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Development and Performance Evaluation of a Modified Active Evaporative Cooling System for Postharvest Preservation of Selected Vegetables

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Abstract

In developing countries, such as Nigeria, postharvest losses of Fruits and Vegetables (FV), especially tomatoes (Solanum lycopersicum), carrots (Daucus carota), and bell peppers (Capsicum annuum), are largely attributed to inadequate cold storage facilities (about 40 – 50%), as conventional refrigeration remains unaffordable for small-scale farmers. In this study, a modified, active direct evaporative cooler with an $8\ m^3$ *chamber was constructed using galvanized mild steel and aluminum. It comprised a suction fan of (183.1* m^3/hr*, 25 W, 1250 rpm), cooling pad (Jute) of 0.05 m thickness and water pump with discharge capacity of 30 l/min as well as a power rating of 0.5 HP. An overhead tank and water reservoir of capacity 500 L (0.5* m^3*) and 230 L (0.23* m^3*) respectively; were connected via PVC pipes to keep the pad continuously wet. The Study evaluated the shelf-life of tomatoes, carrots and peppers over 14 days by comparing the internal storage environment and the state of produce with the same produce stored in ambient conditions in triplicate. The modified cooler achieved an average cooling efficiency of 81% while maintaining the average storage system temperature of 25.6°C and a relative humidity of 76.2%, compared with the ambient averages of 35.8°C and 41.3%. Produce stored in the cooler showed significantly reduced physical weight loss, with satisfactory colour and firmness maintained for up to 14 days, as compared to 4-8 days under ambient conditions. A Student's T-test confirmed significant difference in the storage microenvironment and notable improvements in tomato, and pepper preservation. The analysis indicates that the modified evaporative cooler is an effective, cost-efficient technology for small-scale farmers, offering a practical solution to improve postharvest management, enhance food security, and support livelihoods.*

Keywords: *Evaporative cooling, Postharvest Technology, Vegetable Preservation, Shelf-Life Extension, Low-Cost Storage.*

1.0 Introduction

Vegetables are staple food items of a healthy diet, supplying vital vitamins, minerals and carbohydrates [1] [2] [3]. However, despite their nutritional importance, a high percentage (about 40%) of these highly perishable commodities are lost to post-harvest deterioration in developing countries, particularly Nigeria, largely due to inadequate storage facilities [2] [4]. The degradation rate in perishable commodities is fundamentally tied to postharvest temperature, Variety, maturity stage at harvest, relative humidity and respiration rate determines specific storage requirements and potential longevity [5]. Decreasing temperature and increase in relative humidity slows down respiration and loss of water which in turn prolongs shelf life [6] [7] [8]

Although cold storage is one of the best preservation methods, its high capital cost of installation and operation make it inaccessible for most of the local farmers [8] [9]. Therefore, the need for simple and inexpensive solutions becomes important. Evaporative Cooling involves reducing the temperature of newly harvested produce by passing air through a moisture-saturated medium, such as jute pad [10]. Its efficiency is highest in hot, dry climates where the wet-bulb depression is large [11] [12] [13]. Systems are classified as direct (air in direct contact with water) or indirect (using a heat exchanger), with direct systems being simpler and more common for agricultural storage [14] [15]. An evaporative cooler that utilizes the latent heat of water vaporization that lowers air temperature and increases humidity offers attractive possibilities for such solution especially in hot and dry climates [16] [17].

Research has progressed from simple passive designs (e.g., pot-in-pot, wetted packing sheds) to active systems incorporating fans and water pumps [2] [6] [3]. Pad materials critically influence performance; studies have shown jute, hessian, and celdek to be effective due to good water retention and wicking properties [14]. It is reported by [18] that evaporative cooling extended tomato shelf life from 4 to 11-18 days. Recent advancements focus on optimizing pad design, fan speed, and water flow rate for better control of the storage microenvironment [19].

While several researchers [7] [20] [12] have developed active evaporative cooling systems, significant limitations persist in water management efficiency, storage capacity, and adaptability to different crop types.

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Furthermore, heavy reliance on unreliable grid electricity in rural areas often leads to poor performance and limited scalability. These challenges, including inadequate water distribution, limited scalability, poor performance, lack of crop adaptability, and unstable power sources have been documented across various studies [21] [19] [22] [23]. These constraints highlight persistent gaps in the design and operation of evaporative cooling systems for post-harvest storage in developing regions. In response, this study aims to enhance system efficiency and applicability by improving water utilization, increase adaptability to multiple crop types, scalability to meet the harvest quantities and performance evaluation for sustainable storage of vegetables such as tomatoes, carrots, and peppers in the context of Northern Nigeria.

2.0 Materials and Methods

2.1 Materials

The materials used for this work includes; angle iron (64 mm), aluminum iron (3 mm thickness), PVC pipes (25 mm and 76 mm diameter), water pump (0.5 hp), connecting wires (2.5 mm), overhead tank (500 litres), reservoir tank (250 litres), suction fan (EFW-6P TMT Axial Exhaust Fan), T-joint (25 mm and 76 mm), elbow joint, plug, adaptor, union joint, ball gate and end cap (25 mm), gum (Abro), electrodes (2.5 mm), screws (Rivet pins), bolts and nuts (10 mm), jute bag (5 mm thickness), wire mesh (2 mm), mild steel (5 mm), tap and floater switch (25 mm).

2.2 Methods

2.2.1 Estimation of storage chamber capacity

The required storage volume was determined based on the typical harvest size of smallholder farmers in Northern Nigeria (approximately 5000–7000 kg of mixed vegetables per harvest cycle) [24] [25] [26]. Using the finding by [21] and [27] that 1 kg of mixed vegetables occupies approximately 1162 cm^3, a chamber with internal dimensions of 2 m × 2 m × 2 m (8 m^3) was selected. This yields an estimated maximum capacity of 6884 kg (8×10^6 cm^3 ÷ 1162 cm^3), which is suitable for the target users. The following calculations detail the dimensions and derived parameters.

2.2.2 Design of Front (Pad Area) and Rear Sides of the Storage System

The area of the front side (A_r) of the storage chamber was calculated as the product of its breadth (B_f) and length (L_f), as shown in Equation (1). With B_f = 2 m and L_f = 2 m, the area is 4 m^2. [21]

$$Af = Bf \ x \ Lf \qquad (1)$$

$$Af = 2 \ x \ 2 = 4\text{m}^2$$

with two circular openings spaced appropriately at the rear for insertion of the suction fans. Each having an area as shown in Equation 2; [21]

$$A = \pi r^2 \qquad (2)$$

$$A = 3.142 \text{ x } 0.57^2 = 1.02 \text{ m}^2$$

where A = Area, m^2 r = Radius, m

2.2.3 Design of Left- and Right-Hand Sides of the Storage System (Pad Area):

The area of the left and right-hand side (A_l) of the storage chamber was calculated as the product of its breadth (B_l) and length (L_l), as shown in Equation (3). With B_l = 2 m and L_l = 2 m, the area is 4 m^2. [21]

$$Al = Bl \ x \ Ll \qquad (3)$$

$$Al = 2 \ x \ 2 = 4 \text{ m}^2$$

Therefore, $A_l = A_r = 4$ m^2

where A_l = Area of left side of the storage system, m^2 L_l= Length of left side of the storage system, m B_l= Breadth of left side of the storage system, m.

2.2.4 Design of Top of the Storage System

The area of the top side (A_t) of the storage chamber was calculated as the product of its breadth (B_t) and length (L_t), as shown in Equation (4). With B_t = 2 m and L_t = 2 m, the area is 4 m^2. [21]

$$At = Bt \ x \ Lt \qquad (4)$$

$$At = 2 \ x \ 2 = 4 \text{ m}^2$$

where;A_t = Area of top of the storage system, m^2 L_t = Length of top of the storage system, m

B_t = Breadth of top of the storage system, m

2.2.5 Design of Overhead tank stand

The area of the overhead tank (A_s) was calculated as the product of its breadth (B_s) and length (L_s), as shown in Equation (5). With B_s = 3.5 m and L_s = 1 m, the area is 3.5 m². [21]

$$As = Ls\ x\ Bs \quad (5)$$

$As = 3.5\ x\ 1$ = 3.5 m² Where; A_s = Area of the overhead stand, m² L_s = Length of overhead stand, m B_s = Breadth of overhead stand, m

2.2.6 Volume of the Overhead Storage System

The overhead tank volume was sized based on the estimated evaporation rate of the jute pads. Total pad area = 12 m². Using a conservative evaporation rate of 2.5 L/h·m² (typical for jute in hot-dry conditions [14]), the water consumption is 30 L/h. For 16 hours of continuous operation, 480 L is required. A standard 500 L tank was therefore selected, providing a small safety margin. The recirculation pump minimizes actual water loss, making this capacity sufficient for daily use and continuous operation without frequent refilling.

In this study, the term overhead tank (or storage tank) refers to the 500-L container positioned above the cooler that supplies water to the jute pads by gravity.

The capacity of the storage system was determined using Equation 6; [21]

$$V_b = \pi r^2 H \quad (6)$$

V_b = 3.142 x $(0.44)^2$ x 0.82 = 0.499 m³

But 1 m³=1000 L, therefore, 0.499 x 1000 = 499 L

Therefore, a 500 L tank was selected

where V_b = Volume of the storage system, m³ r = radius of the tank, m H = height of the storage system, m

2.2.7 Volume of Reservoir

The reservoir (or bottom tank) refers to the 230-L container placed at ground level that collects drained water for recirculation via the pump.

The volume of the reservoir was determined using Equation (7); [28]

$$V_r = \pi r^2 H \quad (7)$$

V_r = 3.142(0.285)2 x 0.92 = 0.234 m³

But 1 m³=1000 L, therefore, 0.234 x 1000 = 230 L

where; V_r = volume of reservoir, m³ π=*3.14, r*=radius of reservoir, m H = height of reservoir,m

The water distribution network consists of pipes, an overhead tank and a bottom pipe network to collect the excess water that drips from the jute. The pipe network also consists of a control valve which was used to regulate the flow rate.

2.2.8 Pump power requirement.

The water flowrate of 13.54 L/min, 50% pump efficiency and a delivery head of 4.4 m, using this flow rate, pump efficiency and delivery head yields a calculated pump power of approximately 194.4 W. A standard, locally available 0.5 hp (374 W) water pump was therefore selected. This pump has a rated capacity of 30.5 L/min at a 4.4 m head, which closely matches the corrected system requirement and provides operational margin. This selection ensures reliable and continuous water recirculation to keep the jute pads fully saturated for optimal evaporative cooling.

The determination of the pump power requirement for re-circulating dripped water to the overhead tank to attract minimal attention was based on Equation (8); [29] [30] [31]

$$\text{Pump power} = \frac{SG\ x\ H\ x\ Q}{612\ x\ \eta} \quad (8)$$

$$\text{Pump power} = \frac{1\ x\ 4.4\ x\ 13.54}{612\ x\ 0.5}$$

Pump power = 0.1944 kW = 194.4 W

where SG = Specific gravity of water, H = head of delivery (m), Q = water flowrate (m³/s, 13.54 L/min), ŋ = pump efficiency (%), The constant 612 is derived from the conversion of L/min to m³/s.

2.2.9 Selection of Cooling Pad

As part of the general requirements, the efficiency of an active evaporative cooler depends on the rate and amount of evaporation of water from the cooling pad. This is dependent upon the air velocity through the fan, pad thickness and the degree of saturation of the pad, which is a function of the water flow rate wetting the cooling pad [37, 38].

In this work, Jute type of cooling pad of 5mm thickness was used for an efficient performance of the evaporative cooling system as it has good water holding capacity, high moisture content, and percentage dry basis, high bulk density reported [39].

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2.3 Heat Transfer Analysis of the System (Heat Load Design)

The cooled and humidified air from the pad is required to remove the total heat load of the evaporative cooler. The most important parameters determining the design of cooling process and equipment are the processing time and the heat load. The following are the sources of heat to be removed from the cooler. [40, 41]

a. Heat of conduction: Heat entering through the insulated walls
b. Field heat of the produce: This is the heat picked up by the produce on the field. It is proportional to the mass of the produce and storage temperature. It is heat extracted from the produce (the heat energy it contains as it cools to the storage temperature).
c. Heat of respiration: This is the heat generated by the produce as a natural by-product of its respiration.
d. Infiltrations: This is the heat from lights, people, warm and moist air entering through the cracks or through the door when opened.

2.3.1 Overall Heat Transfer (conduction and convection)

Heat gains by the aluminium sheet, air films and jute bag used for the cabinet construction (floor, backside and top) was estimated using Overall Heat transfer Coefficient Equation as given by [32]

$$Q_{hg}= U\ x\ A\ x\ \Delta T \qquad (9)$$

$$\frac{1}{U} = \frac{1}{hi} + \frac{L}{k} + \frac{1}{ho} = \frac{1}{U} = \frac{1}{10} + \frac{0.002}{247} + \frac{1}{15} = 0.166$$

$U = 6.02\ W/m^2.K$

$$Q_{hg}= 6.02\ x\ 4\ x\ (34 - 26)$$

$Q_{hg}= 192\ W$

Therefore, heat gains for the three sides were;

Total heat of conduction= 3 x 192 = 576 W

where

Q_{hg}=quantity of heat gained by the material (W)

K= Thermal conductivity of the material, 247 W/ m.K (for aluminium)

A= Area of the material (m^2)

ΔT=Temperature difference (K)

h_i (inside convection) = 10 $W/m^2.K$

h_o (outside convection) = 15 $W/m^2.K$

U = overall heat coefficient (6.02 $W/m^2.K$)

2.3.2 Field Heat of the produce

The field heat of the produce was calculated using Equation (9) given by [33]

$$Q_f = \frac{(MpCp)\Delta T}{tc} \qquad (10)$$

$$Q_f = \frac{6884\ x\ 3.9x\ (37-24)}{43200} = 6.84\ W$$

Therefore, the total field heat of the produce is the summation of heat produce of all the produce.

where

M = Mass of the product (kg)

Q_f = Field heat picked up by the produce, W

Cp = Specific heat capacity of the produces (tomato 3.98 kJ/ kg ^{0}C, carrot and pepper 3.81 kJ/ kg ^{0}C).

tc = time for cooling in secs, which is 12hrs (8am to 8pm).

ΔT = change in temperature.

2.3.3 Respiration heat of the produce

The field heat of respiration is given by [25]

$$Q_r = MrPr \qquad (11)$$

$$\text{And, } P_r = f\left(\frac{9Tm}{5} + 32\right)^g \qquad (12)$$

$Q_r = Qrt + Qrr + Qrp$

$Q_r = 0.015 + 3.75 + 0.00477$

$Q_r = 3.77\ W$

where

Q_r = heat of respiration, W

Q_{rt} = respiration heat of tomato, W

Q_{rc} = respiration heat of carrot, W

Q_{rp} = respiration heat of pepper, W

M_r = mass of the product, kg.

P_r = rate of respiration of heat production, W/ kg hr.
f and g = coefficients for a given product (tomato 2.007 x 10^{-4} and 2.835, carrots 0.05002 and 1.793 and Pepper 6.361 x 10^{-5} and 3.204 respectively) [28]

2.3.4 Infiltrations heat

This is estimated to be from 10% to 20% of the total load from the respiration heat of the produce, overall heat transfer and field heat of the produce [34]

$$Q_i = Qc + Qr + Qf \text{ x } \frac{15}{100} \quad (13)$$

$$Q_i = (576 + 3.77 + 6.84) \text{ x } \frac{15}{100}$$

Q_L = 88 W
Therefore, the total heat load on the evaporative cooler was estimated as the total sum of all the heat;
Total heat load = $Q_c + Q_r + Q_f + Q_i$
Total heat load = 576 + 3.77 + 6.84 + 88
Total heat load = 674.61 W.

Therefore, the calculated heat load on the system was used as a guide for the initial selection of fans, to ensure they would have sufficient capacity to manage the thermal environment. The actual performance and cooling capacity of the system were subsequently and definitively determined through the experimental no-load and load tests described in Section 2.7.

2.4 Selection and installation of suction fans

The required fan capacity was determined from the total heat load of 674.61 W using the sensible heat equation for air. With a temperature rise of 7°C across the cooling chamber, the required volumetric airflow rate was calculated as 0.051 m^3/s. A design safety factor of 1.2 was applied, giving a required airflow rate of approximately 0.0612 m^3/s.

The selection of fan was achieved using Equation 14 [32]

$$Q = (mCp\Delta T) = (\rho VCp\Delta T) \quad (14)$$

$$674.61 = (1.2 \, x \, V \, x \, 1005 \, x \, (34 - 27))$$

$$674.61 = (8{,}442 \text{ x V})$$

V = 0.051 m^3/s
Safety factor = 1.2 x 0.051 m^3/s = 0.0612 m^3/s
where
Q = Total heat load = 674.61 W
ρ = density of air = 1.2 kg/m^3
Cp = Specific heat of air = 1005 J/kg.K
V = Volumetric airflow rate (m^3/s)
ΔT = average air temperature rises across cooler

To meet this requirement, two commercially available axial exhaust fans (EFW-6P TMT) were selected. Each fan has an airflow rating of 0.0354 m^3/s (75 cfm). The combined total airflow of the two fans is 0.0708 m^3/s, which provides a 6% safety margin above the calculated requirement, ensuring adequate air exchange even under conditions of slightly reduced fan performance or additional flow resistance from the cooling pads. Two square openings of 175 mm x 175 mm were made at the rear side where suction fans were fitted.

2.5 Power requirement of the System

Two fans with specifications each: 220-240 V, 50 Hz, 25 W (power rating) and 75 cfm (0.0354 m^3/s) air-flow rate were used since the calculated required fan capacity amount to 0.0612 m^3/s.

Therefore, the total power requirement of the system is pump power requirement + fan power requirement
Total power requirement = 374+2(25)
Power requirement = 424 W

2.6 Design and construction of overhead tank stand

The design of the overhead stand against failure was done using Equation 15 [35]

$$W = (volume \ of \ water \ (v) x \ unit \ weight \ of \ water \ (w)) \quad (15)$$

$$W = \left((v) x \ (w)\right)$$

$$W = (500 \, x \, 0.0001 \, x \, 9.807)$$

W = 500×10^{-3} × 9.807
W = 4.9035 kN
where V = 500 L (500×10^{-3} m^3)

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W = Weight rquire by the stand, kN

Converting kN to kN/m^2
Surface area of the tank, S.A=πr^2
S.A = $\pi \times (\frac{0.9}{2})^2$
S.A = 0.636 m^2

a. Pressure at the base of the tank

P = $\frac{W}{S.A}$ [35]
P = $\frac{4.9035}{0.636}$ = 7.71 kN/m^2

b. To calculate if the steel can support the load compression

$\sigma = \frac{P}{A}$
where
W = total weight of the water tank, kN (W = 9.807 kN/m^3)
S.A = surface area of the tank, m^2
P = pressure at the base of the tank, kN/m^2
A = Cross-sectional area of the stand, m^2
$A_s = (Ls \ x \ Bs)$
As= 1 x 1= 1 m^2
where A_s = Area of reservoir stand (m^2) L_s = Length of reservoir stand (m) B_s = Breadth of reservoir stand (m)

$\sigma = \frac{7.71}{1}$ = 12.12kN/m^2
for safety, $\sigma_{\text{allowable steel}} > \sigma$
but $\sigma_{\text{allowable steel}}$ = 250,000 kN/m^2
Therefore, since $\sigma_{\text{allowable steel}} > \sigma$. It is safe to carry the weight of the overhead tank

The reservoir stand was designed against failure and was found to be safe (for safety $\sigma_{\text{allowable steel}} > \sigma$). The calculated stress on the stand, σ was 12.12kN but $\sigma_{\text{allowable steel}}$ = 250,000 kN/m^2. Therefore, since $\sigma_{\text{allowable steel}} > \sigma$. It is safe to carry the weight of the overhead tank

2.7 Construction of the Evaporative Cooler

2.7.1 Design and construction

The evaporative cooling system consisted basically of the cabinet, cooling fan and the transmitting medium (cooling pad). It was of a cubic shape, made of galvanized mild steel, aluminium iron, a suction fan, cooling pad (Jute) and water pump were installed. An overhead tank of 500 litres and drained water reservoir of 200 litres capacity were provided. The PVC pipes supplied the water to the cooling pad continuously. The basic principle relies on cooling by evaporation, when the system is set in operation, the dry air from the suction fan and environment passes over the wet surface (cooling pad) and evaporates the soaked water away from the cooling pad. When water evaporates, it draws energy from its surroundings (storage chamber) which produce considerable cooling effect in the storage chamber.

2.7.2 Framework of the Evaporative Cooler system

The evaporative cooler was made up of aluminum wall. The wall is a cuboid (2000 mm long x 2000 mm wide x 2000 mm deep) shaped galvanized steel storage structure with partitions for storage of tomatoes. Galvanized steel was chosen because of its low conductivity of heat and is abundantly available. Square angle iron and sheets were measured, cut and assembled to form a cube storage chamber with three sides left open for the insertion of jute pads and mesh wire according to specifications of the design. Jute was used as the wetted pad.

2.7.3 Piping networks and tanks selection

There were two water tanks of 500 litres and 250 litres capacity used, one below the cooler and the other above the cooler as overhead tank or reservoir. A 0.5 hp electric pump lifts water from the bottom tank through a 25 mm diameter PVC pipe to the overhead tank as water passing through the pad drains back to the bottom tank. An opening of 12.5mm radius was made near the bottom of the drain reservoir tank which was of volume of 250 liters. A PVC pipe of 25 mm diameter was inserted in opening, T-joint, and elbow joint were used to connect the pipe networks together using gum to hold the pipe in position and a stopper at the end of the pipe network to stop water flow. The pipes were assembled so that two pipes run over the jute pad area. A sharp object was used to perforate the pipe at certain intervals creating opening so the water flows over the jute pad when the control valve is opened. The pad was held with wire mesh of 1 by 2 inch to allow air pass through the Pad easily.

2.7.4 Storage chamber and reservoir stand

The storage chamber has three trays of dimensions (1.8 m length x 1.8 m breadth).
The trays were made of 1 by 1-inch square pipe as the frame and a wire mesh of 1 by 2 inches the pipes and sheets were assembled with the aid of screws. The storage chamber was divided into three shelves using mesh wire. The reservoir stand is made of galvanized mild steed, with dimensions 1 x 1 x 3.5 m and supporting brace.

2.7.5 System Components and Assembly

- **a.** Storage Chamber: A 2 m x 2 m x 2 m (8 m^3) cubic frame was constructed from galvanized mild steel angle iron (64 mm). Three sides were covered with wire mesh to hold the cooling pads, while the fourth side was sealed with a 3 mm aluminum sheet.
- **b.** Cooling Pad: Jute bag material (5 mm thickness) was selected as the wetted pad due to its high water-holding capacity and proven efficiency [19].
- **c.** Air Circulation: Two axial exhaust fans (EFW-6P TMT, 25 W each, 127.4 m^3/hr each) were installed on the aluminum side to draw air through the wetted pads into the chamber.
- **d.** Water Circulation System: A 0.5 hp electric pump lifted water from a 250 L base reservoir to a 500 L overhead tank. A network of perforated PVC pipes distributed water evenly over the jute pads. Drained water was collected and recirculated, ensuring constant pad saturation.
- **e.** Internal Structure: Three mesh wire trays (1.8 m x 1.8 m) were installed inside the chamber to hold the produce.

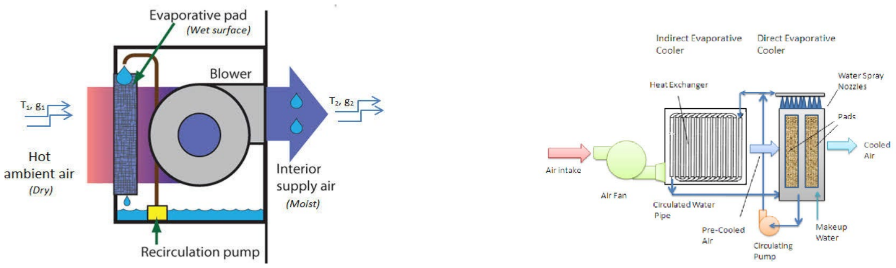

Figure 1: (a) Direct Evaporative Cooling [16] (b) Indirect Evaporative Cooling. Source: [36]

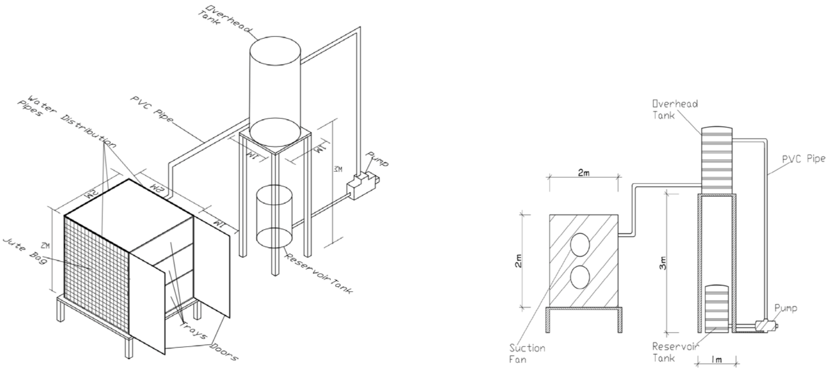

Figure 2: Isometric drawing of the fabricated evaporative cooling system

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Plate 1: Photograph of the completed evaporative cooler framework

2.8. Performance Evaluation

The cooler was evaluated under both no-load and load conditions in Kano, Nigeria, during January-March 2023.

2.8.1. No-Load Test

The system was operated without produce to determine its baseline cooling efficiency (SE) using Equation 16; [21] [37] [38]

$$\text{SE}\ (\%) = [(\frac{\text{T1(db)} - \text{T2(db))}}{\text{(T1(db)} - \text{T1(wb))}})] \times 100 \qquad (16)$$

where

(SE) Sytem cooling efficiency, T_1(db) and T_2(db) are the ambient and chamber dry-bulb temperatures, and T_1(wb) is the ambient wet-bulb temperature

2.8.2. Load Test

Fresh, mature tomatoes, carrots, and peppers were obtained, weighed, and placed in the cooler and in a shaded ambient environment (control).

Parameters Monitored (at 4-hour intervals from 8 am to 8 pm for 14 days)

a. Temperature and Relative Humidity: Measured using a digital hygro-thermometer.
b. Physiological Weight Loss: Daily weighing of samples. Percentage weight loss was calculated using Equation 2. [39] [23]
c. $$\%\ \text{Weight Loss} = \frac{\text{(Initial Weight} - \text{Final Weight)}}{\text{Initial Weight}} \times 100 \qquad (17)$$
d. Colour and Firmness: Visual assessment and manual tactile evaluation for wilting, shrivelling,and mould growth.

2.8.3 Data Analysis

Data for temperature, RH, and weight loss from the cooler and ambient storage were compared using a student's t-test at a 5% significance level to determine statistical significance.

3.0 Results and Discussions

3.1 Results

3.1.1 Cooling Efficiency and Storage Environment

Cooling efficiency (SE) was calculated by measuring the ambient dry-bulb temperature (T_1(db)), the chamber dry-bulb temperature (T_2(db)), and the ambient wet-bulb temperature (T_1(wb)) at 4-hour intervals during the no-load test. The difference between ambient and chamber temperatures is divided by the wet-bulb depression, then multiplied by 100 to obtain a percentage. All experiments were conducted in triplicate. Data are presented as mean ± standard deviation. The t-test was performed on the mean values.

The no-load test showed the system could achieve a cooling efficiency of up to 90%. Under load, the average efficiency was 81% (Table 1), indicating effective heat and mass transfer.

Table 1: Average Cooling Efficiency over 14-day storage period (mean ± SD, n = 3).

Days	Cooling Efficiency (%)
1	87 ± 1.2
2	85± 1.5
3	86 ± 1.0
4	88 ± 0.8
5	82 ± 1.3
6	80 ± 1.1
7	78 ± 1.4
8	75 ± 1.6
9	72 ± 1.2
10	76 ± 1.0
11	80 ± 0.9
12	81 ± 1.1
13	79 ± 1.3
14	78 ± 1.0

The evaporative cooler successfully created a significantly cooler and more humid microenvironment compared to ambient conditions (Table 2). The average chamber temperature was 5.2°C lower than ambient, while RH was 34.9% higher. The t-test analysis (t-calc = 31.225 > t-critical = 2.160, df=13) confirmed this difference was highly significant ($p < 0.05$). This modified environment is crucial for slowing transpiration and metabolic activity [40]

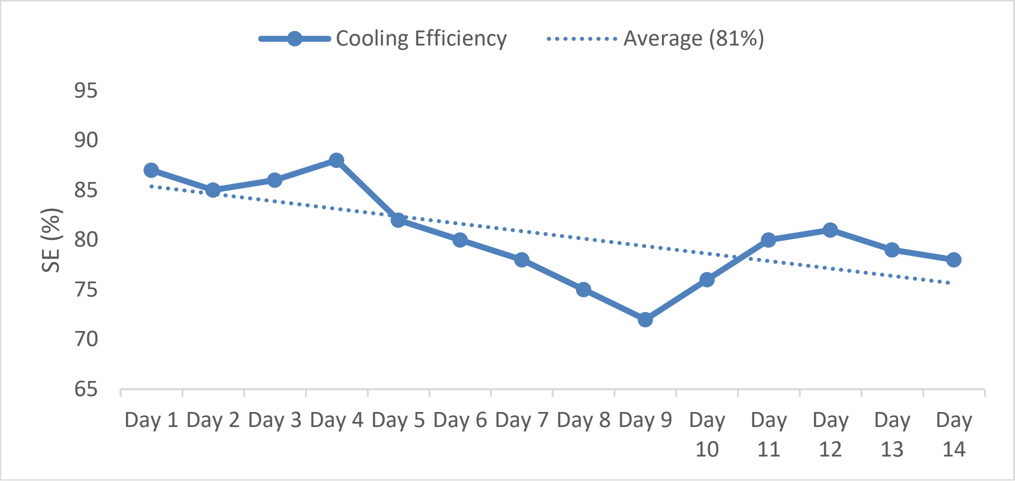

Figure 3: Cooling efficiency (SE%) during the 14-day load test (mean ± Sd, n=3), Dashed line = grand mean (81%)

Table 2: Average temperature and relative humidity readings for both ambient condition and evaporative cooling system (mean ± SD, n = 3)

Days	Ambient condition			Cooler condition	
	DB(°C)	WB(°C)	RH (%)	DB(°C)	RH (%)
1	24 ± 0.4	16 ± 0.3	44 ±1.5	17 ± 0.4	77.5±1.2
2	30 ± 0.5	19 ± 0.4	37 ± 1.2	21 ± 0.5	75.25±1.4
3	29 ± 0.6	21 ± 0.5	47 ± 1.3	22 ± 0.6	75.25±1.3
4	30 ± 0.5	20 ± 0.4	40 ± 1.4	27 ± 0.7	78.75±1.5
5	31 ± 0.6	22 ± 0.5	44 ± 1.2	24 ± 0.6	76 ± 1.2
6	33 ± 0.7	20 ± 0.4	32 ± 1.1	30 ± 0.8	75.75±1.3
7	33 ± 0.7	22 ± 0.5	40 ± 1.3	30 ± 0.7	77.25±1.4

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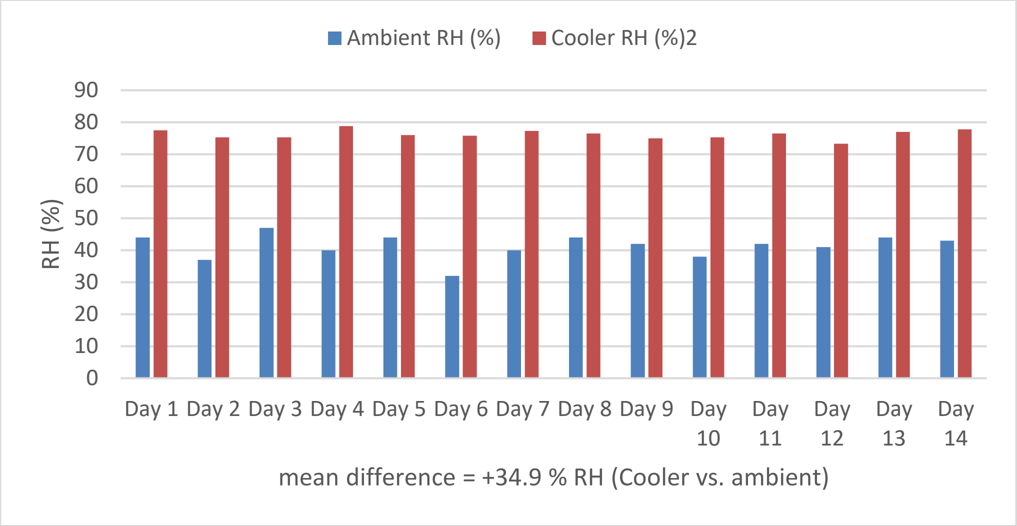
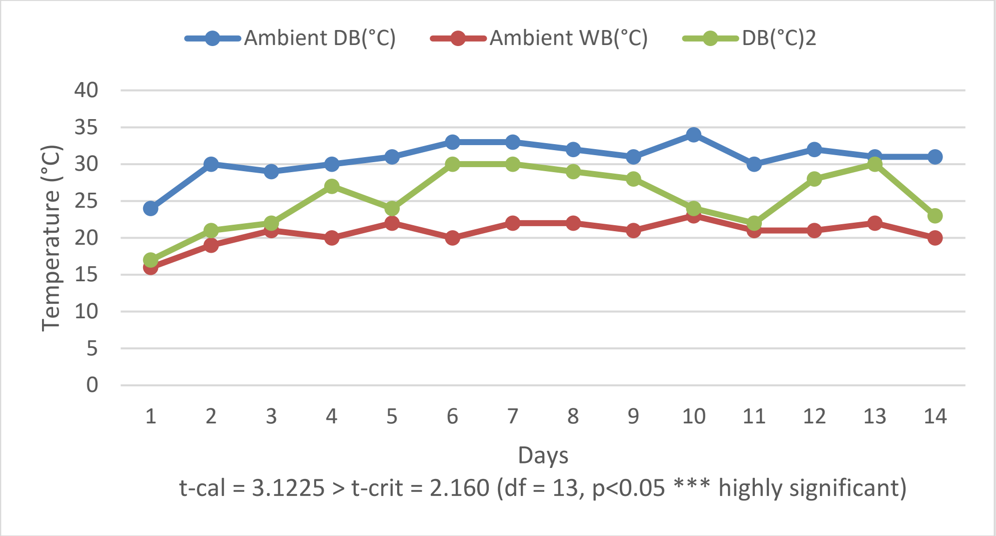
8	32 ± 0.6	22 ± 0.5	44 ± 1.2	29 ± 0.6	76.5±1.2
9	31 ± 0.5	21 ± 0.4	42 ± 1.4	28 ± 0.6	75 ± 1.3
10	34 ± 0.8	23 ± 0.6	38 ± 1.3	24 ± 0.5	75.25±1.2
11	30 ± 0.5	21 ± 0.4	42 ± 1.2	22 ± 0.5	76.5±1.3
12	32 ± 0.6	21 ± 0.5	41 ± 1.3	28 ± 0.7	73.25±1.5
13	31 ± 0.5	22 ± 0.4	44 ± 1.4	30 ± 0.8	77 ±1.2
14	31 ± 0.6	20 ± 0.4	43 ± 1.2	23 ± 0.6	77.75±1.4
Average	**30.8** ± 0.6	**20.7**± 0.5	**41.3**±1.3	**25.6**± 0.6	**76.2**±1.3



mean difference = +34.9 % RH (Cooler vs. ambient)

Figure 4: Daily relative humidity (%) for ambient and cooler storage environments over 14 days (mean ± SD, n = 3)



t-cal = 3.1225 > t-crit = 2.160 (df = 13, p<0.05 *** highly significant)

Figure 5: Daily dry-bulb temperatures (°C) for ambient and cooler conditions and ambient wet-bulb over 14 days (mean ± SD, n = 3)

3.1.2. Physiological Weight Loss

Produce stored in the cooler exhibited markedly lower weight loss than ambient-stored samples (Table 3). The cumulative weight loss for tomatoes was 50%, carrot had 33% and pepper had 42% lower in the cooler. Statistical analysis revealed a significant difference in tomato, carrot and pepper weight loss between storage methods ($p < 0.05$). The reduced weight loss is directly attributable to the higher RH within the cooler, which minimizes the vapour pressure deficit between the produce and the storage air [41].

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Table 3: Total Physiological Weight Loss over 14 days (grams, mean ± SD, n = 3).

Produce	**Evaporative Cooler(g)**	**Ambient Condition (g)**
Tomato	343 ± 12	686 ± 18
Carrot	425 ± 10	544 ± 14
Pepper	299 ± 8	333 ± 11

The above were the total loss of the products over 14 days period.

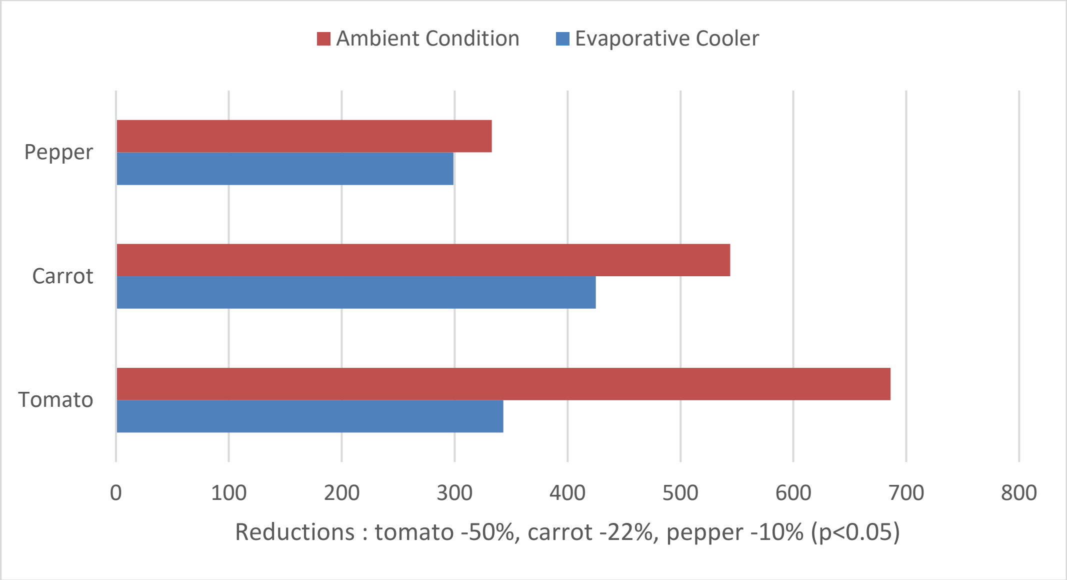

Figure 6: Total physiological weight loss (g) for tomato, carrot and pepper under evaporative cooler and ambient storage conditions (mean ± SD, n = 3)

3.1.3. Colour Retention and Firmness

Visual assessment showed that produce stored in the ambient condition deteriorated rapidly. Tomatoes softened and developed deep red colouration within 4 days, carrots shrivelled significantly, and peppers lost turgidity. In contrast, produce in the evaporative cooler maintained marketable colour (e.g., tomatoes retained a reddish-yellow hue) and firmness for 8-12 days. This preservation of visual and textural quality is vital for consumer acceptance and market value [40]

Plate 2: (a) Fresh Roma Tomato (b) Bell Pepper (c) Carrot before storage

Plate 3: (a) Roma tomato after 14 days in ambient condition (b) Roma tomato after 14 days in Evaporative cooling facility

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Plate 4: (a) Bell Pepper after 14 days in ambient condition (b) Bell Pepper after 14 days in Evaporative cooling facility

Plate 5: (a) Carrot after 14 days in ambient condition (b) Carrot after 14 days in Evaporative cooling facility.

Plate 2a – 5b: Comparative photographs of tomatoes, peppers, and carrots before storage, after 14 days in ambient condition, and after 14 days in the evaporative cooler.

3.2 Discussions

3.2.1 Cooling Performance

The modified evaporative cooling system demonstrated a robust ability to maintain a storage microenvironment significantly better than ambient conditions. The following sections analyze these findings in the context of existing literature and physical constraints. Using the daily average data, the efficiency varies by day and time. Overall, the average efficiency across all 14 days is approximately 65–90%, with the cooler typically achieving 5–10°C temperature drop under dry conditions.

The average cooling efficiency of 81% achieved in this study compares favorably with existing literature on evaporative cooling systems in tropical climates. The 14-day shelf life for tomatoes, carrots and peppers achieved in this study aligns with the range reported for similar active systems in tropical climates, Zakari *et al.* [21]reported 11-18 days and efficiencies in the range of 78–85%; Mahangade and Mani [18] reported 8-10 days with efficiency of 78%. Furthermore, our results align with Isah *et al.* [34], who observed that active systems utilizing suction fans typically achieve 10–15% higher efficiency than passive units.

3.2.2 Shelf Life and Produce Quality

The extension of produce shelf life to 14 days represents a significant improvement over the 4–8 days observed under ambient conditions. This result is comparable to the 11–18 days reported by Siddiqui and Ubale [13] for various tropical vegetables stored in evaporative coolers. Interestingly, carrots showed the most minimal difference in weight loss and firmness between the cooling treatment and ambient storage. This is likely due to the carrot's high initial water content and dense cellular structure, which makes it less susceptible to rapid transpiration compared to the high surface-area-to-volume ratio of tomatoes and peppers.

A notable drop in efficiency was observed between Days 9 and 11. This can be attributed to a spike in external ambient relative humidity as measured and shown in table 2, which reduced the vapor pressure deficit between the jute pad and the air as reported by [25] [29] [38] [42]. Evaporative cooling relies on the transition of water to vapor; when the surrounding air is already saturated, the rate of evaporation and thus the cooling effectstalls. [43]

However, it falls short of the 20+ days achievable with refrigerated cold storage [23], highlighting the inherent limitations of evaporative cooling during periods of high humidity.

3.2.3 Temperature Fluctuations and Limitations

Despite an average internal temperature of 25.6°C, there were instances where the internal environment reached 30°C. This is notably higher than the internationally recommended 13–15°C for optimal tomato storage. These temperature peaks coincided with high ambient humidity (above 65%) where the wet-bulb depression was narrow, limiting the cooler's ability to lower temperatures further. This highlights a fundamental limitation of direct evaporative cooling: it is highly dependent on the ambient dryness of the air. Future iterations incorporating a secondary heat exchanger (indirect cooling) could help bridge this temperature gap.

4.0 Conclusion and Recommendations

4.1. Conclusion

This study successfully developed and evaluated a modified active evaporative cooling system. The system demonstrated high efficiency (81%) which aligns with 60-90% as reported by [21] [25] [37] maintaining an average temperature of 25.6°C and 76.2% RH, which resulted in a significant extension of the shelf life for tomatoes, carrots, and peppers for 14 days period. The cooler reduced physiological weight loss and better preserved the colour and firmness of the produce compared to ambient storage (41.3%). The modification, particularly the automated water recirculation, improved upon previous designs, making the system more practical for end-users. This evaporative cooler is recommended for small and medium-scale farmers, marketers, and household use as a low-cost method to reduce postharvest losses. Future studies should focus on incorporating solar power and conducting proximate nutritional analysis.

References

[1] A. Hossai, M. Akhtaruzzaman, M. H. T. Mondal, and M. R. Islam, "Development and performance evaluation of a refrigerated storage structure for preserving fresh fruits and vegetables," *Discover Food,* vol. 4, no. 1, p. 12, 2024.

[2] A. Nadew, R. Nuguse, "Development of Evaporative Cooling System for Preservation of Tomato," *Scientific Journal of Engineering and Technology,* vol. 1, no. 1, pp. 8-14, 2024.

[3] A. S. N. Husainy, P. M. Sawant, and S. M. Y. Shaik, "Review on Preservation of Post-Harvest Vegetables by Using Evaporative Cooling Method," *Asian Journal of Engineering and Applied Technology,* vol. 10, no. 2, pp. 39-44, 2021.

[4] B. Natarajan, A. C. Kathiresan, and S. K. Subramanium, "Development and performance evaluation of a hybrid portable solar cold storage system for the preservation of vegetables and fruits in remote areas," *Journal of Energy Storage,* vol. 72, no. 108292, 2023.

[5] K. Alabi, "Recent Advances in Cooling Techniques for Fresh Fruits and Vegetables," *Agricultural Engineering International: CIGR Journal,* vol. 26, no. 1, p. 213, 2024.

[6] C. A. Ayele, E. A. Mekonen, and M. S. Kebede, "Assessment of a Solar-Powered Evaporative Cooler for Rural Storage of Fruits and Vegetables: A Case in South Gondar, Ethiopia," *International Journal of Refrigeration,* vol. 170, no. 1, pp. 215-228, 20255.

[7] C. O. Adetunji, D. I. Hefft, D. O. Mbuge, and T. S. Workneh, Evaporative Coolers for the Postharvest Management of Fruits and Vegetables, Academic Press, 2023.

[8] C. O. Adetunji, N. Y. Wike, and F. A. Ogundolie, "Health benefits derived from fruits and vegetables stored using evaporative coolers," in *Evaporative Coolers for Postharvest Management of Fruits and Vegetables*, Academic Press, 2023, pp. 87-100.

[9] D. Ibiyeye, O. Olunloyo, A. Aderemi, T. Bamigboye, and H. Nathaniel, "Development and performance evaluation of a double chamber evaporative cooling system for storage of vegetables," *Food Production Technology,* 2022.

[10] E. Makule, N. Dimoso, and S. A. Tassou, ", Precooling and cold storage methods for fruits and vegetables in Sub-Saharan Africa—A review," *Horticulturae,* vol. 8, no. 9, p. 776, 2022.

[11] F. Ishaque, M. A. Hossain, M. A. R. Sarker, M. J. Rahman, M. Moniruzzaman, J. Baidya, and M. F. Jubayer, "Performance evaluation of a low-cost evaporative cooling storage structure for citrus fruits in Sylhet Region," *Thai Journal of Agricultural Science,* vol. 54, no. 4, pp. 235-257, 2021.

[12] K. Yeneh and M. Walle, "Performance evaluation of evaporative cooling systems for mitigating post-harvest losses in Ethopian horticultural crops," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Process Mechanical Engineering,* vol. 239, no. 7, pp. 2591-2607, 2025.

Received: 07/04/2026; Revised: 24/04/2026; Accepted: 28/04/2026; Published: 23/05/2026

[13] J.A. Siddiqui, S. Ubale, "A computational study on comparative analysis of evaporative cooling system and conventional cold storage for onion preservation," *Transactions of the Indian National Academy of Engineering,* vol. 10, no. 3, pp. 523-541, 2025.

[14] Leonard, N. J. Msacky and L. S., "Performance Evaluation of Evaporative Cooling Systems as Alternative for Increasing the Shelf Life of Perishable Crops at the Farmer Level in Vunjo-Moshi Rural," *International Journal of Environment,* vol. 12, no. 1, pp. 88-104, 2023.

[15] R. H. Hashim, S. H. Hammdi, and A. A. A. Eidan, "Evaporative cooling: A review of its types and modeling," *Basrah Journal for Engineering Sciences,* vol. 22, no. 1, pp. 36-47, 2022.

[16] J. A. Al-Amin, A. I. Suleiman, and E. E. Collins, "Accelerating post-harvest food loss reduction in Nigeria through the development of a pilot-scale vacuum cooling and storage system," *Journal of Biology, Agriculture and Healthcare (Assessment),* vol. 11, no. 20, pp. 13-31, 2021.

[17] N. Y. Wike, C. O. Adetunji, F. A. Ogundolie, O. T. Olaniyan, J. B. Adetunji, W. P. Dauda, I. Victory, O. O. Osemweige, O. I. Edetalehn, "Recent advances in evaporative cooling applications in fruits and vegetables for short-term cooling at the postharvest stage," in *Evaporative Coolersfor Postharvest Management of Fruits and Vegetables*, Academic Press, 2023, pp. 79-86.

[18] I. Mani and P. S. Mahangade, "Design and Development of a Solar PV Based Evaporative Cooled Transit Storage Unit for Horticultural Products," *Journal of Environment and Ecology,* vol. 14, no. 2, pp. 45-59, 2023.

[19] P. Mthethwa, T. S. Workneh, and A. Kassim, "Renewable energy integration into a low-cost evaporative cooling system for fresh produce storage,”," *Modeling and Economics of Evaporative Coolers, Elsevier,* pp. 89-112, 2023.

[20] E. A. Awafo, S. M. Nketsiah, M. Alhassan, E. Appiah-Kubi, "Design, Construction, and Performance evaluation of an evaporative cooling system for tomatoes storage," *Agricultural Engineering,* vol. 24, no. 4, pp. 1-12, 2020.

[21] M. D. Zakari, Y.S. Abubakar, Y.B. Muhammad, N.J. Shanono, N.M. Nasidi, M.S. Abubakar, A.I. Muhammad, I. Lawan, & R.K. Ahmad, "Design and Construction of an Evaporative Cooling System for the Storage of Fresh Tomato," *ARPN Journal of Engineering and Applied Sciences, 11(4), 2372-2378, 2016,* vol. 11, no. 4, pp. 2340-2348, 2016.

[22] Y. Tewodros, "Design, Fabrication and Evaluation of Integrated Evaporative Cooling System for the Storage of Fruits and Vegetables," *ASHRAE Transaction,* vol. 127, no. 1, pp. 450-458, 2021.

[23] A. Yahaya, "Design and construction of an active evaporative cooling system.," *Unpublished B.Eng. Project, Bayero University, Kano.,* 2014.

[24] M. Dharshne, M. Mohanasundari, and P. V. Priya, "Study on brick evaporative cooler for vegetables: An eco-friendly storage facility for vegetable vendors," *AIP Conference Proceedings,,* vol. 2387, no. 1, p. 080006, 2021.

[25] M. H. B. Gouda and A. Duarte-Sierra, "An overview of low-cost approaches for the postharvest storage of fruits and vegetables for smallholders, retailers, and consumers," *Horticulturae,* vol. 10, no. 8, p. 803, 2024.

[26] E. Verploegen, R. Ekka, and G. Gurbinder, "Evaporative cooling for improved vegetable and fruit storage in Rwanda and Burkina Faso," MIT D-Lab Research Report, Massachusetts Institute of Technology, 2019.

[27] T. Defraeye, J. Vrba, J. Cloutier, C. Beland, D. Onwude, Leo Blyth and F.Pereira da silva, "A Cooling Atlas for preserving fruit and vegetables in low-and middle-income countries," *Journal of Agriculture and Food Research,* vol. 21, no. 101806, 2025.

[28] G. P. Fayiah-Tumbay, D. O. Mbuge, and U. N. Mutwiwa, "Evaluation of evaporative cooling chamber using computational fluid dynamics," in *Sustainable Research and Innovation (SRI) Conference*, JKUAT Main Campus, Kenya,, 2022.

[29] M. Sairi, M. S. H. Basri, N. S. Ghazali, J. C. L. Ying, S. Alwi, M. S. Azizan, M. F. Mail, A. M. Noor, N. I. Muhsin, and M. A. A. Hamid, "Assessment of evaporative cooling system potential for short-term storage management of vegetables during transportation," *Journal of Agricultural and Food Engineering,* vol. 3, no. 21, 2020.

[30] M. A. Mekouar, "The State of Food Insecurity in the World.," *Food and Agriculture of the United Nations (yearbook of International Environmental Law,* vol. 34, no. 1, p. 31, 2023.

[31] A. Najim, "Experimental study of passive direct-contact evaporative cooler with rapid cooling for preserving fresh fruits and vegetables," *Chemical Engineering Research and Design,* vol. vol. 227, no. 1, pp. 343-353, 2026..

[32] M. O. Udo, S. O. Oyedepo, S. A. Afolalu, S. O. Ongbali, O. Kilanko, R. O. Leramo, B. Saleh, J. O. Dirisu, J. A. Omoleye, G. Odewole, P. O. Babalola, S. K. Fasogbon, E. C. Solomon, B. Bolarinwa-Odunayo, and I. O. Uchechukwu, "Experimental performance evaluation of a solar powered evaporative cooling system for preservation of agricultural produce in tropical region," *Journal of Thermal Engineering,,* vol. 11, no. 3, pp. 858-879, 2025.

[33] W. Nwankwo, "Role of government and policymakers towards supporting the deployment of evaporative cooler structure," in *Engineering Principles, Modeling and Economics of Evaporative Coolers*, 2023, pp. 187-218.

[34] R. O. Isah, S. E. Adebayo, B. K. Nuhu, E. M. Dogo, and B. U. Umar, "Intelligent Evaporative Cooling Systems for Post-Harvest Fruit and Vegetable Preservation: A Systematic Literature Review," *Preprints,* 2026.

[35] R. S. Khurmi and N. Khurmi , "A textbook of strength of materials.," in *5th Edition.*, S. Chand Publishing, 2019, pp. 693-709.

[36] T. S. Workneh and S. Sibanda , "Determination of performance and associated economic costs of indirect air-cooling combined with evaporative cooling for storage of tomatoes in South Africa," *African Journal of Food, Agriculture, Nutrition and Development,* vol. 23, no. 2, pp. 22410-22439, 2023.

[37] T. G. Hoffmann, A. F. Ronzoni, and D. L. da Silva, "Cooling kinetics and mass transfer in postharvest preservation of fresh fruits and vegetables under refrigerated conditions," *Chemical Engineering Transactions,* vol. 87, pp. 115-120, 2021.

[38] W. Amjad, A. Munir, F. Akram, and A. Parmar, "Decentralized solar-powered cooling systems for fresh fruit and vegetables to reduce post-harvest losses in developing regions: a review," *Clean Energy,* vol. 7, no. 3, pp. 635-653, 2023.

[39] T. S. Workneh, and S. Sibanda, "Potential causes of postharvest losses, low-cost cooling technology for fresh produce farmers in Sub-Sahara Africa," *African Journal of Agricultural Research,* vol. 16, no. 5, pp. 553-566, 2020.

[40] E. K. Ronoh, C. L. Kanali, and S. N. Ndirangu, "Effectiveness of an evaporative charcoal cooler for the postharvest preservation of tomatoes and kales," *Research in Agricultural Engineering,* vol. 66, no. 2, pp. 66-71, 2020.

[41] D. P. Patel, S. K. Jain, S. S. Lakhawat, and P. Singh, "A low-cost storage for horticulture commodities for enhancing farmer's income: An overview on evaporative cooling," *Journal of Food Process Engineering,* vol. 45, no. 10, 2022.

[42] S. Subedi, D. Kattel, and N. Thokar,, "A review on post-harvest precooling methods of fruits and vegetables," *Food and Agri Economics Review (FAER),* vol. 2, no. 2, pp. 96-99, 2022.

[43] P. M.Cuce, "Evaporative Cooling Technologies: From Past to Present," *Global Decarbonisation,* vol. 1, no. 1, pp. 1-40, 2025.

Received: 07/04/2026; Revised: 24/04/2026; Accepted: 28/04/2026; Published: 23/05/2026