DEVELOPMENT OF A PASSIVE EVAPORATIVE COOLING STRUCTURE FOR STORAGE OF FRESH FRUITS AND VEGETABLES

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Abstract* — This work presents the development of an evaporative cooling structure for storage of fresh fruits and vegetables. Before now, it was estimated that losses from inadequate storage of agricultural products especially fruits and vegetables is 40-50% of the production level in Nigeria. These losses have led to wasted human efforts, farm input and investment and at large, it has given rise to food insecurity in the country. A double wall storage structure of outer wall (3.35m long x 3.65m wide x 3.10m high) and inner wall (2.51m long x 2.81m wide x 2.7m high) that uses the principle of evaporative cooling was constructed. Temperature and relative humidity of the storage structure were recorded over time in the morning (8am), afternoon (12noon) and evening (4pm) using a digital temperature/humidity meter. Evaluation of the cooling structure was performed in dry (November-December) and rainy (June-July) weather conditions. Fresh fruits and vegetables were also stored in the structure and the results were compared with those stored at ambient air condition. Average cooler temperature in the morning, afternoon and evening were measured to be 24.77^{o}C, 25.44^{o}C and 26.07^{o}C, while the mean relative humidity were 93.88%, 94.41%, and 93.41% respectively in rainy season. In dry season, the mean cooler temperature in the morning, afternoon and evening were 20.77^{o}C, 24.04^{o}C and 25.21^{o}C while the mean relative humidity were 50.23%, 42.47%, 43.94% respectively. Also, shelf life of 13-15 days was recorded for carrot, okra and garden egg while water melon and tomatoes were able to be stored for 15-18day before spoilage. Similarly, the fruits and vegetables stored at ambient air condition had shelf life of 10-12 days for okra, carrot and garden egg while water melon and tomatoes stored for 13-14 days.

***Index Terms*— Evaporative storage, fruits, vegetables, temperature, relative humidity**

I. INTRODUCTION

Inadequate storage facilities have been identified as the major cause of heavy losses to farmers in many parts of the world especially in developing countries. This have resulted to serious waste of foodstuff and increased cost to the farmers. In the developing countries such as Nigeria, the estimate loss from inadequate storage is 45-50% of the production level of the farm produce (Orji, 2013, Olayemi et. al, 2012, Mikel and Newman, 2012).

The use of evaporative cooling structure has been found to be very efficient and economical in reducing the temperature and increasing the relative humidity in a storage structure. By achieving this, there will be minimal deteriorating effect on the fruit and vegetable thereby enhancing the shelf life, such that the produce are made available over a longer period of time. It will equally reduce the price fluctuation which is associated with lack of storage facilities. Evaporative cooling can provide effective cooling in storage structure without the need for an external energy source (Liberty et. al, 2013). Its concept lie on converting sensible heat to latent heat which causes a decrease in the ambient temperature as water is evaporated providing cooling effect. The sensible heat is associated with change in temperature which due not change the physical state of water while conversely, latent heat transfers only changes the state of the water by evaporation (Liberty et. al, 2013). As the sensible heat of the air is reduces proportionally to the amount of evaporation that take place, water assume the wet-bulb temperature of the air and cooling proceed with enthalpy of the air remaining constant.

II. LITERATURE REVIEW

There have been numerous research work in this area of study and are reviewed as follows;

Wilson et al. (1999) in their report on postharvest handling and cooling of fresh fruits and vegetable and flowers for small farms listed physiological breakdown due to natural ripening process, water loss, temperature injury, physical damage or invasion of microorganisms as the major agents of deterioration of fresh commodities. According to the report, all these factors can interact, and all are influenced by temperature. Furthermore, relative humidity, the temperature of the product and its surrounding atmosphere and air velocity all affect the amount of water loss from fresh fruits, vegetables and flowers. In conclusion, the work recommended proper postharvest temperature management procedures for fresh fruits, vegetable and flowers.

Mbuk et al. (2011) researched on factors influencing postharvest loss of tomatoes in urban markets in Uyo, Nigeria and they collected data from tomatoes retailers. The study used descriptive and Tobit regression model. The descriptive statistics included frequency, percentages and means and was used to categorize tomato retailers under socioeconomic characteristics, to show the extent of tomato spoilage, to categorize the spoilage under the different types and to describe the various management practices employed to reduce the loss. The Tobit regression model, a hybrid of the discrete and continuous models, was used to determine the impact of the explanatory variables on the probability of spoilage of tomatoes. From the study, spoilage of tomatoes depends of the mechanical damage and loss of moisture of the produce. Thus, the work suggested training of tomatoes retails on management practices to reduce tomatoes spoilage.

Amer et al. (2015) did a review of evaporative cooling technologies. The work aimed at reviewing the recent developments concerning evaporative cooling technologies that could potentially provide sufficient cooling comfort, reduce environmental impact and lower energy consumption in buildings. They used extensive literature review to conduct and mapped out the state of the art on evaporative cooling system. The review covers direct evaporative cooling, indirect evaporative cooling and combined direct-indirect cooling systems. The indirect evaporative coolers include both wet-bulb temperature evaporative coolers and dew point evaporative coolers which have been of particular interest because of their high thermal performance. According to them, the dew point evaporative coolers have shown great potential of development and research opportunity for their improved efficiency and low energy use.

Mogaji and Olorunisola (2011) worked on development of an evaporative cooling system for the preservation of fresh vegetables. The cooling system is a pyramidal shaped evaporative cooling system with 0.075m3 storage volume. A suction fan of 4.3m/s air flow velocity and 0.5W motor was used to operate the fan. The cooling pad material used for the study was jute bag and water pump with discharge capacity of 3.5l/min supplies water through a P.V.C. pipe to keep the cooling pad continually wet. Study was conducted to check the freshness of tomatoes and carrots, and data were observed daily. Results of the transient performance tests revealed that the evaporative cooling system chamber temperature and relative humidity depression from ambient air temperature varied over 16-26°C and 33-88% respectively. Ambient air temperatures and relative humidity during the test periods ranged over 26-32°C and 18-31% respectively. The shelf life of the vegetable produce inside the evaporative cooling system was extended by fourteen days relative to ambient storage.

Ndukwu et al. (2013) also developed an active evaporative cooling system for short-term storage of fruits and vegetables in a topical climate in which they used palm fruit fibres as cooling pad materials. The evaporative cooler consisted of three suction fans, automatic water control switch, water pump and the evaporative cooling chambers. The performance of the cooler was evaluated in terms of temperature drop, efficiency of the evaporative cooling and cooling capacity. The temperature drop ranged from 4oC to 13oC while the relative humidity of the ambient air was increased to 96.8%. 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 2,529W. At an ambient temperature of 37oC, the evaporative cooler provided the storage conditions of 23.2 temperature and 85.6% – 96.8% relative humidity.

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

Zakari et al. (2016) designed and constructed an evaporative cooling system for the storage of tomatoes. The system is solar powered and has capacity of 0.6m3 and used jute bag as pad material. The RH and weight loss of the analysis were analyzed using student Y-test and their results revealed that there was significant difference in using the evaporative cooling system for storing tomatoes as compared to ambient condition. The average cooling efficiency recorded was 83% while the temperature drop was 6-10oC and RH is 85%. Also, tomatoes were stored in the system for an average of 5 days with negligible changes in weight, color, firmness and rottenness.

Ndukwu (2011) developed a low cost mud evaporative cooler for preservation of fruits and vegetables. The system which was designed with clay and other local materials was evaluated in terms of temperature drop, evaporative effectiveness and cooling capacity and the results were 8-11^{o}C, 20-92%, and 1207W respectively. There was also increase in relative humidity to 92% in the cooling system. The evaporative cooler was able to preserve freshly harvested tomatoes for 19 days.

Ogbuagu et al. (2017) worked on performance evaluation of a composite-padded evaporative cooling storage bin. The storage bin which has 92kg capacity operate using 24VDC, 0.37kW fan attached to the back of the cooler. The average temperature drop and saturation efficiency in the evaporative cooler during the no-load test were 5°C and 42%, 17 respectively. The facility was able to sustain tomatoes, garden eggs and carrots stored in it for ten days. The weight losses at ambient temperature were found to be 70%, 30%and 45% for tomatoes, garden eggs and carrots, respectively; while those stored at cooler temperature were10%, 25%, and 40% for tomatoes, garden eggs and carrots respectively. The evaporative cooler performed best for storage of tomatoes.

Deoraj et al. (2015) worked on an evaporative cooler for the storage of fresh fruits and vegetables. The cooler comprised of two extraction fans, cooling pad media, heat exchanger, a water tank, a storage and a cooling chamber. The optimal operational parameters were determined by operating the cooler for 180 minutes using three pad media (cedar, teak and coconut fiber), with three fan extraction speeds (4 m/s, 6 m/s and 8 m/s) at two periods of day (morning and afternoon) and the saturation effectiveness of the evaporative pad and temperature differences between ambient conditions and the cooler were measured. The mean saturation effectiveness was 64.42% (cedar), 63.56% (teak) and 53.47% (coconut fiber). The mean values for the temperature difference were 5.00 K (cedar), 4.63 K (teak) and 3.60 K (coconut fiber), showing that cedar was the best material for operating the cooler. The best fan speed was 8 m/s while the cooler operated better in the morning (9.00 a.m.to 12 noon). The evaporative cooler operated at 8 m/s fan speed using the cedar shavings pad was then used to store tomatoes over a 14 day period alongside two other storage methods (refrigeration and ambient conditions). The mean penetration depth of tomatoes was 13.43 mm, 13.82 mm and 18.26 mm for the refrigerator, evaporative cooler and the ambient conditions respectively. The pH and the total solubility solids of the tomatoes stored with the evaporative cooler were the lowest showing that while the refrigerator was the best in terms of maintaining the skin firmness, the evaporative cooler was the best storage method in terms of preserving the acidity of the tomatoes as well as their total solubility solids.

Dagtekin et al. (2011) studied the effect of air velocity on the performance of pad evaporative cooling system. The aim of the work was to determine the relationship between velocity of air passing through a pad material, temperature reduction obtained and cooling efficiency of the system. The study used cellulose based evaporative cooling pad. The experiment was carried out at air velocities (0.5, 0.75, 1.0, 1.25, 1.5, 1.75m/s) at water flow rate of 4 l/min.m^{2}). According to the work, the most appropriate air velocity for the pad used in the test must be higher than 0.5m.s but lower than 1.5m/s.

From the literatures, most of the work on evaporative cooling have always used external device such as suction fans to enhance air movement across the small cooling bins and also most of these bins are too small to handle quantifiable amount of the produce. In other words, there has not been systematic study on large evaporative cooling structure. The aim of this study is to design and construct a passive evaporative cooling structure capable of handling large fruits and vegetable.

III. MATERIAL AND METHOD

Location of the research work:

The evaporative cooling structure was located at the back of faculty of engineering, Enugu State University of Science and Technology, Enugu state, Nigeria.

Design Considerations:

The design considered the size of fruits and vegetables to be stored in the structure, air flow direction, heat and mass transfer through the system. The orthographic views of the designed evaporative cooling structure is shown in Fig.1. Materials selection was also considered based on the thermal heat transfer calculations of the building materials. The designed temperature and relative humidity is also based on the requirements for fruits and vegetables storage conditions.

Material:

Materials used include bricks, sandy soil, PVC ceiling, thermometer, humidity meter, stop watch measurement cylinder, overhead water tank, piping system. The produce for the analysis include water melon, tomatoes, green bean, carrot and garden egg.

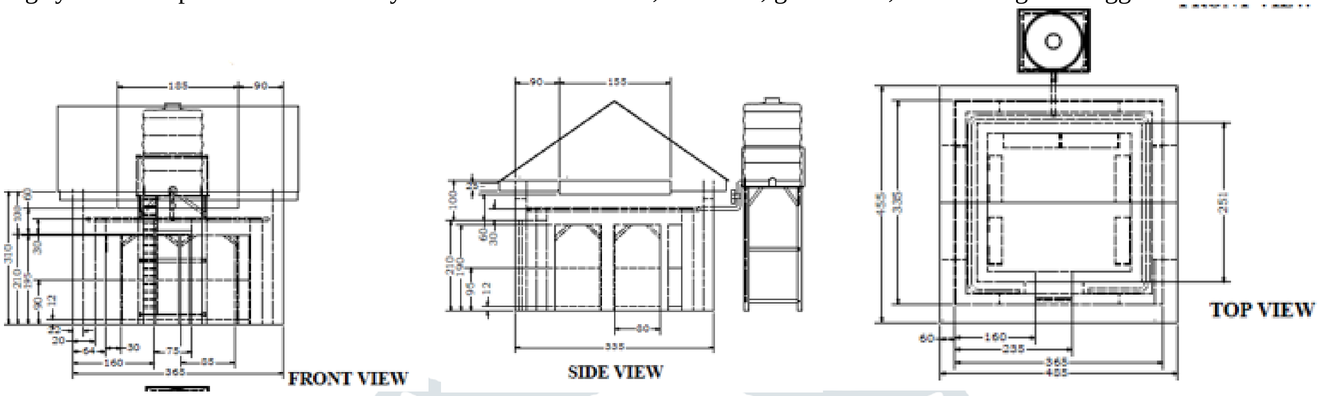

Figure 1: Orthographic views of the evaporative cooling structure

Design Calculations:

Total Heat Load: The cooled and humidified air from the structure is required to remove the heat load for the storage of fruits and vegetables. The following are the sources of heat loads of the cooler;

(i) Heat gain by conduction through the walls, roof and floor of the cooler

The heat transfer by conduction into the store was calculated by multiplying the areas of then various components of the cooler such as walls, floor and roof by their appropriate conductivity values, reciprocal of insulation thickness and by the difference between the outside air temperature and inside air temperature. According to Smith et al. (2009), thermal conductivity of sandy soil is sensitive to packing condition, moisture and porosity such that for tightly packed sand with porosity of 0.322, the thermal conductivity is 2.9W/m.K. Therefore, heat loss per unit area through the insulating material was calculated using eqn. 1-3.

$$Q = \frac{AK\Delta T}{x} \qquad \text{...... (eqn. 1)}$$

Where, Q = heat transfer by conduction (watts); A = area (m^2); K = thermal conductivity of the material (W/m^oK); ΔT = change in temperature (^oC); x = thickness of the material (m);

(ii) Respiration heat load of the produce

The heat of respiration is the energy released by the product as it respires. This heat decreases during the initial cooling of the produce and stabilizes after then required storage temperature is achieved (Olosunde et al., 2009) as given in eqn. 2.

$$Q_r = M_p \times P_r \qquad \text{...... (eqn. 2)}$$

Where, Q_r = respiration heat (watts); M_p = mass of produce (kg), P_r = rate of respiration heat production (W/kg.hr).

(iii) Field heat of the produce

This is the heat picked by the produce on the field. It is directly proportional to the mass of the produce and then storage temperature. Its expression is given in eqn 3.

$$Q_f = \frac{M_p C_r \Delta T}{t_c} \qquad \text{...... (eqn. 3)}$$

Where, Q_f = field heat picked up by produce, (W); C_p = specific heat capacity of produce, (KJ/kg ^oC); t_c = cooling time, (s); ΔT= change in temperature, (^oC).

(iv) Infiltration of air

This heat is estimated to be from 10- 20% of the total load from the other sources (Olosunde et al. 2009). Thus this is given in eqn. 4

$$Q_L = \left(Q_c + Q_f + Q_r\right) \times 0.15 \qquad \text{...... (eqn. 4)}$$

Where, Q_L is the heat transfer through cracks and opening of cooler door

(v) Heat of vaporization

The heat required for vaporization is supplied exclusively by the cooling water and cooling air. The heat transfer equation for cooling water is expressed in eqn. 5 as follows:

$$m = \frac{C_p \Delta T}{Qt} \qquad \text{...... (eqn. 5)}$$

Where, m is the mass of water, (kg); C_p is the specific heat capacity of water (4.18 kJ/kg); t is the time, (s); and ΔT is the temperature difference, (K).

From eqn. 4, it was determined that 35.7 liters of water should suffice for each day of cooling storage. In practical terms, the quantity of water required will be much less due to condensation and re-circulation of water within the closed system. To calculate air flow rate required for temperature reduction in the cooling structure, eqn. (6) was used.

$$Q = \frac{C_p \rho V \Delta T}{3600} \quad \text{...... (eqn. 6)}$$

Where, C_p is the specific heat of air (kJ/kg°C), ρ is the air density (kg/m^3) and V is the airflow rate (m^3/hr)

Total Quantity of Produce to be Stored:

Storage volume (V) was estimated from the volume of the structure given in eqn 6. This was calculated as 19043370cm3. On the average, one kg of produce occupies 1162cm3. Therefore, total estimated quantity that can be stored in the storage bin is 16388.44kg**.**

$$V = \text{length} \times \text{width} \times \text{height} \quad \text{...... (eqn. 7)}$$

a. Flow Rate

The flow rate of water from the reservoir was determined through the use of a stop watch to monitor the time it toke to collect a certain volume of water by the water collector at the entrance to the cooling system. An average discharge rate of 4l/min was recorded

b. Construction of the evaporative cooling structure

The evaporative storage is a modification of Kale et al. (2016) and Roy and Pal, (1994) prototype design but has water reservoir located at the top of the storage bin. The side and front views of the constructed evaporative storage structure is shown in Fig. 2. The structure is made up of two brick walls 20cm apart. The pad materials were filled in the hollow cavity between outer and inner walls. The water distribution network was connected through the overhead water tank located at the back of storage structure.

Fig. 2: Side and Front view of the completed evaporative cooler

Description of the evaporative cooling storage structure:

The cooling structure is a small room with double walls as shown in Fig 2. Outer wall dimensions of the evaporative cooling storage structure are 3.35m long x 3.65m wide x 3.10m high while the inner wall has dimensions of 2.51m long x 2.81m wide x 2.7m high. The two walls are 0.2m apart. The space between the walls was filled with sandy soil to the height of the inner wall. Sandy soil was selected because it is porous and it can be found easily in Nigeria. The sandy soil are wetted intermediately. Water piping system was laid round sandy soil filled chamber by a perforated pipe which is connected to an overhead tank at the back of the structure (Fig.2).

The cooling structure has a door at the front for security purpose and the ceiling was made of polyvinyle chloride (PVC) ceiling to provide insulation to heat transferred from the roof. The floor of the cooling structure is cemented for durability. There are wooden shelves inside the cooling structure where the fresh fruits and vegetables are kept to keep them away from likelihood of infection of soil borne disease and molds. The front and inside of the completed structure is presented in Fig. 2.

IV. Results and Analysis

Performance Evaluation:

The performance evaluation involved no-load and load tests in dry (November – December) and rainy (June – July) weather conditions. The no-load test of the system was conducted to see the effect of the evaporation that is expected to take place whether the process is effective or not in order to determine its efficiency before being loaded with the vegetables that will be stored. This was achieved by recording temperature difference and the relative humidity of the system relative to the ambient condition in the morning (8am), afternoon (12noon) and evening (4pm) for 17 days. For the load test, the stored product were kept inside the evaporative cooling structure and a control experiment kept at ambient air. The initial weight of each product was recorded. The produce stored include tomatoes, garden egg and carrot etc. *See Fig 3.*

Fig. 3: Fresh fruits and vegetables kept in the evaporative cooling structure

No load test of the evaporative structure:

The results of the experiment are given in Figures 4-9. Average cooler temperature in the morning, afternoon and evening were measured to be 24.77oC, 25.44oC and 26.07 while the mean relative humidity were 93.88%, 94.41%, 93.41% respectively in rainy season. In dry season, the mean cooler temperature in the morning, afternoon and evening were 20.77oC, 24.04oC and 25.21oC while the mean relative humidity were 50.23%, 42.47%, 43.94% respectively. From the result, temperature drop of 2oC was recorded while there was 6.82% increase in relative humidity in dry season. Similarly, mean temperature drop of 2oC and 2.5% increase in relative humidity was recorded in rainy season.

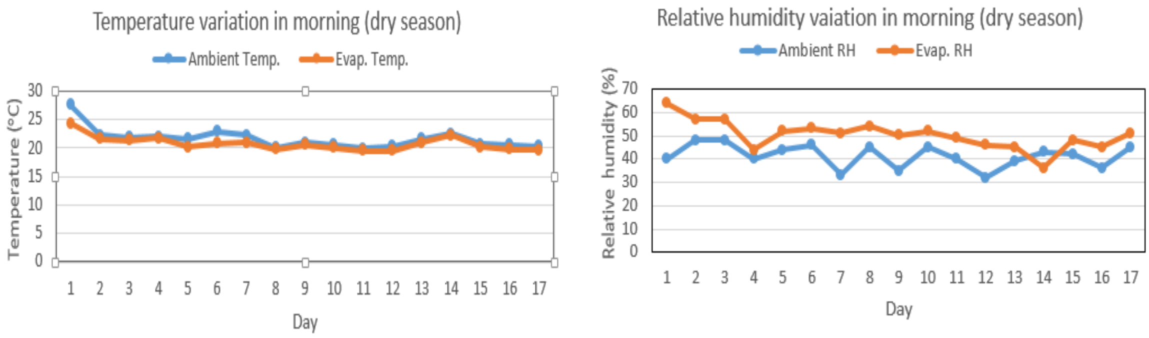

Fig. 4: Temperature and RH in the morning of dry season

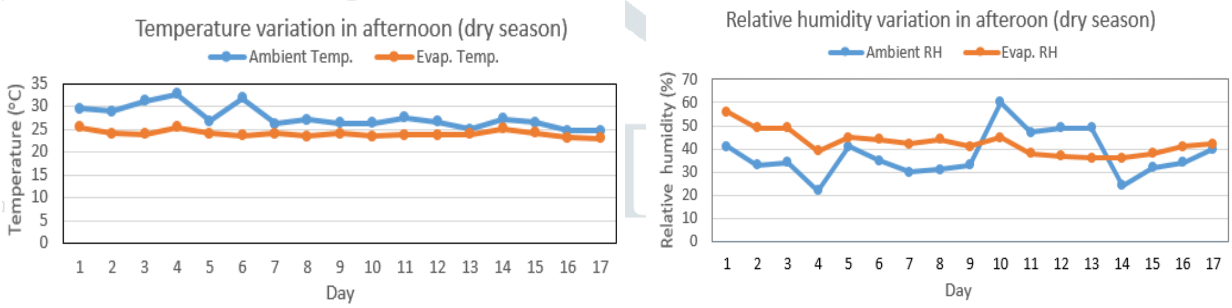

Fig. 5: Temperature and RH in afternoon of dry season

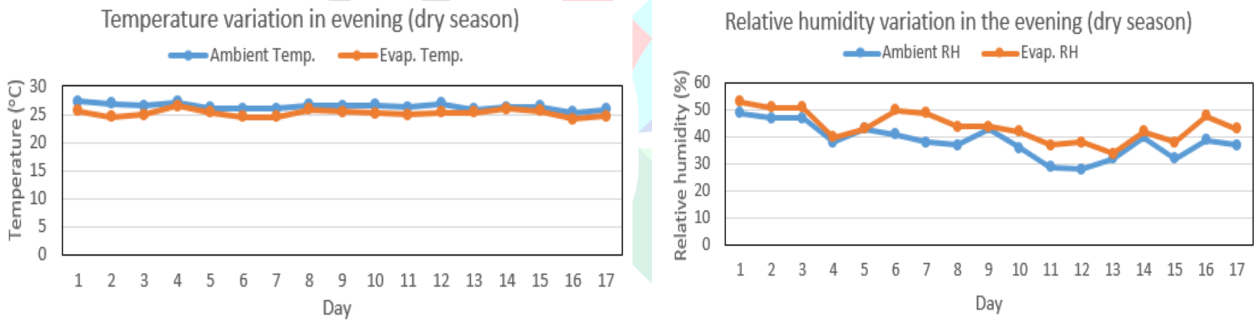

Fig. 6: Temperature and RH in evening of dry season

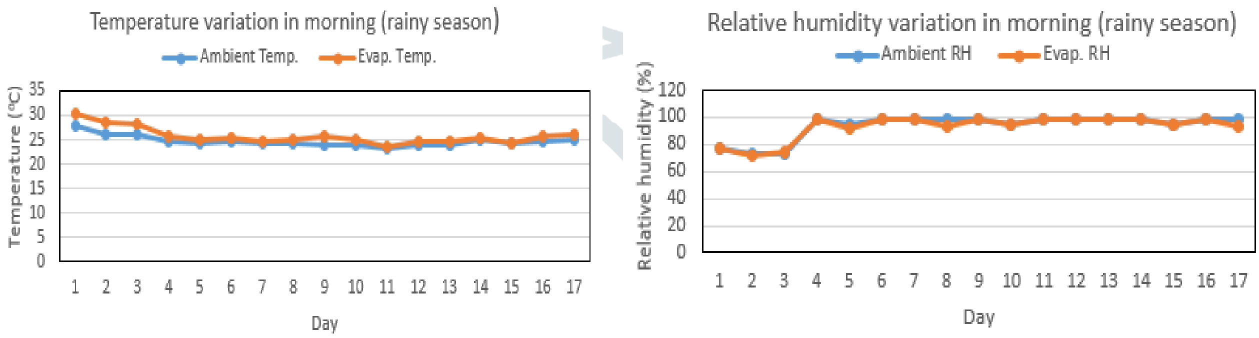

Fig. 7: Temperature and RH in morning of rainy season

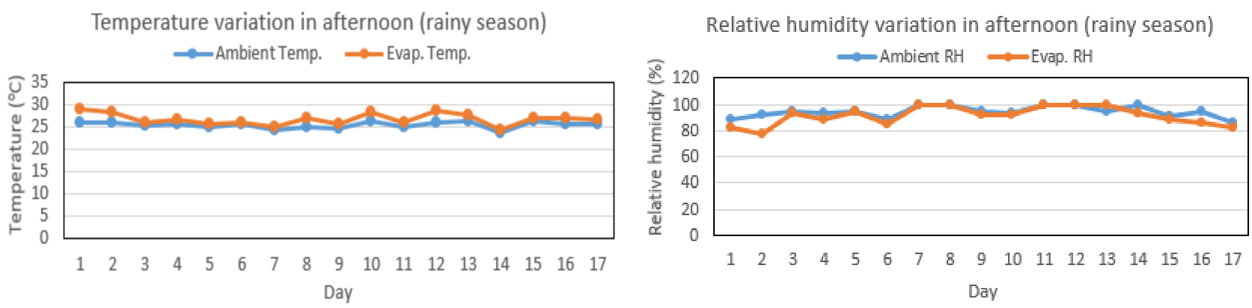

Fig. 8: Temperature and RH in afternoon of rainy season

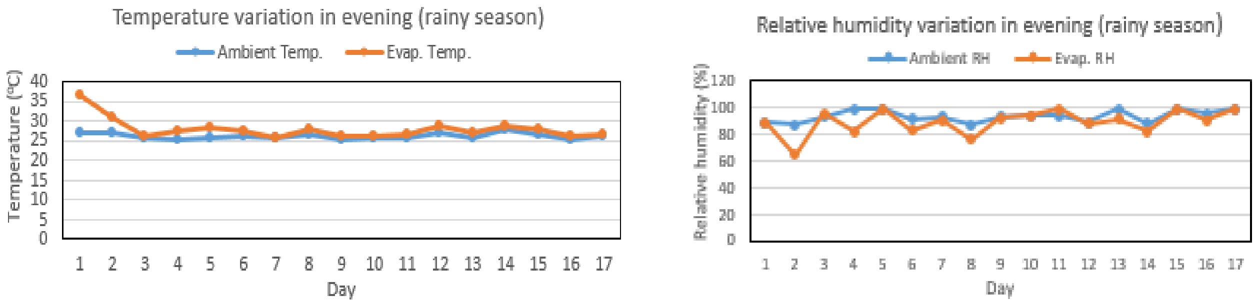

Fig. 9: Temperature and RH in evening of rainy season

Fruit and Vegetable Analysis:

The fresh produce were kept inside the evaporative cooler and they were carefully observed and weighed. Daily records of the observation on the condition of the fruits and vegetables in the cooler and the ones kept at room temperature were recorded and remarks on shriveling, skin color, disease and any other signs of deterioration were recorded. The plot of the weight loss is given in Fig. 10. The weight measurement stopped as soon as there is change in color or wilting in noticed on the body of the produce.

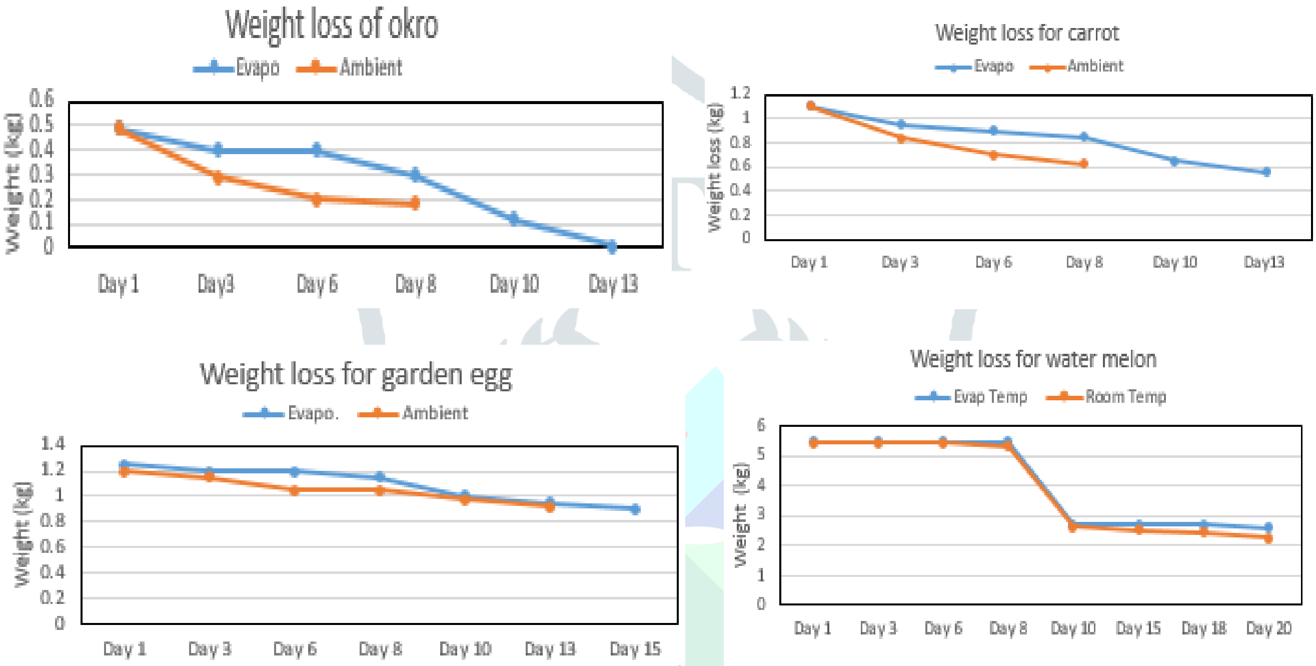

Fig. 10: plot of the weight loss vs samples

The change in colour was more pronounced in the products kept at ambient conditions (Figure7). The colour of the tomatoes did not change until it decayed on the seventh day. This was in agreement with results obtained by Zakari et al (2016). Deoraj et al. (2015) reported successful storage of tomatoes for 14 days in an evaporative cooler, which was better than conventional refrigerator. Colour of garden eggs changed from yellowish green to red. Carrot did not have much change in colour but it started to spoil from the sixth day. It was found that colour changes occurred earlier on the produce kept at ambient conditions.

V. CONCLUSION

A passive evaporative cooling structure was developed for storage of fresh fruits and vegetables. Although the performance evaluation of the cooling efficiency of the cooling structure was below expectation, it can still be used for short term storage of fresh fruits and vegetables such as okro, carrot and garden egg. These products can be stored in large quantity for a longer shelf life in market places.

VI. ACKNOWLEDGEMENT

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