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Design of an evaporative cooling system integrated with ultraviolet light for preservation of fruits and vegetables at variable tropical weather conditions: a case study of Arusha, Tanzania

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DESIGN OF AN EVAPORATIVE COOLING SYSTEM INTEGRATED WITH ULTRAVIOLET LIGHT FOR PRESERVATION OF FRUITS AND VEGETABLES AT VARIABLE TROPICAL WEATHER CONDITIONS: A CASE STUDY OF ARUSHA, TANZANIA

John Pyuza Gunda

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Master's in Sustainable Energy Science and Engineering of the Nelson Mandela African Institution of Science and Technology

Arusha, Tanzania

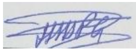
July, 2024

ABSTRACT

Problems with fruits and vegetables spoiling after harvest are particularly acute in tropical regions. This research presents the design, construction, and performance assessment of a solar-powered evaporative cooling storage system incorporating ultraviolet radiation (UV) to preserve foods susceptible to spoilage. Local materials, including sisal, sponge, and bricks, were used to construct the cooling chamber with a UV bulb. We measured the system's efficiency in both sunny and overcast tropical weather conditions by looking at how much air temperature was reduced, how much relative humidity was increased, and how much electricity was used for evaporative cooling. According to research, fruits and vegetables may be kept fresh for much longer after activating the UV light. This method may keep perishable goods for up to 21 days under UV light and 9 days without. An average temperature drop of 5.0℃ and an increase in relative humidity result from active system operation on sunny days. In contrast, the cooling effect is minimal on overcast days, leading to a relative humidity rise of 18% and a temperature drop of around 3.5℃. Based on these results, a solar-powered evaporative cooling system with UV radiation treatment might be a good way to reduce tropical post-harvest losses.

DECLARATION

I, John Pyuza Gunda, do hereby declare to the Senate of the Nelson Mandela African Institution of Science and Technology that this dissertation is my own original work and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.

John Pyuza Gunda		03-07-2024
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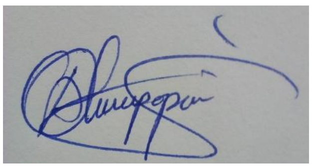
Dr. Baraka Kichonge		31-07-2024
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CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the Nelson Mandela African Institution of Science and Technology, a dissertation titled **“Design of an Evaporative Cooling System Integrated with Ultraviolet Light for Preservation of Fruits and Vegetables at Variable Tropical Weather Conditions: A Case Study of Arusha, Tanzania’’** in partial fulfillment of the requirements for the degree of Master of Science in Sustainable Energy Science and Engineering of the Nelson Mandela African Institution of Science and Technology.

Prof. Alexander Pogrebnoi		03-07-2024
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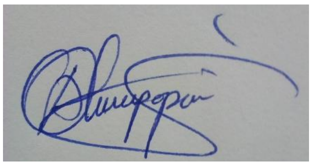
Dr. Baraka Kichonge		31-07-2024
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All in all, I am responsible for any shortcomings in writing or presenting data for this study.

DEDICATION

This work is dedicated to my spouse, Monica Marioth Ching'umba, whose prayers and inspiration signified critical milestones in the successful completion of the work.

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LIST OF ABBREVIATIONS AND SYMBOLS

DC	Direct current
LP	Low-pressure
NM-AIST	Nelson Mandela African Institution of Science and Technology
P_c	Cooling capacity
PE	Polyethylene
PV	Photovoltaic
RH	Relative humidity
RHI	Relative humidity increase
SESE	Sustainable Energy Science and Engineering
TD	Temperature decrease
TEMESA	Tanzania Electrical, Mechanical and Electronics Services Agency
T_{in}	Temperature inside the chamber
T_{out}	Temperature outside the chamber
UV	Ultra Violet
UV	Ultra violet
WISE Futures	Water Infrastructure and Sustainable Energy Futures

CHAPTER ONE

INTRODUCTION

1.1 Background of the Problem

Fruits and vegetables require immediate preservation to minimize potential post-harvest losses. Lossing fruits and vegetables post-harvest is a major challenge in tropical weather conditions (Arah *et al.,* 2016; Dhakulkar *et al.,* 2018; Sibomana *et al.,* 2016).

Perishability of fruits and vegetables is directly linked to rapid quality losses immediately after harvest when subjected to poor handling and storage conditions (Heidari *et al.,* 2019; Oyedepo *et al.,* 2019; Panchabikesan *et al.,* 2018). In tropical areas, spoilage of produce is caused not only by high temperatures but also by bacteria, yeast, mold, and attack by viruses (Gall & Benkeblia, 2022; Freimoser *et al.,* 2019; Pétriacq *et al.,* 2018). The challenge in minimizing fruits and vegetables' post-harvest losses is largely hinged on how to come up with reliable and sustainable storage systems for perishable produce at the minimum initial and running costs (Ambuko *et al.,* 2017; Bendinelli *et al.,* 2020; Bustos & Moors, 2018). Evaporative cooling systems are one of the options for horticultural post-harvest storage because of their environmental friendliness and energy-saving features (Verploegen *et al.,* 2018; Elik *et al.,* 2019; Rajapaksha *et al.,* 2021).

Evaporative cooling systems enable low-cost, high-quality preservation of perishable products. These systems use less energy and have the potential to reduce post-harvest losses for small-scale farmers who do not have the means to invest in expensive systems that also demand a large amount of energy (Chopra & Kumar, 2017; Lal-Basediya *et al.,* 2013; Zakari *et al.,* 2016; Dartnall, 2014).

Ultraviolet light is a kind of electromagnetic radiation with shorter wavelengths than visible light. For this reason, ultraviolet light travels at a greater frequency than visible light. As far as electromagnetic radiation goes, it falls within the 10–400 nanometer (nm) wavelength category. Its advantages include a broad-spectrum ability to kill bacteria, cost-effectiveness, ease of use, and environmentally friendly properties (Gayán *et al.,* 2014). It primarily works by causing genetic damage to microbes, making it an effective tool for disinfecting the surfaces of fruits and vegetables (Deng *et al.,* 2020).

The comprehensive technique has the potential to revolutionize post-harvest preservation, benefiting farmers, consumers, and the environment with its effective and forward-thinking strategy (Chopra & Kumar, 2017; Sibanda & Workneh, 2020b; Odeyemi *et al.,* 2022; Adeniyi *et al.,* 2023, Chopra *et al.,* 2022). Evaporative cooling systems, as detailed earlier, have the potential to provide low-cost and high-quality perishable produce preservation. They are energy-free and have increased potential for reducing post-harvest losses in small-scale farms. Most storage systems could not protect the produce from microbial spoilage well. The current study developed a solar-powered evaporative cooling storage system for perishable foodstuffs such as bananas, mangoes, avocados, and tomatoes.

Solar energy has been suggested for use in this design since it offers excellent prospects for lowering greenhouse gas emissions and indoor air pollution (Andrea *et al.,* 2019; Lingayat *et al.,* 2020; Shahsavari *et al.,* 2018). The system is integrated with UV light to enhance protective capability against microbial spoilage. This study is implemented through experimental testing of the system's performance through decreased air temperature, relative humidity increase, evaporative cooling power capacity, and harvest shelf life under sunshine and cloudy weather in Tanzania. The findings of this study may assist users in improving the cooling system for storing perishable fruits and vegetables.

1.2 Statement of the Problem

Many perishable food crops are only produced at certain times of the year in regions with highly changing tropical climates, such as Tanzania. This means these foods are only accessible for a limited time each year. During this brief period, they are grown more than the market can handle; hence, many of these crops must be processed and stored to prevent food waste and financial hardship for the farmers (Sibanda & Workneh, 2020). However, there was a problem of temperature decrease variation and increase of relative humidity from morning hours, day hours, and evening hours. Also, there is the quick deterioration of construction materials and susceptibility to pathogen microorganisms that attack the produce. This research aims to design and test the performance of a powered evaporative cooling storage system with a UV lamp integrated for the preservation of fruits and vegetables at variable tropical weather conditions: a case study in Arusha, Tanzania, using available material**s** for cooling pads such as a combination of sisal rope, sponge and bricks.

1.3 Rationale of the Study

This study delivers convenient evidence for solar energy application to preserve perishable fruits and vegetables in variable tropical weather conditions. This is because solar energy is a reliable energy source in this area and is environmentally friendly compared to other energy sources. The evidence provides help on the improvement of life shelf, energy-saving, and cost-effective solutions with minimal environmental impact. Thus, the output of this study will help achieve suitable cooling and storage conditions for maintaining the quality of fresh fruits and vegetables.

1.4 Objectives of the Study

1.4.1 General Objective

To design a solar-powered evaporative cooling system integrated with ultraviolet light to store perishable fruits and vegetables in tropical weather conditions.

1.4.2 Specific Objectives

The study aimed to achieve the following specific objectives:

(i) To determine functional parameters for the design performance of a prototype.
(ii) To design and develop the prototype of an evaporative cooling storage system.
(iii) To test the performance of locally available materials for a cooling pad.

1.5 Research Questions

The study intended to answer the following questions:

(i) What is the typical relative humidity of the location where cooling is required?
(ii) Are appropriate materials available for cooling pads and chamber fabrication for the cooling system?
(iii) How were solar energy and UV lamps used in the cooling system? Whether there is sunshine or it's cloudy, evaporative cooling may vary.

1.6 Significance of the Study

This study focused on designing a powered evaporative cooling storage system with a UV lamp integrated to preserve fruits and vegetables in variable tropical weather conditions. The study will provide valuable information for solar energy applications in keeping fruits and vegetables in variable tropical weather conditions. It is suitable for use in rural communities without electricity. It ensures marketing flexibility and food sustainability by allowing the farmers and wholesalers to sell produce at the most appropriate time.

1.7 Delineation of the Study

The delineation of the study was based on the application of solar energy to overcome the post-harvest loss incurred due to improper storage. Among the solutions, the evaporative cooling and storage system was selected for experimental testing in variable tropical weather conditions. The evaporative cooling and storage system was designed and manufactured using locally available cooling pads and chamber materials. The design performance was tested regarding temperature decrease, relative humidity increase, power capacity, and harvest life shelf under sunshine and cloudy weather in Tanzania.

CHAPTER TWO

LITERATURE REVIEW

2.1 Design Considerations of the Evaporative Cooling Systems

According to Dhakulkar *et al.* (2018), evaporative cooling occurs when a liquid cools an item or another liquid that comes into touch with it by evaporating into the air around it. The evaporative cooling process involves the passage of relatively dry air over a wet surface; the cooling effect is proportional to the evaporation rate. All point to artworks from the early era of Ancient Egypt that showed enslaved people fanning water from big, porous clay jars as an early method of evaporative cooling (Ambuko *et al.,* 2017; Anyanwu, 2004; Babaremu *et al.,* 2018; Mogaji & Fapetu, 2011). Air temperature drops and relative humidity rises due to heat evaporating water. The active evaporative cooling system included a pad, fan, storage chamber, and water recirculation pump, as Chinenye *et al.* (2013) reported. Some factors were taken into account throughout the design process: a) The evaporative cooler was relatively light in weight for ease of movement; b) Water recirculation system was incorporated which is to ensure minimal expenses; c) The evaporative cooler has uniform surface area; d) The water flow rate from the upper tank was constant.

2.2 Cooling Pad Materials

Chopra and Kumar (2017) proposed a semicircular-shaped design using Khus instead of cooling pad materials, improving efficiency by up to ~20%. A two-stage evaporative cooler, a modified system, was created to enhance the effectiveness and efficiency of evaporative cooling in low-temperature, high-humidity air conditioning (Gilani & Poshtiri, 2017; Basediya *et al.,* 2013). So, to help smallholder farmers in rural Nigeria, who had practically no access to an electrical power distribution network, extend the shelf life of their produce, a solar-powered evaporative cooling storage system was created (Olosunde *et al.,* 2016). Additionally, a device that uses evaporation and other locally sourced materials was created using clay (Chinenye, 2011).

The performance of the developed cooler was evaluated in terms of temperature drop, evaporative effectiveness, and cooling capacity (Sibanda & Workneh, 2020). The cooling process evaluated the combined system's performance and energy reduction capability using experimental data and appropriate analytical methods (Paul *et al.,* 2021). The results indicated that the cooling load can be reduced by up to 75% during the cooling process; a 55% reduction in electrical energy consumption can be attained.

Evaporative cooling takes advantage of the fact that water has a high enthalpy of vaporization and may absorb a substantial amount of heat, which is why cooling pad materials are used for this purpose (Chopra & Kumar, 2017). According to Oloshode *et al.* (2016), while selecting a material for the pad, many factors are considered, including the material's porosity, water absorption/evaporation rate, availability, cost, and simplicity of building. According to Chinenye *et al.* (2013), the pad material and pad area, thickness, and volume affected the cooling efficiency ℓ and cooling capacity Q_b, which were calculated using the following equations:

$$\ell = \frac{T_{db} - T_s}{T_{db} - T_w} \tag{1}$$

$$Q_b = 1.08 \times V_{sc} \times (T_{db} - T_s) \tag{2}$$

Equation (2) was converted to an SI unit and modified as follows:

$$Q_i = 670.66 \times V_{si} \times (T_{db} - T_s) \tag{3}$$

Where

T_{db} is ambient dry bulb temperature (°C);

T_w is ambient wet bulb temperature (°C);

T_s is dry bulb temperature of cooler storage space;

Q_i is the cooling capacity;

V_{sc} is the flow rate of air in (CFM);

V_{si} is the flow rate of air in (m^3/s).

The results showed that the cooling efficiency was highest for jute because the pad thickness is one of the parameters affecting the cooler's saturation efficiency. The pads of different thicknesses are shown in Fig. 1. It was suggested that a 60 mm thickness jute pad for an evaporative cooler should be used. The area of the pad was chosen in such a way that it covers one side of the storage chamber. This was to ensure uniform distribution of the cool and humid air from the wetted pad into the storage chamber to move over and cool the produce inside the storage chamber (Chinenye *et al.,* 2013; Olosunde *et al.,* 2016; Francis *et al.,* 2012).

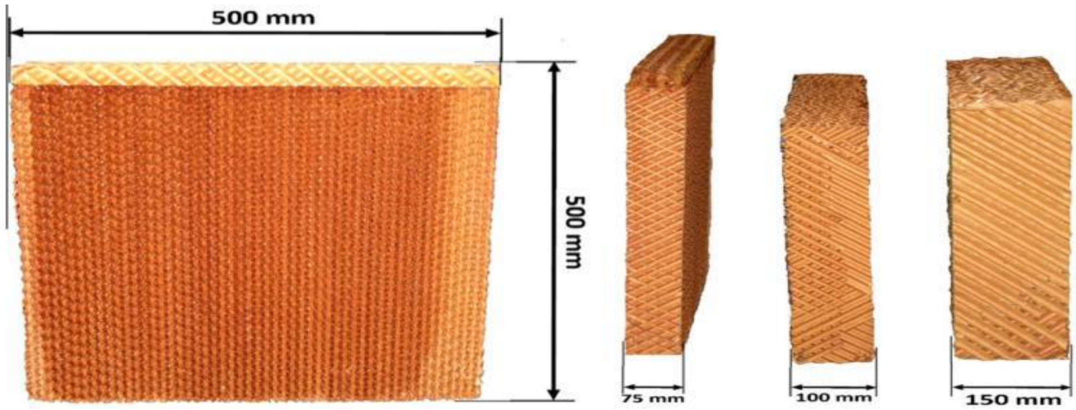


Figure 1: The pads of different thicknesses made of cellulose material (Warke & Deshmukh, 2017)

The assumptions were made in the analytical model to simplify equations, neglecting the least affecting factors, such as the following (Chinenye *et al.,* 2013).

(i) Cooling pad material is wetted uniformly and fully;

(ii) The convective heat transfer coefficient and mass transfer coefficient of moist air on the surface of water film are constant;

(iii) Heat flux transferred from the surroundings is neglected;

(iv) Water-air interface temperature is assumed to be uniform and constant;

(v) Thermal properties of water and air are constant;

(vi) Air temperature changes only in the flow direction.

The cooling or saturation efficiency (η) can be expressed as follows:

$$\eta = \frac{T_1 - T_2}{T_1 - T_s} \times 100 \quad (4)$$

T1 is the inlet dry bulb temperature, T2 is the outlet dry bulb temperature, and Ts is the wet bulb temperature.

2.3 Water Flow Rate Measurement

Figure 2 shows the pump and regulator that work together to manage the water flow rate to the pad. Collecting the quantity of water flowing over the pad for 30 seconds allowed us to estimate the average value, which is then converted to the water flow rate in L/min (Olosunde *et al.,* 2016; Chinenye *et al.,* 2013).

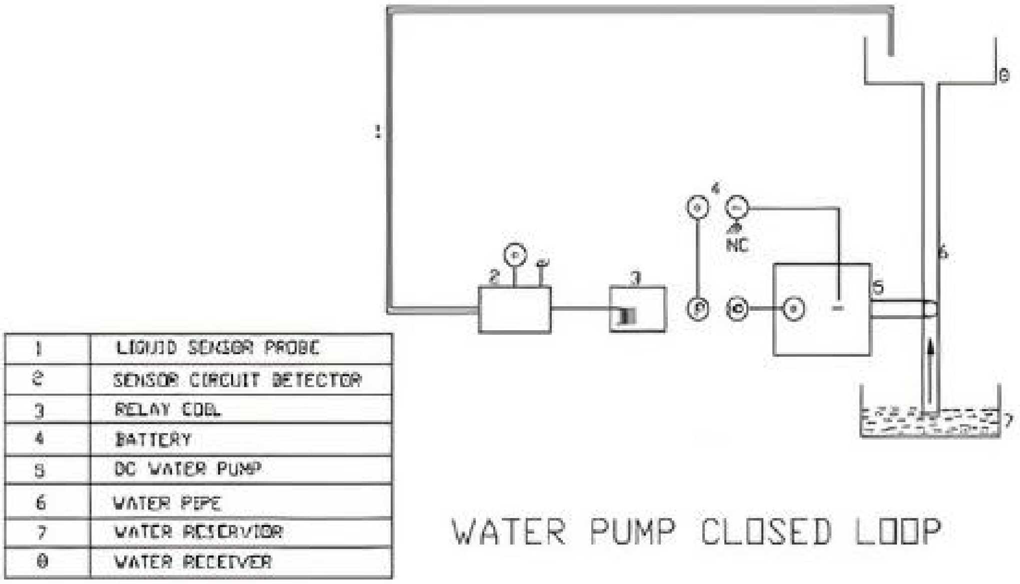


Figure 2: Water pump closed circuit (Olosunde *et al.,* 2016)

2.4 Air Velocity Measurement

Air velocity across the pad is difficult to measure since it changes and fluctuates at every place inside the pad. On the other hand, pad face velocity, the speed of air leaving the pad, was recorded. The hot air flow into the pad will be mirrored by its subsequent cooling, as seen in Fig. 3. A Smart Sensor Digital Anemometer AR826 (Shenzhen Graigar Technology, China) was used to detect the air velocity. The meter vane was attached to the cooler's underside, next to the fan. According to Oloshode *et al.* (2016), the liquid crystal display output will provide the flow rate value.

The evaporation rate is significantly affected by the presence or absence of air movement, whether natural (wind) or artificial (fan). The humidity of the air immediately around a moist surface increases when water vaporizes off it. As humidity increases, evaporation decreases if the humid air stays still. However, evaporation may increase or remain constant if the moist air around the water's surface is continuously displaced and replaced by drier air (Liberty *et al.,* 2013).

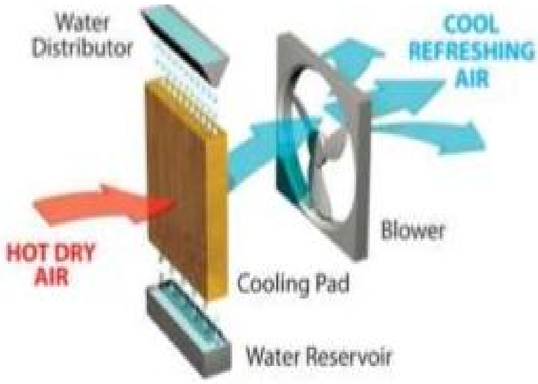


Figure 3: Schematic of the evaporating process (Malli *et al.,* 2011; Oliveria *et al.,* 2017)

2.5 Total Amount of Heat Production in the Storage Chamber

The important parts of different cooling chambers are given in isometric diagrams in Figs. 4 and 5. There are four sources of heat assumed in the storage chamber, which include: (a) field heat, which is the quantity of heat picked up from the field by the produce; (b) respiratory heat, which is the heat of chemical reactions in fruits and vegetables in the chamber; (c) heat transfer by conduction through the walls, roof, and floor of the storage chamber; and (d) infiltration of external air, which is the heat admitted into the cabin through leaks and opening of the door of the storage chamber (Deoraj *et al.,* 2015; Olosunde *et al.,* 2016).

Figure 4: Schematic direct and active evaporative cooler (Chinenye, 2011; Chinenye *et al.,* 2013; Chinenye & Manuwa, 2014)

Figure 5: Solar photovoltaic powered evaporative cooling system (Olosunde *et al.*, 2016)

Most perishable fruits and vegetables may have their shelf life improved by storing them quickly in a way that keeps their freshness intact. Locations with precisely regulated temperature, airflow, relative humidity, and, in certain cases, atmospheric composition may provide the ideal conditions (El-ramady *et al.,* 2013). According to El-ramady *et al.* (2013), several issues might impact goods' shelf life and quality when stored in the same space. These include temperature and relative humidity incompatibilities, chilling and ethylene sensitivity, odor contamination, and much more. However, ultraviolet light may be a good alternative for fresh fruits. Ultraviolet light is particularly attractive because it can prevent the product's microbial spoilage so that no residue is left on foods (Basediya *et al.,* 2013). The experiment indicated that the ultraviolet light treatment of the product favoured a longer shelf life for the harvest, as fresh fruits and vegetables are highly susceptible to microbial spoilage (Pinheiro *et al.,* 2013).

2.6 Experimental Tests

Experimental studies utilizing palm fruit fibre as the cooling pad were detailed by Ndukwu *et al.* (2011) at air velocities of 4.0 m/s. It was placed within the shade to test how well the design worked. This will allow the cooler to be exposed to natural air while reducing the direct impact of the sun. The experiments were conducted in January and February 2013, showcasing the year's temperature extremes. The experiment's temperatures reached 45°C, and relative humidity ranged from 28 to 80%. Once the pad was placed, the top water tank was opened to a water flow rate of 10 cm3/s.

Once the pad is saturated, the water goes into the bottom tank and is recirculated for an hour via the pump. This process is repeated before the cooler is filled with vegetables. After that, the veggies were placed in the cooler, the rheostat was adjusted to 4.0 m/s, and the fan was operated on until the temperature dropped as low as 13ℵ. Environment relative humidity ranged from 28 to 80%, and the ambient temperature reached 45°C during the test period (Chinenye *et al.,* 2013; Ndukwu, 2011; Xuan *et al.,* 2012; Watt, 1997). The cooling capacity and cooling efficiency were estimated to assess the effectiveness of a direct evaporative cooling medium.

Temperature and product reaction were the two metrics used to assess the cooler. According to Ndukwu and Manuwa (2015), researchers looked at how camel milk's quality changed in response to changes in storage temperature, relative humidity, and outside environmental factors. There was a maximum temperature decrease of 13°C. Throughout the experiment, the relative humidity of the cooler ranged from 85.6-96.8%, indicating the highest amount of air saturation that can be achieved with humidification. Indirect evaporative cooling systems cannot reach 100% relative humidity, as Xuan *et al.* (2012) pointed out. This occurs because insufficient contact between the water and the thinly packed pad allows process air to escape readily. Not enough time passes for the air and water to come into contact, leading to inadequate mass and heat transmission.

According to Babaremu *et al.* (2019), evaporative cooling technology may increase the shelf life of tomatoes according to an experimental investigation. Because it was chilly, the tomatoes didn't release as much of their ripening hormone. According to Guo *et al.* (2019), this caused the tomatoes kept in the evaporative cooling system to mature more slowly than the samples kept in the ambient temperature setting.

Ogbuagu *et al.* (2017) determined that the assessment and performance should include no-load and load testing. A no-load test was conducted on the evaporative cooler without any foodstuff. Two temperatures were recorded: the room temperature and the temperature with the cooler. The stored items were placed inside the evaporative cooler during the load test, while a control experiment was carried out in the surrounding air. The experiment recorded the average air temperature as 32°C, whereas the interior cooler temperature was recorded as 27°C. The mean relative humidity inside the cooler was 58%; thus, from the psychrometric chart, the air's wet-bulb temperature was 21.5°C. The saturation efficiency SE was calculated using the following equations:

$$SE = \frac{T_0 - T_i}{T_0 - T_{wb}} \times 100 \quad (5)$$

The value of SE appeared to be 42%, which shows the ability of the device to evaporate water and thus cool at a given relative humidity.

Francis *et al.* (2012) measured temperature and relative humidity inside and outside the cooling chamber. The parameters were recorded every 12 hours of the 15 days, as shown in Figs. 6, 7, 8 and 9.

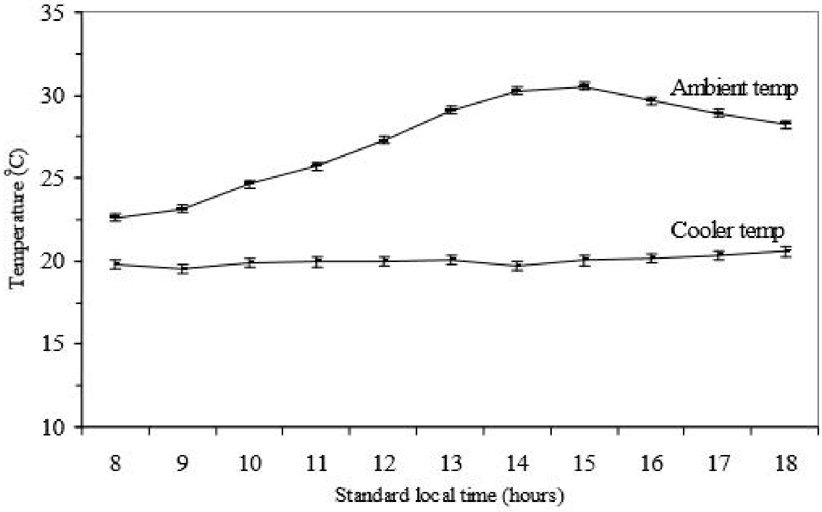


Figure 6: Average hourly variations of temperature for the ambient and cooling chamber

According to Francis *et al.* (2012), the data comprises the means of fifteen replication bars, with the standard errors denoted beside them. While the sun was shining, the evaporative cooling system kept the temperature steady. However, between 800 h and 1400 h, the average temperature of the surrounding air rose steadily. A further drop occurred between 1500 h and 1800 h (Fig. 6). Francis *et al.* (2012) found that cooling was most necessary between 1400 h and 1500 h when temperatures were highest. During this period, there was a larger relative drop in temperature. During this period, the cooler kept the ambient temperature between 29-32℃ lower than its average, 10.5 ± 0.4 degrees. When fruits and vegetables were stored using evaporative cooling, Tilahun (2010) found similar outcomes. The relative humidity within the chamber rose to 86.7%, while the outside RH was around 74.2%.

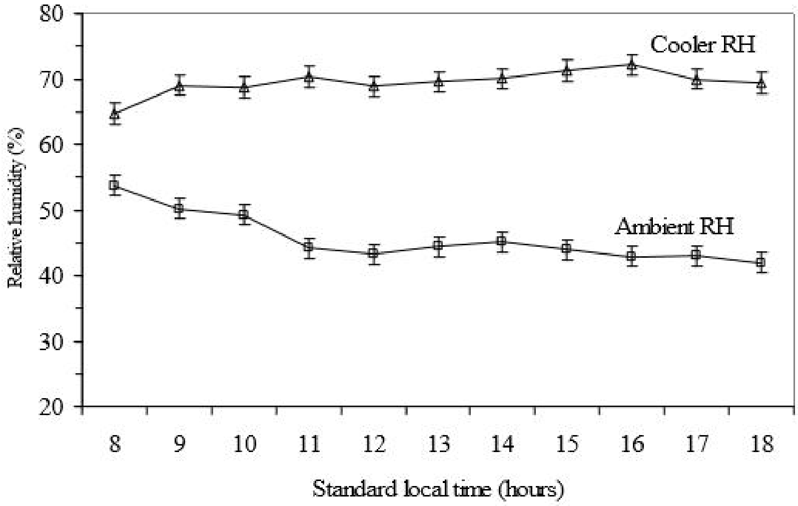


Figure 7: Average hourly variations of relative humidity (RH) for the ambient and cooling chamber

Data are mean values of 15 replications; bars are standard errors recounted that the average cooling efficiency followed the same pattern of average ambient temperature (Fig. 7) (Francis *et al.,* 2012). Cooling efficiency was highest when cooling was most needed during the hottest time of the day (1400 h). The daily variation of cooling efficiency was 74.2─86.7%, which agrees with values for cooling efficiencies reported by Olosunde *et al.* (2009) during evaporative cooling storage of fruits and vegetables.

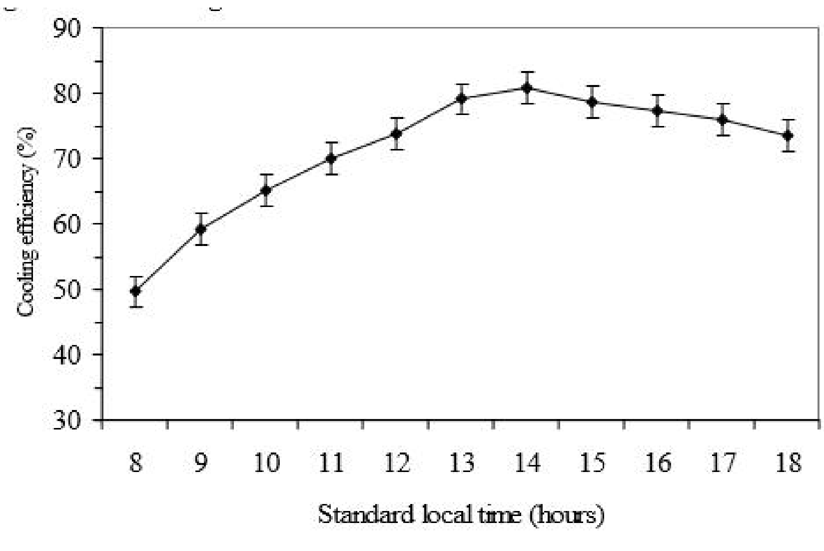


Figure 8: Average hourly variations of cooling efficiency for the evaporative cool chamber

Data are mean values of 15 replications; bars are standard errors (Francis *et al.,* 2012). It was reported in the literature that the maximum depression of the dry bulb temperature reached 19°C (Elmetenani *et al.,* 2010), reduction of the temperature by 35.6% and humidity increase by 0−49% compared to outside parameters (Francis *et al.,* 2013). The current research may contribute to findings described in the literature in terms of methodology, materials, and equipment selection. The presented works have shown some limitations of protective capability against microbial spoilage of the vegetables and fruits, hence restricted life shelf of the produce.

CHAPTER THREE

MATERIALS AND METHODS

In this study, the solar-powered evaporative cooling storage system has been developed to store perishable products such as bananas, mangoes, avocados, and tomatoes. The cooling chamber was integrated with water and air circulation and modified with locally available materials; the ultraviolet light treatment was used to protect the product from microbial spoilage. The design performance regarding temperature decrease, relative humidity increase, power capacity, and harvest life shelf under sunshine and cloudy days has been tested.

3.1 Equipment and Materials

The cooling chamber, cooling fan, DC water pump, and cooling pad were connected as the main components to formulate the prototype with a total storage space of 0.19 m^3. It comprised a square mild steel hollow section, transparent glass, aluminum sheets on the outside, and little bricks inside. Underneath the tank, the cooling pad was linked by a polyethene (PE) pipe supplying water to keep the cooling pad continuously wet. The prototype was built at the Iringa TEMESA and NM-AIST campus *iTECH* workshops. Major components of the design are shown in Fig. 9; equipment and accessories and their functions are summarized in Table 1.

(a) (b) (c) (d) (e)

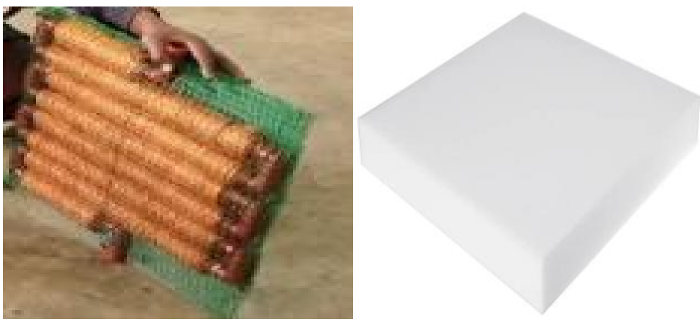
Figure 9: Components of the design: (a) DC pump; (b) DC fan; (c) solar panel; (d) battery; (e) UV bulb

Table 1: Equipment, accessories, and their functions

Description	**Function**

Solar PV 200 W, 10.54 A; 18.9 V size of 16.5×100×5 cm	For conversion of solar irradiance to electricity
Proskit NT-311 temperature-clock/humidity sensor and HTC-1 temperature-clock/humidity sensor	For measuring both temperature and absolute humidity
DC water pump with a capacity of 1 l/min and a power rating of 17.64 W	For water circulation into the cooling pad and cooling chamber
Fan 223 W with a diameter of 40 cm and rate of 4.3 m/s velocity airflow	For air drawn from the atmosphere into the cooling pad
UV bulb 1.5 W	For bacterial disablement
Cooling pad 53×53×8 cm, which consists of PE pipes ½ inch diameter, sponge 53×53×3 cm, bricks 3×2×1 in., and sisal rope 20 m length	For air cooling and water circulation
Water reservoir with 15 l capacity made of steel plate	For supplying water to the cooling pad to keep the cooling pad wet
Cubed cooling chamber 68×53×53 cm with total storage space of 0.19 m^3 made of bricks inside layer, marine board as a base, and aluminum sheet outside layer	For fruit and vegetable storage
Solar battery (12 V; 150 Ah)	For storing charge and maintaining the system's operation at night hours

The cooling pad materials are shown in Fig. 10 (a) and (b), and the cooling chamber setup and materials used are shown in Fig. 11 (a) and (b). The cooling pad was made of a sisal rope wrapped around PE pipes and a sponge to evaporate water and retain moisture.



(a) (b)

Figure 10: Cooling pad materials: (a) sisal rope wound PE pipes with wire mesh; (b) sponge placed in front of the pad

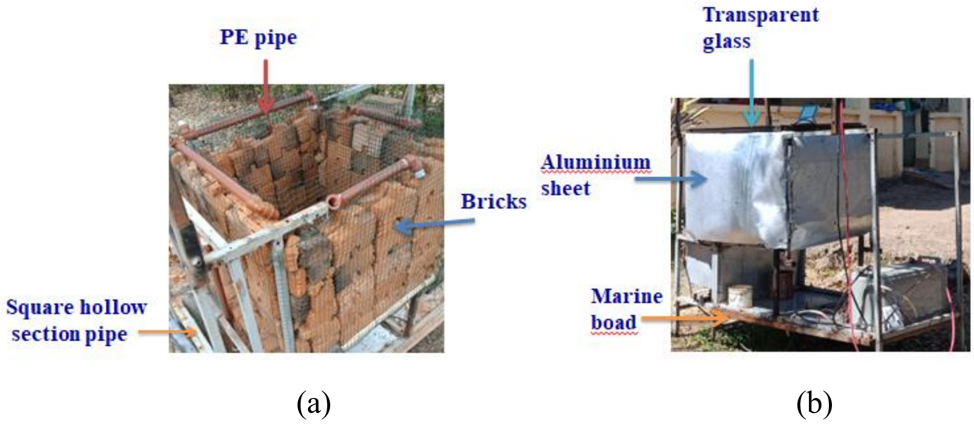


Figure 11: Cooling chamber and materials used: (a) square mild steel hollow section and PE pipes and bricks; (b) aluminum sheet, marine board, and transparent glass

3.2 Experimental Setup

The experimental setup was designed by connecting the cooling chamber and pad, pump, fan, UV light, solar panel, controller, and battery to lower the ambient air temperature as it passed through the evaporative pad. Water circulation in the cooling pad and chamber achieved the setup's cooling effect. Relying on evaporation to cool is the fundamental premise. Once activated, the system's dry air suction fan evaporates the water-soaked cooling pad by passing it across its wet surface. Outside and inside the cooling chamber, we measured the relative humidity and temperature on both overcast and sunny days. For each weather condition, two modes were considered when the pump and fan were "OFF" or "ON". Figure 12 illustrates the experimental setup, and Fig. 13 presents the schematic diagram adopted in this study.

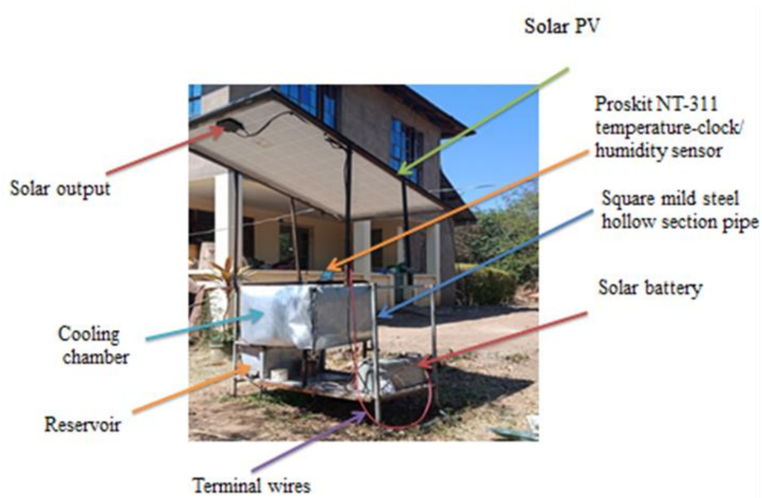


Figure 12: Experimental setup

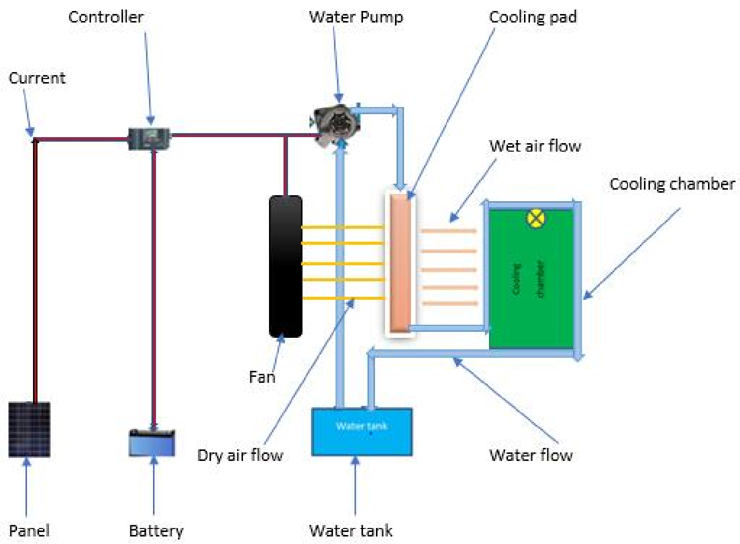


Figure 13: Schematic diagram of the prototype

The prototype setup was developed by utilizing local resources for the cooling chamber, such as sisal rope, sponge, and bricks, which improved the life shelf of fruits and vegetables. The control of weather conditions during sunny and cloudy days didn't require active involvement. Instead, it relied entirely on the presence of a solar panel, which offered partial shade. This approach aimed to replicate tropical weather conditions, allowing sunny and cloudy days to occur naturally. The selected methodology aimed to foster a deeper understanding of how diverse weather conditions characteristic of tropical regions influence the system's operational efficiency and overall performance. The cooling chamber is surrounded by a transmitting medium (cooling pad) made of sisal rope and a sponge. Energy-consuming components, such as an ultraviolet bulb, fan, and DC water pump, were powered through a solar panel and solar battery to maintain the system’s operation during night hours.

To maintain the cooling pad's moisture, a water reservoir was connected to the cooling system at the bottom by PE pipes. The equipment was firmly planted at the NM-AIST main campus, 1206 meters above sea level, looking north toward the equator, at coordinates 03.40° south and 36.79° east. The poles of the panel, as shown in Fig. 12, were fixed to keep the panel at 15° inclination adopted by Chandel (2013) as a rule of thumb; four poles displaced at 54×100 cm from each other with two front poles of 99 cm height and two rear poles of 85 cm height. The four poles were mounted to the cooling chamber by bolts and nuts to carry the solar panel, which also acted as a roof, and the wires from the solar panel were connected to the battery and then to the pump and fan.

3.3 Experimental Measurements and Data Processing

The prototype was tested in terms of temperature decrease, relative humidity increase, and evaporative cooler cooling capacity (Deoraj *et al.,* 2015). Measurements were taken between 1000 h and 1600 h. The temperature and humidity outside and inside were recorded hourly using the sensor. The cooling chamber performance was specified through air temperature decrease *TD*, relative humidity increase *RHI,* and cooling power capacity of the chamber P_c:

$$TD = T_{out} - T_{in} \quad (6)$$

$$RHI = RH_{in} - RH_{out} \quad (7)$$

$$P_c = \dot{m}_{air} C_p (T_{out} - T_{in}) \quad (8)$$

Where T_{out} and T_{in} are the temperature outside and inside the cooling chamber, respectively; similarly, RH_{out} and RH_{in} are the relative humidity outside and inside the chamber, respectively; and $\dot{m}_{air}$ is the mass flow rate of air supply, C_p = 1.005 kJ/ (kg K) is the specific heat capacity of air.

The mass flow rate was calculated using the equation.

$$\dot{m}_{air} = \rho VA, \quad (9)$$

Where ρ = 1.1839 kg/m^3 is the density of air; V is the air supply velocity, V = 4.3 m/s; A is the cross section area air passes through, $A = LH$ = 0.53 m × 0.53 m = 0.28 m^2, L is the width and H is the height of the cooling pad. Hence, mass flow rate $\dot{m}_{air}$ = 1.43 kg/s. The cooling power capacity P_c for the system is equal to air sensible heat as it is related to the temperature decrease *TD*. The cooling effect in the storage chamber is due to water evaporation, which draws energy from the surroundings. The energy required for water vaporization P_w is:

$$P_w = q\dot{m}_w \quad (10)$$

Where q states for latent water evaporation heat, $\dot{m}_w$ is the mass rate of the evaporated water.

3.4 Evaluation of Spoilage in Fruits and Vegetables

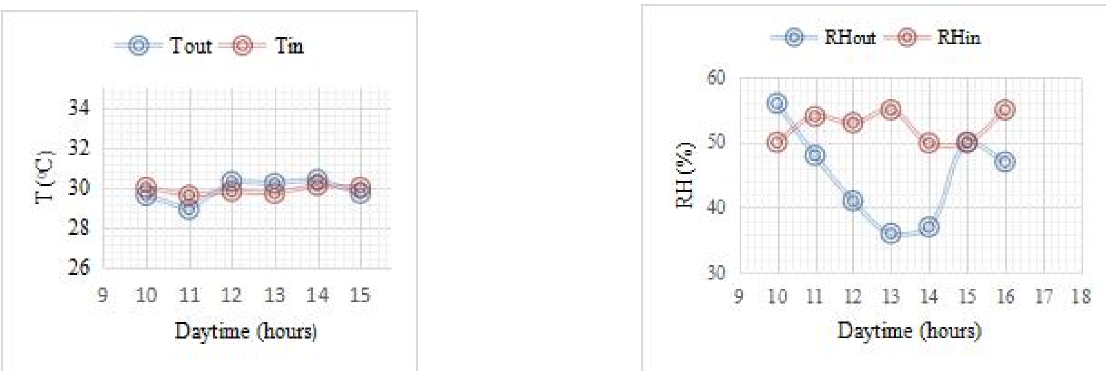
The spoilage of fruits and vegetables was assessed using two techniques: Color Analysis and Sensory Evaluation. Combining these methods offered a more complete understanding of spoilage. In the colour analysis part, a visual examination of colour changes was conducted as indicators of spoilage. At the same time, sensory assessments were used in sensory evaluation to detect changes in flavour, odor, and overall appearance linked to spoilage. This integrated approach enhanced the ability to make informed decisions about the shelf life and overall production quality. The *UV-B* (290–320 nm) conventional low-pressure (*LP*) mercury arc lamp was integrated with a cooling chamber at the center on the top. About 10 kg of fruits and vegetables, namely bananas, mangoes, avocados, and tomatoes, were kept for 21, 14, 24, and 14 days without getting spoiled when the lamp was “ON”.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Variation of Temperature and Relative Humidity During the Sunshine Day

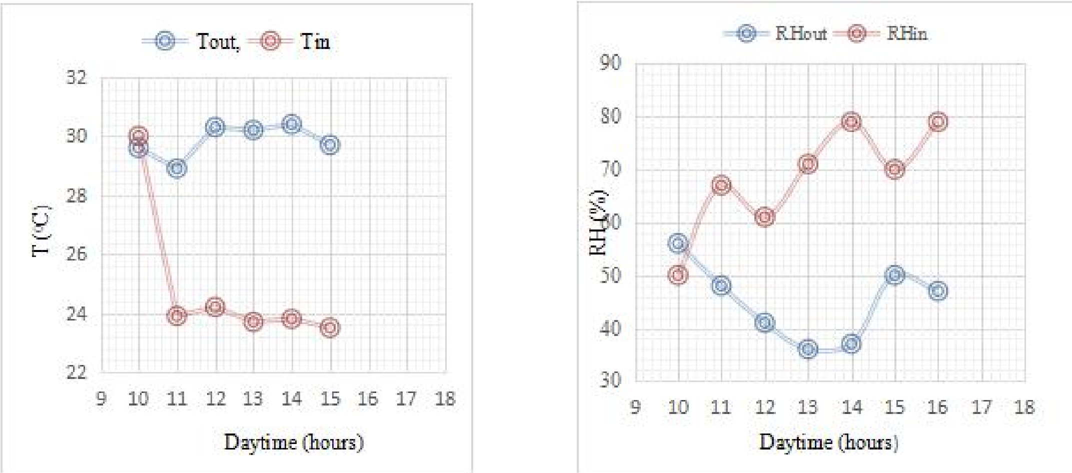
For the sunshine day, the parameters outside and inside the cooling chamber, temperatures, T_{out} and T_{in}, and relative humidity, RH_{out}, and RH_{in} were recorded when the prototype was "OFF," as shown in Fig. 14. It was observed that the ambient temperature inside the cooling chamber was practically the same, about 29–30°C; thus, no temperature decrease occurred in this case. The relative humidity inside the chamber was around 50–55%, but it varied substantially outside. The outdoor relative humidity was greater in the morning at 56% and reduced to 36% by noon. This indicated that humidity decreased as the intensity of the sunshine grew. Thus, for the sunshine day when the prototype was OFF, no cooling occurred in this case.



(a) (b)

Figure 14: Sunshine day test when both the pump and the fan were "OFF": (a) temperature variation, T_{out} and T_{in}; (b) relative humidity variation, RH_{out}, and RH_{in}

Variation in temperature and humidity on sunny days when the system was active is shown in Fig. 15. According to the experimental outcomes, the indoor temperature ranged from 23-30°C. In contrast, humidity ranged from 50-79%. Within the chamber, the temperature decreased by 5–7°C, remaining relatively consistent between 1100 h and 1600 h. In this timeframe, relative humidity was notably 19–42% higher than outside conditions. This decline in temperature and the rise in relative humidity inside the chamber were attributed to the coordinated operation of the pump and fan. The cooling pad exhibited enhanced efficiency as air coursed through the damp cooling pad. These results are consistent with the observations made by Nkolisa *et al.* (2018) and Nkolisa *et al.* (2019b), who emphasized that (a) optimal evaporative cooling occurs when reasonably dry air interacts with a moist surface, intensifying the cooling effect due to accelerated evaporation rates; (b) the effectiveness of evaporative cooling when moderately dry air interacts with a moist surface, leading to an intensified cooling effect through accelerated evaporation rates.



(a) (b)

Figure 15: Sunshine day test when both the pump and the fan were "ON": (a) temperature variation, T_{out} and T_{in}; (b) relative humidity variation, RH_{out}, and RH_{in}.

The performance parameters of the prototype, temperature decrease, relative humidity increase, and cooling power of the chamber for the sunshine day are summarized in Table 2. The calculated performance parameters presented in Table 2 were derived using Equations (6)−(9).

Table 2: Performance parameters of the design for a sunshine day

Time (hrs)	T_{out} (°C)	T_{in} (°C)	*TD* (°C)	RH_{out} (%)	RH_{in} (%)	*RHI* (%)	P_c (kW)
10:00	29.6	30.0	–0.4	56	50	-6	–0.6
11:00	28.9	23.9	5.0	48	67	19	7.2
12:00	30.3	24.2	6.1	41	61	20	8.8
13:00	30.2	23.7	6.5	36	71	35	9.3
14:00	30.4	23.8	6.6	37	79	42	9.5
15:00	29.7	23.5	5.2	50	70	20	7.5
16:00	28.2	23.0	5.2	47	79	32	7.5

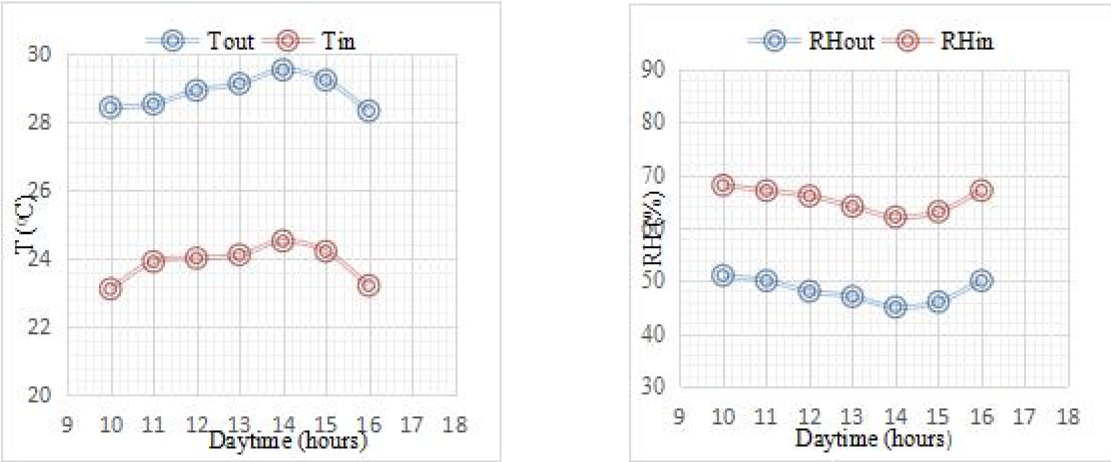
Throughout a sunny day, as depicted in Table 2, the prototype demonstrates varying temperature decrease (*TD*) ranging from -0.4 to 6.6°C, with the most prominent drop occurring at 1400 h, signifying the peak cooling effect. Relative humidity (*RH*) fluctuates for both the external air (RH_{out}) and internal air (RH_{in}), with RH_{out} ranging from 36-56% and RH_{in} varying between 50-79%. The cooling process correlates with an elevation in relative humidity within the chamber. The increase in RHI within the chamber ranged from −6-42%, where negative values suggest a reduction in humidity due to the cooling process. Cooling power varies from −0.6-9.5 kW, initially being negative at 1000 h and reaching its peak at 1400 h, aligning with the highest temperature decrease and relative humidity increase. This alignment highlights the effectiveness of the cooling process during that time. The results outline storage parameters ranging from 23-30°C for T_{in} and 50-79% for RH_{in} throughout the day. A negative temperature difference *TD* at 1000 h implies that the air inside the chamber is warmer than the external air.

Similarly, negative *RHI* values suggest that the ambient air is more humid than the air inside the cooling chamber. The maximum cooling effect is observed at 1400 h, characterized by a temperature decrease *TD* of approximately 7°C and a relative humidity increase *RHI* of 42%, accompanied by a cooling power of 9.5 kW. In general, literature suggests that optimal conditions for produce storage under evaporative conditions include a temperature range of 10–21°C, cooling capacity of ~5–7 kW, and relative humidity levels of 80–95% (Lal-Basediya *et al.,* 2013, Nkolisa *et al.,* 2019a, Lotfizadeh & Layeghi, 2014, Mustafa & Jasim, 2018, Vala *et al.,* 2014). While the designed cooling chamber does not precisely meet these criteria, it does approach them, particularly in terms of T_{in} and RH_{in}, making it suitable for storing less perishable items like bananas or avocados.

4.2 Variations of Temperature and Relative Humidity During a Cloudy Day

Temperature and humidity were recorded when the setup was turned “OFF” on a cloudy day, as shown in Fig. 16. The ambient temperature was about 28–29°C and 23–24°C inside the cooling chamber; thus, the temperature difference was ~5°C. The relative humidity was 45–51% outside and 62–68% inside the chamber. Similar persistent discrepancies between the outside and inside parameters were maintained throughout the day.

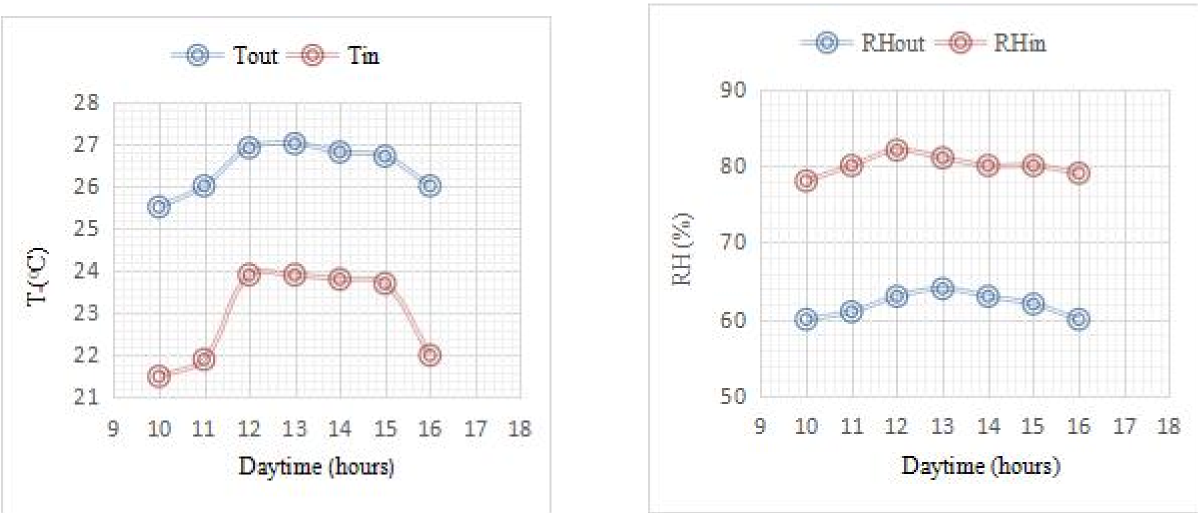
Variations of temperature and relative humidity during the cloudy day when the prototype was “ON” are shown in Fig. 17; the outside and inside temperatures and relative humidity were observed to be 25.5-21.5°C, 60-78%, respectively, at 1000 h. On average, the temperature decreased by 4°C, and relative humidity increased by 18%. The parallelism between recorded outside and inside parameters during the day is worth noting.



(a) (b)

Figure 16: Cloudy day test when both the pump and fan were "OFF": (a) temperature variation, T_{out} and T_{in}; (b) relative humidity variation, RH_{out}, and RH_{in}.

The performance indicators of the prototype, including temperature decrease, rise in relative humidity, and the cooling capacity of the chamber on a cloudy day, are shown in Fig. 18. The storage parameters ranged between 21.5-23.9°C for temperature, 78-82% for relative humidity inside the chamber, and 4.3-5.9 kW for cooling power. Thus, a slight cooling effect was observed; the temperature decreased by 3–4°C, and humidity increased by 17–19%.



(a) (b)

Figure 17: Cloudy day test when the pump and the fan are ON: (a) temperature variation, T_{out} and T_{in}; (b) relative humidity variation, RH_{out}, and RH_{in}.

When the chamber performance for the two cases was compared, when the pump and fan were "OFF," as shown in Fig. 17, and when they were "ON," as shown in Fig. 18, there was no significant difference. These results suggest that when the setup was "OFF," cool and wet conditions inside the chamber were maintained due to the physical ability of materials, sisal rope, bricks, and sponge, to retain moisture for a long time.

Throughout the day, from 1000 h to 1600 h, the RHI values ranged from 17-19%. This indicates a notable increase in humidity compared to the conditions outside the chamber. Additionally, the prototype's cooling power ranged from 4.3-5.9 kW during the same timeframe, showing that the chamber moderately cooled the interior. The highest cooling power was recorded at 1100 h, reaching 5.9 kW. These combined findings highlight the chamber's ability to moderately reduce the temperature and increase humidity levels on cloudy days, demonstrating its potential to create a comfortable indoor environment.

The performance parameters of the design, temperature decrease, relative humidity increase, and cooling power of the chamber for a cloudy day are summarized in Table 3.

Table 3: Performance parameters of the design for a cloudy day

Time (hrs)	T_{out} (°C)	T_{in} (°C)	*TD* (°C)	RH_{out} (%)	RH_{in} (%)	*RHI* (%)	P_c (kW)
10:00	25.5	21.5	4.0	60	78	18	5.8
11:00	26.0	21.9	4.1	61	80	19	5.9
12:00	26.9	23.9	3.0	63	82	19	4.3
13:00	27.0	23.9	3.1	64	81	17	4.5
14:00	26.8	23.8	3.0	63	80	17	4.3
15:00	26.7	23.7	3.0	62	80	18	4.3
16:00	26.0	22.0	4.0	60	79	19	5.8

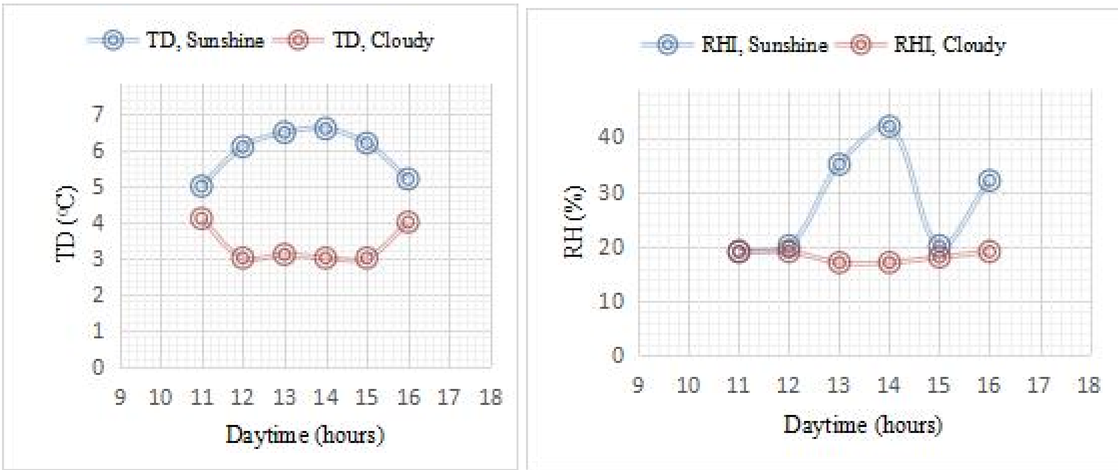
The storage parameters ranged between 21.5-23.9°C for temperature, 78–82% for the *RH* inside the chamber, and 4.5–5.9 kW for cooling power. Thus, a slight cooling effect was observed; the temperature decreased by 3–4°C, and humidity increased by 17-19%.

Suppose we compare the chamber performance for the two cases; when the pump and fan were OFF (Fig. 17) and ON (Fig. 18), there was no difference. We suppose that when the setup was OFF, cool and wet conditions inside the chamber were maintained due to the physical ability of the materials, sisal rope, bricks, and sponge to retain moisture for a long time.

4.3 Prototype Performance Comparison

It was anticipated that weather conditions would affect the performance of the cooling setup, with the increase or decrease of the parameters being dependent on solar irradiance. The performance parameters of the prototype, temperature decrease *TD* and humidity increase *RHI*, for two cases, the sunshine and cloudy day, are shown in Fig. 9. It was observed that inside the chamber, the temperature decreased by 3–4°C for cloudy weather and 5–7°C for the sunny day while humidity increased by 19% and up to 42%, respectively; that is to say that the cooling effect of the setup is less in the cloudy weather compared with the sunshine day. As is seen from Equations (1) and Equation (3), disregarding the weather conditions, the trend in the cooling power (P_c) followed that one for the *TD* in Fig. 9(a).

The water evaporating rate $\dot{m}_w$ can be estimated assuming a balance between the P_c and energy required for water vaporization *P*w, Equation (5), where latent water evaporation heat is q = 2450 kJ/kg at room temperature and normal pressure. The mass rate of water evaporation is $\dot{m}_w \approx 4$ g/s (for sunshine day and *TD* = 6.6°C), which is in accordance with available literature finding $\dot{m}_w \approx 6$ g/s reported for evaporative cooler tested under Algerian climate (Elmetenani *et al.,* 2011).



(a) (b)

Figure 18: Comparison of the prototype performance parameters between sunshine and cloudy day: (a) temperature decrease *TD*, (b) relative humidity increase *RHI*

Results show that when there were clouds, the heat inside and outside the setup was reduced, requiring less energy for the cooling operation. The cooling effect was maintained by the prototype and was ensured by moist materials, sisal rope, sponge, and bricks. According to Amer *et al.* (2015), a stronger cooling effect can be achieved when air drawn with a fan flows faster through the cooling pad into the chamber; however, due to the speed controller's limitations, variation of the fan speed was not attempted in this work.

4.4 Effect of Ultraviolet Light in the Cooling Chamber

In this study, the ultraviolet lamp was integrated inside the cooling chamber to prevent microbial spoilage of the product; when the UV lamp is on, it produces light which kills the bacteria. However, when the *UV* lamp was switched off, it took only 9, 8, 7, and 5 days without showing signs of spoilage. Regarding weather conditions, during 21 days of lamp use, eight days were cloudy and 13 days were sunshine, while during nine days of storage without lamp, three days were cloudy and six days were sunshine. Thus, the benefits of exposing the product to UV light extended the harvest's storage life. Potential dangers include incompatibilities with humidity and temperature, susceptibility to chilling and ethylene, contamination by odor, and other problems affecting nutritional value and shelf life (Zakari *et al.,* 2016). Surface treatment, which must be as delicate as possible to preserve the product's integrity and freshness, might prevent or lessen the damage. Based on what we saw in the experiment, these criteria can be satisfied with minimal processing methods like UV light treatment. As shown by Turtoi (2013) and Yan *et al.* (2020), UV light has effectively reduced microbial loads of diseases on the harvest, improving the quality and shelf life of products.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The solar-powered evaporative cooling system, integrated with ultraviolet light, was designed and tested in sunshine and cloudy weather conditions. Measurements of temperature and humidity were taken inside and outside the cooling chamber from morning (1000 h) to afternoon (1600 h) for each weather scenario, exploring various operational modes of the system involving the pump and fan being turned to "ON" or "OFF" mode. The results highlighted the relationship between weather patterns and the system's performance. During active operation on sunshine days, the system achieved an average temperature reduction of 5.0°C and a considerable 23% rise in humidity. On cloudy days, however, the cooling effect was somewhat lessened, resulting in temperature decreases of roughly 3.5°C and an 18% increase in humidity throughout the day.

Furthermore, integrating UV light treatment was revealed to be a critical element, significantly extending the storage time of numerous produce types such as bananas, mangoes, avocados, and tomatoes. Under UV light, these may be preserved for 21, 14, 24, and 14 days, respectively, compared to considerably shorter periods without it. However, challenges concerning the cooling system's efficiency in humid conditions were also revealed, including the potential for moisture-induced corrosion that could endanger electronic components and the necessity to prevent mold growth and microorganisms on damp cooler pads. Considering these findings, the potential for further improvement of the system's design and operation becomes evident. Strategies involving changes to the cooling chamber's design, operational modes, and material selection give viable options for improving its performance. These observations underline the system's potential in addressing the problem of decreasing post-harvest losses in tropical conditions and indicating possibilities for ongoing innovation and optimization.

5.2 Recommendations

Further studies about solar energy applications for preserving fruits and vegetables in variable tropical weather conditions are required. However, challenges concerning the cooling system's efficiency in humid conditions were also revealed, including the potential for moisture-induced corrosion that could endanger electronic components and the necessity to prevent mold growth and microorganisms on damp cooler pads.

Considering these findings, the potential for further improvement of the system design and operation becomes evident. Strategies involving changes to the cooling chamber design and operational modes, data should be collected throughout the year during day and night, and proper material selection will give viable options to improve its performance. Also, the testing procedures should be considered between the load test and the no-load test; thus, the evaporative cooler should be tested without putting any food material in it and with produce in it.

These observations underline the system's potential in addressing the problem of decreasing post-harvest losses in tropical conditions and indicating possibilities for ongoing innovation and optimization.

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RESEARCH OUTPUTS

(i) Research Paper

Gunda, J. P., Pogrebnoi, A., & Kichonge, B. (2023). Design of a Cooling System Integrated with Ultraviolet Light for Preservation of Fruits and Vegetables at Variable Tropical Weather Conditions: A Case Study of Arusha. *Tanzania. Tanzania Journal of Science, 49*(3), 741-753.

(ii) Poster Presentation

Poster Presentation

DESIGN OF SOLAR-POWERED EVAPORATIVE COOLING STORAGE SYSTEM WITH UV LAMP INTEGRATED FOR PRESERVATION OF FRUITS AND VEGETABLES AT VARIABLE TROPICAL WEATHER CONDITIONS: A CASE STUDY IN ARUSHA, TANZANIA

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ABSTRACT

This study deals with design and testing of the solar powered evaporative cooling storage system for preserving perishable fruits and vegetables. The cooling chamber integrated with water and air circulation has been developed and modified with locally available materials: sisal, sponge and bricks. In addition, the ultraviolet light was used to protect the product from microbial spoilage. The performance of the designed system has been tested in terms of temperature decrease, relative humidity increases and cooling power capacity of the evaporative cooler for sunshine and cloudy tropical weather in Tanzania. The achieved maximum differences between the parameters inside and outside of the chamber were ~7 °C for temperature and 42% for humidity. The system was able to store perishable crops, banana, mango, avocado and tomato for 21 days with ultraviolet light and 9 days without it. The designed system provides effective storage of fruits and vegetables at tropical weather conditions.

2. Materials and Methods

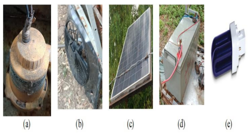

Figure 1. Components of the DESIGN: (a) DC pump; (b) DC fan; (c) solar panel; (d) battery; (e) UV bulb

2.1. Experimental setup

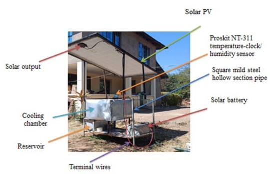

Figure 2: Experimental setup

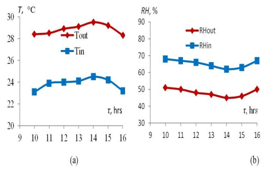

Figure 5: Cloudy day test when both pump and fan are OFF: (a) temperature variation and (b) relative humidity variation.

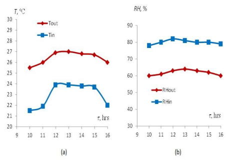

Figure 6: ICloudy day test when both pump and fan are ON: (a) temperature variation and (b) relative humidity variation.

3. Result and discussion

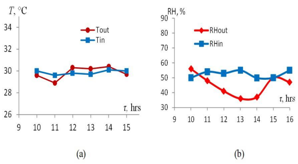

Figure 3: Sunshine day test when both pump and fan are OFF: (a) temperature variation and (b) relative humidity variation.

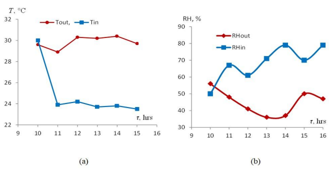

Figure 4: Sunshine day test when both pump and fan are ON: (a) temperature variation and (b) relative humidity variation..

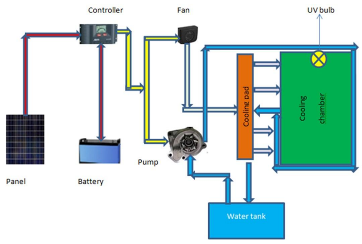

Figure 7: Schematic diagram of the DESIGN

4. Conclusion

The solar-powered evaporative cooling system comprising the cooling chamber, fan, DC water pump, and cooling pad, was designed and tested during sunshine or cloudy days. For each weather condition, temperature and relative humidity were measured outside and inside of the cooling chamber from morning to afternoon hours; two cases were considered when the pump and fan were OFF and ON. It was observed that the cooling effect depended on the weather and operation mode of the system. For sunshine day's active operation, the temperature decreased, on average, by 5.0 °C and relative humidity increased by 23%. For cloudy days, the cooling effect was less, temperature decrease 3.5 °C and relative humidity increase 18%, and steadier during the day. The ultraviolet light treatment of the product favored longer shelf life: with the ultraviolet light, it was 21, 14, 24, and 14 days for banana, mango, avocado, and tomato, respectively, against 9, 8, 7, and 5 days for storage without ultraviolet light. Based on the findings, one can recommend that design strategies should focus on modifying the cooling chamber constructional features, operational modes, and materials for further performance improvement.