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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

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Abstract

Post-harvest losses of fruits and vegetables pose significant challenges, especially in tropical climates. This study introduces the development and performance evaluation of a solar-powered evaporative cooling storage system integrated with ultraviolet light (*UV*) designed for preservation of perishable fruits and vegetables. The cooling chamber supplied with ultraviolet lamp was developed using locally available materials such as sisal, sponge, and bricks. The performance of the system was evaluated in terms of air temperature decrease, relative humidity increase, and evaporative cooling power capacity both for sunny and cloudy tropical weather conditions. The study reveals that activating the *UV* light considerably extends the shelf life of fruits and vegetables. The system was able to extend the shelf life of perishable products by up to 21 days when exposed to ultraviolet light and by 9 days when not exposed to ultraviolet light. On sunny days, active system operation leads to an average temperature reduction of 5.0 °C, along with a relative humidity increase of 23%. On the contrary, on cloudy days, the cooling impact diminishes slightly, resulting in temperature decrease of approximately 3.5 °C and relative humidity increase of 18%. These findings emphasize the potential of the solar-powered evaporative cooling system, combined with *UV* light treatment, as a viable approach to combat post-harvest losses in tropical environments.

Keywords: Evaporative cooling, cooling power capacity, post-harvest losses, ultraviolet light.

Introduction

Fruits and vegetables require immediate preservation to minimize potential post-harvest losses. The loss of fruits and vegetables during 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 bacteria, yeast, mold and attack by viruses (Gall and 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 and 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 and Kumar 2017, Lal Basediya et al. 2013, Zakari et al. 2016, Al-Zubaydi and Dartnall 2014). Chopra and Kumar proposed a semicircular shaped design using Khus in place of cooling pad materials which then resulted in efficiency improvement of up to ~20% (Chopra and Kumar 2017). A modified system named ‘two-stage evaporative cooler’ was developed to improve the efficiency and performance of evaporative cooling for high humidity and low-temperature air conditioning (Gilani and Poshtiri 2017, Sharma et al. 2016, Lal Basediya et al. 2013). Olosunde developed a solar-powered evaporative cooling storage system which able to increase the shelf life of fruits and vegetables for small-holder farmers in rural Nigeria where an electrical power distribution network was almost nonexistent (Olosunde et al. 2016). An evaporative cooler was also developed with clay and other locally available materials (Chinenye 2011). The performance of the developed cooler was evaluated in terms of temperature drop, evaporative effectiveness, and cooling capacity (Sibanda and Workneh 2020a). Using experimental data and appropriate analytical methods, the performance and energy reduction capability of the combined system was evaluated through the cooling process (Paul et al. 2021). The results indicated that the cooling load can be reduced by up to 75% during the whole process of cooling; and a 55% reduction in electrical energy consumption can be attained.

Ultraviolet (*UV*) light, which falls within the wavelength range of 100–400 nm (Sneha and Patil 2022), has several advantages, including 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). In the context of preserving perishable fruits and vegetables after harvest, the combination of ultraviolet light treatment with evaporative cooling systems presents an innovative approach. This method leverages the natural disinfection abilities of *UV* light, along with the benefits of cooling systems, to control spoilage microorganisms, enhance product quality, and reduce losses post-harvest, all while remaining cost-effective and energy-efficient (Abdipour et al. 2020, Adeniyi et al. 2023, Mansuri 2019). The simplicity and adaptability of this approach make it suitable for various types of farming, promoting sustainability and economic feasibility. This comprehensive technique has the potential to revolutionize post-harvest preservation, benefiting farmers, consumers, and the environment with its effective and forward-thinking strategy (Chopra and Kumar 2017, Sibanda and Workneh 2020b, Odeyemi et al. 2022, Adeniyi et al. 2023, Chopra et al. 2022).

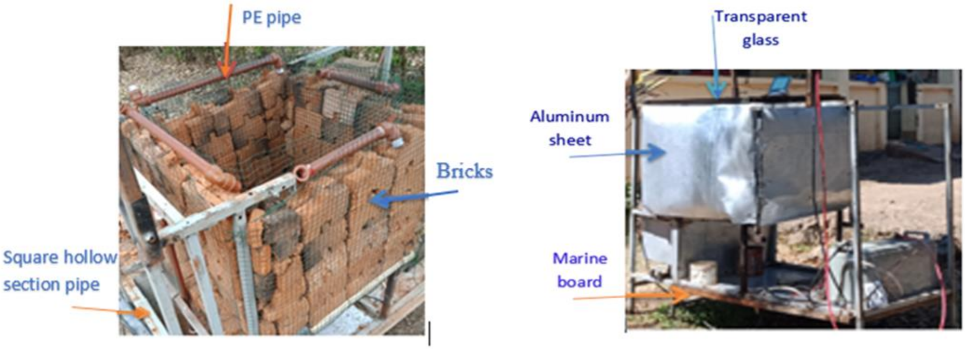
Evaporative cooling systems, as detailed earlier, have the potential to provide low-cost and high-quality perishable produce preservation. They are energy-free and have increased potential of reducing post-harvest losses in small scale farms. Most of the storage systems were not able to protect the produce from microbial spoilage well. The current study developed a solar-powered evaporative cooling storage system for perishable foodstuffs such as bananas, mangoes, avocadoes, and tomatoes. Solar energy has been suggested for use in this design since it offers excellent prospects for lowering *GHG* emissions and indoor air pollution (Andrea et al. 2019, Lingayat et al., 2020, Shahsavari et al. 2018). In order to enhance protective capability against microbial spoilage, the system is integrated with UV light**.** This study is implemented through experimental testing of the performance of the system through the air temperature decrease, relative humidity increase, the evaporative cooling power capacity and harvest shelf life under sunshine and cloudy weather in Tanzania. The findings of this study may assist users in improvement of the cooling system for storage of perishable fruits and vegetables.

Materials and Methods

Equipment and materials

The cooling chamber, cooling fan, *DC* water pump, and medium cooling pad were developed as the main components of the prototype with a total storage space of 0.19 m^3. It was composed of a square mild steel hollow section, transparent glass, aluminium sheets on the outside, and little bricks on the inside. Underneath the tank, the cooling pad was linked by a polyethylene (PE) pipe supplying water to keep the cooling pad continuously wet. The prototype was built at the Iringa *TEMESA* workshop and the *NM-AIST* campus *iTECH* workshop.

Figure 1: Cooling pad.



(a)

(b)

Figure 2: Cooling chamber materials: (a) square mild steel hollow section, PE pipes and bricks; (b) aluminium sheet, marine board, and transparent glass.

The cooling pad materials are shown in Figure 1, the cooling chamber setup and materials used are displayed in Figure 2. The cooling pad is made of a sisal rope wrapped around PE pipes and a sponge, with the function of evaporating water and retaining the medium moisture.

Experimental setup

The experimental setup was designed to lower the temperature of ambient air as it passed through the evaporative pad. The cooling effect within the setup was achieved through the circulation of water in both the cooling pad and chamber. The basic principle relies on cooling by evaporation, when the system is set in operation the dry air from the suction fan passes over the wet surfac (cooling pad) and evaporates away th soaked water from the cooling pad. When water evaporates, it absorbs energy from its surroundings, resulting in a cooling effect in the storage chamber. Temperature and relative humidity were recorded both inside and outside of the cooling chamber on both sunny and cloudy days. For each weather condition, two modes were considered when the pump and fan were “OFF” or “ON”. Figure 3 illustrates the experimental setup, and Figure 4 presents the schematic diagram adopted in this study.

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, ultraviolet bulb, fan and DC water pump, were powered through a solar panel and solar battery for maintainability of the system’s operation during night hours. A water reservoir was linked to the cooling system at the bottom through PE pipes supplying water to keep the cooling pad wet. The setup was grounded at *NM-AIST* main campus 03.40° south and 36.79° east at the altitude of 1206 meters above sea level facing north to the equator. The poles of the panel as shown in Figure 3, were fixed to keep the panel at 15° inclination adopted from (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 then to the pump and fan.

Experimental measurements and data processing

The performance of the prototype depends on several factors including designing and materials. The prototype was tested in terms of temperature decrease, relative humidity increase, and evaporative cooler cooling capacity using the procedure outlined in (Deoraj et al. 2015). Measurements were taken between 10:00 and 16:00 hours. The temperature and humidity outside and inside were recorded hourly. The cooling chamber performance was specified through air temperature decrease TD, relative humidity increase RHI and cooling power capacity of the chamber P_c:

$$TD = T_{out} - T_{in} \quad (1)$$

$$RHI = RH_{in} - RH_{out} \quad (2)$$

$$P_c = \dot{m}_{air} C_p (T_{out} - T_{in}) \quad (3)$$

where T_{out} and T_{in} is the temperature outside and inside the cooling chamber, respectively; similarly, RH_{out} and RH_{in} is 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 has been calculated by using equation

$$\dot{m}_{air} = \rho V A, \quad (4)$$

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

$$P_w = q\dot{m}_w \quad (5)$$

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

Evaluation of Spoilage in Fruits and Vegetables

In this study, the spoilage of fruits and vegetables was assessed using two techniques: 'Colour Analysis' and 'Sensory Evaluation'. Combining these methods offered a more complete understanding of spoilage. In the colour analysis part, visual examination of colour changes was conducted as indicators of spoilage, while in sensory evaluation, sensory assessments were used to detect changes in flavour, odour, and overall appearance linked to spoilage. This integrated approach enhanced the ability to make informed decisions about the shelf life and overall quality of the produce.

Results and Discussion

This section presents results and discussions from an experimental study evaluating the performance of an evaporative cooling system. It explores temperature variations, humidity increase, cooling capacity, and harvest shelf life effects. The investigation covered diverse weather conditions, including sunny and cloudy scenarios in Tanzania.

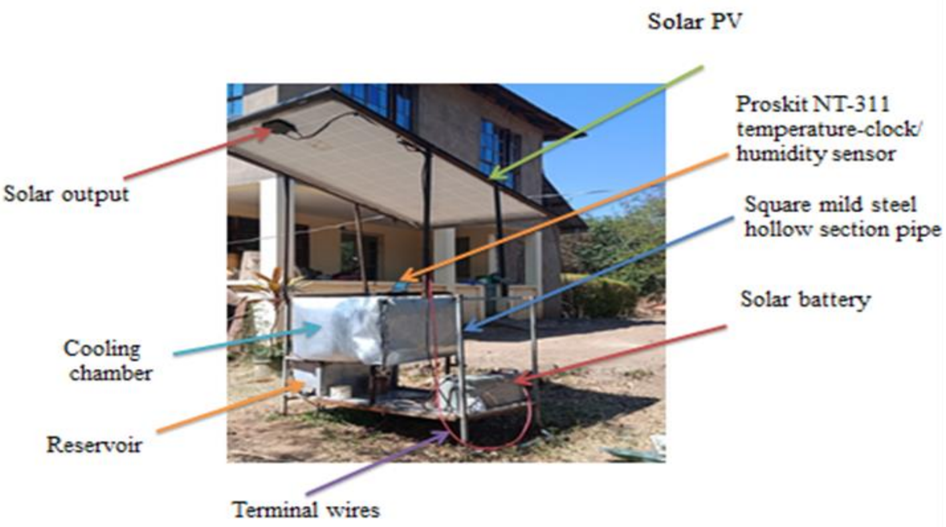


Figure 3: Experimental setup.

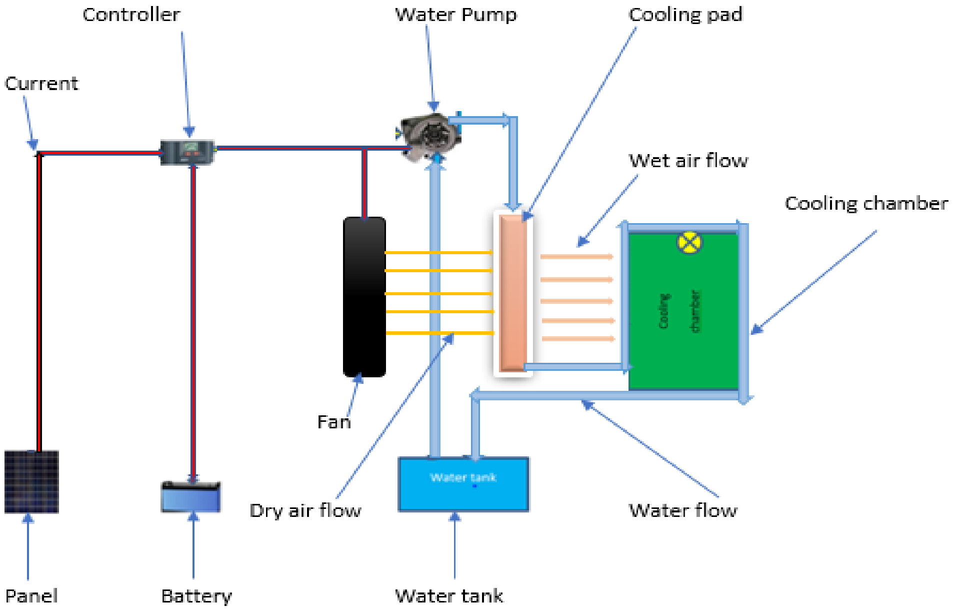
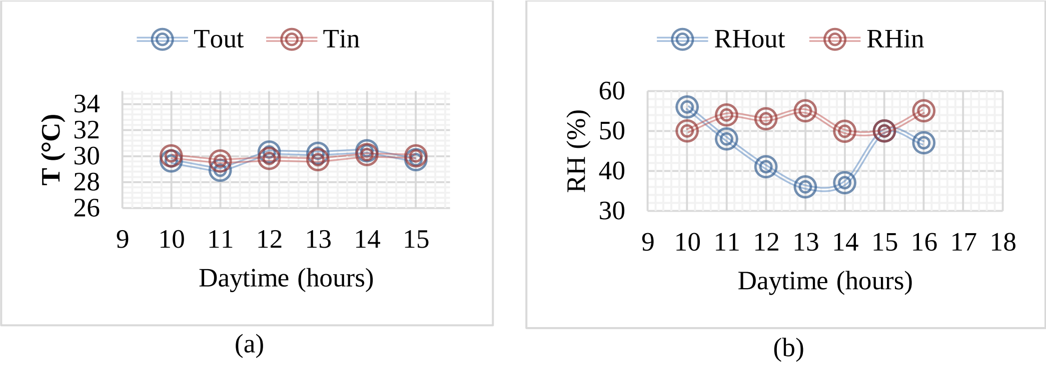


Figure 4: Schematic diagram of the prototype.

Variations 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 Figure 5. It was observed that the ambient temperature and that inside the cooling chamber were 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 was an indication that as the intensity of the sunshine grew, humidity decreased. Thus, for the sunshine day when the prototype was OFF, no cooling occurred in this case.



(a)

(b)

Figure 5: 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}

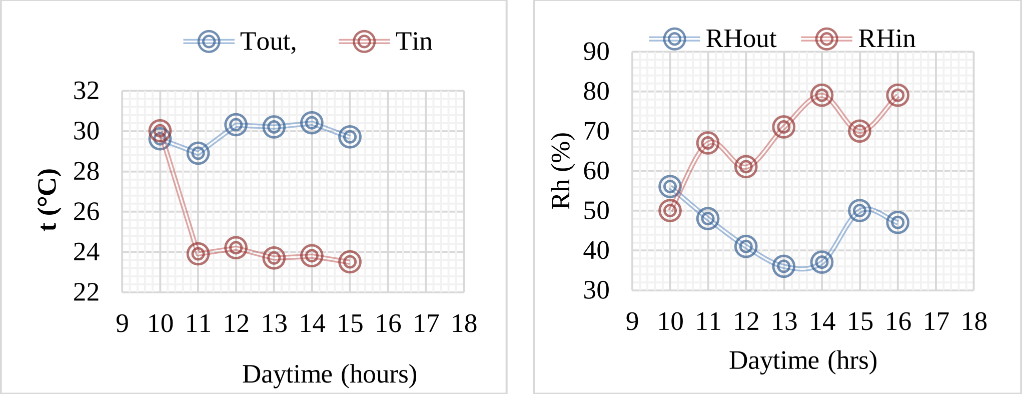
Variation in temperature and humidity during sunny days when the system was active is shown in Figure 6. According to the experimental outcomes, indoor temperature ranged from 23 to 30 °C, while humidity spanned from 50 to 79%. Within the chamber, the temperature decreased by 5–7 °C, remaining relatively consistent between 11:00 and 16:00 hours. 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 both the pump and fan. Importantly, 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 optimal evaporative cooling occurs when reasonably dry air interacts with a moist surface, intensifying the cooling effect due to accelerated evaporation rates. These findings correspond with the observations by Nkolisa et al. (2018) and Nkolisa et al. (2019b), emphasizing the effectiveness of evaporative cooling when moderately dry air interacts with a moist surface, leading to an intensified cooling effect through accelerated evaporation rates.

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 1. The calculated performance parameters presented in Table 1 were derived using Equations (1) −(3).

Throughout a sunshine day as depicted in Table 1, the prototype demonstrates varying temperature differences (*TD*) spanning from -0.4 to 6.6 °C, with the most prominent drop occurring at 14:00, 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 to 56%, and RH_{in} varying between 50 and 79%. The cooling process correlates with an elevation in relative humidity within the chamber. The decrease in relative humidity

(*RHI*) within the chamber spans from −6% to 42%, where negative values suggest a reduction in humidity due to the cooling process. Cooling power varies from −0.6 to 9.5 kW, initially being negative at 10:00 and reaching its peak at 14:00, aligning with the highest temperature decrease and relative humidity increase. This alignment underscores the effectiveness of the cooling process during that time.



(a) (b)

Figure 6: 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 results outline storage parameters ranging from 30 to 23 °C for T_{in} and 50 to 79% for RH_{in} throughout the day. A negative temperature difference *TD* at 10:00 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 compared to the air inside the cooling chamber. The maximum cooling effect is observed at 14:00, 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 encompass 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 and Layeghi 2014, Mustafa and 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.

Table 1: Prototype performance parameters on a sunshine day

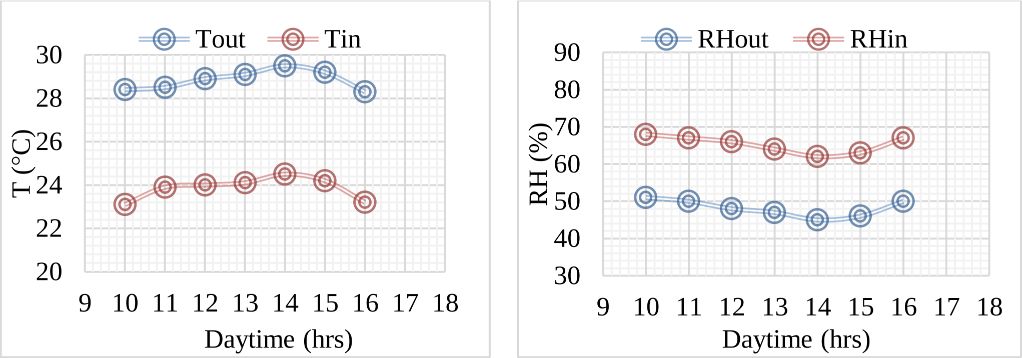
Time, hrs	T_{out}, (°C)	T_{in}, (°C)	TD, (°C)	RH_{out}, (%)	RH_{in}, (%)	RHI, (%)	P_c, (kW)
10:00	29.6	30.0	–0.4	56	50	–6	–0.6
11:00	28.9	23.9	5.0	48	67	19	7.2
12:00	30.3	24.2	6.1	41	61	20	8.8
13:00	30.2	23.7	6.5	36	71	35	9.3
14:00	30.4	23.8	6.6	37	79	42	9.5
15:00	29.7	23.5	5.2	50	70	20	7.5
16:00	28.2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

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 Figure 7. 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. Throughout the day, similar persistent discrepancies between the outside and inside parameters were maintained.

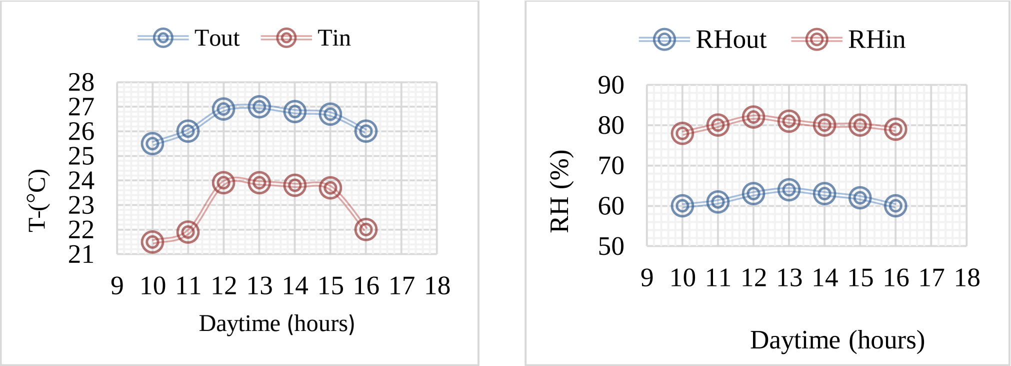
Variations of temperature and relative humidity during the cloudy day when the prototype was “ON” are shown in Figure 8, the outside and inside temperatures and relative humidity were observed to be 25.5 and 21.5 °C, 60 and 78%, respectively, at 10:00 hours. On average, the temperature decreased by 4 °C and relative humidity increased by 18%. It is worth noting parallelism between recorded outside and inside parameters during the day.

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 depicted in Figure 8. The storage parameters ranged between 21.5 and 23.9 °C for temperature, 78–82% for relative humidity inside the chamber with 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%. When the chamber performance for the two cases was compared, that is, when the pump and fan were "OFF," as shown in Figure 7, and when they were "ON," as shown in Figure 8, 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.



(a) (b)

Figure 7: 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}.



(a) (b)

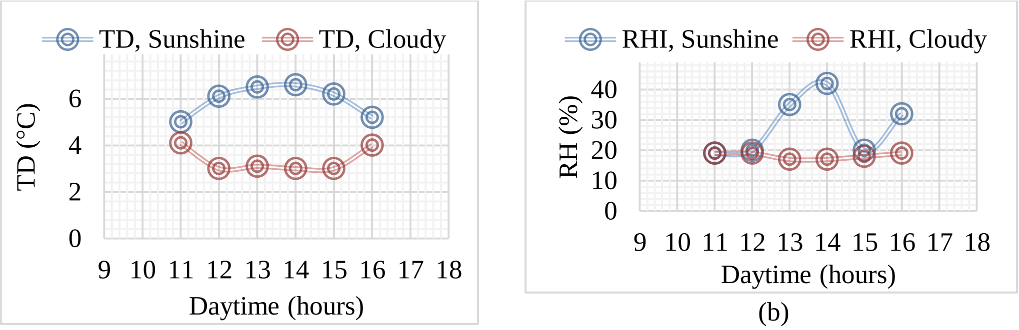
Figure 8: Cloudy day test when both the pump and the fan are ON: (a) temperature variation, T_{out} and T_{in}; (b) relative humidity variation, RH_{out} and RH_{in}.

The measurements of relative humidity increase and cooling power as depicted in Figure 8 provide valuable information about how well the cooling system in the chamber worked. Throughout the day, from 10:00 to 16:00, the RHI values ranged from 17 to 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 to 5.9 kW during the same timeframe, showing that the chamber moderately cooled the interior. Importantly, the highest cooling power was recorded at 11:00, reaching 5.9 kW. These combined findings highlight the chamber's ability to moderate reduce temperature and increase humidity levels on cloudy days, demonstrating its potential to create a comfortable indoor environment.

Prototype performance comparison

It is anticipated that weather conditions would affect the performance of the cooling setup, the increase or decrease of the parameters being dependent on the solar irradiance. The performance parameters of the prototype, temperature decrease *TD* and humidity increase *RHI*, for two cases, the sunshine and cloudy day, are displayed in Figure 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 (3), disregarding the weather conditions, the trend in the cooling power P_c should follow that one as for the *TD* in Figure 9(a). One can estimate the water evaporating rate $\dot{m}_w$ assuming a balance between the P_c and energy required for water vaporization *P*w, Eq. (5), where latent water evaporation heat is q = 2450 kJ/kg at room temperature and normal pressure then the mass rate of water evaporation is $\dot{m}_w \approx 4$ g/s (for sunshine day and *TD* = 6.6 °C) that 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).

It is worth noting 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.



(a)

(b)

Figure 9: Comparison of the prototype performance parameters between sunshine and cloudy day: (a) temperature decrease *TD*, (b) relative humidity increase *RHI*

Effect of ultraviolet light in the cooling chamber

In this study, the ultraviolet lamp was integrated inside the cooling chamber to prevent the microbial spoilage of the product. The *UV-B* (290–320 nm) conventional low-pressure (*LP*) mercury arc lamp was integrated with cooling chamber at the centre on the top of it. About 10 kg of fruits and vegetables, namely, bananas, mangoes, avocados and tomatoes, were kept for 21, 14, 24 and 14 days, respectively without getting spoiled when the lamp was “ON”. However, when the *UV* lamp was switched off, it took only 9, 8, 7 and 5 days, respectively, without showing signs of spoilage. Regarding weather conditions, during 21 days of lamp use, 8 days were cloudy and 13 days were of sunshine, while during 9 days of storage without lamp, 3 days were cloudy and 6 days were of sunshine. Therefore, the UV light treatment of the product apparently favoured a longer shelf life of the harvest. It is obvious that storing of different products in similar storage facilities might lead to product degradation. The possible harm is mostly related to temperature and humidity incompatibility, chilling and ethylene sensitivity, odour contamination, and other issues impacting shelf life and nutritional values (Zakari et al. 2016). However, the damage can be avoided or mitigated by the application of surface treatment which has to be as gentle as possible for keeping the integrity and the freshness of the product. Minimal processing techniques such as ultraviolet light treatment meet these requirements as was observed in the experiment. Previously, the use of ultraviolet light proved to be effective at reducing microbial loads of pathogens on the harvest enhancing the shelf life and quality of produce as was demonstrated in Turtoi (2013) and Yan et al. (2020).

Conclusion

The solar-powered evaporative cooling system integrated with ultraviolet light, was designed and tested in both sunshine and cloudy day’s weather conditions. Measurements of temperature and humidity were taken inside and outside the cooling chamber from morning to afternoon for each weather scenario, exploring various operational modes of the system involving the pump and fan being turned "ON" or "OFF." The results particularly highlighted the intricate relationship between weather patterns and the system's performance. During active operation on bright days, the system achieved an average temperature reduction of 5.0 °C, as well as 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 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 the growth of mould and microorganisms on damp cooler pads. Taking these findings into account, 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 to improving its performance. Ultimately, these observations underline the system's potential in addressing the problem of decreasing post-harvest losses in tropical conditions, while also indicating possibilities for ongoing innovation and optimization.

Conflict of Interest

The authors would like to declare that they have no conflicts of interest that might have predisposed the performance or presentation of the work described in this paper.

Data Availability

The data used to support the findings of this study are available from the corresponding authors upon request.

Acknowledgments

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