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Research Article

Experimental performance evaluation of a solar powered evaporative cooling system for preservation of agricultural produce in tropical region

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ABSTRACT

Lack of suitable power supplies and storage facilities are major contributors to post-harvest loss of fruits and vegetables in low- and middle-income nations. The problem of food security can be greatly alleviated by solar-powered cooling systems that store agricultural produce in a decentralized manner. In addition to decreasing food loss and waste, this approach promotes green economic growth by lowering greenhouse gas emissions. In view of this, a direct active solar-powered evaporative cooling system is developed and its performance was assessed. In this investigation, the temperature and humidity within the evaporative cooling system were recorded using a Floureon RC-4HC data logger. The data logger was configured to capture data every half an hour for six to seven hours. The wet and dry bulb temperatures of the surrounding area were recorded using a combination wet bulb and dry bulb hygrometer. To determine the relative humidity values, a psychometric chart was utilized in conjunction with the hygrometer data. To measure the air velocity entering the evaporative cooling system, a digital anemometer was employed. Readings were taken consecutively over four days with varying pad thicknesses (from 20mm to 80mm) under no load conditions and for eight days under load conditions. Results of the study shows that the temperature of the cooling chamber reduced to 25°C with a drop range from 3 to 10°C and the highest relative humidity of 88.2% was recorded inside the cooling chamber while relative humidity of 66.5% was recorded for the surroundings. The cooling efficiency of the cooling chamber was found to vary from 61.4 to 87.5% under no load conditions and 47.06 to 91.1% under load conditions. Moreover, the rate of evaporation, cooling capacity and saturation efficiency vary respectively from 0.00116

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kg/s to 0.00198 kg/s; 5.284 kW to 7.736 kW and 61.40% to 87.50%. Additionally, it was observed that agricultural produce such as tomatoes, peppers, and okra stored in the evaporative cooler retained their freshness and color after 8 days, whereas those stored under room conditions lost both after 3 days. This demonstrates effectiveness of the developed solar-powered evaporative cooling system to preserve agricultural produce. Small-scale farmers in rural areas, which account for about two-thirds of all farm produce losses, the private sector, Non-Governmental Organisations and some government agencies working to promote decentralized cold-storage facilities are expected to find great value in this study.

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INTRODUCTION

One of the challenges of farmers at harvest is how to preserve the produce in non-deteriorated and fresh condition for some time after the harvest till those produce get to the consumers [1]. Some produce like yam and cassava tubers, grains like maize and rice can last for longer time after harvest than fruits and vegetables such as mangoes, oranges pepper, tomatoes and okra. These agricultural produces have to be preserved if they are to last for some time after harvest. If not adequately preserved, fruits and vegetables undergo some changes that reduce their shelf life and quality. According to Dvizama [2], color change, weight loss, hardness changes, and soluble solids alterations are among the changes that occur in agricultural produce that affect their quality. The oldest method of keeping fruits and vegetables, as well as other agricultural products, is to cool them. The quality and freshness of these products are most frequently maintained by this method as well. The natural methods involve the use of ice, evaporative cooling, nocturnal cooling and endothermic mixing of substances. The artificial methods include the use of vapor compression refrigeration system, air refrigeration system, vapor absorption system, magnetic refrigeration and thermoelectric refrigeration [3].

Refrigeration seems to be a promising way of bringing about such preservation since the storage area will be cold and humidified [4]. But it has been observed that the artificial methods of preservation of agricultural produce such as use of conventional vapour compression refrigeration system has adverse effects on the stored fruits. Prominent among such adverse effects on agricultural produce are chilling injury and colour change. This method of refrigeration is also costly to acquire and involves the use of electricity, which may not be readily available to a local farmer.

The preservation of agricultural produce has been discovered to be greatly facilitated by evaporative cooling. The primary method used for the preservation of agricultural produce is evaporative cooling, a type of natural refrigeration. This type of natural cooling occurs when a substance's temperature drops as a result of the body-cooling effects of water evaporation [5]. Due to the fact that evaporated water transforms a substance's temperature into a cooling form, the conversion of sensitive heat into latent heat results in large environmental losses [6]. Keeping agricultural produce at a temperature that is more favorable than the surrounding air temperature is crucial because it helps to extend its shelf life and maintain its quality. An evaporative cooling system cools an object in contact with it by evaporating a liquid, often into the surrounding air. Agricultural produce can be effectively cooled via evaporative cooling, which provides low air temperature and high relative humidity. By comparing the air dry-bulb temperature to the air wet-bulb temperature while accounting for the fact that water evaporates into the air, the effectiveness and potential for evaporative cooling are determined [7, 8]. The cooling effect increases with the difference in temperatures between the two [9]. Evaporative cooling uses a system for moving air along with the natural process of water evaporation to produce a cooling atmosphere. The wet cooling pad allows the warm, fresh air from outside to pass through, cooling the air through water evaporation [10]. Pad media, water supply, distribution pipes, gutting, swamping and pump are the key components of the system. The air stream evaporates part of the moisture, as air flows past the surfaces of the moist pad. During this process heat is removed from the air and the air leaves the tubes at a higher moisture content at lower temperature. The fan then circulates the cool air to the cabinet chamber, in which the fruit and vegetables are kept, and conserves the agricultural produces by reducing the ambient temperature and increasing the relative humidity. If the driving force for the outside warm and fresh air is a set of blowers or fan, then the evaporative system is said to be active evaporative system but if the driving force is natural air circulation without a separate fan, the system is said to be passive evaporative system. This study focuses on active evaporative cooling system. Figure 1 shows the illustrative diagram of an active evaporative cooling system. The working fluid for this system is water. The major components of the cooler comprise essentially of a pad medium through which water to be evaporated circulates, water pump to cause the circulation of the water from the water tank through the pad and back to the water tank, the blower or fan to draw air from surrounding across the pad, electricity source as means of powering the pump and the blower, a water reservoir and evaporative cooler cabinet where the agricultural produce to be preserved are kept.

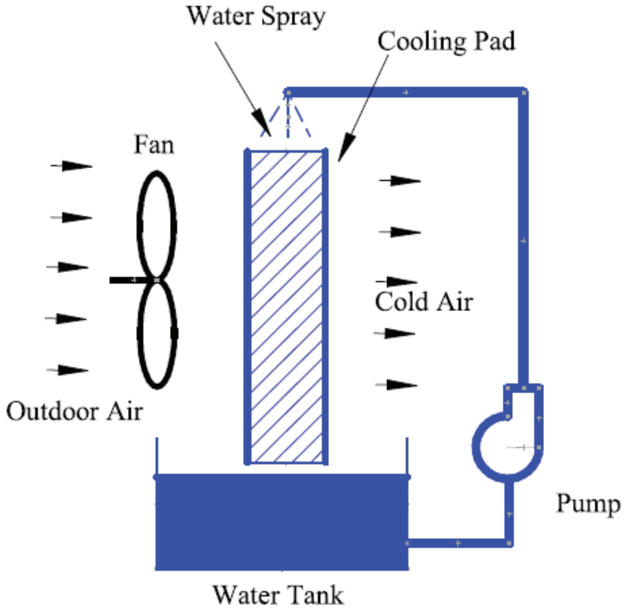

Figure 1. An illustrative sketch of an active evaporative cooler [From Kapilan et al. [11], with permission from Elsevier].

Water is evaporated during the evaporation process, and heat is transferred from the wet cooling pad material [11]. The flow of air and its saturation determine the system's cooling capacity, which in turn depends on the pad's features, air velocity through the pad, and water flow rate [12]. A number of variables, including wind, temperature, surface area, humidity, air velocity, water flow rate, and pad thickness, have an impact on the wet pad's ability to evaporate. The saturation rate and air temperature have an impact on how much water can be removed from the cooling pad by air [13]. The cooling pad may be made from various materials. Water retention capacity and porosity are the major properties expected of a material that can be used as cooling pad [14]. Most pad media for the evaporative cooling system are made from agricultural residue, although there are some commercially created pad media for sale in the market. Among materials that have been used for cooling pad manufacturing include jute, cellulose, aspen, PVC, hessian, wood shaven, rice straw, cotton fleece, charcoal, latex, foam and luffa fiber. To form a cooling pad, the pad materials are bundled together in sizes of 2 - 12 inches with an interval of 2 inches, (1inch = 25.4 mm). The higher the size of the pad the greater the cooling efficiency. A typical 12 inches pad can provide 123 square inches of surface area of cooling per cubic foot of media. Al-Suleiman [15] conducted a survey that viewed the performance criteria of a wetted cooling pad media based on cooling efficiency and mold forming resistance and found that jute recorded cooling efficiency of 62.1%, luffa 55.1%, commercial pads 49.9% and palm 38.9% also luffa and palm filaments had the most outstanding protection mold while jute and commercial pads had lower resistance. Olosunde et al. [16] also found out that jute cushion has 86.2% has cooling productivity and highest saturation efficiency of all pad cushions.

The air may be drawn across the cooling pad to meet the produce in cooling chamber by natural convection or forced convection across the pad using fans or blowers. In the latter case a power source is required to power the blowers and the pump [17, 18]. Electricity is a good power source but in rural areas and farm settlement where electricity is not available or affordable, an alternative power source is being sorted to power the evaporative system. This informs why this study investigates into using solar energy to power the developed evaporative cooling system. Erratic power supply and inadequate facilities hinder storage of perishable crops, leading to postharvest losses among the rural dwellers in tropical region in Africa, especially in Nigeria. Therefore, decentralized cold storage system can significantly help reduce post-harvest losses at production sites and generate income and secure livelihoods in rural communities in Nigeria [19, 20]. Solar energy is a viable solution to power evaporative cooling (storage) systems in developing countries, especially in Nigeria. Tropical Region in Africa receives a large amount of solar radiation all year round—an average of 4 – 7 kWh/m^2d, giving an energy amount of about 21 MJ over the year [21]. Researches showed that a national average global solar energy of 5.5 $kWh/m^2/day$ and average solar radiation time of 6 h/day are favorable conditions for PV power generation in Nigeria [22].

Numerous researchers have worked on evaporative cooling system for preservation of agricultural produce. Among which includes the work of Adebisi et al. [23] that developed an evaporative cooler for preservation of fruit and vegetable in Western Nigeria. Samples of fruits and vegetable preserved with this cooler were found to maintain their freshness for 14 days under storage temperature of 16°C against ambient temperature of 32°C. Mogaji and Olorunisola [24] and Ndukwu [25] respectively developed an evaporative cooler aimed at extending the shelf life of some ranges of fruit and vegetable in Nigeria. In each case samples preserved were tested and found to have extended shelf life and freshness for many days over the similar fruit and vegetable samples that were not subjected to such treatment. The evaporative coolers were also able to maintain the cooling cabinet lower temperature than what obtain in their surroundings. In the former the temperature of the cooler cabinet reached 16°C when the ambient temperature ranged between 26°C and 32°C and the relative humidity in the cooler cabinet was up to 88% as against the ambient relative humidity of 18% - 31%. In the later the cooler cabinet temperature was 25.2°C and relative humidity 85.6% to 95.8%. In the above cases source of power of the evaporative cooler is electricity which may not be readily available in a rural setting or will make the procurement and/or running cost to be too high for such setting. A study on the effectiveness of direct evaporative coolers in hot, humid climates was reported by Abdulrahman et al. [26]. Based on weather information from Kuala Lumpur, Malaysia, the experimental investigation was conducted. The cellulose pad employed by the direct evaporative cooler had a surface area to volume ratio of 100 m^2/m^3. The investigation revealed that the saturation efficiency ranged from 63.5% to 77.3%. Under the conditions of Kuwait, Hisham et al. [27] developed a two-stage evaporative cooling system. The study was conducted in the summer when the air's dry bulb temperature was above 45°C. The study's findings showed that whereas direct evaporative cooling had an efficiency range of 63% to 93%, indirect evaporative cooling had a range of 20% to 40%.

In their study, Zakari et al. [28] examined how the thickness of the evaporative cooling pad affected the efficiency of the evaporative cooler for four Cities in China. According to the study, the ideal pad thickness depends on the face velocity and meteorological factors. Jain et al. [29] carried out an experiment on the fundamental analysis of some new pad materials for evaporative cooling system. The selected materials for the study are coconut fibers and tree roots. The experiment was set up under the same and constant air flow rate. The study revealed that for the palash fibers, the cooling effectiveness was 13.2% and it was 26% more than that of aspen pads and khus pads tested. While the cooling effectiveness of the coconut fibers was observed to be 8.15% more than that of khun pad tested. Oyedepo et al. [30] reported dataset on the performance of a solar-powered agricultural produce cooling storage system when used in tropical climates. According to the study, the pad thickness affects how well an evaporative cooling system works.

This present study aimed at performance evaluation of a cost saving solar powered evaporative cooling system for preservation of agricultural produce under tropical conditions. The prime objectives of the study are to determine the cooling efficiency, rate of evaporation and cooling capacity of the evaporative cooler under varying pad thicknesses and fan speed at both no load and load conditions. This study is significant because, there is low cost of production in comparison to the mechanical storage methods (vapour compression refrigeration), reduction in cost of energy as it makes use of solar energy and it prevents chilling injury as it is free of chemicals unlike mechanical refrigerators Furthermore, this study incorporates a solar PV system with the evaporative cooler, making it applicable in rural areas where there is no access to electricity. To the authors' best knowledge there are few studies of this kind in the literature. About 70% of the materials used for this project were sourced locally. Hence, from socio-economic benefits, the project encourages local contents as there is possibility of developing Small and Midsize Enterprises (SMEs) in rural areas and also could provide job opportunities for the rural dwellers.

MATERIALS AND METHODS

Description of the Developed Solar Powered Evaporative Cooling System

The developed solar powered evaporative cooling system has a cooling chamber of 0.125m^3 cubical storage capacity having the outer wall made of galvanized mild steel and inner walls made of aluminum. It was mounted on a steel frame and had trays inside to serve as compartment for storing the agricultural produce inside. An insulator of polystyrene material is in between the inner and outer walls of the cooling chamber to prevent heat transfer between the cooling chamber and the surrounding. A fan is mounted behind the cooling pad to force air through the wet cooling pad (made of jute material). Directly above the cooling chamber there is a plastic water tank for storing water. A 5W electric water pump was used to pump water via a rubber pipe to the cooling pad at a rate of 240 L/h to wet the cooling pad. The cooling pad (made from jute) was folded to suitable thickness and placed behind the cooling chamber which has been perforated at the back. The evaporative cooler was powered by a 110W solar panel, and a 225Ah solar deep charge battery connected to a 3A solar charge controller. The solar setup powered the pump and the fan which makes the whole system function. The solar panel was placed on the topmost layer of the frame (Fig. 2) to facilitate receiving direct solar energy. The development of the system was carried out subject to thorough design considerations and construction.

Working Principle of Evaporative Cooling System

The evaporative cooling system's operation is based on natural convection and is used to store agricultural produce (fruits and vegetables). Converting sensible heat to latent heat is the basic idea of direct evaporative cooling [31]. Dry air is drawn through wet paddling or a fine mist of water in an evaporative cooling system

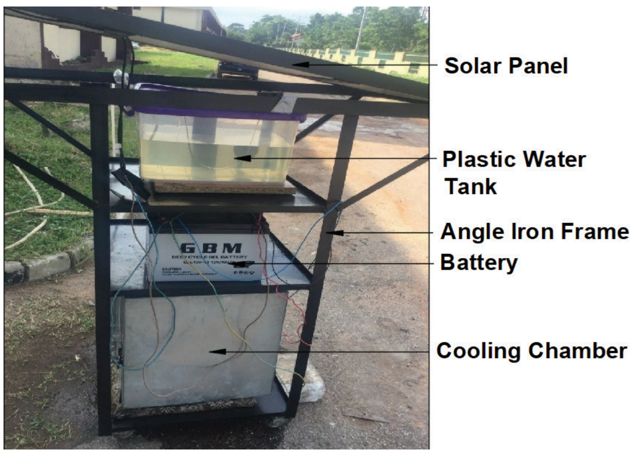

Figure 2. Solar powered evaporative storage system.

(EC). When ambient air flows through a cooling pad, the cooling pad uses latent heat to evaporate water droplets on the pads, which cools the surrounding air [32]. This cooled air decreases the temperature and increases the humidity in evaporative cooler, which results in increase of the humidity in evaporative cooling chamber. This process leads to extension in the shelf life of agricultural produce stored in the evaporative cooling chamber. The direct evaporative cooling principle is cost-effective and efficient approach for lowering the temperature of agricultural produce. The vents between the product containers are used to pull in the air that has thus been cooled. The warm season crops such as tomato, cucumber, okra, eggplant, and peppers are shown to be ideal for this strategy. Successful evaporative cooling requires a minimum exterior air temperature of above 32°C as well as a reasonably low wet bulb temperature (WBT), ideally less than 21°C. Better EC of outdoor air conditions are created by high dry bulb temperature and low WBT [33]. In the psychometric chart (Fig. 3), the interaction between air and water is depicted. To water, air functions as a sponge. The main distinction is that more water can be held by the air as temperature rises. The constant energy line D is traveled by air as it absorbs water. This chart can be used to estimate how much cooling will occur if the air's ambient conditions are known. The evaporative cooling mechanism and the adiabatic cooling principle are schematically depicted on psychometric charts in Figures 3 and 4, respectively.

Materials Selection for the Developed Evaporative Cooling System

Agricultural produce used for the experiment

The agricultural produce used for assessing the performance of the developed solar powered evaporative cooling system are tomatoes, pepper and okra.

Cooling pad

The cooling pad is required to produce cool and humidified air into the cooling chamber and hence reduces the total heat load present in the system. The sources of heat present in the cooler are:

(a) heat of conduction - heat coming in through insulated walls.
(b) heat within the fruits - this is the heat picked up by the fruits on the field it is directly proportional to the mass of the fruits and the storage temperature. It's the heat energy contained in the agricultural produce as it cools to the temperature of the cooling chamber.
(c) heat of respiration - this is the heat generated by the agricultural produce.

- The pad used for the experiment is jute fibre, because it has been found to give the highest cooling efficiency among known materials used for cooling pad as it offers low resistance to air flow due to tiny holes it contained [15].

Water pump

An AD20P - 1230A DC brushless circulation water pump was employed in this study. Due to the fact that this pump

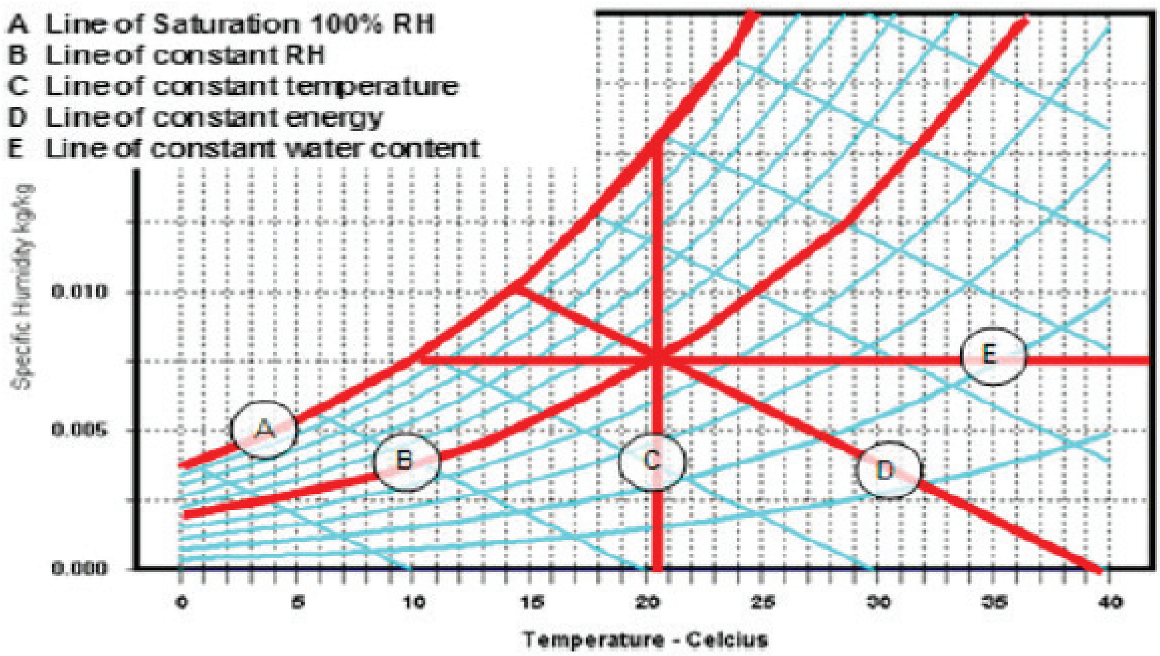

Figure 3. Schematic of evaporative cooling process on psychrometric chart [From Wyehead Design [34], http://www.workspacecooling.co.uk/psychr.html].

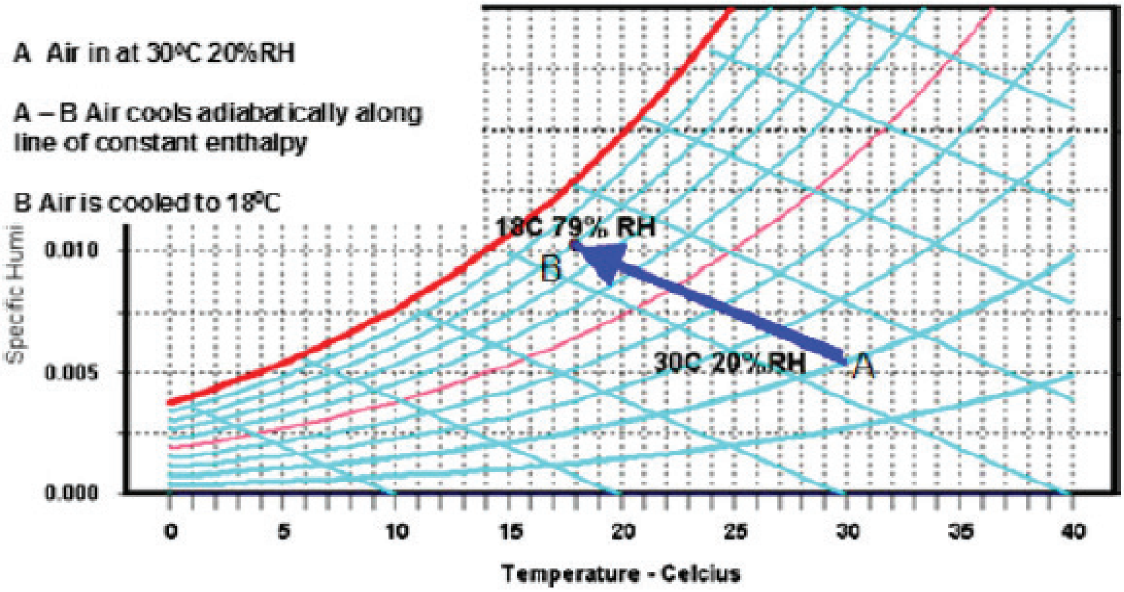

Figure 4. The principle of adiabatic cooling on a psychometric chart [From Wyehead Design [34], http://www.workspace-cooling.co.uk/psychr.html].

does not produce electromagnetic interference, it is frequently employed in the water supply for small household appliances in both the medical and industrial sectors. Brushless DC driven pumps can transfer fluid in a number of ways by utilizing direct current from the motor, battery, or solar power.

The water pump used for this study has the following parameters: power rating = 5 W, Input Voltage = 12V, water discharge = 240 l/hr and maximum static head = 3 m. In order to determine the volumetric heat generation inside a participating media, the spectral intensity must be integrated over the entire spectrum within all wavelengths and directions [15, 16].

Cooling chamber

Aluminum was selected for construction of the inner walls of the cooling chambers because of its high heat reflectivity and high resistance to corrosion.

Schematic diagram of the solar PV evaporative cooling system connection is presented in Figure 5. The figure shows the connection of each component of the evaporative coolin system.

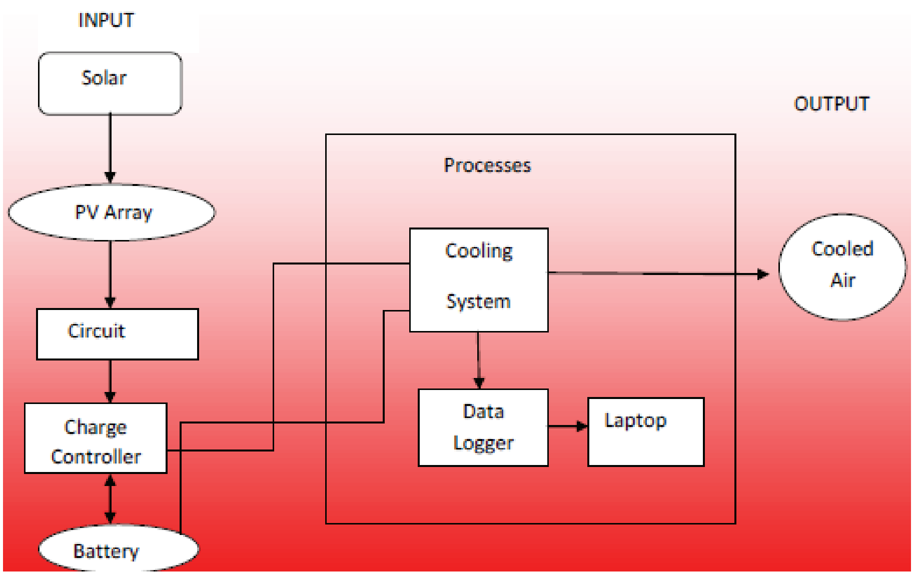

Figure 5. The schematic diagram of the solar PV evaporative cooling system [From Ndukwu et al. [35], with permission from MDPI].

Instrumentation and Measurements of Readings

This study including experimental tests undertaken to measure various operational parameters, e.g. inlet and outlet temperatures of the cooling chamber, humidity and air velocity which were used to determine the real performance of the evaporative cooling systems under the specified operating conditions. Tests were performed as per the ANSI/ASHRAE 133-2015 Standard 'Method of Test for Rating direct Evaporative Coolers'. All measurements were carried out with instruments comply with national standards and the measurement methods were in accordance with ISO 5801. Temperature measuring range from -30°C to +60 °C with accuracy of ±0.6 °C and Humidity ranges from 0 to 99% RH with accuracy of ±3% RH. These are in line with ISO 5801 standards.

Various instruments were used in taking the readings of the data needed for the performance assessment of the evaporative cooling system. These include the following:

- Floureon RC-4HC Data logger: The floureon data logger was used to record the temperature and humidity inside the cooling system, the data logger has an inbuilt sensor and works with a software that is to be installed into the P.C and used to program the data logger, and also set the data logger to record the temperature and humidity at a preset interval. For the course of this study, the data logger was set to record data at every 30 minutes through a period of 6 - 7 hours. It has maximum capacity of 16,000 values.
- Wet bulb & dry bulb hygrometer: The combined wet bulb and dry bulb hygrometer was used to record the wet and dry bulb temperatures of the atmosphere; it is an analog instrument, hence, there is need for constant checking of the temperature every 30 minutes for a period of 8 hours. The data gotten from the hygrometer was used alongside a psychometric chart in order to get the values for the relative humidity.
- Digital Anemometer: The anemometer was used to determine the air velocity entering the evaporative cooling system while making use of the fan regulator to control the speed. For the speed control, the anemometer was placed at different part of the system to measure the speed of the fan, at each of the control level.

Design Calculation

Electrical load calculation

Determination of the number of solar panels required

Hours of operation of the evaporative cooler per day = 6 hours

Power rating for water pump = 5 Watt

Watt-hour for water pump = 6 h x 5 W = 30 Watt-hour

Power rating for fan = 50 Watt

Watt-hour for fan = 6 h x 50 W = 300 Watt-hour

Total Watt-hour for the evaporative cooler = 300 + 30 =330 Watt-hour

Total Watt-hour solar panel must deliver = 330 x 1.3 = 429 Watt-hour

Where, a factor of 1.3 is regarded as the energy lost in the system to get the total Watt-hours per day which must be provided by the panels.

Different-sized photovoltaic modules will generate varying amounts of power. The total peak watts produced must be known in order to determine the size of the PV module. The peak watt (Wp) generated varies based on site climate and PV module size. The panel generation factor, which varies according to the site location, must be taken into account. The panel generation factor is 3.625 for Nigeria [35]. The PV module's size is determined as follows:

Panel generation factor for tropical region (Nigeria) = 3.625

∴ Total peak watt available = 429/3.625 = 118.34 Watt-hour

The rated peak solar panel available = 110 Watt

The number of solar panel required = 118.34/110 = 1.08

The actual PV panel requirement = 1 module

The evaporative system is to be powered by 1 module of 110 Wp PV module.

Determination of size of battery required

$$Battery\ Capacity\ (Ah) = \frac{TotalWatt-hours\ per\ day\ used\ by\ appliances}{0.85\ x\ 0.6x\ norminal\ battery\ voltage}\ x\ days\ of\ autonomy$$

Total Watt-hour of the evaporative cooler = 429 Watt-hour

Battery loss factor = 0.85

Battery depth of discharge factor = 0.6

Norminal battery voltage available = 12 V

Days of autonomy considered in this study = 3 day

Total Watt – hour for a Deep Charge Battery = (429 x 3)/(0.85 x 0.6 x 12)=210.29= 210.29 Ah

The required ampere-hour =210.29 Ah

The battery for the evaporative cooling system should be rated 12 V 225 Ah for 3-day autonomy.

Determination of solar charge controller

The PV array voltage and the batteries utilized in this study were taken into consideration when choosing the solar charge controller. We made sure the solar charge controller had sufficient capacity to handle the current coming from the PV array. Also used was a series charge controller type. The short circuit current (Isc) of the PV array is multiplied by 1.3 [36] in accordance with Standard procedure when sizing a solar charge controller

The solar charge controller is typically rated against Amperage and Voltage capacities. The solar charge controller for this study is computed as follows:

PV module specification, Pm = 110 Wp

Vm = 16.7 Vdc

Im = 6.6 A

Voc = 20.7 A

Isc = 7.5 A

The required solar charge controller rating = (1 string x 7.5 A) x 1.3 = 2.21 A

Hence, the solar charge controller for the evaporative cooler should be rated 3 A at 12 V.

Determination of fan capacity

Fan capacity was determined in accordance with Linden [37] as given in equation (1) below

$$C = Hn \times A \quad (1)$$

Where C = battery capacity, Hn = number of hours between sunset and sunrise and A = fan current rating

Experimental Procedure

Details experimental procedure adopted in this study can be found in Oyedepo et al. [30]. For the purpose of this investigation, the cooling chamber's internal temperature and humidity were measured using the Floureon RC-4HC data logger device. The data logger was programmed to record data every 30 minutes while the readings were being obtained for 8 hrs. When the computer is linked to the Floureon RC-4HC temperature and humidity data logger, the program immediately reads the data and creates reports. It contains an LCD panel that shows the time, temperature, as well as the maximum and minimum temperatures. For long-term temperature recording, two sensors—one internal and one external—are employed. With an accuracy of 0.6°C, the temperature measuring range is from 30°C to +60°C. The humidity is accurate to within 3% RH and ranges from 0 to 99% RH. Record length can be adjusted from 10 seconds to 24 hours, and record capacity is RC-4HC 16000 points (MAX). The wet bulb and dry bulb temperatures of the surrounding were measured using wet bulb and dry bulb hygrometer alongside with psychometric chart. Digital anemometer was used to determine the air velocity entering into system.

Thermodynamic Performance Assessment of Evaporative Cooling System

The evaporative cooling system is characterized as an adiabatic process since it maintains a constant enthalpy [38]. In a direct evaporative cooling system, the air and water are in direct contact; warm, dry air passes over wet surfaces to lose sensible heat and drop temperature. As the air travels through the wet padding material, the sensible heat (SH) in the incoming air is converted into latent heat (LH), which is used to evaporate moisture from the pad. Ultimately, this results in a decrease in the dry bulb temperature and an increase in the relative humidity (RH) of the air coming into the cooling chamber. Enthalpy and WBT are not changed.

Figure 6 displays the flow chart for the energy analysis of the solar powered evaporative cooling system from thermodynamics point of view. Its potential for sustainable and energy-efficient cooling solutions is demonstrated by the figure, which shows the energy flow of the solar evaporative cooling system. While the embodied energy is the energy used in the materials and construction of the system, the input solar energy is the energy from the sun that powers the cooling process. Energy Output, on the other hand, shows the cooler's cooling energy potential and the evaporative cooler's ultimate objective of producing cooling energy.

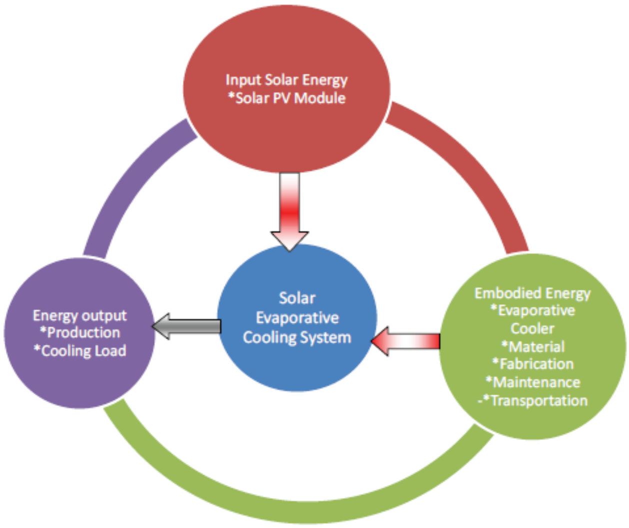

Figure 6. Flow chart of energy analysis for the solar powered evaporative cooling system [From Ndukwu et al. [35], with permission from MDPI].

Thermodynamic performance assessment of the cooling media in evaporative cooling system is presented as follows [39]:

Convective heat transfer coefficient calculation

Convective heat transfer coefficient hc (W/m^2K) can be calculated from the Nusselt number as follows [33]:

$$\boldsymbol{h_c = \frac{Nu.K_{air}}{L_c}} \quad (2)$$

Where,

L_c is the characteristic length of the surface (m)

k_{air} is the thermal conductivity of the air ($kW\ m^{-1}\ K^{-1}$)

The characteristic length is given by

$$L_c = \frac{V_p}{A_w} \quad (3)$$

where A_w is the total wetted area and Vp is the volume occupied by the wetted media.

Total wetted surface area (Aw) of the rectangular pad is given as:

$$A_w = A_1 \times H \times W \times t \quad (4)$$

A_1= Wetted surface area of pad material per unit volume m^2/m^3

H = height of pad; W = width of pad, t = thickness of pad

The Nusselt number (Nu) in a rigid pad evaporative media is computed from the following equation [40, 41]:

$$\boldsymbol{Nu = 0.1\left(\frac{L_c}{t}\right)^{0.12} Re^{0.8} Pr^{0.33}} \quad (5)$$

Where:
t is the pad thickness (m)
The Reynold's number, Re, can be calculated as follows:

$$Re = \frac{U_{air}.L_c}{\nu} \quad (6)$$

Where,
U_{air} is the velocity of air (m s^{-1})
ν is the kinematic viscosity of the fluid (air) (m^2 s^{-1})
The Prandtl number, Pr, can be calculated as follows:

$$\mathrm{Pr} = \frac{\nu}{\alpha} \quad (7)$$

Where,
α is thermal diffusivity of the fluid (air) (m^2 s^{-1}) and measures the rate of heat transfer of a material from the hot side to the cold side. It is mathematically expressed as:

$$\alpha = \frac{K_{air}}{\rho.C_{pa}} \quad (8)$$

Evaporative cooling efficiency of cooling pad

The evaporative cooling efficiency (saturation efficiency) of the jute pads can be written as [42]:

$$\boldsymbol{\varepsilon = \frac{T_{a,in} - T_{a,out}}{T_{a,in} - T_{a,in,wet}}} \quad (9)$$

Where $T_{a,in}$ is the dry bulb temperature of inlet air; $T_{a,out}$ is the dry bulb temperature of outlet air; $T_{a,in,wt}$ is the wet bulb temperature of inlet air.

Outlet air temperature, T2

The outlet air temperature, T_2 can be calculated from the following equation [42]:

$$T_2 = T_1 - \varepsilon(T_1 - T_{wbt}) \quad (10)$$

Where, T_1 is the inlet dry bulb temperature of air in (°C), T_2 is the supply air temperature of air in (°C) and T_{wb}t is the wet bulb temperature of outside air (°C).

Cooling capacity of evaporative cooling system

The cooled and humidified air from the pad is required to remove the heat load of the evaporative cooler for the storage of agricultural produce (fruits and vegetables). Hence, in this study, the total cooling capacity (load) is calculated from sensitive cooling load and latent cooling load as follows:

Sensible heat (SH)

The sensible cooling capacity (cooling capacity) of the evaporative cooling system is calculated using the following relation [43]:

$$Q_{SH} = \dot{m}_a C_{pa}(T_{a,in} - T_{a,out}) \quad (11)$$

Where, C_{pa} is the specific heat of inlet air, and $\dot{m}_a$ is the mass flow rate of air in (kg/s) and it is computed as

$$\dot{m}_a = \rho u_a HW \quad (12)$$

Where, Ua is the velocity of air blew by the electric fan. In this study, the average value of the air velocity calculated during the experiment is 3.9 m/s.

Latent heat (LH)

The latent cooling capacity (cooling load) of the evaporative cooling system is calculated using the following relation [43]:

$$Q_{LH} = \dot{m}_a h_{fg}(\omega_{a,out} - \omega_{a,in}) \quad (13)$$

Total cooling capacity of evaporative cooling system

The total cooling capacity of the evaporative cooling system is computed using the following equation [41]:

$$Q_{EC} = Q_{SH} + Q_{LH} = \dot{m}_a C_{pa}(T_{a,in} - T_{a,out}) + \dot{m}_a h_{fg}(\omega_{a,out} - \omega_{a,in}) \quad (14)$$

Where, h_{fg} = latent heat of evaporation of water at temperature t_2, kJ/kg, $\omega_{a,in}$, $\omega_{a,out}$ = specific humidity of air entering and leaving the evaporative cooler, kg/kg of dry air.

Specific humidity of air can be calculated from the following equation

$$\omega_a = 0.622\left(\frac{P_v}{P - P_v}\right) \quad (15)$$

where P and P_v is the atmospheric pressure and saturation pressure of water vapour, respectively.

Rate of evaporation (water consumption)

Rate of evaporation or Water consumption in the evaporative cooling system can be expressed as follows [44]:

$$\dot{m}_w = \dot{m}_a(\omega_{a,out} - \omega_{a,in}) \quad (16)$$

where $\omega_{a,in}$ and $\omega_{a,out}$ is specific humidity of inlet and outlet air of the cooling pad.

RESULTS AND DISCUSSION

Data Acquisition and Analysis

Readings were taken every 30 minutes throughout the experiment, as mentioned in section 2.6, and data were recorded using a data logger for a period of 8 hours. Using a psychometric chart and a wet bulb and dry bulb hygrometer, the surrounding wet and dry bulb temperatures were determined. To measure the air velocity entering the system, a digital anemometer was employed. The average values of the experimental data obtained under no load conditions are shown in Table 1. Tc stands for cooling chamber temperature, RHc for cooling chamber relative humidity, DBT for dry bulbs, WBT for wet bulbs, and RHa for ambient relative humidity. These data were utilized to evaluate the designed evaporative cooling system's performance.

Table 2 presents the design parameters of the evaporative cooling system used to carry out experimental performance assessment.

The calculated thermodynamic properties of air using data presented in Table 1 (i.e average dry bulb temperature and wet bulb temperature) for different pad thicknesses (under no load condition) are presented in Table 3.

Table 1. Average experimental data collected for different cooling pad thicknesses under no load

Parameters	Pad Thickness			
	20 mm	**40 mm**	**60 mm**	**80 mm**
T_{DB} (°C)	33.2	34.6	33.4	31.5
T_C (°C)	29.7	29.4	28.8	27.3
T_{wbt} (°C)	27.5	27.4	27.6	26.7
RH_C (%)	78	76.9	82.4	78.6
RH_a (%)	65.1	57.5	64.8	69.4

Tc – Temperature of cooling chamber, RHC – Relative humidity of cooling chamber, TDB – Dry bulb temperature, TWB – Wet bulb temperature, RHa – Relative humidity of the surroundings

Table 2. Design parameters used in performance assessment of evaporative cooler

Parameter	Units	Value
Characteristic Length, Lc	m	0.015625
Height of pad, H	m	0.40
Width of pad, W	m	0.40
Volume of wetted pad, V_p	m^3	0.025
Pad thicknesses, t	m	0.02, 0.04, 0.06, 0.08
Velocity of air, U_a	m/s	3.9

Table 3. Calculated thermodynamic properties of air for different pad thickness under no load

Parameters	Pad Thickness			
	20 mm	**40 mm**	**60 mm**	**80 mm**
ρ_a (kg/m^3)	1.1652	1.1664	1.1688	1.1748
C_{pa} (kJ/kg.K)	1.007	1.007	1.007	1.007
m_a (kg/s)	0.7271	0.7278	0.7293	0.7331
K_{air} (kW/m.K)	0.02586	0.02584	0.02579	0.02568
v (m^2/s) x 10^{-5}	1.605	1.602	1.597	1.583
α (m^2/s) x 10^{-5}	2.204	2.200	2.192	2.172
Re	379.73	3803.84	3815.75	3849.49
Nu	63.86	58.85	56.20	54.69
Pr	0.7282	0.7282	0.7286	0.7288
$\omega_{a,in}$ (kg kg^{-1})	0.0210	0.0218	0.0220	0.0225
$\omega_{a,out}$ (kg kg^{-1})	0.0226	0.0235	0.0242	0.0252
T_2 (°C)	28.35	27.96	27.85	26.78
h_{fg} (kJ/kg)	2338.6	2340.5	2339.8	2341.5

Performance Assessment for Selection of Cooling Pad Thickness

The first performance test carried out to evaluate the performance of the developed solar powered evaporative cooling system was to assess the cooling pad thickness that will give highest R.Hc and lowest cooling chamber temperature. Four different pad thicknesses (20 mm, 40 mm, 60 mm and 80 mm) were tested and the results are as presented in Figures 7 – 14. The average relative humidity (cabinet chamber) (R.Hc), ambient relative humidity (R.Ha), cabinet chamber temperature (Tc), ambient dry bulb temperature (DBT), and ambient wet bulb temperature (WBT) for pad thickness of 20 mm, 40 mm, 60 mm, and 80 mm are 78%, 65.1%, 29.7°C, 33.2°C, 27.5°C; 76.9%, 57.5%, 29.4°C, 34.6°C, 27.4°C; 82.4%, 64.8%, 33.4°C, 27.6°C; 78.6%, 26.7%, 27.3°C, 31.5°C and 26.7°C, respectively.

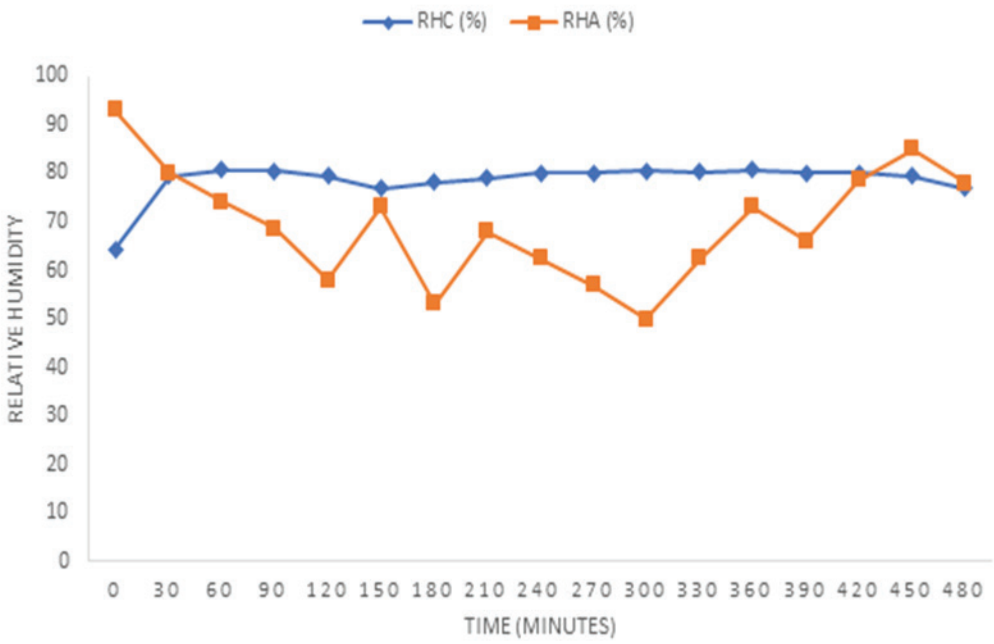

Figure 7. Relative humidity readings for pad thickness of 20 mm.

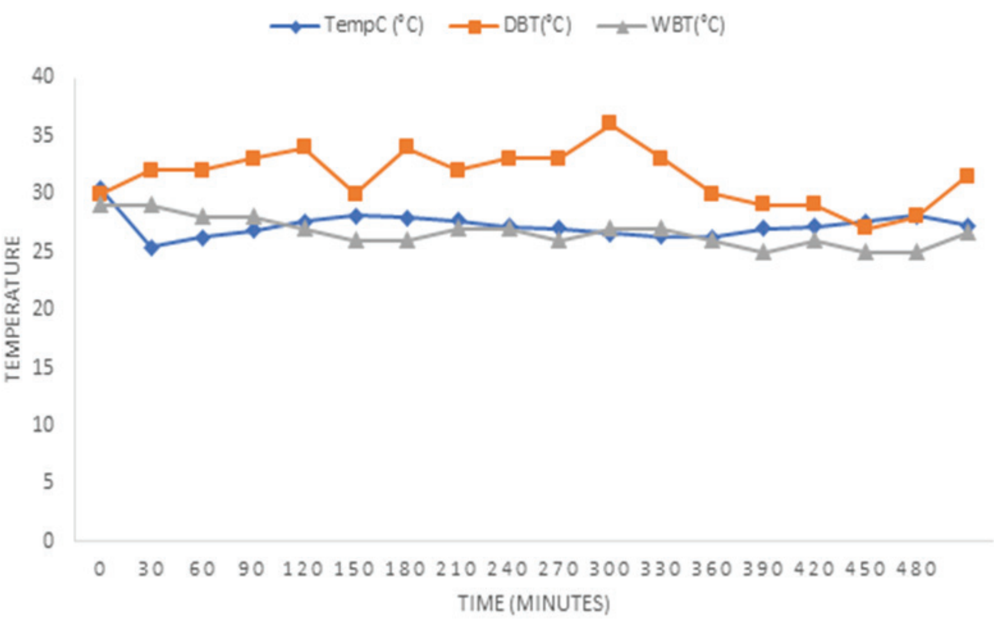

Figure 8. Temperatures (DBT and WBT) readings for pad thickness of 20 mm.

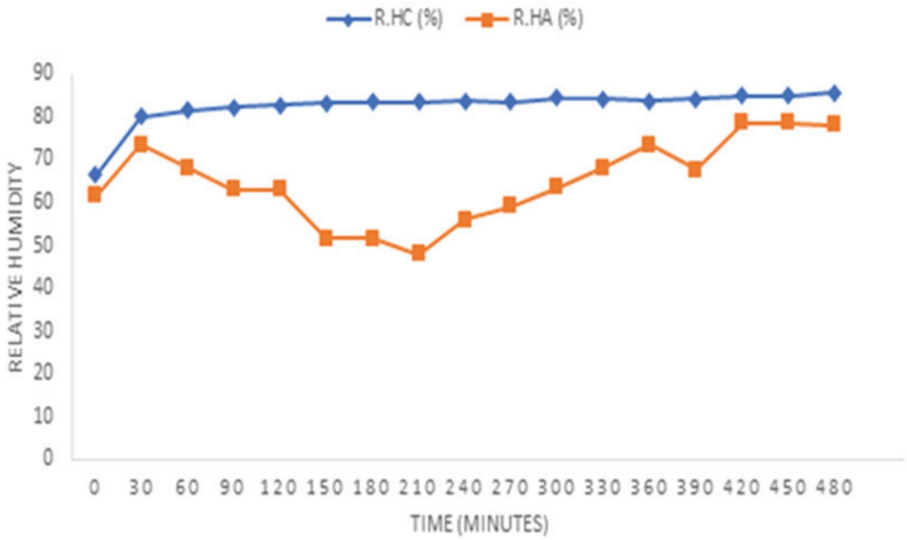

Figure 9. Relative humidity readings for pad thickness of 40 mm.

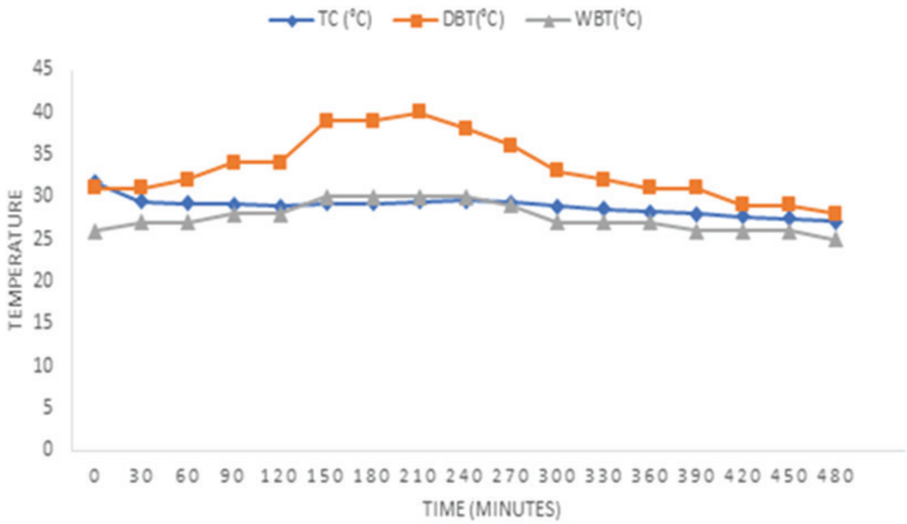

Figure 10. Temperature (DBT and WBT) readings for pad thickness of 40 mm.

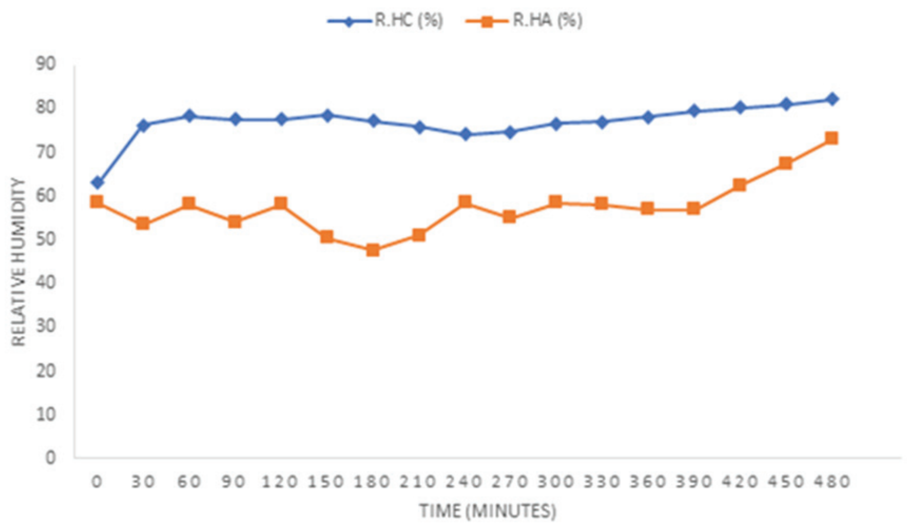

Figure 11. Relative humidity readings for pad thickness of 60 mm.

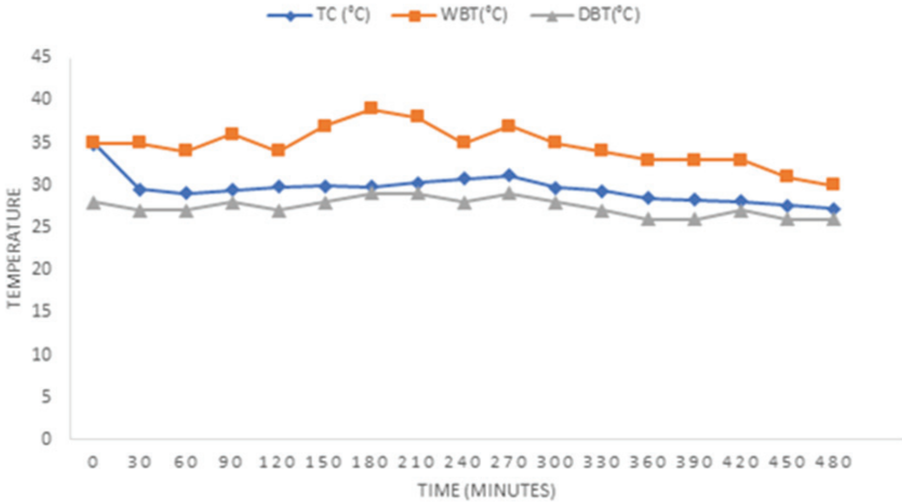

Figure 12. Temperature (DBT and WBT) readings for pad thickness of 60 mm.

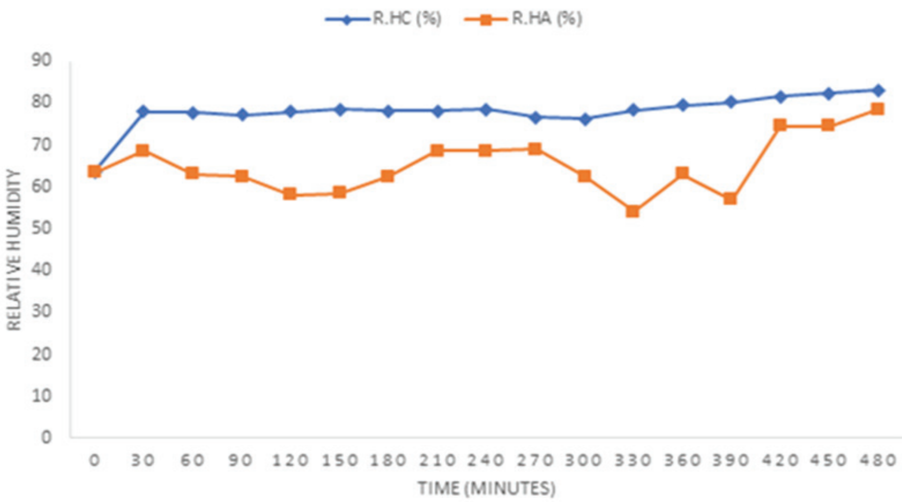

Figure 13. Relative humidity readings for pad thickness of 80 mm.

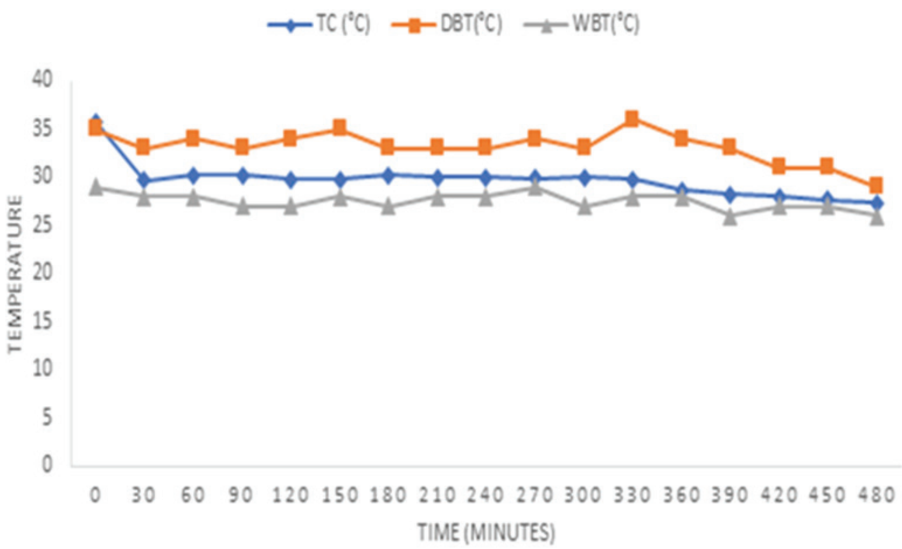

Figure 14. Temperature (DBT and WBT) readings for pad thickness of 80 mm.

The thermodynamic performance parameters of the evaporative cooling system for each pad thickness under no load condition were calculated using equations (2), (9), (11), (13), (14) and (16). The result is presented in Table 4. From Table 4, the pad thickness of 80 mm gave the highest cooling efficiency (87.5%), cooling capacity (7.736 kW) and rate of evaporation (water consumption (0.00198 kg/s). Result of variation in water consumption rate (rate of evaporation) is similar to that of Sachdeva et al. [41]. Based on the above factors, the pad thickness 80 mm was used to evaluate the performance of the designed evaporative cooling system for the next 8 days (under load condition).

Performance Assessment of Evaporative Cooler Under no Load Condition

The evaporative cooling system's performance was first evaluated while it was running with no load for five days. This is done to see if the cabinet chamber's temperature drops and its relative humidity rises when compared to the surrounding air. Following the pad thickness test, the performance evaluation under load conditions was conducted using the pad thickness of 80 mm, which provided the best cooling capacity and efficiency under no load conditions. Figures 15 and 16, respectively, show the results of the cabinet temperature, the dry bulb and wet bulb temperatures of the surroundings, and the relative humidity of the cabinet chamber and that of the surroundings under no load conditions. From Figure 15, it can be seen that the temperature of the cabinet chamber under no load condition varied from 26.5^{o}C to 29.1^{o}C while the ambient dry bulb temperature and web temperature varied from 27.8^{o}C to 33.4^{o}C and 25.2^{o}C to 27.6^{o}C, respectively. This confirmed temperature drops between the ambient condition and the cabinet condition. From Figure 16, the Relative Humidity of the cabinet chamber varied from76.1% to 78.6% while the R.H of the environment varied from 55.1% to 69.1%. This also

Table 4. Thermodynamic performance of evaporative cooler with different pad thickness under no load

Pad Thickness (mm)	Cooling Performance Parameters			Convective Heat Transfer Coefficient (W/m²K)	Rate of Evaporation (kg/s)	Saturation (Cooling) Efficiency (%)
	Sensitive Heat (Q_S) of Cooling (kW)	Latent Heat of (Q_L) Cooling (kW)	Total Heat of Cooling (Q_{EC}) (kW)			
20	2.563	2.721	5.284	105.69	0.00116	61.40
40	3.811	2.896	6.707	97.32	0.00124	72.22
60	3.378	3.754	7.132	92.76	0.00160	79.31
80	3.101	4.635	7.736	89.88	0.00198	87.50

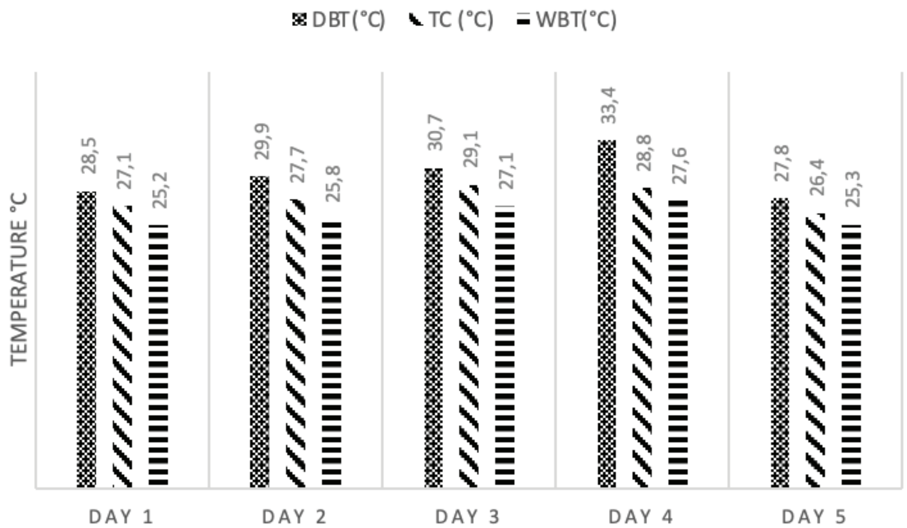

Figure 15. Comparison of cabinet chamber temperature and ambient temperatures (WBT & DBT) under no-load condition.

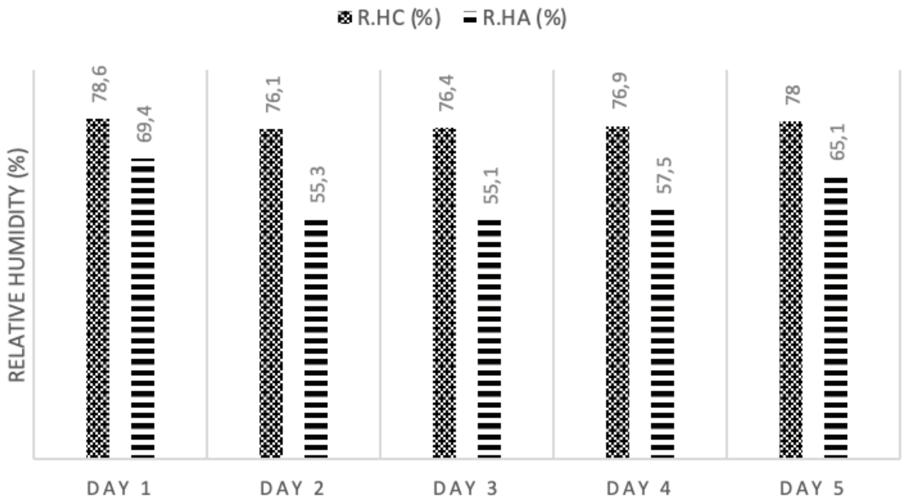

Figure 16. Comparison of cabinet chamber relative humidity and ambient relative humidity under no- loading conditions.

confirmed an increase in relative humidity between the surroundings and the cabinet chamber. Hence, there is possibility of preserving the agricultural produce by the developed evaporative cooling system.

Performance Assessment of Evaporative Cooler Under Load Conditions

In this work, experimental performance tests were conducted using a cooling pad made of jute (with 80 mm thickness) at air velocities (forced convection) of 3.9 m/s. In order to test the efficiency of the developed evaporative cooler, 5 kg of peppers, okra, and tomatoes were placed inside the evaporative cooler, while another quantity of peppers, okra, and tomatoes were kept outdoors for 8 days (under normal ambient conditions). Throughout the experiment, the evaporative cooling system's temperature and relative humidity, as well as the surrounding conditions, were monitored. Tomato, okra, and pepper physiological color changes were also assessed. For a period of eight days, the average variations in cabinet temperature (Tc), ambient temperature (dry bulb and wet bulb temperature), average cabinet relative humidity (RHc), and ambient relative humidity (RHa) are shown in Figures 15 and 16, respectively. From Figure 17, the wet bulb temperature and dry bulb temperature ranged from 25.5°C to 28°C

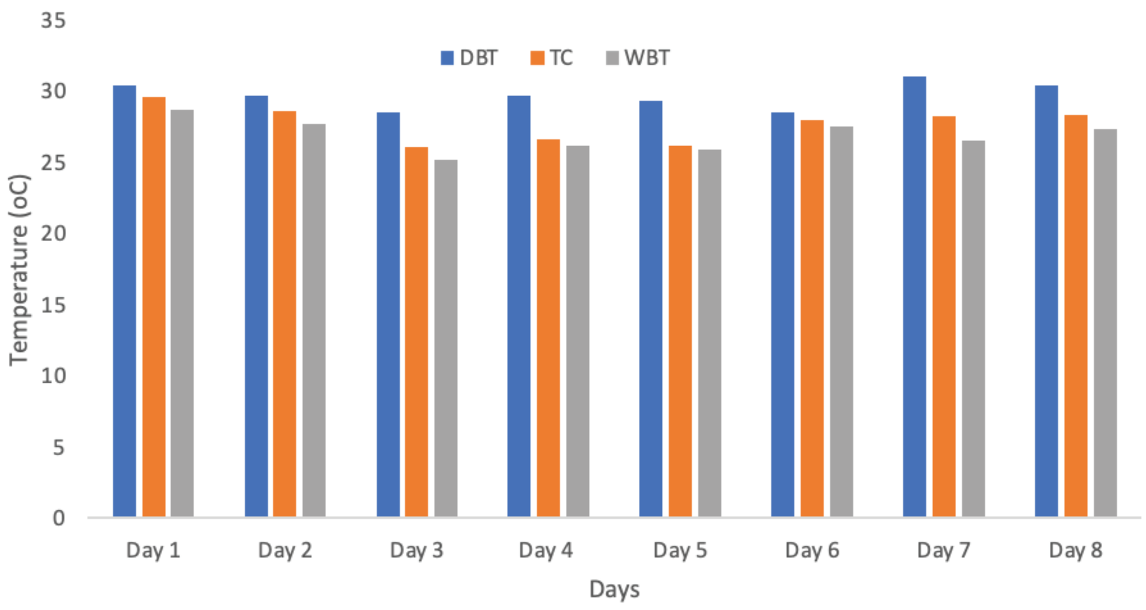

Figure 17. Comparison of cabinet chamber temperature and ambient temperatures (WBT & DBT) under load condition.

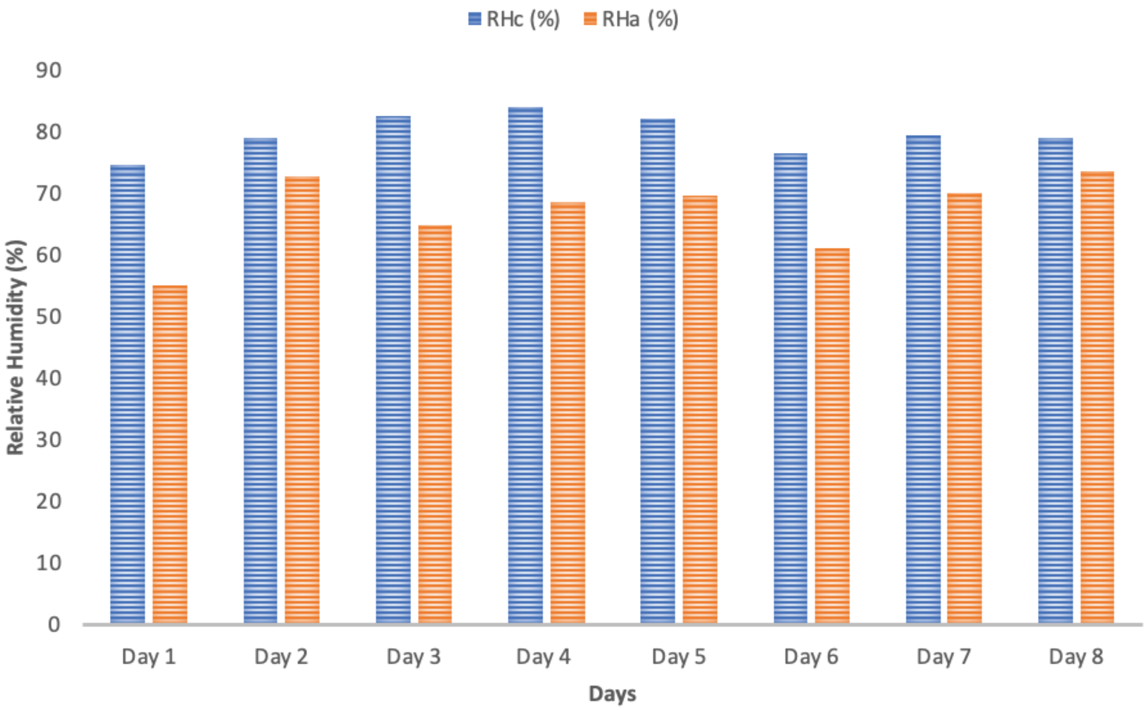

Figure 18. Comparison of cabinet chamber relative humidity and ambient relative humidity under loading conditions.

and 28.5°C to 31°C, respectively. The cabinet temperature ranged from 26.1°C to 29.6°C. The temperature difference between the ambient air and the evaporative cooling system was observed to be between 3 and 5 degrees Celsius, which differs from the ranges of temperature difference reported by Zakari et al. [28], who reported differences between 6 and 10 degrees Celsius. This variation could result from the fact that several researchers developed and used evaporative cooler with different pad materials and structures. Evaporative cooler performance variations could also be related to the season of year the studies were carried out. In the summer, evaporative coolers function better than they do in the winter [45–49]. According to Figure 18, the relative humidity in the cabinet ranged from 74.8 to 87.1% while that in the surrounding air ranged from 55.1% to 73.6%. It has been noted that the relative humidity of evaporative cooling system increased by 13% to 34% compared to the ambient humidity. According to ASHRAE [50], vegetables and tomatoes need to be stored at relative humidity levels between 85 and 90%. As a result, the relative humidity ranges for the developed evaporative cooling systems are between 74.7 and 87.1%, which is quite similar to the values published by ASHRAE [50] and Mogaji and Fapetu [51]. Because of this, the designed evaporative cooling system can extend the shelf life of fresh tomato and vegetable storage. The result of the ambient relative humidity which ranged from 55.1 to 73.6% is found to be below that recommended by ASHRAE [50] and hence this will reduce the shelf life of fresh tomatoes and vegetable storage under the ambient conditions.

The results of the developed evaporative cooling system's cooling efficiency computed are shown in Table 5, which was based on the drop in temperature and relative humidity. Table 5 shows the developed evaporative cooling system's cooling efficiency under load conditions over an 8-day period. According to Table 5, cooling efficiency ranged from 50% to 91.1%, with the highest value being observed on the fifth day of the test. A considerable drop in ambient temperature or when the fan is not operating at maximum speed are the two main causes of low cooling efficiency of evaporative cooling system. Furthermore, in this study, the average cooling efficiency is 66.8%, which is comparable to that of Nkolisa et al. [52] and Woldemariam and Abera [53] who reported a cooling efficiency of 67.17% and 67.6%, respectively.

Table 5. Cooling efficiency under load conditions

Days	Cooling Efficiency (%)
1	47.1
2	55
3	72.7
4	88.5
5	91.1
6	50
7	62.2
8	67.7

From the result of this study, it can be concluded that the designed evaporative cooling system has capacity to preserve agricultural produce with little or no changes in the texture and firmness of tomatoes, okra and pepper thereby increasing their shelf lives to benefit farmers and marketers in Nigeria and other countries in tropical region in general.

Uncertainty Analysis

In this study, the uncertainty analysis was carried out to establish the parameters measured which are the source of errors in the experimental tests. The uncertainty in measuring temperature, relative humidity, air mass flow rate, cooling efficiency etc is determined by using equation (17) [43, 54]:

$$\delta Y = \left[\left(\frac{\partial Y}{\partial X_1}\delta X_1\right)^2 + \left(\frac{\partial Y}{\partial X_2}\delta X_2\right)^2 + \cdots \ldots \ldots + \left(\frac{\partial Y}{\partial X_n}\delta X_n\right)^2\right]^{1/2} \quad (17)$$

Where δY is the uncertainty of the required parameter Y which is a function of the set of independent variables X_1, X_2, ..., X_n, ∂Y/ ∂Xn is the partial derivative of Y with respect to Xn and δX_1, δX_2, ..., δX_n are the uncertainties of the independent variables.

During evaporative cooling process, the overall uncertainties for each measured and calculated parameters are presented in Table 6 according to the uncertainty for each instrument used in this study. It was confirmed that all uncertainties found to be in acceptable ranges and agreement with previous works [55].

Quality Assessment of Agricultural Produce

Firmness change of the agricultural produce

To assess the performance of the developed evaporative cooling system, about 5kg of tomatoes, peppers and okra was kept inside the evaporative cooler and another portion of the

Table 6. Uncertainties of the parameters during evaporative cooling process

Parameters	Unit	Uncertainty
Measured Parameters		
Uncertainty on Temperature	°C	±0.6
Uncertainty on Relative Humidity	%	±3.0
Uncertainty on air Velocity	m/s	±0.5
Computed Parameters		
Uncertainty on Cooling Efficiency	%	±0.85
Uncertainty on Rate of Evaporation	kg/s	±3.04
Uncertainty on Total Cooling Capacity	kW	±3.10

Figure 19. Agricultural produce after stored for 8 days in the cabinet cooler.

Figure 20. Agricultural produce after stored for 8 days at ambient condition.

agricultural produce was kept at room temperature under ambient conditions for 8 days. When the tomatoes, peppers and okras kept inside the cabinet was checked after 8 days, it was discovered that most of the produce kept in the cabinet were still in good and firm shape. Whereas, the agricultural produce stored at ambient conditions had already lose firmness and shape on the third day. On the fifth day of the experiment, the firmness of the tomatoes, peppers and okra had gone totally. Figures 19 and 20 respectively depict the state of the agricultural produce stored in the cooling chamber and at room temperature after eight days. During the ripening phase, the firmness of agricultural produce changes, which is a biochemical shift. High temperatures speed up the change in the firmness of agricultural produce [56]. This explains why agricultural produce stored in ambient conditions, which is at a greater temperature than the evaporative cooler, experiences a rapid change in firmness.

Color changes of the agricultural produce

It was also observed as shown in Figures 17 and 18 that the agricultural produce kept in the evaporative cooler retained their color and didn't undergo drastic color change unlike those kept at room temperature, whose color changed and became rotten after 6th day. According to studies, lowering the storage temperature slows down all aspects of the farm produce's metabolism, including firmness and color change. According to this study, the developed evaporative cooling system was able to preserve the firmness and color of tomatoes, okra, and peppers stored compared to that kept under ambient temperatures. This supports the idea that the developed evaporative cooler can help extend the shelf life and preserve the quality of agricultural produce. Therefore, the evaporative cooler is appropriate for farmers who reside in remote areas and do not currently have a proper storage facility for their farm produce.

CONCLUSION

In this study a direct active solar powered evaporative cooling system was developed for preservation of agricultural produce. Jute was used as the cooling pad. The tested agricultural produce with the evaporative cooler includes tomatoes, peppers and okra. Under no-load condition, the cooling (saturation) efficiency varied from 61.40% to 87.50%, the cooling capacity of the cooler varied from 5.284 kW to 7.736 kW and rate of evaporation varied from 0.00116 kg/s to 0.00198 kg/s. The cooling efficiency of the designed evaporative cooling system when loaded with agricultural produce varied from 47.1% to 91.1%.

From the experimental study, the following observations are made:

1. The temperature drop was observed to be high under hot and sunny conditions and low under cloudy and rainy conditions.
2. The lowest temperature drop was recorded when the environment was less sunny or during the evening period.
3. The presence of fan increases the rate of evaporation efficiently and the periods when the fan stopped working or decrease in speed, the temperature of the cooler rose up and humidity decreased within the cooling chamber.

4. The relative humidity of the evaporative cooler was observed to be much higher as compared to the ambient relative humidity. This is responsible for the freshness and firmness of the produce within the days they were kept in the cabinet.
5. The temperature of the evaporative cooler was less compared to the dry bulb ambient temperature.
6. The cooling system was tested with highly respiring tomatoes and pepper and was able to achieve favorable temperature and relative humidity for safe storage for 8 days without much colour changes.

From the foregoing observations it can be concluded that:

1. The developed solar powered evaporative cooling system can preserve agricultural produce in non-deteriorated fresh state for a longer time than leaving the produce under normal environmental condition.
2. The relative humidity and temperature of the evaporative cooler is close to the optimum values needed to preserve agricultural produce.
3. The solar power can be harnessed to effectively run an evaporative cooling system. Therefore, it is possible to operate the evaporative cooling system in areas that do not have regular electricity like farm settlements
4. The highest recorded cooling efficiency of the cooling system using cooling pad of thickness 80mm was found to be 87.50% under no load conditions and 91.1% under load conditions. With these efficiencies the farm produce can be preserved from the farm to where consumers can have access to them and can also be preserved in the shops in good condition before they are purchased.
5. Evaporative cooling system can solve the problem of truly preserving farm produce like fruits in fresh condition without chilling injury and colour change normally experienced in refrigerators. There is also no fear of poisoning since the evaporative condenser does not make use of the refrigerants used by regular refrigerators.

NOMENCLATURE

Abbreviated Terms

A_1	Wetted surface area of pad material per unit volume (m^2/m^3)
Ah	Ampere hour
A_w	Total wetted surface area (m^2)
C	Battery capacity
C_{pa}	Specific heat of inlet air
DBT	Dry bulb temperature (°C)
EC	Evaporative Cooler
H	Height of pad (m)
Hn	Number of hours between sunset and sunrise
hc	Convective heat transfer coefficient h_c (W/m^2K)
h_{fg}	Latent heat of evaporation of water (kJ/kg)
K_{air}	Thermal conductivity of the air (kW m^{-1} K^{-1})
L_c	Characteristic length of the surface (m)
LH	Latent heating
m_a	Mass flow rate of air in (kg/s)
Nu	Nulsset number
P	Atmospheric pressure
Pr	Prandtl number
P_v	Saturation pressure of water vapour
Q_{EC}	Total Cooling Capacity of Evaporative Cooling System
Q_{LH}	Sensible cooling capacity
Q_{SH}	Sensible cooling capacity
Re	Reynold number
SH	Sensible heating
t	Thickness of pad (m)
$T_{a,in}$	Dry bulb temperature of inlet air (°C)
$T_{a,out}$	Dry bulb temperature of outlet air (°C)
$T_{a,in,wt}$	Wet bulb temperature of inlet air (°C)
U_{air}	Velocity of air (m s^{-1})
Vp	Volume occupied by the wetted media (m^3)
W	Width of pad (m)
WBT	Wet Bulb Temperature (°C)

Greek symbols

α	Thermal diffusivity of the fluid (air) (m^2 s^{-1})
ε	Evaporative cooling efficiency (%)
ρ	density of fluid (kg/m^3)
ν	Kinematic viscosity of the fluid (air) (m^2 s^{-1})
ω_a	Specific humidity of air

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work. Every author listed in this paper has contributed substantially in preparation of the manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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