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PERFORMANCE ASSESSMENT OF AN ARDUINO-CONTROLLED SOLAR-POWERED EVAPORATIVE COOLING SYSTEM FOR POST-HARVEST PRESERVATION OF TOMATOES AND HOT PEPPER IN SEMI-ARID NIGERIA

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Abstract

Post-harvest losses of fruits and vegetables remain a significant challenge in developing regions due to inadequate storage infrastructure and limited access to reliable energy. The present designed and developed an Arduino-controlled solar-powered evaporative cooling system for postharvest preservation of tomatoes and hot pepper under semi-arid conditions. The system integrates a natural jute fiber evaporative pad, a solar photovoltaic power supply, a water recirculation unit, and a microcontroller-based control mechanism to regulate the storage microclimate. Performance evaluation was conducted through no-load and load tests. Under no-load conditions, the system consistently reduced internal temperature while increasing relative humidity, reaching up to 98%, thereby establishing a stable cooling environment based on adiabatic evaporation. For the load test, 2 kg of tomatoes and 1 kg of hot pepper were stored inside the chamber and compared with equal quantities kept under ambient conditions. The system maintained high relative humidity levels (approximately 80–98%) and achieved moderate reductions in temperature relative to ambient conditions. Although cooling performance was influenced by ambient humidity, the system effectively minimized vapour pressure deficit, reducing moisture loss and slowing physiological deterioration of the produce. The findings demonstrate that the system having Saturation efficiency (SE) of 95% offers a low-cost, energy-efficient and sustainable approach for postharvest storage. Its capacity to maintain high humidity and moderate temperature conditions supports extended shelf life of perishable produce in environments where conventional Energy is not readily available but has abundant Solar energy.

Keywords: Solar-powered, Energy, operational efficiency, Colour degradation, physiological changes

1.0 Introduction

Post-harvest losses of fruits and vegetables remain a critical challenge in developing countries, where inadequate storage infrastructure and unreliable electricity limit the adoption of conventional preservation systems. Fresh produce such as tomatoes, peppers, and leafy vegetables are highly perishable due to their high moisture content and continued physiological activities respiration, transpiration, and ripening after harvest, (*Twum-Dei et al.,2025*). Under high ambient temperatures and low relative humidity, these processes accelerate deterioration, resulting in significant losses estimated at 20–50% in developing regions, compared to 5–25% in developed countries, (*Affognon et al., 2015*), Food and Agriculture Organization (FAO), 2019;2023. In Nigeria and similar semi-arid environments, this challenge is further exacerbated by high ambient temperatures and poorly developed cold-chain systems (*Arah et al., 2020*). Although mechanical refrigeration remains the most effective preservation method, its high capital cost, dependence on electricity, and maintenance requirements make it largely inaccessible to smallholder farmers and rural traders (Kitinoja, 2018). This limitation underscores the urgent need for affordable, energy-efficient, and locally adaptable storage technologies. Evaporative cooling has emerged as a promising alternative due to its simplicity and low energy requirement *(Daniel et al., 2023)*. The system operates on the principle of adiabatic cooling, where water evaporation absorbs heat from the surrounding air, thereby lowering air temperature while increasing relative humidity—conditions that are favorable for extending the shelf life of fruits and vegetables (*Basediya et al., 2013;* Alemu, 2022;). Empirical studies have shown that properly designed evaporative cooling systems can significantly reduce storage temperature and improve humidity levels, thereby slowing down physiological deterioration and preserving produce quality (*Elik et al., 2019).* However, despite these advantages, many existing evaporative cooling systems exhibit inconsistent performance due to poor design configuration, inadequate airflow control, and suboptimal material selection (Odesola & Onyebuchi, 2009). Consequently, their potential to significantly reduce post-harvest losses has not been fully realized. Previous studies have largely focused on general system evaluation, with limited emphasis on experimental validation using key performance indicators such as temperature reduction, relative humidity improvement, and physiological weight loss of stored produce under local environmental conditions (*Arah et al., 2020;*Alemu, 2022;). To address this gap, this study adopts an experimental approach to evaluate the performance of an evaporative cooling system developed using locally available materials under real climatic conditions. Key parameters—including ambient and storage temperature, relative humidity, and physiological weight loss of selected vegetables—are systematically measured to assess system effectiveness. The study specifically aims to evaluate the thermal performance of the system, determine its effectiveness in improving storage conditions, assess its impact on shelf life, and identify design improvements suitable for small-scale applications. By directly linking system design, environmental conditions, and measurable performance outcomes, this study contributes to the development of cost-effective and sustainable post-harvest storage solutions capable of reducing losses, improving food security, and enhancing the livelihoods of smallholder farmers.

2.0 Materials and Methods

2.1 ***Description of the Smart Evaporative Cooling System***

The developed evaporative cooling system shown in fig.1 consists of a storage chamber, evaporative pad assembly, suction fan, overhead water reservoir, recirculation pump, photovoltaic (PV) module, deep-cycle battery, and a microcontroller-based control unit. The storage chamber is designed to house perishable produce while maintaining a controlled microclimate characterized by reduced temperature and increased relative humidity. A natural jute fiber pad was selected as the evaporative medium due to its high water retention capacity, biodegradability, affordability, and availability. Similar natural fiber materials have been reported to enhance evaporative performance due to their porous structure and moisture absorption characteristics (*Basediya et al., 2013*; Alemu, 2022).

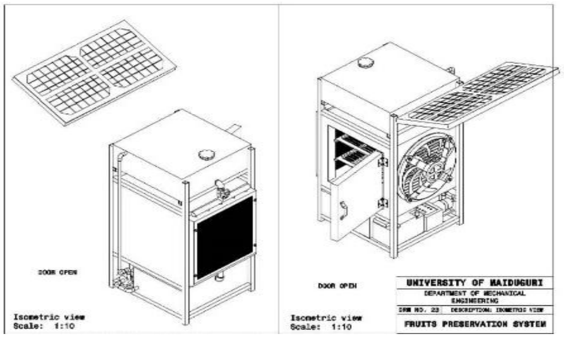

Fig.1. Solar Powered Evaporative Cooling System

Water is stored in an overhead reservoir and distributed uniformly over the pad through a perforated lateral pipe to ensure consistent wetting. Excess water is collected in a lower tank and recirculated using a low-power electric pump, thereby minimizing water wastage and maintaining continuous operation. Airflow is induced by a suction fan, which draws ambient air through the wetted pad into the storage chamber, enabling heat exchange through evaporation and lowering the internal air temperature.

The electrical subsystem is powered by a solar photovoltaic module coupled with a deep-cycle battery to ensure uninterrupted operation. An Arduino UNO microcontroller depicted in plate 1 governs the system, automatically managing power distribution and switching between solar input and battery supply depending on energy availability. This configuration aligns with modern smart cooling systems that integrate renewable energy and embedded control for autonomous operation (*Elik et al., 2019;Arah et al., 2020*).

Plate 1. Microprocessor Arduino *UNO*

2.2 Experimental Procedure and Measurements

The experimental programme consisted of both no-load and load tests conducted over three consecutive days. Measurements were recorded hourly between 11:00 am and 6:00 pm, corresponding to peak ambient temperature periods.The following parameters were measured:

- Ambient and chamber temperature using digital thermometers
- Relative humidity determined using psychrometric relationships based on dry-bulb and wet-bulb temperatures

- Product weight using a precision weighing balance
- Qualitative observations including colour and firmness

Temperature and humidity measurements were used to evaluate the microclimatic performance of the system, while weight measurements were used to assess produce quality deterioration over time (Alemu, 2022).

2.3 No-Load Test

The no-load test was conducted without any produce in the storage chamber to determine the inherent cooling capacity of the system. Ambient temperature, chamber temperature, and relative humidity were measured simultaneously. This test provides insight into the system's ability to modify internal environmental conditions independent of product load, which is essential for evaluating baseline performance (*Basediya et al., 2013*).

2.4 Saturation Efficiency

The performance of the evaporative cooling system was evaluated using saturation efficiency, which expresses the effectiveness of the system in achieving the maximum possible cooling relative to the wet-bulb temperature depression.

The saturation efficiency (SE) is given as:

$$SE = \frac{T_{1db} - T_{2db}}{T_{1db} - T_{1wb}} \text{...............}(1)$$

where:

$T_{1db} = outdoor\ dry - bulb\ temperature$

$T_{2db} = dry - bulb\ temperature\ inside\ the\ cooler$

$T_{1wb} = outdoor\ wet - bulb\ temperature$

This parameter is widely used in evaporative cooling studies to quantify system performance under varying environmental conditions (Alemu, 2022).

2.5 Load Test

For the load test, fresh tomatoes (2 kg) and hot peppers (1 kg) were stored inside the evaporative cooling chamber, while equal quantities were kept under ambient conditions as a control. Temperature and relative humidity were monitored throughout the storage period.

In addition to environmental measurements, produce quality was evaluated using the following indicators:

2.5.1 Temperature and Relative Humidity Measurement

Temperature readings were obtained using dry-bulb and wet-bulb thermometers, while relative humidity was estimated using psychrometric charts. Measurements were taken hourly between 11:00 am and 6:00 pm for three consecutive days to capture diurnal variations (*Elik et al., 2019*).

2.5.2 Colour Changes and Firmness

Changes in colour and firmness were observed visually and manually. Colour variation was used as an indicator of ripening and deterioration, while firmness provided insight into textural quality. These qualitative assessments are commonly used in post-harvest studies to evaluate produce freshness (*Arah et al., 2020*).

2.5.3 Physiological Weight Loss

Physiological weight loss was determined by measuring the initial and final weights of the produce over the storage period. The percentage weight loss was calculated using:

$$percentage\ Weightloss = \frac{Original\ weight - Final\ weight}{Original\ weight} \times 100 \text{......}(2)$$

Weight loss serves as an important indicator of water loss due to transpiration and overall produce deterioration during storage (FAO, 2019).

3.0 Results and Discussions

3.1 No-Load Test Results

A no-load test was carried out to evaluate the standalone performance of the smart evaporative cooling system without any stored produce. The objective was to determine its effectiveness in reducing temperature and increasing relative humidity relative to ambient conditions. The results are presented in Table 1.

Table 1. Temperature and relative humidity for no-load test

Time	Ambient DB (°C)	WB (°C)	RH (%)	Cooler DB (°C)	RH (%)
11:00 am	31.6	31.2	85	31.3	95
12:00 pm	33.2	31.6	80	31.8	92
1:00 pm	34.4	32.2	78	32.7	85
2:00 pm	35.7	33.6	75	32.9	80
3:00 pm	33.9	31.4	79	31.8	89
4:00 pm	33.2	31.1	82	31.3	95
5:00 pm	31.9	28.8	90	28.9	98
AVERAGE	33.4	31.4	81	31.5	90

The results indicate consistent reduction in dry-bulb temperature and a corresponding increase in relative humidity within the cooling chamber compared to ambient conditions. Relative humidity reached up to 98%, reflecting efficient evaporation and effective microclimate control. This confirms the principle of adiabatic evaporative cooling, where water evaporation absorbs heat from the air, lowering temperature while increasing humidity—conditions favorable for postharvest storage (Jain & Tiwari, 2020*; Zhao et al., 2020*). The sustained high humidity observed is important for minimizing moisture loss by reducing vapour pressure deficit (Alemu, 2022). The relatively stable cooling performance across the test period suggests adequate pad wetting and airflow continuity, which are critical for system efficiency. This aligns with findings that emphasize proper water distribution and ventilation as key factors influencing evaporative cooling effectiveness (Kitinoja, 2018; Odesola & Onyebuchi, 2009). Overall, the no-load test demonstrates that the system can reliably create a cooler and more humid internal environment, with saturation efficiency (SE) of 95% from average DB and WB temperatures confirming its suitability as a passive postharvest storage solution under semi-arid conditions.

3.2 Load Test Results of the Smart Evaporative Cooler

The load test was conducted using 2 kg of Tomatoes and 1 kg of Hot Pepper, with equal quantities stored under ambient conditions as controls, to evaluate system performance under practical operating conditions. The focus was on the system's ability to regulate temperature and relative humidity and its implication on produce preservation over a three-day period.

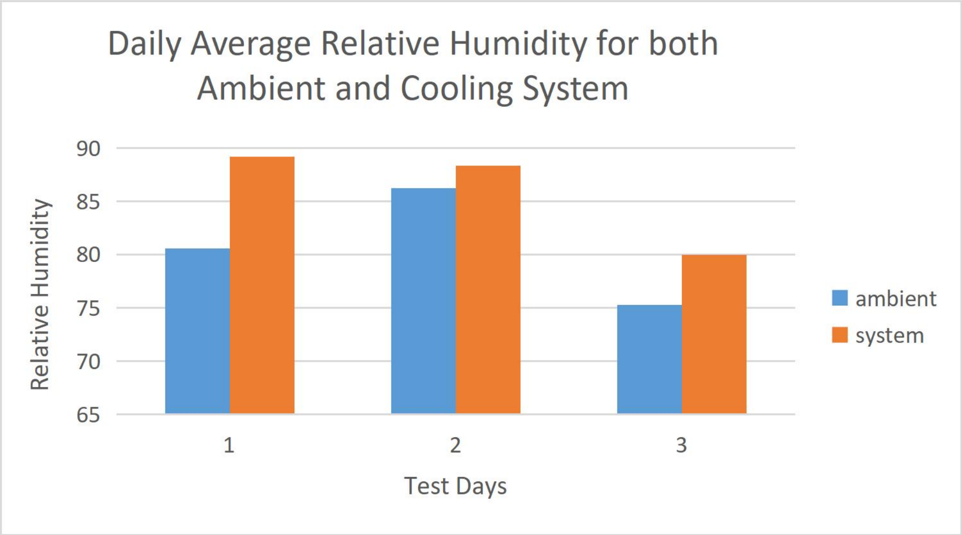

Fig. 1 Average Temperature and Relative Humidity readings for ambient condition and evaporative cooling system for Tomatoes.

Results in figure 1 indicate that the evaporative cooling chamber maintained consistently high relative humidity (≈80–89%) and only slight reductions in temperature compared to ambient conditions. The temperature differences were generally small, particularly on Day 2, when ambient relative humidity was high (≈80–86%). Under such near-saturated conditions, the wet-bulb depression is minimal, which restricts evaporation and limits cooling capacity. This behavior agrees with established findings that evaporative cooling efficiency decreases as ambient humidity increases (Jain & Tiwari, 2020; *Zhao et al., 2020*).

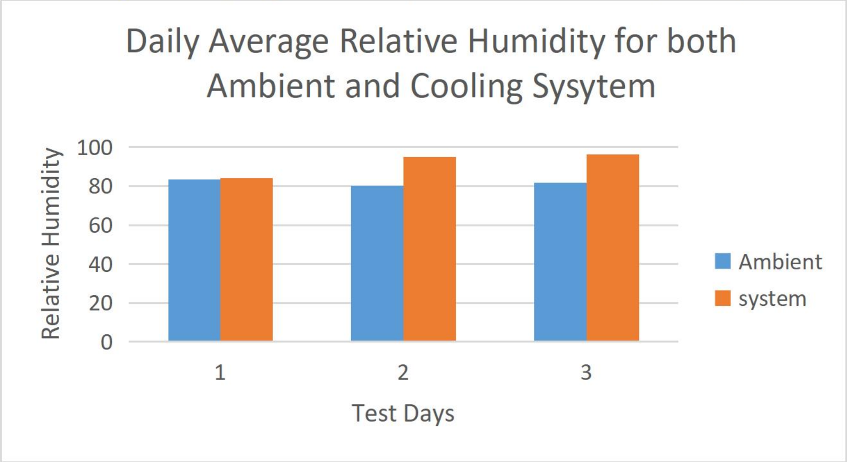

Fig. 2 Average Temperature and Relative Humidity readings for both ambient condition and evaporative cooling system for Hot Pepper.

The results for both Tomatoes and Hot Pepper as depicted in fig. 1 and fig. 2 the system maintained a stable high-humidity microclimate, which is critical for postharvest preservation. Although temperature reduction was modest, the consistently elevated humidity reduced vapour pressure deficit, thereby limiting moisture loss and slowing physiological deterioration, see plates 2 and 3. Similar observations have been reported, where high relative humidity in evaporative systems contributed more significantly to shelf-life extension than temperature reduction alone (Alemu, 2022).

(a) Before storage (b) 3days after storage in system (c) 3 days under ambient

Plate 2. (a-c) showing various Test results of Tomatoes conditions

(a) Before storage (b) 3days after storage in syst. (c) 3 days under ambient

Plate 3. (a-c) showing various test results for Hot Pepper

3.3 Physical Weight Loss Test Results

Figure 3 showed the results of physical weight loss of Tomatoes while Figure 4 also shows the daily Physical weight loss of Hot Pepper during the experiment.

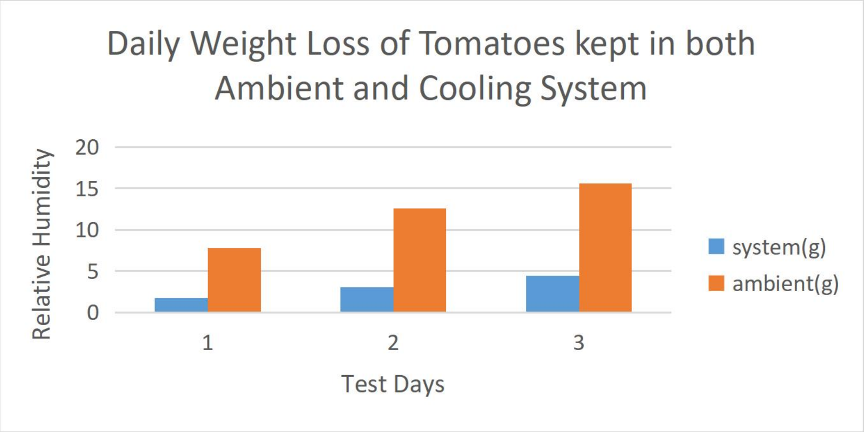

Fig. 3. Daily weight loss of Tomatoes kept in both ambient and cooling system.

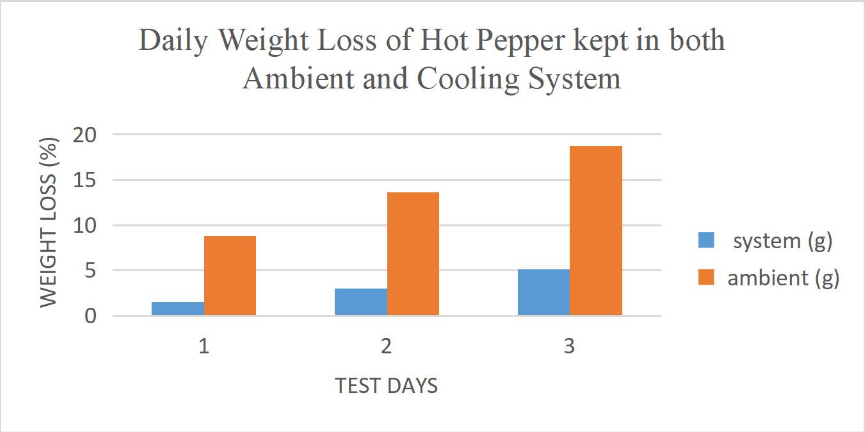

Fig. 4. Daily weight loss of Hot Pepper kept in both ambient and cooling system.

Across the test period, fluctuations in internal conditions were relatively minor and largely influenced by ambient weather variations and system operating dynamics such as airflow and pad wetting as vividly shown in figures 3 and 4. The ability of the system to maintain stable conditions suggests effective water distribution and ventilation, which are key determinants of evaporative cooling performance (Odesola & Onyebuchi, 2009). Overall, the load test demonstrates that while the cooling effect is constrained under high ambient humidity, the system still provides a favorable storage environment characterized by high relative humidity and moderate temperature moderation. These conditions are sufficient to reduce postharvest losses and preserve produce quality, particularly in contexts where refrigeration is not available. The results confirm that evaporative cooling systems are most effective in hot, dry climates, but still offer practical benefits in humid environments by improving storage microclimate (Kitinoja, 2018; Elik et al., 2019; *Zhao et al., 2020*). Plate 4 shows the smart solar powered evaporative cooler in a test day.

Pate 4. Evaporative cooler in a test day

4.0 Conclusion

Performance Assessment of an Arduino-Controlled Solar-Powered Evaporative Cooling System for Post-Harvest Preservation of Tomatoes and Hot Pepper in Semi-Arid Nigeria, demonstrated reliable performance in both no-load and load conditions. Under no-load operation, it consistently reduced temperature while maintaining very high relative humidity and an adequate (SE) efficiency (95%), confirming its ability to create a stable and favorable microclimate through evaporative cooling. When tested with Tomatoes and Hot Pepper, the system maintained elevated humidity levels and achieved moderate temperature reductions compared to ambient conditions. Although cooling performance was influenced by higher ambient humidity, the system still provided improved storage conditions that help minimize moisture loss and slow produce deterioration. The results show that the system is a practical, low-cost solution for postharvest storage, particularly in areas where Electricity is not available and have abundant Solar energy. Its strength lies more in maintaining high humidity than in achieving large temperature drops, making it effective for extending the shelf life of fresh produce in real-world conditions.

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