous roots with four replications for 12 weeks, revealed that moisture loss from the two varieties were approximately the same (13%). The moisture content of the root tubers decreased linearly from 68% to 59% and 60% to 52% (wb) over a storage time. Literature [43] studied the applicability of evaporative cooling system in three regions of Ethiopia for livestock. Two types of evaporative pad were studied and the effect of air velocity and water flow rate on saturation efficiency and pressure drop across the pad was presented. The study on the effect of salt solution on mycelial growth of fruit spoilage fungi in passive evaporative cooling structures in northern Nigeria has been reported[44]. Five sets of 5 cm and 7 cm inter pot space of four different types of pot in pot passive evaporative cooling structures made of two different materials, clay and aluminum were constructed. They calculated the total fungi count for each day for the orange. They concluded that the space between the pots is a factor in evaporative cooling preservation of orange.

3.2 Direct evaporative coolers for preservation of produce (mechanical types)

Climatic conditions can differ from regions of a particular country. In Nigeria the weather in southern and northern are very different. While the south is humid most parts of the year, the north is always dry. Therefore the northern weather allows for passive cooling because of the availability of regular wind. However in an area that does not have this advantage, mechanical method can be adopted to drive the air towards the cooling pad. This can be achieved through the use of fan or blowers or any method that can suck in air towards the pad. However this usually comes with increased cost. A review of literature showed that a lot of such coolers have been developed to cool produce. Literature [33] presented an active evaporative cooler for preservation of fruit and vegetable (Figure 9). The evaporative cooler operates on the principle of direct evaporative cooling system. The cooler is equipped with a vortex wind machine while chicken wire was used to construct two thin boxes on opposite sides of the cooler that hold wet chunk of charcoal or straw.

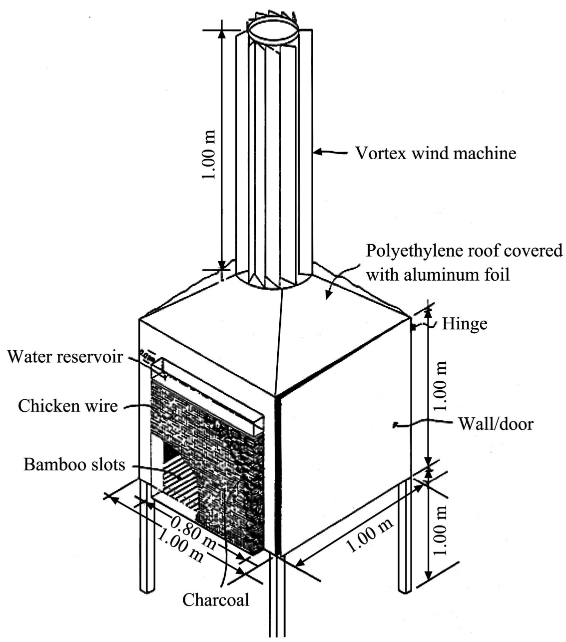

Figure 9 Evaporative cooler with vortex wind machine

Water is dripped onto the charcoal or straw, and the wind turns the turbine, sucking moist, cool air through the load of produce inside the cooler. This cooler reduced the inside temperature to 3-5℃ (6-10℉) below the ambient air temperature, while relative humidity is about 85%. Literature [45] described an evaporative cooler, which they used in improving the performance of cold storage rooms in Egypt to control air relative humidity inside the storage. The cooler consists of two centrifugal fans (2.0 m^3/s discharges) rotating in a volute casing was used for forced-air cooling. The blowers powered directly by a single-phase electric motor 0.75 hp with a rotating speed of 1 440 r/min. A blower and duct for forcing air were located at one side of the pads, to force dry air stream through the wetted pads and blows the new cooled air throughout the storage. A vertical pad (30 cm×100 cm) filled uniformly with rice straw pad material in a wire net at a specific pad thickness (10 cm) was used to retain water for cooling. The storage ability of the cooler is shown in Table 2.

Table 2 Storage ability and firmness of tomatoes fruits as affected by cooled storage room conditions before and after modification

Storage conditions	Storage ability (Total loss/%)	Fruit firmness/N		
		Before storage period	After storage period	Firmness loss/%
Cooling room without evaporative cooler (Before modification)	14.69	65.42	48.66	25.62
Cooling room with evaporative cooler (After modification)	7.62	65.42	59.84	8.52

Note: Tomatoes fruits were stored under conditions of 20°C and 80%-90% RH.

Literature [14] developed an evaporative cooler which they used in preservation of some fruits and vegetables in south western Nigeria. The cooler consists of a pad with dimensions of 475 mm×980 mm, a storage cabin withdimensions of 475 mm×475 mm×980 mm, made of plywood and internally insulated with 25.4 mm polystyrene materials, a suction fan of 20 watts power rating. Three different absorbent materials (jute, hessian and cotton waste) were used to test the cooler. The results showed that the cooling efficiency is highest for jute at 86.0% with an average temperature of 22°C and relative humidity of 7%RH. Also cotton waste has 76.1% cooling efficiency with an average temperature of 23°C and relative humidity of 81%RH and 61.2% while hessian with an average temperature of 25°C and relative humidity of 73%RH. Literature [46] described an active cooler used to store produce. The cooler consists of a porous pad, water supply, a suction fan and water collection sump, which is to be re-circulated. The fan draws the cold air stream through the wetted pad media into the cold storage room. The water is collected in the sump and re-circulated back to the pad. Literature [47] presented an evaporative cooler (Figure 10) for preservation of tomato in south western Nigeria. The evaporative cooling system consists of a cabinet, a cooling fan and a cooling pad. It consists of a pyramidal shaped storage chamber with total storage space of 0.075 m^3, made of galvanized mild steel, and internally insulated with 0.025 m polystyrene foam. A suction fan of delivering 4.3 m/s velocity airflow and 0.5 W (1 250 r/min) delivers ambient air to the cooling pad (jute). Water pump with discharge capacity of 3.5 L/min and power rating of 0.5 W delivers water to the pad. A water reservoir of capacity 62.5 m^3 was linked to the cooling system at the bottom through a PVC pipe supplying water to keep the cooling pad/mesh continuously wet. Tested samples maintained their fresh condition for 14 days within which they were tested. The required storage temperature for the preservation of the selected vegetable samples was achieved at 16°C for the cabinet temperature at an ambient temperature of about 32°C.

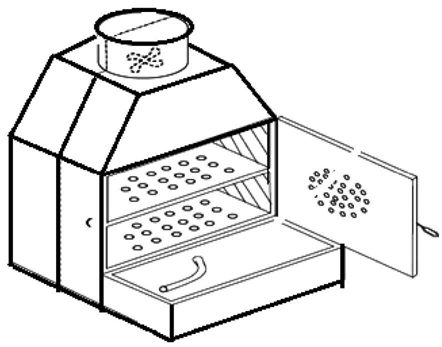

Figure 10 Evaporative cooler

Literature [28] reported an active evaporative cooler for short-term storage of fruits and vegetable for small holder farmers in Southern Nigeria. The evaporative cooler uses palm fruit fiber as cooling pad material which is considered a waste in palm oil production in Nigeria and consists of three suction fan, an automatic water control switch, a water pump and evaporative cooling chambers. The performance of cooler was evaluated in terms of temperature drop, efficiency of the evaporative cooling and cooling capacity. The temperature drop ranged from 4°C to 13°C while the relative humidity of the ambient air was increased to 96.8%RH The cooler could drop the temperature close to wet bulb depression of ambient air and provided up to 98% cooling efficiency with a maximum cooling capacity of 2 529 W. At an ambient temperature of 37°C, the evaporative cooler provided the storage conditions of 23.2°C and 85.6% – 96.8% relative humidity, which can enhance the shelf life of wide range of fruit and vegetables of moderate respiration rates. The power consumption of the cooler was half that of a typical vapor compression refrigerator of the same volume.

3.3 Indirect or two stage evaporative coolers for preservation of produce

The leaving air temperature from the cooling pad decreases by converting the sensible heat to the latent heat through water evaporation in direct evaporative cooling equipment. Therefore the process air temperature decreases, however, the humidity of the air increases[5]. This result above may not satisfy the need of many users depending on the purpose of cooling. However, in indirect evaporative cooling, the draft air is processed twice or more by the equipment designers. They make use of pre-cooler for the primary air before passing it to the next stage of cooling[48]. Basically, there are two types of indirect evaporative coolers, the dry and wet surface type. They are classified based on the mode of heat and mass transfer process in the heat exchangers. Dry surface type cools the secondary air using direct evaporative cooling before entering indirect heat exchanger. Then, this evaporative cooled secondary air through heat transfer cools primary air in a conventional air-to-air heat exchange[49]. This method removes moisture from the air and will be suitable for cooling residential homes. For wet surface type, a wet surface heat exchanger is used where a non-adiabatic evaporation takes place. According to literature [50], two streams of air are used, namely alternative wet and dry passages, which are separated from each other. Primary air is cooled in dry passages which is separated from wet passages where secondary air and water flow. Evaporation occurs in wet passages and heat is removed from primary air through impermeable separating wall and evaporates water into the secondary air. Indirect evaporative coolers can also be classified based on the configuration of the heat exchanger. Therefore, there are tubular type, heat pipe type, plate type and dew point type. There is little literature on two stage coolers for preservation of agricultural produce, many of the work on this are for cooling residential houses, green houses, production process in metallurgical shops, cooling automobile engine and tractor cabins[5]. However, literature [21] presented an indirect active evaporative cooler (Figure 11) which called a two stage evaporative cooler to improve the efficiency of evaporative cooling for higher humidity and low temperature air conditioning for preservation of fruits and vegetables in India. This is based on wet surface type and consists of a plate type heat exchanger and two evaporative chambers. The outdoor air is passed through the cooling pad to be filtered before passing into the heat exchanger. The humidifying pad is kept vertically across the airflow. The sensibly cooled fresh air from heat exchanger is humidified through first cooling pad. The conditioned air is allowed to enter into the storeroom. The air inside the storage room exits and is humidified through the second cooling pad and passes vertically upwards through the heat exchangers to serve as coolant-air (second stream). The second stream provides cooling to the air in first stream and exhausts to the storeroom. The temperature drop through the cooler ranged from 18-16°C . The cooling effectiveness of the two stages cooler was 1.1-1.2 over the direct evaporative cooler. It provided a room condition of about 50%-75% relative humidity, which is very low for fresh storage and this may be because some moisture was removed during the primary cooling of the draft air.

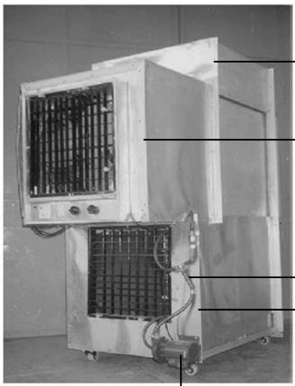

Figure 11 Indirect active evaporative cooler

Most of the evaporative cooler studied above has the problems of quality construction material, water wastage, need for constant attention and method of data collection, and analysis was not error proof. Most of the conclusion reached on the quality of stored product was by visual examination and mere weight measurement. Very few authors conducted quality food analysis to verify the statues of what they preserved. The researchers continued to use different kinds of material as humidifier and this shows lack of satisfaction on the already existing once (see Table 3). The coolers are prototypes with low capacity, environmental specific and might not perform if the testing condition varies. Therefore there is the need for further research in this area.

Table 3 Summary of some evaporative coolers for preservation of fruits and vegetables and their pads

S/No	Name	Type	Pad media	Source	Year
1	Straw packinghouse	passive	straw	FAO	1986
2	drip cooler	passive	Burlap sack	Redulla et al.	1984
3	Simple cooler	passive	jute	Acedo	1997
4	Simple cooler	passive	Rice husk	Acedo	1997
5	Attic evaporative cooler	passive	-	Thompson And Scheureman	1992
6	low cost cooling chamber	passive	sand	Roy	1989
7	Janata cooler	passive	jute	Neil noble	2008
8	Zeer pot cooler	passive	sand	Mohammed	2000
9	Bamboo cooler	passive	Hessian cloth	Neil noble	2008
10	Almirah cooler	passive	jute	Neil noble	2008
11	Charcoal cooler	passive	Charcoal	Neil noble	2008
12	Neya celler storage	passive	sand	Neil noble	2008
13	porous evaporative cooler	passive	Coco nut husk	Anyanwu	2004
14	clay evaporative cooler	passive	Wood shaven	Ndukwu	2011
15	Vortex wind cooler	active	Charcoal, straw	Redulla et al	1984
16	Magda and Abd- El Rahman	active	rice straw	Magda and Abd- El Rahman	2009
17	Olosunde	active	jute, hessian and cotton waste	Olosunde et al	2009
18	Mogaji and Fapetu	active	jute	Mogaji1 and Fapetu	2011
19	Dilip Jain	active	Wood shaven	Jain Dilip	2007

3.4 Performance and optimization of evaporative coolers

The factors affecting evaporative cooling system performance have been determined by numerous researchers[51-53]. They listed them as weather conditions (inlet temperature and relative humidity), pad material, pad thickness and density, pad air face velocity and water flow in pads. Some literatures[4,54,55] showed that in designing evaporative cooler with cooling pad that is mounted vertically, adequate cooling efficiency can be achieved with good distribution of water on pad surface. Literature [26] stated that water consumption is affected by climate, media effectiveness, media air velocity, water distribution system and bleed rate. Literature [14] showed that the types of absorbent material and agricultural products affect the performance of the coolers in product's preservation. This is because controlling the rate of respiration of produce determines its shelf life in a cold storage system. Although some researchers[26,27] observed that increasing pad thickness increases cooling efficiency of evaporative coolers, however this will require increased fan capacity which will increase cost. Various comparisons presented based on variation of parameters were subjective and generalized because testing of the effects of parameters like air mass flow rate on room temperature and humidity was undertaken on different days. Therefore, it was not easy to draw a comparison amongst the results because of the variation in climatic conditions. The performances of some evaporative coolers at different design and weather condition are presented in Table 4. Just like in most literature reviewed, energy efficiency and evaporation loss from the pads are absent in the results as also shown in the Table 4. This is one of the weaknesses observed in the analysis of most researches in evaporative coolers for preservation of agricultural produce presented. Most of the researches focused on the effect of inlet relative humidity, inlet dry bulb temperature, air flow rate and pad thickness on the cooling efficiency[21-25]. Generally the review shows that lower outlet temperature of the processed air can be realized if the temperature and relative humidity of the air is lower at the inlet. Empirical formulas and models showing the interaction of these factors have been developed and presented with their optimum performances under defined boundary conditions. The cooling capacity and cooling efficiency defined by Equation (1) and (2) are widely used empirical indexes for evaluating the performance of direct evaporative cooling media[21,27,28,47].

$$\text{Cooling efficiency} = T_{db} - T_s / T_{db} - T\text{w} \quad (1)$$

$$\text{Cooling capacity} = 670.66 \times V_{si} \times (T_{db} - T_s) \quad (2)$$

where, T_{db} is ambient dry bulb temperature, °C; T_w is ambient wet bulb temperature, °C; T_s is dry bulb temperature of cooler storage space; V_{si} is the flow rate of air, m^3/s.

Also literature [21] defined the effectiveness of indirect evaporative cooler over direct evaporative cooling system for preservation of tomatoes as equation (3) and cooling capacity of two stage evaporative coolers as equation (4).

$$\text{Evaporative effectiveness} = \frac{T_{db} - T_k}{(T_{wa})\ \text{cooling efficiency}} \quad (3)$$

$$\text{Cooling capacity} = m\text{a} \times (h_1 - h_2) \quad (4)$$

where, T_k is the temperature of conditioned air, °C; T_{wa} is the wet bulb depression of air entering the system, °C; m_a is mass flow rate of air, kg/s; h_1 and h_2 are the enthalpy (kJ/kg) of entering and leaving air of the cooler.

Table 4 System performance at different affecting factors for some evaporative coolers

S/no	Author	Pad material	Pad thickness/ mm	Air flow rate/(m·s^{-1})	Cooling efficiency/%	Cooling capacity/W	Energy efficiency ratio	Evaporation loss/%	Ambient condition	Room condition
1	Jain. D[21]	Wood shave	50	3.0 intake air	85-90	2125 - 4500	-	-	21-33°C 15%-40%RH	17-25°C, 50% -75%RH
2	Abenoet al [42]	Jute	0.9	-	127	-	-	-	31.5 °C 67.5%RH	25°C 90%RH
3	Mogaji and Fapetu[47]	Jute	60	4.3 intake air	-	-	-	-	26-32℃ 18%-31% RH	16-26℃ 33%-88%RH
4	Manuwa and Odey[22]	Jute	25	0.51-1.37	93.5	-	-	-	20.6-33.3℃ 65%-95%RH	22-26℃ 95%-98%RH
		Latex foam	25	0.69-1.25	91.4	-	-	-	20.6-33.3℃ 73%-93%RH	22 -25.5℃ 91%-97%RH
		Charcoal	25	0.98- 1.45	91.3	-	-	-	20.6-33.3℃ 61%-90%RH	22.5-24.5℃ 92-97%RH
		Wood shave	25	0.35-1.125	91.9	-	-	-	20.6-33.3℃ 74%-94% RH	22.3-26.5℃ 98%RH
5	Ndukwu[25]	Wood shave	80	-	20-92	1207	-	-	32-40℃ 40.3%RH	24–29℃ 92%RH
6	Ndukwu et al[28]	Palm fruit Fiber	30	4.0	98	2, 529	-	-	29.9-37℃ 34%-73%RH	23.2℃ 85.6%-96.8%RH
7	Anyanwu[23]	Coconut husk	50	1.5	-	-	-	-	28-35℃ 70%–90%RH	22.3-26.8℃

Note: RH-relative humidity.

However, it was observed that, most model equations for analyzing the heat and mass transfer process for most evaporative coolers have been evaluated with the use of house air conditioners, in green houses or cooling towers[56–64]. Very few model equations have been evaluated with the use of evaporative coolers designed for preservation of agricultural products[65-68]. This is necessary because of the peculiar nature of these products, as they highly respire when in storage. They build up large amount of heat into the system which may change as the storage progresses and require much lower temperature than comfort cooling. The analytical model presented by literature [65] and evaluated with evaporative coolers for preservation of fruits and vegetables was observed to have a higher deviation from the experimental cooling efficiency when the ambient temperature drops sharply around 16:00 local time. The average mean efficiency difference on the first day for cooling efficiency and the predicted efficiency was 0.8% while the second day gave average mean difference of 3.45%. Also the third day gave an average mean difference of 3.72%. The good thing about these equations developed for evaporative cooling purpose is that they can be adopted to suit several conditions. However, these equations were specific for either direct or indirect cooling systems and conceder's the type of mechanism for lowering the temperature or elevating the humidity of the draft air. These models have been reviewed in details by some authors for house cooling especially those designed for Chinese climate[5]. The equations has been solved either manually, numerically analyzed or by the use of computer programs[5, 64].

3.5 Some parametric of evaporative cooling models

The major parameters involved in most of the equations for evaluating evaporative cooling performance are, the heat transfer coefficient, area of the pad, pad thickness, air mass flow rate, water flow rate and the specific heat of air[69–73]. Most of the parameters in the model formulas are easily measured or determined, since their values or range which can be interpolated are available in standard thermodynamic text books, if the temperature and relative humidity values are known. However, convective heat transfer coefficient has been the major problem to quantify. Therefore some authors have developed empirical correlation to calculate this. Most of these formulas involve the nusselt number, Reynolds number or Prant'l number with their determinants. A typical correlation for convective heat transfer coefficient for a rigid pad was given by literature [59]. They gave a relationship of the heat transfer coefficient and the characteristic length of the cooling pad in terms of nusselt number as equation (5). The convective heat transfer coefficient was calculated from the nusselt number as follows:

$$N_U = \frac{h_l}{k} \tag{5}$$

where, h is the convective heat transfer coefficient; k is the thermal conductivity of air; l is the characteristic length and is given as [56]:

$$l = \frac{Q}{A} \tag{6}$$

where, Q is the volume occupied by the pad.

Equation (5) has been used by many authors with high degree of success[50,56,57,65] for both evaporative cooling systems designed for fresh produce preservation and comfort cooling. Other correlation for heat transfer coefficient can be found in literature [74,75] especially when the cooling system involves a kind of heat exchanger.

4 Issues with commercialization of evaporative cooling preservation in developing countries

Looking at the energy problem of developing countries globally and agricultural losses faced by them, evaporative coolers have great potential in these countries. Undocumented market survey done in Nigeria, Ghana, Mali, Togo, Benin republic and Sierra Leone showed that evaporative coolers are yet to be commercialized because it is difficult to find a cooling system based on evaporative cooling for preservation of agricultural produce in any market or shops. Despite that in these countries, the climatic conditions will support evaporative cooling application during the period of harvest of many fruits and vegetables. Literature [76] stated that the greatest problem of commercialization is the lack of consistency in services offered to the farmers or end users. According to this, farmers are biologist in nature, therefore need an industry to service them by providing their technological needs. Developing and marketing evaporative coolers for storage of fresh agricultural produce is a fertile ground for cooling industries in most developing countries. Unfortunately it is clear that most of these researches on evaporative cooling preservation is for mere academic purpose and has ended up in the class room and research institute or at most in the government produce out post. There was inadequate involvement of companies in this technology in developing countries rather the once involved concentrates on residential buildings and hotels for comfort cooling like China and India. Probably they felt that the farmers will not buy over the technology. However, to drive home the benefit of this technology to the farmers, there is need for collaboration between the researchers, the farmers and the companies. The engagement of the services of rural sociologist and extension service provided by research institutes is very important to increase the interest of the farmers and the companies in this technology. Secondly is to transfer these technologies to the industry for improvement and production with manuals of operation.

5 Issues with maintenance and operation of evaporative cooling systems

Analysis of different designs of evaporative coolers presented so far shows that they require a lot of attention though easy to operate. The cost of fabrication might be cheap as observed but some of the parts required to be changed regularly may be at a relatively low cost since most of the materials of fabrication can be locally sourced. The major maintenance required includes (i) changing of the cooling pads made mostly from agricultural residues and are prone to microbial growth[14]; (ii) Replacement of lost water; (ii) Evaporative coolers require protection from weather since they will be kept or mounted outside; (iii) Bleeding off water from the sumps; (iv) Checking for water leakages incase of crack because some are made from clay like the zeer pot; (v) Inspection of water pumps, fans and switches in the case of active systems; (vi) Checking of fouling incase heat exchangers are involved in the design like literature [21]. Quality of water used in evaporative cooling systems should be given special attention because hard water will likely deposit some salts on the pads which might block the air spaces. This will be a problem in rural areas where this technology will be much useful because they rely on rivers and shallow wells for water sources. Provision of appropriate training on installation and maintenance will make the technology easily acceptable to the users.

6 Conclusions and recommendations

1) A comprehensive review of evaporative coolers used for preservation of fresh agricultural produce in developing countries was presented. Field evaluation of various evaporative coolers showed that climatic adjustments favour the operation of the system during the harmattan and dry seasons when the relative humidity is low in tropical countries. The length at which this season occurs varies from country to country, therefore in introducing this technology to these countries, the end users should be away of this and the season of application should be well established in each locality.

2) There exist different types of evaporative cooler designs, which include (i) Direct evaporative cooling system; (ii) Indirect evaporative cooling systems; (iii) Indirect/direct evaporative cooling systems. However the study shows that most of the evaporative cooler designs employed direct evaporative cooling methods which are simple but with lower thermal performance, and can only be used for short term storage of agricultural produce in restricted regions with favourable ambient conditions. Research into novel technologies in evaporative cooling like application of dew point type, heat pipe type heat exchangers, membrane air treatments etc., in indirect/direct evaporative cooling application and its feasibility in agricultural storage would be a positive way forward. Application of these technologies in designing evaporative cooling system for storage with rigorous field validation and possible modification to suit this purpose will have more thermal effect and improve performance.

3) Some kinds of materials used as cooling pads in evaporative coolers were investigated. The research showed that in the past decades different pad materials have been explored in developing countries and they are mostly agricultural residues. Evaluation of the pad materials have focused mainly on the effect of air flow rate and pad thickness on the performance of the pads. Research should extend further into the rate of evaporation loss from this material because evaporative system is a water utilization system and introduction of hot air through any hot spot on the surface of the pad will

affect the performance of the entire system. Also knowledge of evaporation loss is useful in rating calculations of evaporative cooling systems. Also there is unavailability of the projected life span, water quality, solid and microbial build up and reactive nature of all the pads presented. Methods of treating this agricultural residue to resists degradation would be a step in the right direction.

4) Efficient and durable cooling pad is still a problem and has limited the quality of result obtained in most research in many countries. This problem can be solved holistically by various countries in partnership with cooling companies through (i) Establishment of research institutes basically for cooling pad materials using local contents and this institute will develop standards for acceptable materials with regular improvement; (ii) Effort should be made to characterize this pad materials based on climatic conditions to provide an acceptable chart based on storage condition of various agricultural produce using evaporative cooling system. This will help the farmers to make a choice of using the system depending on how long they wish to store their produce; (iii) Appropriate material for design for evaporative coolers should be established for optimum performances. Also based on various research appropriate design codes and handbook which are lacking should be developed for standardization and quality control. Automation in most of the design needs in-depth research and improvement to minimize attention.

5) The study also shows that most of the evaporative coolers presented were mostly prototypes and environmental specific. They require further field validation in the large scale utilization because the data generated might be erroneous in large scale application when the environmental condition changes as the uncertainties in those experiments were not included. In addition, experimental results and data obtained from various researches reviewed show that evaporative coolers cannot be used all the year round for preservation of agricultural produce. They can only serve as a stop gap energy saving device for storage of agricultural produce during the favourable weather. Therefore energy saving and energy efficiency analysis is required to explore the energy saving potential of evaporative cooler in fresh storage. This is important as energy savings is a function of heat load removed from the produce and power input of a specific system.

6) Furthermore, very few model equations have been evaluated with evaporative coolers designed specifically for preservation of agricultural products. This is important because agricultural produce are peculiar in storage, they build up a lot of heat into the system and higher cooling load is required to be overcome. Therefore in-depth theoretical analyses on heat and mass transfer process of evaporative coolers in cold preservation of agricultural produce are needed to save time, cut cost and for ease of adaptability and improvement of performance.

7) Finally, the prospect of commercialization of evaporative cooling systems in developing countries is hampered by lack of awareness, and also robust economic and cost analysis to convince the farmers of its cost benefits as it is lacking in most literature reviewed.

[References]

[1] The World at Six Billion. A report from the United Nations regarding population dynamics in the future. 2008 available: http://www.huwu.org/esa/population/publications/sixbillion/sixbilpart1.pdg

[2] Kael E. Design and testing of an evaporative cooling system using an ultrasonic humidifier. Department of Bioresource Engineering, Room MS1-027, Macdonald-Stewart Building, 21111 Lakeshore Road Ste. Anne De Bellevue, Quebec H9X 3V9. 2008: 1- 45

[3] Issues and Challenges in Rice Technological Development for Sustainable Food Security. Keynote Address: Twentieth Session. International Rice Commission (IRC), 2002. IRC: 02/05.

[4] FAO production yearbook, Rome, 1983, 34; 149

[5] Xuan Y M, Xiao F, Niu X F, Huang X, Wang S W. Research and application of evaporative cooling in China: A review (I). Renewable and Sustainable Energy Reviews, 2012; 16(5): 3535–3546. http://dx.doi.org/10.1016/j.rser.2012.01.052

[6] Wang, S K. Evaporative cooling and evaporative coolers. Handbook of air conditioning and refrigeration, 1993 Chapter 13

[7] Evaporative Air Cooling. The ASHRAE Handbook, the American Society of Heating, Refrigerating and

Air-Conditioning Engineers, Inc. Millstar Electronic Publishing, 1998.

[8] Campos A T, Kolosowski E S, Gasparino E. Study of the air temperature reduction potential through the evaporative cooling system in the region of Maringa- PR Brazil. Acta Sci., 2002; 24 (5): 1575-1581.

[9] Gutenberg A W. The Economics of the evaporative cooler industry in the Southwestern United States. Stanford University Graduate School of Business. 1955. p. 167. http://books.google.com/books

[10] Zellweger J "Air filter and cooler". *U.S. patent 838602*. 1906. http://www.google.com/patents _m.

[11] Essick B."Pad for evaporative coolers". *U.S. patent 2391558*. 1945. http://www.google.com/patents.

[12] Landi S. The workshop book. Taunton Press, 1998: 120.

[13] Baird C D, Bucklin R A, Watson C A, Chapman F A. Evaporative cooling system for aquacultural production. Florida extension services, Institute of Agricultural Science University of Florida. Fact sheet EES-100: 1- 5

[14] Adebisi O W, Igbeka J C, Olurin T O. Performance evaluation of absorbent materials in evaporative cooling system for the storage of fruits and vegetables. International Journal of Food Engineering, 2009; 5(3): 1-15. http://dx. doi.org/10.2202/1556-3758.1376

[15] Otterbein R. Installing and maintaining evaporative coolers. May/June 1996. Home Energy Magazine. http://www. homeenergy.org/archive/hem.dis.anl.gov/eehem/96/960511.h tml

[16] Watt J R. Evaporative cooling handbook. 2nd edition. Chapman and Halt, New York 1986.

[17] Al-Sulaiman F. Evaluation of the performance of local fibers in evaporative cooling. Energy Conversion and Management, 2002; 43: 2267-2273. http://dx.doi.org/10. 1016/S0196-8904(01)00121-2

[18] Mu`azu M. Novel evaporative cooling systems for building applications. PhD Thesis submitted to the University of Nottingham, UK, 2008: 1- 264

[19] Wei Z, Geng S. Experimental research on direct evaporative cooling of organic padding Contamination. Control and Air-conditioning Technology, 2009; 22–26.

[20] Darwes M, Abouzaher S, Fouda T, Helmy M. Effect of using pad manufactured from agricultural residues on the performance of evaporative cooling system. Jordan Journal of Agricultural Sciences, 2009; 5 (2): 111–125.

[21] Jain D. Development and testing of two-stage evaporative cooler. Building and Environment, 2007; 42: 2549–2554: doi:10.1016/j.buildenv.2006.07.034

[22] Manuwa S I, Odey S O. Evaluation of pads and geometrical shapes for constructing evaporative cooling system. Modern Applied Science, 2012; 6(6): 45–53. http://dx.doi. org/10.5539/mas.v6n6p45

[23] Anyanwu E E. Design and measured performance of a porous evaporative cooler for preservation of fruits and vegetables. Energy Conversion and Management, 2004; 45: 2187–2195. doi:10.1016/j.enconman.2003.10.020

[24] Ndirika V I O, Asota C N. An evaporative cooling system for rural storage of fresh tomato. Journal of Agricultural Engineering and Technology, 1994; 2(4): 56–66.

[25] Ndukwu M C. Development of clay evaporative cooler for fruits and vegetables preservation. Agricultural Engineering International: CIGR Journal, 2011; 13(1): 1-8.

[26] Palmer J D. Evaporative cooling design guidelines manual for New Mexico schools, and commercial buildings. NRG Engineering, 2626 Central Ave. SW Albuquerque, New mexico, 87104 USA. 2002: 1– 99.

[27] Ndukwu M C, Manuwa, S I Olukunle O J, Oluwalana I B. Development and performance evaluation of active evaporative cooling system for preservation of fruits and vegetables. A PhD thesis, Federal University of Technology Akure, 2013.

[28] Ndukwu M C, Manuwa S I, Olukunle O J, Oluwalana I B. Development of an active evaporative cooling system for short-term storage of fruits and vegetable in a tropical climate. Agric Eng Int: CIGR Journal, 2013; 15(4): 307－313.

[29] Greenshill T M. Growing better vegetables. Evans brothers, London, 1968.

[30] Katsoulas N, Baille A, Kittas C. Effect of misting on transpiration and conductance of a greenhouse rose canopy. Agricultural and Forest Meteorology, 2001; 106: 233–47.

[31] Boyette M D, Wilson, L G, Estes E A. Introduction to proper postharvest cooling and handling methods. North Carolina Cooperative Extension, AG-414-1, 2013. USDA Handbook no. 66. http://www.bae.ncsu.edu/programs/ extension/publicat/postharv/ag-414-1/index.html.

[32] FAO Yearbook. FAO Statistics Series No. 132. Rome.1995

[33] Redulla A. Keeping perishables without refrigeration: use of a drip cooler. Appropriate Postharvest Technology, 1984; 1(2): 13–15.

[34] Acedo A L. Storage life of vegetables in simple evaporative coolers. Tropical Science, 1997; 37: 169–175.

[35] Thompson J F, Scheuerman R W. Curing and storing California sweet potatoes. Merced County Cooperative Extension, Merced, California 95340. 1993

[36] Roy S K. A low cost cool chamber: an innovative technology for developing countries (tropical fruits storage). Johnson G I, (Commonwealth Scientific and Industrial Research Organisation, StLucia (Australia). Division of Horticulture), editor. Post Harvest Handling of Tropical Fruits. Canberra, A.C.T., Australia: Australian Centre for International Agricultural Research, 1994: 393–5.

[37] Neil N. Evaporative coolers. www.practicalaction.org. 2008.

[38] Mohammed B A. Appropriate technology number 4 volume 27 oct/ dec. 2000

[39] Thiagu R, Chand N, Habibunnisa E A, Prasad B A, Ramana K V R. Effect of evaporative cooling storage on ripening and quality of tomato. Journal of Food Quality, 1990; 14: 127–144.

[40] Mordi J I, Olorunda A O. Effect of evaporative cooler environment on the visual qualities and storage life of fresh tomatoes. Journal of Food Science Technology, 2003; 40(6): 587–591.

[41] Dadhich M S, Dadhich H, Verma R. Comparative study on storage of fruits and vegetables in evaporative cool chamber and in ambient. International Journal of Food Engineering, 2008; 4(1): 1–11.

[42] Abano E E, Teye E, Ainoah R S, Tetteh J P. Design, construction and testing of an evaporative cooling barn for storing sweet potatoes in the tropics. Asian Journal of Agricultural Research, 2011; 1-11. DOT: 10.3923fajar.2011

[43] Mekonnen A. Evaporative cooling and its applicability to live stock housing in Ethiopia. Agricultural Engineering 1994; 49(2): 44–8.

[44] Sunmonu M O, Chukwu O, Osunde Z D, Alabadan B A. Effect of salt solution on the mycelia growth of orange fruit spoilage fungi in passive evaporative cooling structures. Agric Eng Int: CIGR Journal, 2013; 15(3): 166–170.

[45] Magda M, Abd-El R. Improving the refrigerated vegetables storage rooms performance. Agricultural Engineering and Variables of the Present Epoch, 2009: 1631–1646.

[46] Kader A A. Postharvest Technology of Horticultural Crops. University of California, Division of Agriculture and Natural Resources, Publication 3311. 1992

[47] Mogaji T S, Fapetu O P. Development of an evaporative cooling system for the preservation of fresh vegetables. African Journal of Food Science, 2011; 5(4): 255–266.

[48] Watt J R. Evaporative air conditioning. the Industrial Press, New York, 1963

[49] Zhao X, Liu S, Riffat S B. Comparative study of heat and mass exchanging materials for indirect evaporative cooling systems. Building and Environment, 2008; 43: 1902–11.

[50] Ghassem H, Mojtaba B, Shahram D, Jafar E. Experimental investigation of two-stage indirect/direct evaporative cooling system in various climatic conditions. Building and Environment, 2009; 44: 2073–2079. doi:10.1016/j.buildenv. 2009.02.017.

[51] Abdalla A M E. Lower energy wind assisted indirect evaporative cooling for building application. A PhD thesis submitted to the University of Nottingham, 2008; 1–211.

[52] Liao C M, Chiu K H. Wind tunnel modeling the system performance of alternative cooling pads in Taiwan region. Building and Environment, 2002; 37: 177–187.

[53] Teitel M, Barak M, Zhao Y. Temperature and humidity gradients in fan-ventilated greenhouses under two cooling modes. Acta Horticulture, 2003; 614(2): 469–475.

[54] Wilson L G, Boyette M D, Estes E A. Postharvest Handling and Cooling of Fresh Fruits, Vegetables and Flowers for Small Farms. Leaflets 800–804. North Carolina Cooperative Extension. 1995/

[55] Hugh W Fraser. Tunnel forced-air coolers for fresh fruits & vegetables. Ontario Ministry of Ag., Food and Rural Affairs, The 16th Annual Conference of the Misr Society of Ag. Eng., 25 July, 2009 1645 (OMAFRA). Canada.

[56] Camargo J R, Ebinuma, C D, Cardoso S. A mathematical model for direct evaporative cooling air conditioning system. Engenharia Termica, 2003; 4: 30–34.

[57] Ghasem H, Mojtaba B. Heat and mass transfer modeling of two stage indirect/direct evaporative air coolers: ASHRAE Thailand Chapter. ASHARE Journal, 2007 – 2008 : 2–8.

[58] Qureshi B A, Zubair M. A comprehensive design and rating study of evaporative coolers and condensers. Part I. Performance evaluation. International Journal of Refrigeration, 2006; 29: 645–658. doi:10.1016/j.ijrefrig. 2005.09.014.

[59] Dowdy J A, Karabash N S. Experimental determination of heat and mass transfer coefficients in rigid impregnated cellulose evaporative media. ASHRAE Transactions, 1987; part 2, 93: 382–395.

[60] Peterson J L. An effectiveness model for indirect evaporative coolers. ASHRAE Transactions; 1993, 99(2): 392–399.

[61] Stoitchkov N J, Dimitrov G I. Effectiveness of cross flow plate heat exchanger for indirect evaporative cooling. International Journal of Refrigeration, 1998; 21(6): 463–471.

[62] Dai Y J, Sumathy K. Theoretical study on a cross-flow direct evaporative cooler using honeycomb paper as packing material. Applied Thermal Engineering, 2002; 1417–1430.

[63] Hisham E D, Hisham E, Ajeel A Z. Performance analysis of two stage evaporative coolers. Chemical Engineering Journal, 2004; 102: 255–66.

[64] Chukwuneke J L, Ajike C O, Achebe C H, Okolie P C. A mathematical model of an evaporative cooling pad using sintered nigerian clay. Journal of Minerals and Materials Characterization and Engineering, 2012; 11: 1113–1120.

[65] Ndukwu C, Manuwa S, Olukunle O, Oluwalana B. A simple model for evaporative cooling system of a storage space in a tropical climate. Scientific Journal Agricultural Engineering, 2013; 38: 27–39. UDK: 536.7

[66] Dzivama A U. Performance evaluation of an active cooling system for the storage of fruits and vegetables. Ph.D. Thesis, Department of Agricultural Engineering, University of

Ibadan, Ibadan Nigeria. 2000. In proceeding of Nigeria Institution of Agricultural Engineering, 2013; 34: pp 560–575. Paper No. 991

[67] Umbarker S P, Bonde R S, Kalase M N. Evaporative cooled storage stature for oranges (citrus). Indian Journal of Agricultural Engineering, 1991; 1(1): 26–32.

[68] Olosunde W A, Aremu A K, Onwude D I. Olosunde W A, Aremu A K, Onwude D I. Development of software for monitoring performance of evaporative cooling system for storage of fruits and vegetables. Proceedings of the Nigerian Institution of Agricultural Engineers, 2013; 34: 560–575. Paper No. 991

[69] Lemouari M, Boumaza M, Kaabi A. Experimental analysis of heat and mass transfer phenomena in a direct contact evaporative cooling tower. Energy Conversion and Management, 2009; 50: 1610–1617, doi:10.1016/j.enconman.2009.02.002.

[70] Braun J E, Klein S A, Mitchell J W. Effectiveness models for cooling towers and cooling coils. ASHRAE Trans 1989; 95 (2): 164–74.

[71] Kittas C, Bartzanas T, Jaffrin A. Temperature gradients in a partially shaded large greenhouse equipped with evaporative cooling pads. Biosystems Engineering, 2003; 85(1): 87–94. doi:10.1016/S1537-5110(03)00018-7.

[72] Lertsatitthanakorn C, S Rerngwongwitaya, Soponronnarit S. Field experiments and economic evaluation of an evaporative cooling system in a silkworm rearing house. Biosystems Engineering, 2006, 93 (2); 213–219. doi:10.1016/j.biosystemseng.2005.12.003.

[73] Dilip J, Gopal N T. Modeling and optimal design of evaporative cooling system in controlled environment greenhouse. Energy Conversion and Management, 2002; 43: 2235–2250. PII: S01 96-8904(01)001 51-0.

[74] Niitsu Y, Naito K, Anzai T. Studies on characteristics and design procedure of evaporative coolers. Journal of SHASE, Japan, 1969; 43 (7).

[75] Pascal S, Dominique M. Simplified model for indirect-contact evaporative cooling-tower behavior. Applied Energy, 2004: 78: 433–451. doi:10.1016/j.apenergy.2003.09.004.

[76] Banhazi T M, Lehr H, Black J L, Crabtree H, Schofiel P, Tscharke M, et al. Precision livestock farming: An international review of scientific and commercial aspect. Int J Agric. & Bio Eng, 2012; 5(3): 1- 9. doi:10.3965/j.ijabe.20120503.001.