Evaluation of the Performance of an Evaporative Cooling Structure on the Shelf Life of Stored Tomatoes in Morogoro Region, Tanzania

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Abstract

The losses on perishables have been a challenge in most developing countries. The current status is critical and its control for small scale farmers and retailers has not been adequately addressed. The lack of simple storage facilities in the tomato supply chain contributes to high postharvest losses of tomatoes in Tanzania. The aim of this study was to design an evaporative cooling structure for the storage and shelf-life extension of tomatoes. An Improved wind operated passive evaporative cooler (IWOPEC) was developed and its performance was evaluated. The experimental design was a Randomized Complete Block Design (RCBD). The storage environment conditions considered were ambient (AT), cold room (CR), and IWOPEC structure. The results on the effects of temperature and relative humidity (RH) were significantly different (p<0.05) under the studied storage environments and time. Total soluble solids and percentage weight loss significantly increased (p<0.05) for all studied environmental conditions, whereas firmness and titratable acid significantly decreased (p<0.05) in response to storage time and studied environmental conditions. The IWOPEC structure reduced temperature, increased RH, and gave peak and daily average cooling efficiency of 84.89% and 61.67%, respectively. In areas with high PHLs under AT, using the IWOPEC structure to improve shelf life of tomatoes is economically feasible. Improvement of the IWOPEC structure by having a water boot sump and a water pump to increase the cooling efficiency of the storage atmosphere is recommended.

Keywords: Tomato, IWOPEC, Evaporative cooling structures (ECS), shelf-life extension, cooling efficiency, postharvest losses

Introduction

Tomato (*Lycopersicon esculentum* mill.) is one of the most important widely cultivated and consumed horticultural crops globally. The nutritional and economic importance of this crop has led to its extensive production (Ochida *et al.,* 2019). The World Processing Tomato Council (WPTC) reported that the world production estimate for 2020 was 39.2 million metric tonnes, with China as the largest producer, estimated to produce about 5.6 million metric tonnes which is 14.3% of global production (Incrocci *et al.,* 2020) while Africa contributes 11.8% (4.6 million metric tonnes) of total global tomato production. In Tanzania, annual total production of 129, 578 metric tonnes, represents 51% of the total vegetable production (Luzi-Kihupi *et al.,* 2015). Tomatoes are grown in many areas within Tanzania, with significant production being by smallholder farmers (Mutayoba and Nguruko, 2018; Kapeleka *et al.,* 2020).

Although tomato postharvest issues are a major problem in most developing countries Tanzania included, most of the scientific researchers have mainly focused on the production part (Sibomana *et al.,* 2016; Duarte Sierra *et al.,* 2020). This has resulted in better harvests in recent years. However, these better harvests have not translated into higher profits due to high post-harvest losses (PHLs). Tomato has a very high moisture content and therefore it is very difficult to store at ambient temperatures for a long time. Meanwhile, storage in the value chain is usually required to ensure the availability of tomatoes throughout the season

(Arah *et al.,* 2016). Tomato losses are estimated at 40 to 50% annually between harvesting and consumption stages of the distribution chain and mostly occur during storage (Moges *et al.,* 2019). In most cases the losses are caused by improper handling practices, limited knowledge on how to avoid PHLs, inadequate storage facilities, limited resources, climate change, poor road network and inability of the small scale farmers to afford cost-intensive cooling and storage systems (Mahajan *et al.,* 2017; Kasso and Bekele, 2018).

Refrigeration storage is one of the best options for tomato storage. The technique is used to achieve low storage temperatures and controlled relative humidity. However, its application and adaptability to small-scale farmers in developing countries is limited due to high initial capital, unreliable electricity supply, high running costs and lack of managerial skills (Lal Basediya *et al.,* 2013). These favourable conditions can be achieved by using less expensive methods of cooling such as evaporative cooling technology which seems to be more appropriate for small scale farmers in developing countries since it is relatively cheap, does not require high managerial skills and does not depend on electricity which is expensive and unreliable. The available evaporative cooling structures for storage of perishable crops have been observed to have low cooling efficiency due to existing harsh weather, poor structural design and operating system (Ndukwu and Manuwa, 2014; Sibanda and Workneh, 2020). In such structures, fresh tomatoes can be stored for an average of five days with minimum changes in weight, and firmness (Tasobya, 2019). This depends on the design of the evaporative cooling structure and mode of operation. Conical, Pyramidal, Cylindrical and Hexagonal evaporative cooling structures work better compared with square shaped ones for perishable crops (Mogaji and Fapetu, 2011; Manuwa and Odey, 2012; Deoraj *et al.,* 2015). Detailed research results on other designs, specific for tomatoes are missing.

Wind operated passive evaporative cooling (WOPEC) structures have shown great potential for further development, research opportunity for improved efficiency and high thermal performance. The cooling performance in cylindrical evaporative cooling structure is higher by more than 1°C compared with square one. However, the storage capacity for square structure is high compared with cylindrical (Sunmonu *et al.,* 2016). Based on the stated limitations above, there was a need to develop an improved evaporative cooling structure, which will be efficient, affordable, and user friendly by using wind as a freely available energy source to operate the structure.

This study focused on developing an improved wind operated passive evaporative cooling (IWOPEC) structure which will be capable of increasing shelf life of stored fresh tomatoes while maintaining their quality and eventually reducing PHL in stored produce. The focus was on designing a frustum shaped IWOPEC structure for storage of fresh tomatoes. Adoption of this technology will significantly minimize tomato postharvest losses, leading to the availability of more fresh tomatoes in the market. Furthermore, it will lead to enhanced quality, and increased shelf life and making the produce readily marketable.

Material and methods

Study location and climate

This study experimental and laboratory work were conducted at School of Engineering and Technology (SoET) of Sokoine University of Agriculture (SUA) in Morogoro Municipality, located (6° 49’ 15.67” South in latitude and 37° 39’40.39” East in longitude with an elevation of around 500 m above mean sea level) in the eastern part of Tanzania. The monthly weather information is presented in Figure 1.

Design of the IWOPEC structure

The design criteria for the IWOPEC structure was based on locally available materials at the level of tomato farmers and retailers in their respective areas while considering evaporative cooling design principles. The choice of the materials was based on availability and suitability under the specific working conditions, cost of the materials, water holding capacity, strength, hardness, toughness and reaction of the materials with food and water as suggested by Luhar *et al.,* 2019. As

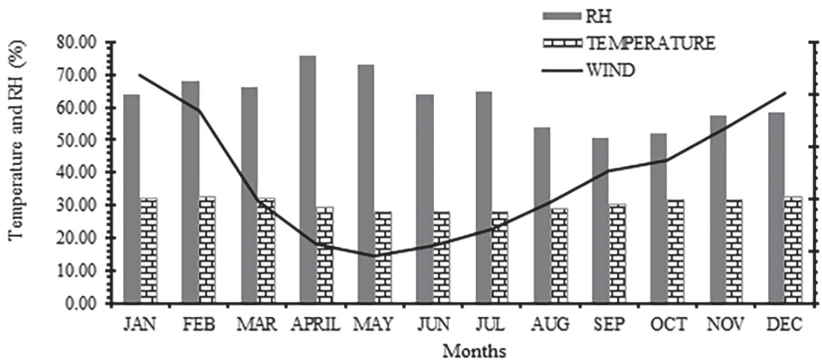

Figure 1: Monthly weather data at the study location for 5 years (TMA – SUA)
Note: RH, is the relative humidity (%); Temperature °C; and Wind, is the wind speed (m/s).

part of the general requirements, the efficiency of a passive evaporative cooler depends on the rate and amount of evaporation of water from the respective saturated material. This is dependent upon the air velocity, the filling material thickness and the degree of saturation of the filling material which is a function of the water flow rate wetting the filling materials (Tasobya, 2019). The interspace filling and covering materials used were sand and sisal bags, respectively similar to those used in the studies by Babarinsa, (2006); Sunmonu *et al.,* (2016) and; Balogun and Ariahu, (2020).

Structural Design Considerations

Design and fabrication of the IWOPEC structure considered durability, storage capacity and efficiency of the system. Other factors were surface area for air movement, light weight for easy relocation, and perforated base and vented top wood cover for easy air flow and insulation. Design of the IWOPEC structure was a stepwise investigation of the whole design process from the cooling chamber capacity to its efficiency when loaded with stacked webbed plastic crates carrying tomatoes without failure during its intended lifespan.

Structural dimensions

A frustrum shaped IWOPEC structure (Fig. 2) replicated three times was developed using an aluminium sheet 1 mm thick. The inner and outer frustrum was separated by 7 cm thick sand layer. Average volume (cm3), volume of plastic crates and samples number (or size) of tomato fruit to be stored guided the choice of structural dimensions. As shown in Figure 2, the structure has an internal radius of 20 cm (R_1) at the bottom and 10 cm (R_2) at the top, a height (H) of 50 cm, and a side length (S) of 51cm. The corresponding outside dimensions were 27 cm radius at the bottom and 17 cm radius at the top, and the same height of 50 cm. The structure was covered by sisal sack material on the outside surface which was constantly wetted with ambient temperature water. The bottom aluminium plate was perforated with 16 holes of 8 mm diameter at different locations scattered throughout the plate to allow cold wet air to enter the cooling chamber. The inner chamber of the structure is covered by a wood piece at the top with an air vent around the bearing.

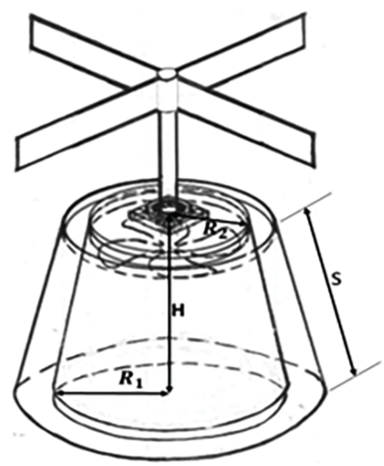

Figure 2: Shape of the designed IWOPEC structure
(***Note:*** R_1, is the bottom radius; R_2, is the top radius; S, is the side length and H, is the height).

The side length (S) was calculated by using Equation 1 described by Easa, (1991).

$$S = \sqrt{((R_1 - R_2)^2 + H^2)} \ldots\ldots(1)$$

Where: R_1 = the bottom radius, R_2 = the top radius, S = the slope, H = structure height. $(S=\sqrt{((20-10)^2+50^2)})=50.99=51$ cm (approximately)

Cooling chamber volume

To calculate the cooling chamber volume (cm3) a height of 10 cm was considered as the fan working position in the cooling chamber, meaning the two stacked plastic crates that carry samples of tomato in the chamber can reach up to this height from the bottom (Fig. 3). A height of 2.5 cm separates the chamber bottom and first plastic crate and in between the plastic crates respectively to allow airflow. The dimensions of the plastic crate were 26cm long, 15 cm high, and 18cm wide with the two crates occupying 14040 cm^3 in total of the chamber volume. Consideration was also made of the empty spaces between tomatoes, structures, and crates (Fig. 3).

The designed cooling chamber dimensions with consideration of the fan led to the calculated volume (V) of 29321.53 cm3 using the formula (Equation 2) described by Butuner, (2015).

$$\text{Volume} = \frac{1}{3} * \pi * H * (R_1^2 + R_1 * R_2 + R_2^2) \ldots\ldots(2)$$

Where: R_1, is the bottom radius; R_2, is the top radius; S, is the slope and H, is the height of stored materials in a cooler chamber

$$Volume = \frac{1}{3} * 3.14 * 40 * (20^2 + 20 * 10 + 10^2) = 29321.53\text{cm}^3$$

The volume of individual tomato fruit was calculated by using Equation 3 described by Bütüner, (2018).

$$\text{Volume} = \frac{4\pi r^3}{3} \ldots\ldots(3)$$

Where: r, is the average radius value of selected

$$Volume = \frac{4 * 3.14 * (2.8)^3}{3} = 91.91 = 92cm^3\ approximately$$

tomato fruits (which was 2.8cm as measured using Vernier calliper)

Design of fan blades

To capture enough wind and for the IWOPEC system to work properly a four blades vane system was designed and located at the top of the structure with a 1.2 m rotor radius of the blade vane and at 2.2 m above the ground level since wind speed increases with elevation. Inside the cooling chamber, a five blades fan constructed from a 1 mm thick aluminium sheet was fixed to the shaft linked to the vane made to rotate with the speed of the vane. Although wind is intermittent, the fan blades were tilted at 15 degrees to enhance air radially sucking from the cooling chamber to achieve better efficiency. According to Kimambo *et al.,* (2019) reported wind speed in Morogoro is estimated to range between 2.24m/s and 3.8 m/s which gives us confidence to meet enough power for an IWOPEC system. Data collected for 5 years (SUA Meteorological station data, 2015 to 2020) near the experimental area depicted maximum wind speeds ranging from 1.27 to 2.18 m/s from September to January. The average wind speed for 5 years in the month of June averaged 0.56m/s. In one complete vane revolution, the length L advanced was calculated using Equation 4 by Etzkowitz and Leydesdorff, (2000), as:-

$$L = 2\pi r\theta \ldots\ldots(4)$$

Where: r is the rotor radius of the blade vane (1.2 m) see Figure 4

$$L = 3.14 * 2.4 \times \frac{3.14}{2} = 11.83 \text{ m}$$

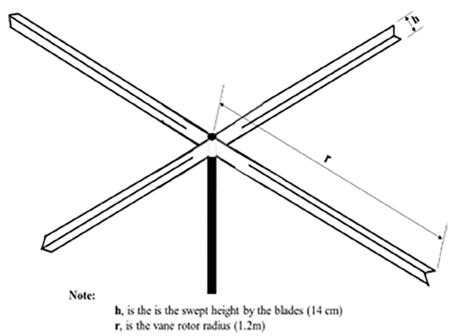

Figure 4: Details parameters on vanes of IWOPEC structures

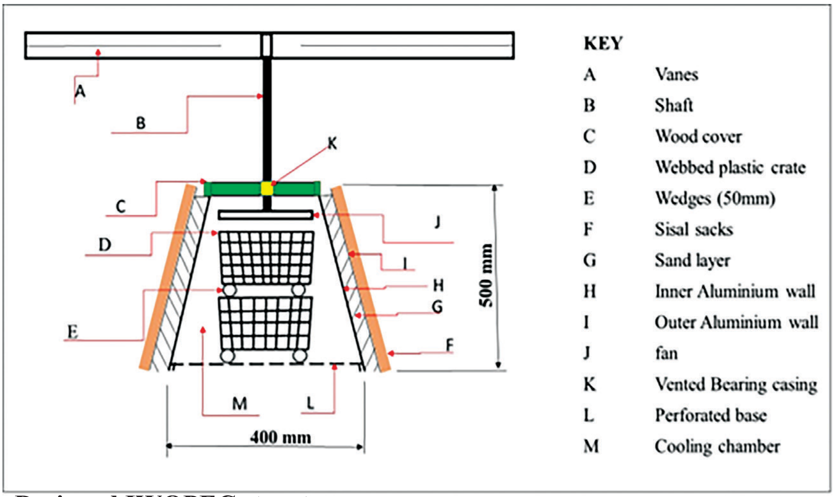

Figure 3: Designed IWOPEC structure

θ is the angle of inclination of the fan blade = 90° = π/2 , Since it uses the principle of the centrifugal fan to move the air radially

The amount of air moved in one revolution, Q

The amount of air moved by the vane in one revolution was estimated using the relationship by Sunmonu *et al.,* 2016 (Equation 5).

$$Q = (\frac{\pi D^2}{4})L \quad \text{........(5)}$$

Where: D is the diameter of the vane rotor blade and L is the length (m)

Then, $Q = \left(\frac{\pi * 2.4^2}{4}\right) * 11.83\frac{m^3}{s} = 53.52cm^3/s$

The number of vanes revolutions per minute (rpm), n

The number of vanes revolutions per minute was calculated using (Equation 6) as described by Valenti *et al.,* (2013).

$$n = \frac{v * 30}{\pi * r} \quad \text{..........(6)}$$

Where: v, is the assumed mean wind velocity = 2.18 m/s (The maximum wind speed from 5 years of TMA weather data)

r, is the vane radius; n is the number of vanes revolution per minute

$$n = \frac{2.18 * 30}{3.14 * 1.2} = 17.3567 = 17\ rpm$$

However, using the same Equation 6 (in reference to 5 years of SUA meteorological minimum wind data of 0.46 m/s) gives approximately 4 rpm.

The tip velocity of the fan blade

The tip velocity of a fan blade is a good reference in calculating the angular velocity of the fan blade using the relationship by Seo et al., (2008), as:-

$$v = \frac{w * D}{2} \quad \text{..........(7)}$$

Where: v = is the tip velocity of the fan blade

w = is the angular velocity which is the ratio of the total angular measurement through which the blade rotates in a given unit of time and this was calculated from the relationship (Equation 8)

$$v = \frac{w * D}{2} = \frac{6408.85 * 2.4}{2 * 3600} = 2.14\ m/s \quad \text{........(8)}$$

The wind power

The theoretical power available in the wind was calculated using Equation 9, if the swept area of the blades and the wind speed are known as described by Sarkar and Behera, (2012)

$$pw = \frac{1}{2}\rho A v^3 \quad \text{..........(9)}$$

Where; pw, is the wind power

ρ , is the air density= 1.293kg/m3

v, is the tip velocity of the blade fan =

2.14 m/s

A, is the vertical swept area of the fan impeller calculated from the relation below by Cevik, (2010).

$$pw = \frac{1}{2} * 1.293 * 0.336 * 2.14^3 = 2.13\ Watts$$

$A = D*h = 2.4*0.14 = 0.336\ m^2$

Where:

D, is the vane rotor diameter (see Figure 4); and

h, is the swept height by the blades (14 cm)

Therefore,

However, using the same Equation 9 (in reference to 5 years of SUA meteorological minimum average wind speed data of 0.46 m/s) gives the available wind power of 0.021 Watts.

The fan pressure

The fan is designed to produce a pressure difference, and hence force, to cause a flow through the fan. Factors that determine the performance of the fan include the number and shape of the blades (Panigrahi, 2014). As the number of blades goes up, the fan tends to be quieter and increase the proportionality distribution of dragged air, the standard design is four or five blades. Fan pressure was calculated from the formula Equation (10) by Shim *et al.,* (2014).

$$pw = PQ * number\ of\ blades \qquad \ldots\ldots\ldots(10)$$

Where: Q, is the discharge (m^3/s)

pw, is the wind power (Watts)

P, is the fan pressure (N/m^2)

Then,

$$P = \frac{pw}{\text{number of blades} * \text{Q}} = \frac{2.13}{5 \times 53.52} = 0.008 N/m^2$$

Using the same Equation (10) in reference to the fan power of 0.021 Watts in the wind yields a minimum fan pressure of 7.85 x 10^(-5) N/m2. This minimum fan pressure shows despite intermittent wind, there is availability of free energy most of the time to power the IWOPEC structure.

Experimental Materials and setup

The experiment was carried out in June 2021 at the School of Engineering and Technology, Sokoine University of Agriculture, Morogoro, Tanzania. Eight hundred unblemished mature green tomato fruits of fairly uniform size of Asila F1 and Imara F1 varieties were harvested in Mlali village. Harvesting was done during evening hours, packed in wooden crates and immediately transported to the experimental site at SUA. A total of 450 fruits were manually sorted and graded. Then tomatoes were divided into three lots of 75 fruits from each variety, labeled, weighed, and packed in 18 small plastic crates, each with 25 tomato fruits, and stored in different conditioned environments.

The experiment was laid out in a completely randomized block design in three replicates. The treatments consider a 2×3 factorial combination of variety and storage environment. Three storage environments in three replicates were used in this study i.e. IWOPEC, cold room (CR), and ambient temperature (AT). According to Godana *et al.,* (2020), temperature and relative humidity in the cold room was controlled at 12°C and 94% respectively with dark light intensity at the laboratory in the Food Quality and Technology department at Sokoine University of Agriculture, SUA. The variation in temperature and relative humidity for the IWOPEC and AT storage environments were measured using Arduino sensors (Model: UNO R3, Italy) at 20 minutes' intervals.

Data Collection

Tomato storage performance of the IWOPEC structure were evaluated through analysis of stored tomato. A sample of five (5) tomatoes of each variety was randomly selected from each storage unit to assess the deterioration rate as it defines the storage performance of the storage environment (IWOPEC structure, CR, and AT). The performance was evaluated at the interval of five days for 20 days storage period (Zakari *et al.,* 2016; Nkolisa *et al.,* 2018). The following parameters were collected to assess the performance of IWOPEC: Temperature, Relative humidity, Wind speed, percentage weight loss, Firmness, Total soluble solids, and Total Titratable acids.

Temperature and relative humidity

In IWOPEC and ambient storage

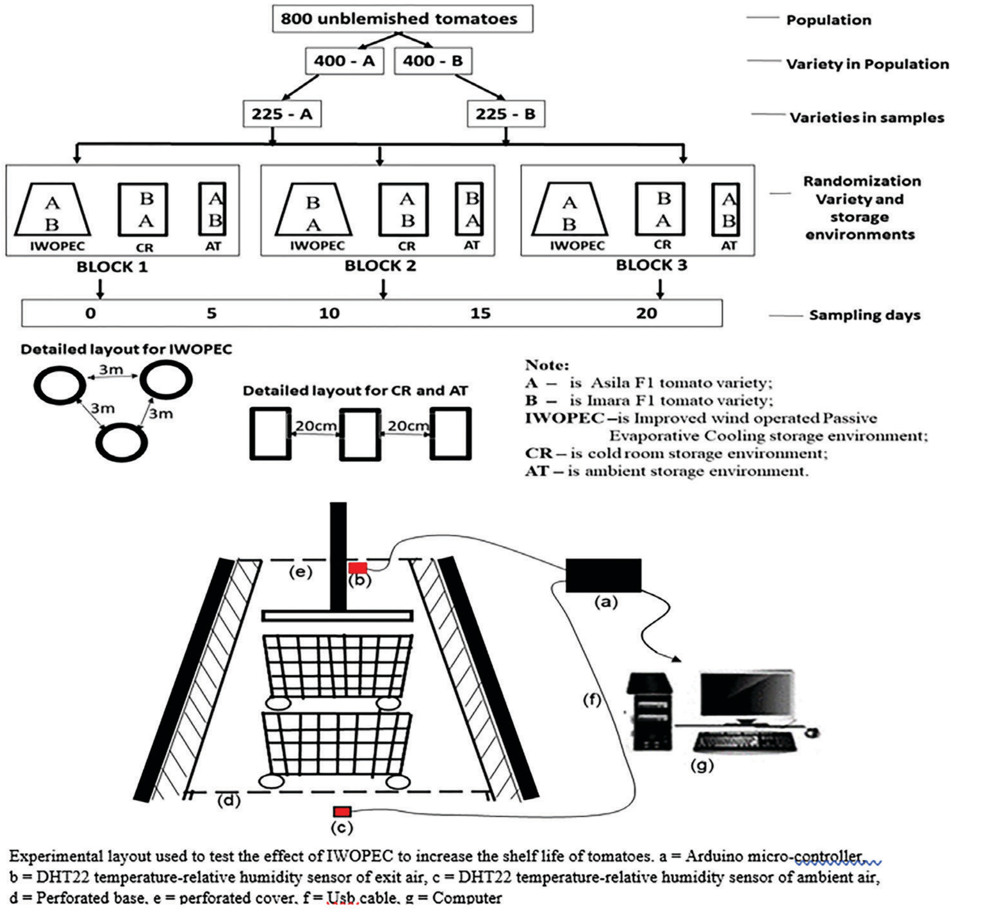

Figure 5: Experimental layout of the study

environment data for temperature and relative humidity were collected using an Arduino sensors data logger (Model: UNO R3, Italy) accuracy of ± 0.0 after every 20 minutes during the 20 days study period. Also wind speed data was collected using a calibrated Testo 416 vane thermometer (Model: Best ell-Nr., Germany) with accuracy of ± (0.2 m/s + 1.0 % of mv). The readings were taken at 8.00am, 11.00, 14.00 and 17.00 pm daily.

Cooling efficiency

Cooling efficiency was determined by using the relationship described by Lotfizadeh and Layeghi (2014) (Equation 11).

$$\text{Cooling Efficiency} = \frac{\text{Tdb} - \text{Tc}}{\text{Tdb} - \text{Twb}} x\ 100 \ldots\ldots(11)$$

Where:

Tdb is the ambient dry bulb temperature °C,

Tc is the dry bulb temperature in the cooling structure in °C,

Twb is the wet bulb temperature (from psychrometric chart) in °C.

Percentage weight loss

The percentage weight loss of the stored tomato fruits was determined using (Equation 12) as described by Nkolisa, (2017). The evaluation was done every five days for the period of storage of the tomato fruits. Weight of tomato samples from the different storage environments were weighed using an electronic balance with an accuracy of ± 0.0001 gram.

% Weight loss in Tomato = (Total weight stored

$$\%\ \text{Weight loss in Tomato} = \frac{\text{Total weight stored }(M1) - \text{ Final weight }(M2)}{\text{Total weight stored }(M1)} * 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(12)$$

Firmness changes after storage

The firmness (N/mm) of tomato fruits was measured using an Instron universal testing machine (M10-16280-EN, United States of America) with load accuracy: ± 0.5% of the reading, using T372 – 34 punching probe test anvil which is specifically for soft fruits. The probe was placed on two different points of each fruit (opposite each other and free of blemishes) with a constant pressure to test the firmness as described by Nicolaï *et al.,* (2008).

Total soluble solids (TSS)

Total soluble solids of each sample fruit were determined using a digital refractometer CNT95 with a Brix scale between 0 to 35%, division of 0.1% and accuracy of ± 0.2. The samples were prepared using the method explained by (Taha and Mustafa, 2018) where a tomato sample was macerated and filtered with a cloth to get clear juice, then using 2 to 3 clear juice drops to measure TSS. The measurements obtained were recorded in % Brix. One degree Brix is equal to 1 gram of sucrose in 100 grams of solution, which is equal to 1% Brix.

Total Titratable acids (TTA)

Total titratable acids were obtained by mixing 6 g of tomato juice with 50 ml of distilled water then adding 3 drops of phenolphthalein indicator and titrating the mixture with 0.1N NaOH up to a point where the sample changed from a clear colorless to pink colour. Percentage of acid was then calculated using Equation 13 (Sadler and Murphy, 2010).

$$\%\ \text{TTA} = \frac{\{\text{mls NaOH}\}\ \text{x}\ \{\text{Milliequivalent acid factor})}{grams\ or\ ml\ of\ sample} x100 \qquad \text{...........(13)}$$

Data Analysis

Collected data were subjected to two-way Analysis of Variance (ANOVA) using Genstat® 15th Edition statistical software. Duncan's multiple range tests (DMRT) were used to establish the multiple comparisons of mean values at 5% significant level.

Results

Temperature and relative humidity variation

The effect of different storage environments on temperature and relative humidity variation for daytime hours over the storage period was studied and the results are presented in Figures 4 and 5. Results from the study indicated that storage temperature and relative humidity had a significant effect ($p<0.05$) among different storage environments over the entire storage period (Fig. 4 and 5). Temperature differences amongst the three storage environments (AT, IWOPEC, and CR) were highly significant ($p=0.009$) during day hours throughout the study period. However, ambient environment data had higher variation and recorded higher temperatures and lower RH compared to CR and IWOPEC storage environments. Temperature and RH under ambient ranged between 22.9 °C to 30.7 °C and 55.38% to 71.44% respectively. For the IWOPEC structures, temperature and relative humidity ranged between 21.7°C to 25.1°C and 78.34% to 90.85 % respectively (Figure 6 and 7). Cold room, temperature and relative humidity ranged between 11.7°C to 12.3°C and 91.69% to 95.31% respectively.

Cooling Efficiency of the IWOPEC structure

The cooling efficiency of IWOPEC structure loaded with tomato fruits was investigated based on daytime hours over the entire storage period presented in Figure 8. The cooling efficiency of the IWOPEC system increased with time and varied from 32.48% at 6:00 am to 65.50% at 12.00 pm. At 13:00 pm cooling efficiency increased sharply to 84.89% with the recorded ambient temperatures of 30.76°C. Results showed that there was a decreasing trend in cooling efficiency from 82.27% at 14.00 pm to 40.67% at 18:00 pm (see Figure 8 below).

Weight loss during storage period

The observed weight loss in all the two tomato varieties was due to the storage environments and time. It was found that the rate of weight loss was significant ($p<0.05$) affected by storage time in all conditioned storage environments for both tomato varieties (Fig. 7 and 8). The mean rate of weight loss for Imara F1 variety was significant ($p=0.008$) in the conditioned storage environment during storage time. The rate of weight loss in the

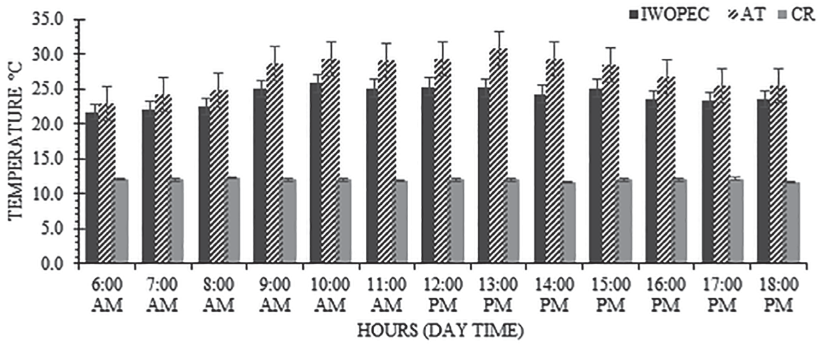

Figure 6: Temperature variation for IWOPEC, AT and CR

Key: IWOPEC, Improved wind operated passive evaporative cooler
AT, ambient storage condition; CR, Cold room storage condition.

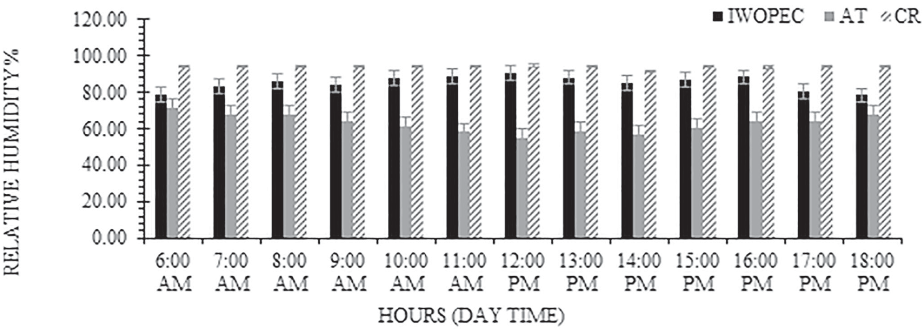

Figure 7: Relative humidity variation for IWOPEC, AT and CR

Key: IWOPEC, Improved wind operated passive evaporative cooler
AT, ambient storage condition; CR, Cold room storage condition

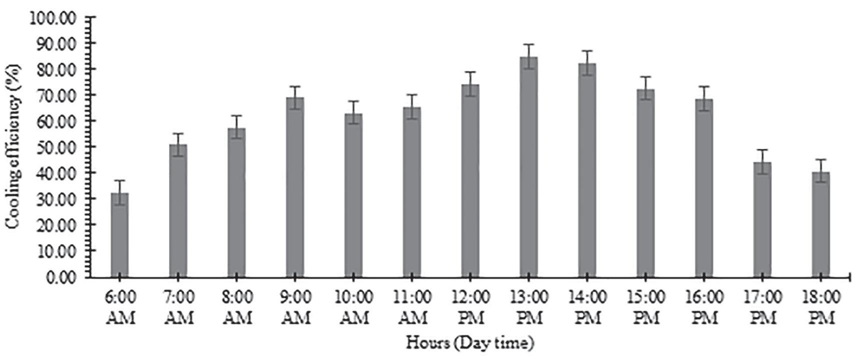

Figure 8: Average daily percentage cooling efficiency of the IWOPEC structure for daytime hours

two tomato varieties was higher in tomatoes stored under AT compared to tomatoes stored in IWOPEC and CR.

Results show that at day 20, ambient environment weight losses were 7.35% and 8.62% for Asila F1 and Imara F1 varieties, respectively. The percentage weight loss in the IWOPEC environment was observed to be 3.16% and 3.47% for Asila F1 and Imara F1, respectively, CR recorded the lowest percentage weight losses compared to the other storage environments which was 2.26% and 1.98% for Asila F1 and Imara F1 varieties, respectively.

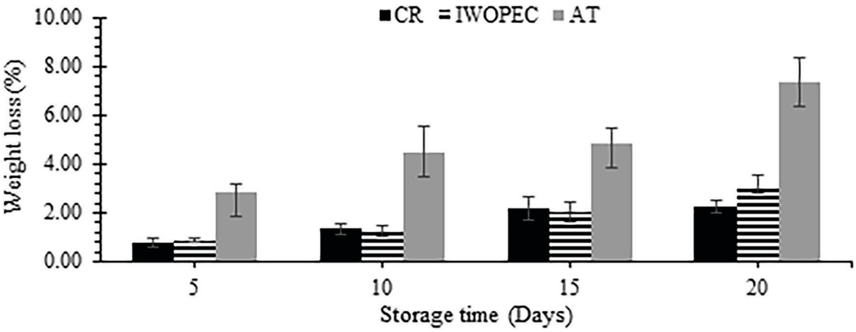

Figure 9: Average percentage weight loss for Asila F1 tomato variety during storage

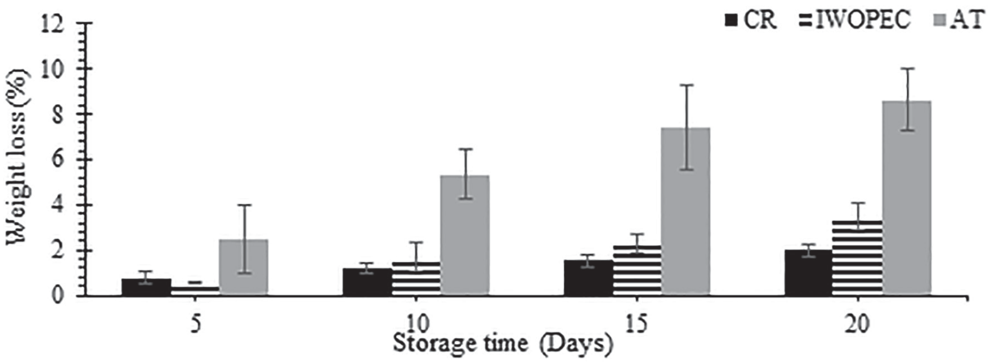

Figure 10: Average percentage weight loss for Imara F1 tomato variety during storage

Firmness during storage period

The results on firmness of stored tomatoes are presented in table 1. It was found that all the storage environments had effect on tomato firmness. The results indicated that there was decrease in firmness of stored tomatoes with storage time and storage environments for both varieties. At the end of storage, tomato (Imara F1 and Asila F1) stored in CR had larger firmness value 34.15N and 24.59N respectively, followed by those stored at IWOPEC 24.41N and 19.39 N respectively, and for ambient condition was 22.27N and 16.92N respectively (table 3).

At the beginning of storage (day 0), firmness data show no significant difference ($p<0.001$) within tomatoes varieties. However, there was significant difference ($p<0.001$) between the two varieties (Table 1). The average firmness values for Asila F1 and Imara F1 varieties were 31.24 and 54.34 Newton (N), respectively. After 5 storage days, there was no significant difference ($p<0.001$) on the firmness of tomatoes stored under CR and IWOPEC for Asila F1 variety. Results for firmness in Asila F1 variety stored in AT, CR and IWOPEC were 25.45, 29.37and 28.62 N, respectively. In case of Imara F1 variety, firmness were 37.68, 46.06 and 39.89 N for AT, CR and IWOPEC, respectively (Table 1). For storage day 10 and 15, there was significant ($p<0.001$) variation on firmness in different storage environment. At day 15, results for firmness in Asila F1 variety stored in AT, CR and IWOPEC were 19.83N, 26.78N and 22.45 N, respectively. In case of Imara F1 variety, firmness were 24.33N, 38.00N and 26.61N for AT, CR and IWOPEC, respectively (Table 1). Lastly, after 20 days, a highly significant difference ($p<0.001$) was seen only on tomato varieties stored in AT against CR and IWOPEC. Results for firmness in Asila F1 variety stored in AT, CR and IWOPEC were 16.92N, 24.59N and 19.39N, respectively. In case of Imara F1 variety, firmness was 22.27N, 34.15N and 24.41N for AT, CR and IWOPEC, respectively (Table 1).

Total soluble solids (TSS) during storage period

Results on total soluble solids for tomato samples stored at different storage environments

Table 1: Average changes in firmness, total soluble solids (TSS) and total titratable acids (TTA) of two varieties stored under the three different storage environments

Variety	Storage Environment	Days	Firmness	TSS	TTA
Asila F1	AT	0	31.24 h	2.66 a	9.835 h
		5	25.45 de	3.087 bc	7.662 f
		10	21.88 c	3.477 de	7.098 f
		15	19.83 b	3.725 fg	5.253 cd
		20	16.92 a	4.056 h	2.678 a
	CR	0	31.24 h	2.66 a	9.835 h
		5	29.37 g	2.682 a	9.082 g
		10	28.79 g	3.160 bc	7.640 f
		15	26.78 ef	3.567 efg	5.896 de
		20	24.59 d	3.655 efg	4.339 b
	IWOPEC	0	31.24 h	2.66 a	9.857 h
		5	28.62 g	2.983 b	8.762 g
		10	27.92 fg	3.283 cd	6.322 e
		15	22.45 c	3.525 ef	4.689 bc
		20	19.39 b	3.800 g	3.040 a
Imara F1	AT	0	54.34 h	3.020 a	10.376 h
		5	37.68 e	3.396 cd	7.151 efg
		10	30.63 c	3.717 ef	6.720 cdef
		15	24.33 ab	3.950 gh	5.698 bc
		20	22.27 a	4.202 i	4.222 a
	CR	0	54.34 h	3.020 a	10.376 h
		5	46.06 g	3.267 bc	9.371 h
		10	41.59 f	3.518 de	7.618 fg
		15	38.00 e	3.758 fg	6.076 bcde
		20	34.15 d	3.925 gh	5.043 ab
	IWOPEC	0	54.34 h	3.020 a	10.376 h
		5	39.89 ef	3.125 ab	8.213 g
		10	31.66 cd	3.617 ef	6.929 def
		15	26.61 b	3.720 ef	5.809 bcd
		20	24.41 ab	3.982 h	4.606 a
	P-value for Asila F1 variety	$p < 0.001$	$p< 0.05$	$p< 0.05$	
	P-value for Imara F1 variety	$p < 0.001$	$p< 0.05$	$p< 0.05$	

Note: Means with similar letters within the same column are not significantly different
Key: AT, CR and IWOPEC are ambient condition temperature, cold room and improved wind operated passive evaporative cooling system; TSS is the total soluble solids and TTA is the total titratable acids.

are presented in Table 1. The results showed that there was increase in TSS for both varieties under all storage environments until the end of storage period. Both Asila F1 and Imara F1 varieties indicated there was significant difference ($p<0.05$) on TSS as affected by different storage environments and storage time during the experiment. The results at the beginning of storage, TSS average values in Asila F1 and Imara F1 varieties were 2.66 and 3.02% Brix respectively. After 5 days for Asila F1 variety indicated the change of TSS was not significant ($p<0.05$) in CR environment. Also, at day 10 Imara F1 variety indicated the change of TSS was not significant ($p<0.05$) in AT and IWOPEC environment. Also, at day 15 still there were no significant difference ($p<0.05$) in IWOPEC environment (Table 1). From day 5 to day 20 of the experiment, total soluble solids ranged between 3.087 to 4.056 in Asila F1 variety tomato stored in AT. Under the CR and the IWOPEC total soluble solids ranged between 2.682 to 3.655 and 2.983 to 3.655, respectively. Imara F1 variety, total soluble solids ranged between 3.396 to 4.202 for tomato stored under AT, 3.267 to 3.925 for those stored under CR and between 3.125 to 3.982 for those stored in the IWOPEC.

Total titratable acids (TTA) during storage period

Total titratable acids values measured from tomato juice samples for both varieties indicated that they were affected significantly ($p<0.05$) due to the storage environments and storage time. Before storage (at 0 day), results showed there was no significant difference ($p<0.05$) in titratable acids for both varieties (Table 1). The average TTA values in Asila F1 and Imara F1 varieties were 9.835 and 10.376, respectively. At day 5, there was no significant difference ($p<0.05$) existed between tomatoes stored in CR and in IWOPEC for Asila F1 variety. Total titratable acid values in Asila F1 variety samples from AT, CR and IWOPEC were 7.662, 9.835, and 8.762, respectively (Table 3). For Imara F1 variety TTA values were 7.151, 9.371 and 8.213 for tomatoes stored in AT, CR and IWOPEC, respectively. After 10 storage days, results show there was a significant difference ($p<0.05$) in TTA for both varieties under all storage environments. However, at day 20 there were no significant difference ($p<0.05$) on total titratable acids for tomatoes stored in AT and IWOPEC environments for both varieties (Table 1).

Discussion

Temperature and Relative humidity

Temperature and relative humidity are among the major environmental factors affecting the postharvest quality of most fruits and vegetables (Arah *et al.,* 2015). The current study results demonstrated the efficiency of the IWOPEC structure against the ambient environment on the shelf life of stored tomatoes. The IWOPEC structure achieved an average temperature reduction of 5.54oC and an increase in relative humidity of 29.5 % against the ambient condition for the three replications of the IWOPEC structures loaded with tomatoes. The average relative humidity of CR was 94% while 89.04% was achieved in the IWOPEC cooling chamber compared to 58.79% under AT as measured in this study (Fig. 13 and 14).

This may be attributed to the cooling effect of the IWOPEC design structure including the fan effect, wetting the sisal sacks and sands, the structure shade, evaporation of water from sand around the cooling chamber, vents on the base and on wooden cover to allow for air circulation. Additionally, higher saturation efficiency of sisal bags might also have contributed to higher values of relative humidity in evaporative cooling structures (Sunmonu *et al.,* 2016). The observed higher relative humidity in the IWOPEC is in line with relative humidity of 82% to 100% reported in the studies by Babarinsa, (2006); Mogaji and Fapetu, (2011); and Jahun *et al.,* (2013).

Similar results are due to Lal Basediya *et al.,* (2013); Ndukwu and Manuwa, (2014); Sunmonu *et al.,* (2016); and Verploegen *et al.,* (2019), reported temperature reduction of up to 10 °C and increase in relative humidity of the air from 40% under ambient condition to 92% of the ECSs storage chamber which is favorable for most fruit and vegetables. Also the current study findings are similar to the findings from the studies by Mogaju and Fapetu, (2011); and Nkolisa *et al.,* (2017) who reported that an evaporative cooling structure can maintain temperature between 16 and 26 °C and relative humidity between 43 and 98% during the hottest time of the day.

Cooling Efficiency of the IWOPEC structure

The results from the current study have shown that the IWOPEC structure performed efficiently, with significant effect on cooling of stored tomatoes in daytime hours (Fig. 6). The findings indicate that the average peak cooling efficiency of 84.89% was achieved around 13:00 hrs when dry bulb temperature recorded higher value of 30.7°C (Fig. 6). The peak efficiency was attained around 13:00 hrs, probably as a sign of hours with high solar radiation intensity with low variation. This could also be contributed by the working fan speed because noon hours were observed to have high wind speed compared to the morning and evening hours. Average wind speed ranged between 1.57 and 2.03 m/s across daytime hours. These results are supported by the findings from the study conducted by Bell *et al.,* (2000); and Hussin *et al.,* (2010) who stated that the pattern of temperature distribution slightly rise with increasing solar irradiance from 7:00 am to the peak value at 13:00 hrs after which it falls smoothly until midnight around equatorial climate. The average cooling efficiency of IWOPEC was 62.01%. This result is supported by the results from the study conducted by Nkolisa, (2017), who reported the average cooling efficiency of evaporative cooling structures of 67.6% and 67.17%, respectively. Others include the findings of Zakari *et al.,* (2006) who reported an average cooling efficiency of 83%, and Chinenye *et al.,* (2013) who reported an average cooling efficiency of 77 to 98%.

The current study findings on cooling efficiency are nevertheless slightly lower than some of the reported findings above, this could be attributed to the dependence on wind which is intermittent and the fact that the IWOPEC structure differs from other evaporative coolers developed and used by the different researchers. Some of the structural differences as sourced from the literature with regard to the developed ECSs by other researchers include provision of solar panels, water pumps and suction fans. Also, the other researchers mentioned did not indicate the time of the year their studies were done as it is known in a year there are different seasons with different weather conditions. Though it can be admitted that the cooling efficiency of the IWOPEC was relatively lower than the values reported by other researchers on ECSs, the IWOPEC can still be considered to be good for the storage of tomatoes at small scale farmers' and retailers' levels, pending some design improvements.

Percentage weight loss during the storage period

There was a significant difference ($p<0.05$) in tomato weight loss due to the effects of the storage environments and storage time (Fig. 7 and 8). It was observed in this study that within the period of evaluation the IWOPEC system registered lower temperatures and higher relative humidity compared to the AT storage environment at all times. The tomato stored in the IWOPEC structure registered a lower average percentage of weight loss compared to those stored at ambient temperature. Temperature and relative humidity inside the different storage environments are the major driving forces to the stored produce weight loss (Jalali *et al.,* 2020). The average percentage weight loss for Asila F1 tomato variety within 10 storage days kept in the IWOPEC structure and AT was 1.25% and 4.46% respectively. For Imara F1 variety kept in the IWOPEC structure and AT, the observed percentage weight loss was 1.69% and 5.34%, respectively (Fig. 9 & 10).

This study findings correlate to the findings of Mogaji and Fapetu, (2011); Abiso *et al.,* (2015); and Nkolisa *et al.,* (2018) who kept tomato fruits in the evaporative cooling system and reported percentage weight loss to be around 2.58% to 11.45% within 10 days of storage. The study by Liberty *et al.,* (2014); and Arah *et al.,* 2015 reported that higher temperatures and lower RH caused moisture losses consequently resulting in the decrease of the produce weight by 5% to 10% of its fresh. Furthermore, the percentage weight loss observed in this study progressively increased with the increase in storage time irrespective of the type of the storage environment and variety. However, at the end of the experiment, tomatoes stored inside the IWOPEC structure were still usable but tomatoes stored under ambient conditions were not at all usable. Differences in weight loss between the investigated Asila F1 and Imara F1 varieties in this study could have been attributed to differences in their material properties and genetic composition.

Firmness changes during storage period

Under normal circumstances firmness can be tested by personal feelings by using finger or thumb pressure but the more precise objective measurement is the one that gives a numerical expression of firmness done with a fruit firmness tester (Askar and Treptow, 2013). The findings of this study have shown that there was a decreasing trend in firmness with storage days for both tomato varieties (Table 1). It was also observed that firmness decreased more for tomatoes kept at AT, with the decrease hypothesized to occur due to high temperatures and lower relative humidity. These findings are in line with those of Habib *et al.,* (2017) who reported that firmness is related to storage temperatures. Also in support of this study are the findings by Al-Dairi *et al.,* (2021), where it was stated that temperature affected firmness in stored grape tomatoes. The findings in support of firmness as reported by the different researchers reveal that temperature affects the ripening rate of any stored produce and in turn it affects the firmness. The IWOPEC structure was able to maintain the firmness of tomatoes for a longer period of time compared to ambient condition due to its atmospheric condition having lower temperatures and higher relative humidity.

Total soluble solids (TSS) changes during storage period

There was a significant difference ($p<0.05$) on TSS due to the effects of storage environment and time for all tomato varieties (Table 1). TSS was observed to be higher on tomato samples stored at AT compared to those stored in CR and IWOPEC due to higher detected temperature in this storage environment. This implies that tomato samples in AT succumbed to higher rate of metabolism in comparison to samples in the other storage environments. The findings of this study are in coherent to the findings by Nkolisa *et al.,* (2018) and Wang *et al.,* (2021) who explained that the increase in TSS value is the outcome of conversion of pectin substances, starch, hemicellulose or other polysaccharides into soluble sugars. Similarly, in this study TSS values increased with time probably due to ripening of the tomato samples. It can be hypothesized that the tomato fruits stored at AT ripened faster because they were exposed to the environment that had the highest temperatures. The IWOPEC structure was able to retard the ripening rate of tomato fruits compared to the AT as a result registered lower TSS values compared to AT environment. Consequently, the IWOPEC was revealed to have the ability to increase shelf life of the stored products compared to storage under AT. Siddiqui *et al.,* (2015) established that TSS content in tomatoes is varietal dependent and is frequently correlated with higher tomato yield. This explains the differences in TSS content observed between Asila F1 variety and Imara F1 variety, with the former bearing relatively higher yields.

Total titratable acids (TTA) changes during storage period

In this study, it was observed that, there was a significant difference ($p<0.05$) on TTA due to the effects of storage environment and storage time. Acidity is often used as an indicator of maturity, which decreases during ripening of fruits (Julhia *et al.,* 2019; Yeshiwas and Tolesa, 2018). There was more decrease in TTA for tomatoes stored under AT compared to those stored in IWOPEC and CR environments (Table 1). This could be due to higher respiration rate as a result of higher temperature in the AT storage environment. The current study findings for the two tomato varieties showed there was a higher rate of TTA decrease in Asila F1 compared to Imara F1 variety with respect to storage time. In line with the findings from this study, Siddiqui *et al.,* (2015) explained that observe acid ratio ranging between 9 and 9.7 was due to the different tomato varieties investigated. Messina *et al.,* (2012) reported a similar decreasing trend in the changes of titratable acid of tomatoes during ripening and storage. Furthermore, Tilahun *et al.,* (2018) described that titratable acidity in tomatoes decreases with increasing storage due to the conversion of organic acids into sugars and their utilization in respiration. Sadler and Murphy, (2010) and Nkolisa *et al.,* (2018) further argued that variations in titratable acids in tomatoes could be affected by differences in fruit weight.

Conclusion

Development of the IWOPEC, as a simple, affordable and effective system of reducing post-harvest losses of fresh tomatoes was successfully done. The designed and fabricated IWOPEC structure was able to reduce temperature, increase relative humidity and gave peak and daily average cooling efficiency of 84.89% and 61.67%, respectively. The IWOPEC structure was a better means for retarding tomato metabolic rate and efficient in maintaining firmness, weight loss, total soluble solids and total titratable acids for tomatoes stored for 20 days with little visible deterioration. Therefore, it can be concluded that the IWOPEC structure can be used as a storage facility for small scale tomato retailers and farmers who currently have no suitable storage facility to help increase shelf life and maintain the quality of their tomatoes. For future studies we recommend improvement on the IWOPEC structure by installing a water boot samp under the structure platform and a wind powered water pump to help in automatic wetting and circulating water in the system from the water reservoir in order to increase cooling efficiency of the storage atmosphere. Also, testing of IWOPEC to other perishables. Testing an IWOPEC without using crates (high density packaging). It can influence the efficiency to a large extent Progress on technological economic performance is required for policy making and adoption by tomato stakeholders.

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