Effects of indirect air cooling combined with direct evaporative cooling on the quality of stored tomato fruit

Sipho Sibanda* and Tilahun Seyoum Workneh

*Institute for Agricultural Engineering, Agricultural Research Council, Pretoria, South Africa; †Bioresources Engineering, School of Engineering, University of KwaZulu-Natal, Pietermaritzburg, South Africa

ABSTRACT
A 53 m³ solar-powered evaporative cooler for temporary storage of tomato fruit was developed to improve the shelf life of tomatoes under hot and humid climatic conditions. This study investigated the effect of indirect air-cooling combined with evaporative cooling (IAC+EC), maturity stage at harvesting and period of storage on the quality of tomatoes. The effect of total soluble solids, firmness, color, physiological weight loss (PWL), and marketability of tomatoes (star 9037) was investigated by monitoring the storage of green and pink maturity stage harvested fruit over 28 days under both IAC+EC and ambient conditions. The three factors had a significant effect (*P < .001) on the overall quality of tomatoes. The tomatoes stored in the IAC+EC system were 18.9% firmer, maintained 10.5% lower concentration of sugars, increased the hue angle by 4.9%, had 6.6% lower total soluble content, and were 24.8% more marketable than the tomatoes stored under ambient conditions. This study clearly demonstrated the efficacy of IAC+EC under sub-humid and hot conditions in improving the quality and marketability and increasing the shelf life of tomatoes by reducing the rate of ripening and utilization of sugar.

1. Introduction
Tomato fruit is climacteric with a short shelf life of 2 to 3 weeks and exhibits high postharvest losses (HPL) of 20–50% and requires immediate cooling after harvesting to slow the ripening process and maintain quality (Macheka, Spelt, Van Der Vorst, & Luning, 2017). These limiting factors have necessitated the selection of the tomato as an experimental fruit for this study. A reduction in HPL is crucial for increasing market participation, improving the welfare of tomato growers, and increasing food availability. Appropriate post-harvest technologies for fresh tomato fruit that provide optimum conditions of low temperature of 10°C to 15°C and high relative humidity (RH) of 85–95% from the time of harvesting, storage, and transportation to the market are indispensable (Babaremu, Omodara, Fayomi, Okokpujie, & Oluwafemi, 2018). The quality of fresh tomatoes is determined by considering parameters classified into physical, chemical,
biochemical, and sensory properties. The physical properties are firmness, skin color, and physiological weight loss (PWL) (Vinha, Barreira, Castro, Costa, & Oliveira, 2013). The main chemical properties are total soluble solids (TSS), citric acid, and pH (Beckles, 2012). The sensory properties of tomatoes include flavor and marketability (Haile, 2018). TSS are a measure of tomato quality (Anthon, LeStrange, & Barret, 2011). The TSS is a refractometric index that indicates the percentage proportion of dissolved solids in a solution expressed as °Brix (Saad, Ibrahim, & El-Bialee, 2016). TSS (°Brix) are one of the physical and chemical parameters used as an index of determining tomato ripening. The color of the tomato is the first external characteristic that determines both consumer acceptance and ripeness (Pinheiro et al., 2015). The determination of skin color of produce assists in determining the maturity stage of produce immediately after harvest.

Modern-day cooling systems like mechanical refrigeration, hydro-cooling, and vacuum cooling delay or halt the deterioration in fruit and vegetables (F&V) qualities of color, firmness, soluble sugar content, and pH. However, modern cooling technologies require high-throughput operations and besides have high installation and maintenance costs and high energy input normally from the grid which small-scale farmers (SSFs) in most remote areas in sub-Saharan Africa (SSA) have no access to (Kim & Ferreira, 2008). Evaporative cooling (EC) has a potential of adoption by SSF because of low, initial investment requirements, installation and maintenance costs, and energy requirements (Fernandes, Saraiva, Pereira, Casal, & Ramalhosa, 2018). For example, the cost per metric tonne for forced air EC to 13°C using a 0.5 HP fan is US$0.14/kWh of electricity compared to US$22–30 for hydro cooling (inversion type) to 0 to 2°C. A small-scale mechanical refrigeration system with a storage capacity of 2 tonnes requires about 7 kW of electricity and costs US$8,500, while a same storage sized forced-air EC system powered by a 0.5 HP fan will cost US $1300 (Kitinoja & Thompson, 2010). Most of the research in EC in the developed countries have focused on cooling buildings as opposed to cooling fresh agricultural produce. The EC systems studied so far in SSA for preservation of F&V are prototypes with low storage capacity. A lot of this work has been limited to west and east Africa; the technology might not perform accordingly if extended southern Africa as alluded by Thipe, Workneh, Odindo, and Laing (2017). EC works best in hot and dry conditions as it relies on the removal of sensible heat and for it to be extended to hot and humid regions will require that the air be indirectly cooled by incorporation of desiccation medium before EC (Misra & Ghosh, 2018). Use of indirect air-cooling combined with evaporative cooling (IAC+EC) in for provision of cool environment for storage of fresh produce is undocumented and a new research focus (Manaf, Durrani, & Eftekhar, 2018).

An investigation into the efficacy of IAC+EC on the ability to maintain quality or extend shelf life of tomatoes is required as recommended by Ogbuagu, Oluka, and Ugwu (2017) which this study has responded to. This study seeks to provide performance data on the efficacy of solar-powered IAC+EC for preservation of F&V quality under hot and humid conditions. Therefore, the objective and scope of the study was limited to determining the quality and shelf extension of tomatoes through evaluation of changes in physical changes, chemical changes, and sensory qualities of tomato variety harvested at two maturity stages and stored under an IAC+EC and ambient conditions.

2. Materials and methods

2.1. Study site and description

The study was carried out at Ukulinga Research Station in Pietermaritzburg (29.67° S and 30.40° E, at an altitude of 721 m) which is a research farm for the University of KwaZulu Natal. The IAC+EC consisted of a storage chamber, indirect heat exchanger, multiple charcoal cooling pads, buried water tank, a pump, and two fans and Figure 1 shows a schematic diagram of the system. The storage chamber had white double-jacket walls and roof of 1 mm zintec (mild steel) on the outside and on the inside and a floor of concrete mortar. The inner dimensions of the unit were 2340 mm high x 5880 mm long x 3880 mm wide to hold a capacity of 3.8 tonnes. The cooler had a 60 mm zinc wall thickness with 58 mm polyurethane insulation in between the zintec layers. The indirect heat exchanger was included for sensibly cooling of the air before coming into contact with water as it passes through the pads for adiabatic cooling. The material selected for cooling pad was charcoal and the pads were vertically mounted. The water

![Figure 1. Schematic diagram of the indirect air-cooling combined with evaporative cooling unit.](image-url)

![Figura 1. Diagrama esquemático del enfriamiento por aire indirecto combinado con la unidad de enfriamiento por evaporación.](image-url)
continuously pumped from an underground storage using a 0.26 kW Pedrollo PVm 55 centrifugal pump placed at the surface. The water circulated throughout the cooling system (through the heat exchanger and sprinkled water on the EC pads) and a return valve released it back to the storage tank. These design specifications provided in the storage chamber, environmental conditions of dry bulb temperature of 14–20°C and RH of 87–97% with the system have a cooling efficiency of 86–96% depending on the time of the day during the period of the experiment. Nine solar panels connected in three series-three strings were used with a 48 V battery bank of twelve 230 AH batteries to power the electrical appliances. Each panel was rated 330 W with short circuit current and open circuit voltage of 8.69 A and 44.8 V, respectively, translating to a nominal power output of about 3500 W which was enough to power the electrical appliances. The total cost of the solar-powered IAC+EC structure was US$8500 (Solar power system US$7000) with a payback period of 1.9 years.

2.2. Performance assessment

Evaluation of the cooler performance through the determination of physical and chemical properties and marketability of the tomato Star 9037 cultivar in storage over a 28-day period was undertaken. The warm and dry season is the period when cooling intervention is most useful, and experiments were therefore done during this time from 26 August 2017 to 22 September 2017. The environmental conditions of temperature and RH in the storage chamber and under ambient were 14°C–20°C, 87.8%–97.4% and 20.0°C–31.9°C, 46.6%–80.7%, respectively, depending on the time of the day. For the fullest advantage of harnessing the IAC+EC effect, the cooler was located in an area with good ventilation. The experimental procedures focused on the IAC+EC performance within 7-day cycle period. Investigations of patterns of tomato quality changes in both the storage chamber and under ambient conditions were undertaken. The shelf lives and quality attributes of the tomato fruit, i.e., firmness, PWL, and color, were evaluated between the fruit stored in the IAC+EC storage chamber against ambient conditions.

2.3. Sample preparation

Tomato Star 9037 cultivar was harvested early in the morning before 10h00 into plastic crates at physiologically matured and ripen stage with half at green and the other at pink mature stage from a nearby farm in Pietermaritzburg. The tomatoes were immediately loaded in a vehicle and transported to Ukulinga research station located 31 km away. The tomatoes were visually inspected to discard those with bruises and signs of infection from the fruit used as samples (Saad et al., 2016). Selection of tomatoes which were uniform, unblemished, and having similar size and color was done and these were washed under a running tap to remove any dirt and to reduce microbial population on the surface (Nath et al., 2012). After washing, the tomatoes were surface dried with a soft clean cloth, which was free from contaminating materials and then the fruit was subdivided into plastic crates. The crates were then stored under room temperature in food processing laboratory and under IAC+EC conditions in the storage chamber in three replications. The crates were stacked on a 200 mm stand to prevent any transfer of disease from the ground to the tomatoes (FAO, 2011). A sample from each treatment and replication was analyzed periodical for physical and chemical properties, and sensory qualities.

2.4. Treatment and experimental design

The experimental design consisted of a factorial combination of one tomato variety, two storage conditions (IAC+EC storage chamber, and ambient), two maturity stages at harvesting (green-breaker stage and pink). Figure 2 shows the experimental design. Each storage condition-maturity stage was replicated three times (three crates). A total of 150 kg of tomatoes in 12 crates (12.5 kg of tomatoes per crate) were prepared for the experiment. Three crates each of green and pink harvested tomatoes were stored under IAC+EC conditions, while another three crates each of the same was stored under ambient conditions. In each replica, 25 tomatoes were marked and five were selected for quality attribute assessment of physical (firmness and color) and chemical (PWL and TSS) and sensory (marketability) properties over five-storage periods of day 0, day 7, day 14, day 21, and day 28.

2.4.1. Firmness

The firmness of the tomato fruit was determined through puncturing the surface using an Instron Universal Testing Machine (Model 3345) in combination with the Instron Bluehill 2 Version 2.25 software as described by Sirisomboon, Tanaka, and Kojima (2012). A probe of diameter 2 mm punched tomatoes mounted horizontally on a curved platform (to ensure stability during the compression test). The probe attached to a load celldrove into the tomato at a crosshead speed of 3 mm.s⁻¹ to travel to a depth of 7.5 mm according to the procedure used by Tolesa and Workneh (2017).

2.4.2. Colour

The tomato color indicators were determined, using a digital CR-400 Chroma meter according to Nath et al. (2012). The chromo meter was calibrated with a white paper before taking measurements at day 0, day 7, day 14, day 21, and day 28. Each sampled tomato was measured for L*, a* and b* at three equatorial positions (blossom end, stem-end, and mid-way), which were averaged to determine the overall values using the procedure by Cherono, Sibomana, and Workneh (2018). The values are based on a reference scale where a* (“+” value

![Figure 2. Experimental design.](image-url)
indicated redness and “−” value indicated greenness), b* ("+" value indicated yellowness and “−” value indicated blueness) and L* (varies from 0 to 100 where "100" indicated white and "0"indicated black). The changes in the color of tomatoes were measured in terms of the L* value and the hue angle (h°). The hue angle (h°) for each tomato fruit was calculated from the equation (Saad et al., 2016)

\[ 
\text{Hue angle} = \tan^{-1} \left( \frac{b^*}{a^*} \right) 
\]

**2.4.3. Physiological weight loss**

Five sampled stored tomatoes from each treatment were weighed using a Teraoka DIGI SM 300 scale at the start of the experiment and on 7-day intervals at days 7, 14, 21, and 28. PWL was calculated as cumulative percentage weight loss based on the initial tomato sample weight (before storage) and loss in weight recorded at the time of sampling during storage (Caron, Tessmer, Mello, & Jacomino, 2013). The equation by Islam and Morimoto (2016) computed the percentage differential weight loss for each sample per each interval as percentage weight loss of the initial weight.

\[ 
\text{%Weight loss} = \frac{\text{Weight}_{t=0} - \text{Weight}_{t=t}}{\text{Weight}_{t=0}} \times 100 
\]

**2.4.4. Total soluble solids**

Cleaning, cutting into smaller slices using a knife and crushing (using a blender) each sample tomato from each treatment produced a blended and homogenized tomato puree. A clean cloth then sieved the puree into a small container and the puree was used for estimation of TSS. The TSS were determined using an RFM 340° digital refractometer (± 0.1% Brix) by placing a few drops of the puree on the prism (Getinet, Workneh, & Woldetsadik, 2008). TSS measurements were taken at day 0, day 7, day 14, day 21, and day 28. Between samples, the prism was cleaned with distilled water using a soft clean cloth according to Saad et al. (2016)

**2.4.5. Percentage marketability**

The marketability of tomatoes was determined subjectively on the day of sampling by randomly choosing five tomatoes from each treatment and observing the level of visible mold, color, surface defects, decay, shriveling, and shine (Workneh, Osthoff, & Steyn, 2012). Four expert panels consisting of two researchers and two laboratory technicians were used to rate the tomato samples. Based on a rating, with 1 being “unsalable,” 3 being “unsalable,” 5 being “fair,” 7 being “good,” and 9 being “excellent,” fruits were evaluated. Tomatoes that received a rating of “5” and above were considered marketable, while those receiving a rating less than “5” were considered unmarketable. Damaged, decayed or overripe tomatoes, which were considered unmarketable, were removed from the stored samples (Cherono et al., 2018). The percentage of the marketable fruit was calculated from the equation:

\[ 
\text{%Marketability} = \frac{\text{Total no. of tomatoes receiving a rating of five and above}}{\text{Total no. of tomatoes at start of experiment}} \times 100\% 
\]

2.5. Data collection and analysis

Data were recorded on days 0, 7, 14, 21, and 28 from the start of the experiment (after storage), in order to determine the change in the tomato quality. On each sampling date, samples from the marked tomatoes were selected randomly from each treatment for quality analysis. The following parameters evaluated the change in the quality of the tomatoes: physical properties; texture/firmness and skin color; chemical properties; PWL and TSS; sensory qualities; marketability. Analysis of variance (ANOVA) by means of the GENSTAT statistical software, 18th edition determined the differences between treatments. Duncan’s Multiple Range Test, with a significance level of 0.05 separated the means.

3. Results and discussions

During the storage period, the ambient dry bulb air temperature and the RH varied from 20.0°C to 31.9°C and 46.6–80.7%, respectively. Inside the IAC+EC, the dry bulb temperature and RH varied from 14°C – 20°C and 87.8% – 97.4%, respectively.

3.1. Tomato firmness

The effects of storage conditions, maturity stage at harvesting, and storage period on the firmness of the tomato star 9037 cultivar that were stored under IAC+EC and ambient conditions were significant (P < .001) as shown in Figure 3. The tomatoes stored in the IAC+EC storage chamber were 18.9% more resistant to puncture, with 8.84 N, than those stored under ambient conditions with 7.17 N, which are averages over the 28-day period. A firmness value of greater than 8.46 N mm.\(^{-1}\) indicates that tomatoes are very firm and suitable for supermarket shelves (Batu, 2004). The unbridled ambient conditions accelerated the tomato fruit ripening process, which was most evident in the conversion of the skin color from green/pink to pink/red and the rapid reduction in firmness. This was more evident for pink harvested tomatoes, which on average were 20.2% softer, had 6.6% higher concentration of sugars, 3.1% higher PWL, 4.9% increase in hue angle and were 11.6% less marketable. The result indicates that IAC+EC kept the tomato structure intact and firm under the hot and humid conditions, which might contribute to the preservation of F&V quality leading to an extended shelf life. This is in agreement with findings of Zakari et al. (2016) using EC under dry and arid conditions who concluded through pictorial images though without providing actual figures that loss of firmness was very obvious in the tomatoes stored under ambient as compared to EC system.

Higher ambient temperatures and lower RH encourage increased tomato physiological activity resulting in loss of fruit firmness due to the breakdown of cellulose, pectin, and lignin by pectinesterases (PE), polygalacturonase (PG) and β-galacturonase (β-gal) in the cell wall (Tigist, Workneh, & Woldetsadik, 2013). It is based on this background that the
The use of IAC+EC performs as effectively as EC in dry and arid conditions for storing fresh tomatoes is significant and cannot be overemphasized.

Comparison of the firmness between the two harvesting maturity stages showed that the overall average firmness for the green-harvested tomatoes was 20.2% higher, with 8.74 N, than that of pink-harvested, which had an overall average of 7.27 N. The reduced firmness in pink harvested tomatoes is attributable to a physiological breakdown of the fruit cell wall as the fruit ripened from green to pink. The average firmness of tomatoes decreased significantly with storage period from 11.16 N-day 0, 9.76 N-day 7, 7.81 N-day 14, 7.03 N-day 21, and 4.28 N-day 28. The decline over the 28-day period is 61.6%. The longer the storage period, the longer enzymatic activity continues causing more tissue softening and affecting firmness. Toleasa and Workneh (2017) obtained a similar pattern in their study where they observed a decline in tomato firmness of 23.3 N to 11.5 N over a 21-day storage period. The decrease in firmness is attributable to physiological deterioration in tomato as the fruit continues to transpire, respire and further ripen (Saltveit, 2018). By day 21, the firmness of green-harvested tomatoes stored under IAC+EC was 8.86 N. The maturity stage at harvesting affects the firmness of the tomato fruit (Vinha et al., 2013).

The green stage harvested tomatoes when subjected to IAC+EC conditions gave the highest average firmness of 9.82 N followed by the pink harvested tomatoes with a breaking force of 7.86 N while the green and pink harvested fruits under ambient conditions had 7.66 N and 6.68 N breaking force, respectively. The indication from the results is that storage of less mature tomatoes under IAC+EC provides firmer tomatoes over the storage period compared to all other combinations. Sirisomboon et al. (2012) in their study made similar observation where they obtained an average firmness of 3.59 N.m⁻¹, 1.61 N.m⁻¹ and 1.19 N.m⁻¹ for green, pink and red harvested tomatoes, respectively. Subsequently, Sirisomboon et al. (2012) concluded that a lower firmness of tomatoes regardless of the stage of maturity at harvesting indicates a weaker flesh skin often associated with ripe and soft fruit resultant of physiological deteriorations because of more rapid metabolism.

The combinations of storage condition x storage period and maturity stage x storage period show green-breaker stage tomatoes stored under IAC+EC conditions retained firmness (above 8.76 N) for an extended period of 21 days while the pink harvested retained firmness up to 14 days. According to Batu (2004), a firmness of 8.76 N is the minimum firmness requirement for very marketable fruit in supermarkets. Tomatoes in cold storage maintained higher firmness over the storage period than ambient air-stored tomatoes. The puncture force carried out on the sampled tomatoes indicate that the average firmness is a textural parameter that is sensitive to the storage environment, maturity stage at harvesting and the storage period.

### 3.2. Color

Table 1 shows that both the h° and L* value were significantly (P ≤ 0.05) influenced by storage condition, maturity stage at harvesting, and the storage period. The tomatoes stored in the IAC+EC storage chamber had an overall 1% higher L* value and 3% higher h° value for the 28 days of storage, compared to those stored under ambient conditions. The h° and L* values decreased progressively over the period of storage from 76.61% at day 0 to 49.45% at day 28 and 53.47% at day 0 to 35.36% at day 28, respectively. A decrease in values of h° and L* both were indicative of the green to red color change with storage period as the fruit ripens. Cheroni et al. (2018) had similar observation of color changes with storage time where the h° value significantly reduced between sampling days 0, 4, 8, and 16 though there was no significant variation between day 16 and day 24 of sampling. Zakari et al. (2016) on their work on EC made observed that the tomatoes changed from yellowish red to a deep-red color by the sixth day of storage. As a tomato ripens, there is color change from green to white through chlorophyll degradation, then white to red by carotenoid biosynthesis (Hahn, 2002). The lowest values coincide with time when the tomatoes have attained a deep-red color. The average L values over the 28 days of observation for green tomatoes were 44.44% and 42.36% for pink tomatoes, while the average h° values were lower.
61.13% and 56.26%, respectively. These results indicate that tomatoes become redder with the passage of time and changes in color are accelerated more in higher temperatures under ambient conditions. These observations underscore the importance of using postharvest handling practices such as IAC+EC for storage of fresh produce that reduce the rate of deterioration.

The three-way interaction of storage conditions x maturity stage x period of storage had a significant (P < 0.05) effect on the values of h° and the L* of the sampled tomatoes under IAC+EC. The green harvested tomatoes had the highest values of h° and the L* when storage in the IAC+EC storage chamber when observed over the period of storage (Table 1). The combination of green harvested tomatoes and IAC+EC environment is ideal for maintaining the quality of tomatoes under sub-humid conditions. Tolesa and Workneh (2017) made similar observations in three-way interaction of storage conditions x maturity stage x period where an h° of 103° to 45° and 73° to 45° was obtained for green and pink harvested tomatoes, respectively, over a 21-day storage period. Therefore, storage temperature, variety, storage period and maturity stage at harvesting factors influence the skin color of fresh produce as alluded to by Baltazar, Aranda, and González-Aguilar (2008). The result shows the best quality of tomatoes over 21 days is obtained from a combination of less ripe tomatoes (harvested whilst still green) under IAC+EC storage environment.

### 3.3. Total soluble solids content

Table 2 presents the TSS of green and pink harvested tomatoes subjected to either ambient conditions or IAC+EC storage conditions over 28 days. The storage conditions, the stage of maturity at harvesting and the storage period significantly (P < .001) had an influence on the TSS. A general increasing trend in the TSS was observed but was most evident at ambient conditions, compared to the IAC+EC storage conditions. The tomatoes stored in the IAC+EC storage chamber had on average TSS values of 4.10 compared to 4.58 for ambient conditions while on average green harvested and pink harvested tomatoes had TSS values of 4.19 and 4.49 over the storage period. Lower TSS values imply a lower concentration of sugar. Maftoonazad and Ramaswamy (2008) observed similar findings on the storage of mangoes where °Brix increased with storage period and storage environment (temperature) and the rate of increase was greater at higher temperatures. °Brix tends to increase as the ripening proceeds (Sammi & Masud, 2007). At low temperature and high RH storage conditions, the rate of increase was slower, compared to storage at ambient conditions. The increased temperature and reduced RH at ambient conditions are attributed to the increased hydrolysis of carbohydrates stored within the tomatoes into soluble sugars. This, therefore, resulted in a higher TSS content and a reduced tomato shelf life, which is undesirable.

### Table 1. Changes in L values and hue angle of tomatoes subjected to treatments of storage conditions, maturity stages and storage period (n = 5).

| Treatment | Day 0 | Day 7 | Day 14 | Day 21 | Day 28 |
|-----------|------|------|-------|-------|-------|
| Green, ambient | 57.49a | 46.16bc | 41.52g | 39.16cd | 34.12a |
| Pink, ambient | 49.95a | 45.16bc | 41.36g | 37.95bc | 35.12a |
| Green, cooler | 57.08a | 46.71bc | 47.13bc | 38.96d | 36.12ab |
| Pink, cooler | 49.35a | 46.77bc | 42.47bc | 38.95d | 36.07ab |

**Significance level**

Storage (A) | <0.05 | Maturity (B) | <0.001 | Day (C) | <0.001 | A x B | N.S | A x C | N.S | B x C | <0.001 | A x B x C | <0.05 | LSD$_{0.05}$ = 1.168, CV (%) = 4.2, SE = 0.812

### Table 2. Total soluble solids content of tomatoes subjected to treatments of storage conditions, maturity stages and storage period (n = 5).

| Treatment | Day 0 | Day 7 | Day 14 | Day 21 | Day 28 |
|-----------|------|------|-------|-------|-------|
| Green, ambient | 84.68a | 56.31abc | 51.55a | 52.91a | 48.31a |
| Pink, ambient | 69.33c | 53.83a | 53.74a | 52.14a | 49.43a |
| Green, cooler | 84.78a | 58.10abc | 68.53bc | 55.73ab | 50.43a |
| Pink, cooler | 67.64bc | 59.35abc | 53.13a | 54.38ab | 49.64a |

**Significance level**

Storage (A) | <0.05 | Maturity (B) | <0.001 | Day (C) | <0.001 | A x B | N.S | A x C | N.S | B x C | <0.001 | A x B x C | <0.05 | LSD$_{0.05}$ = 6.803, CV (%) = 9.2, SE = 3.416
The two-way interactions between storage conditions and storage period significantly ($P < 0.05$) influenced the TSS accumulation. The tomatoes that were stored in the IAC+EC storage chamber regardless of the maturity stage at harvest had lower TSS than those stored under ambient conditions throughout the storage period. This agrees with the study of Getinet et al. (2008) who observed that the mature green and turning stage Roma VF tomatoes had lower TSS up to the 10th day of storage when stored in the evaporative cooler than under dry and hot ambient conditions. Young, Juvik, and Sullivan (1993) concluded changes that occur in sugar content during the development of tomato fruit increases progressively throughout the storage period as the fruit matures and ripens associated with the first appearance of yellow pigment in the walls of the fruit at the breaker stage through to red. Therefore, tomatoes become softer with the passage of time and changes in softness are accelerated at higher ambient storage environments.

Soluble solids determine the sweetness of tomatoes, but there are other compounds responsible for flavor characteristics, such as acids and volatiles. When tomatoes mature, the sugar levels increase, due to the metabolism of stored carbohydrates, lipids and proteins (Garcia & Barrett, 2006). At a later stage, these sugars are utilized for maintenance during growth, thus resulting in senescence (Beckles, 2012). TSS are a good index for the quality control of tomatoes. It is therefore very critical that for adoption postharvest cooling technologies, such as IAC+EC to slow down respiration and ethylene production and to thus retard ripening and senescence. In this study, the changes in TSSs of tomatoes over the storage period clearly indicated that integrating less ripe tomatoes with IAC+EC storage environment could maintain quality and improve the shelf life.

### 3.4. Physiological weight loss

During the period of observation the storage conditions, the maturity stage and the storage period tomato star 9037 cultivar that were stored under IAC+EC and under ambient conditions were found to be highly significant ($P \leq 0.001$) with regard to the tomato PWL (Figure 4). The highest PWL was found in tomatoes stored under ambient conditions (11.8%) due to the considerably higher temperatures (>26°C) and lower RH (<60%), compared to the IAC+EC storage conditions (3.9%) over the 28-day storage period. Sampled tomatoes stored under ambient conditions had PWL of 9.4% by day 7 and 14.5% by day 28 compared to 2.2% and 6.4% for IAC+EC for the same period. According to Acedo (1997), a PWL of 10% is the threshold acceptable for the quality of fresh tomatoes. These findings are consistent with reported observations by Islam and Morimoto (2016) and Zakari et al. (2016) who observed that tomatoes stored under ambient conditions had PWL of 0.30% to 0.60% per day (8.4% to 16.8% over a 28-day period) compared to ECof 0.05% to 0.18% per day (1.4% to 5.04% over a 28-day period). Pink harvested tomatoes exhibited a higher PWL (7.9%) compared to green harvested tomatoes (4.8%) over the 28-day storage period. Getinet et al. (2008) made similar observations in the storage of light-red harvested and mature-green harvested tomatoes in an evaporative cooler for 32 days had PWL 19.2% and 14.6%, respectively. These conditions induced a larger vapor pressure deficit between the fruit and the surrounding external environment, as a result creating a driving force for moisture loss from the fruit (Thompson, Prange, Bancroft, & Puttongsiri, 2018). The rate at which the moisture was lost by the tomatoes under ambient conditions occurred at a faster rate than under IAC+EC consequently contributing to a higher increase in the PWL.

PWL increased progressively over the period of storage and the highest values were reached on the last day of observation. There was continuous loss of moisture over time due to transpiration from the tomatoes and respiration under ambient conditions. This is the reason was PWL increased with storage period as the tomato fruit continues to ripen. The PWL was more pronounced under ambient conditions implying that senescence may occur earlier and, therefore, result in a shorter shelf life. Cherono et al. (2018) in their research study had similar observations where PWL
The results obtained mean that the rate at which the moisture was lost by the tomatoes occurred at a faster rate, when the fruit was subjected to ambient storage conditions and thus translating to an increase in the PWL. The implications are that senescence may occur earlier resulting in a shorter shelf life for both stages of tomato maturity. The physiological moisture loss from tomatoes varies and is dependent on the magnitude of the surrounding air temperature and RH. High temperature and low RH induce high respiration rate, which is the main cause of PWL (loss in saleable weight) and wilting. The physiological nature of tomato that includes high moisture content, high respiration rate, and soft texture make it more vulnerable to postharvest qualitative changes and losses and therefore requires storage facility systems like IAC+EC. The IAC+EC conditions provide a low temperature–high RH environment that inactivated the enzymes responsible for the ripening process. The results indicate that tomatoes can be stored under an IAC+EC environment for 28 days without breaking the PWL threshold level (10%) of good quality fresh tomatoes.

### 3.5. Marketability

Visual signs in fresh fruit are the first quality attributes that consumers consider when making decisions to buy and these largely influence marketability (Siddiqui, Patel, & Ahmad, 2015). The storage conditions, maturity stage at harvesting and the storage period significantly (P ≤ 0.001) influenced the marketability (Figure 5).

The percentage of marketability of tomatoes was at 100% on day 0 and decreased with storage period for all treatments. Tomatoes stored in the IAC+EC storage chamber had on average a higher percentage marketability (70.38%) than those under ambient conditions (48.61%). Furthermore, green stage of maturity harvested tomatoes had a higher marketability of 38.4% by day 28 compared pink harvested tomatoes of 20.6%. The higher percentage of marketability of tomatoes under IAC+EC is attributable to the low-temperature storage conditions of the storage chamber, which resulted in lower moisture losses. The results are in conformity with the work done on strawberries by Rahman, Moniruzzaman, Ahmd, Sarker, and Alam (2016) where fruits harvested at one-third maturity stage had a shelf life of 7.80 days, while fully matured fruits had the lowest shelf life, which was only 2.40 days. Higher ambient temperatures translate to higher moisture loss in fresh produce causing loss of marketable weight and inadvertently affecting appearance (wilting and shriveling) resulting in less marketability. As moisture is lost, the textural quality of tomatoes reduces thereby enhancing softening, loss of crispness and juiciness, and reduction in nutritional quality.

Marketability drastically decreased at ambient conditions from 100% to 42.9% by day 14 and could have decreased significantly increased between sampling days 0, 4, 8, 16, and 24 for both cold and ambient stored tomatoes from 0% to 6% and 12%, respectively. Therefore, the use of IAC+EC system for preserving and improving the shelf life of tomatoes cannot be avoided. Zakari et al. (2016) reported that water constitutes a large portion of most F&V and when lost from fresh produce translates to reduction in weight results in wilting and less marketability; hence, it is important to maintain the weight of fresh tomatoes to maximize profit.

The three-way interaction between storage conditions x stage of maturity x storage period was found to have a significant (P ≤ 0.05) effect on the tomato PWL. Pink tomatoes stored under ambient had a PWL of 12.45% over a 7-day storage period while the green-breaker stage harvested tomatoes had a PWL of 13.86% by day 14 of storage. The green-breaker stage and pink harvested tomatoes subjected to the IAC+EC conditions had a PWL of 3.61% and 4.97%, respectively, by day 21 of storage. This implies that by day 21 the tomatoes under IAC+EC had not lost freshness and had no wilting appearance as such characteristics only exhibit after 5% PWL according to Sondi and Salopek-Sondi (2004). The PWL of green harvested tomatoes and stored in the IAC+EC storage chamber was 4.99% by day 28, exhibiting the lowest decrease. The green harvested and pink harvested tomatoes were stored under IAC+EC stored over 28 days had a PWL below 8%, which is within the region that sustain good quality of tomatoes. According to Getinet et al. (2008), a 10% PWL corresponds to the threshold level for the termination of shelf life of fresh produce.

Figure 4. Changes in physiological weight loss (%) over a 28-day storage period for tomatoes harvested green and pink and subjected to ambient and IAC+EC conditions (n = 5), where amb-green is green harvested tomatoes stored under ambient conditions, amb-pink is pink harvested tomatoes stored under ambient conditions, EC-green is green harvested tomatoes stored under IAC+EC conditions, EC-pink is pink harvested tomatoes stored under IAC+EC conditions.

Figure 4. Cambios en la pérdida de peso fisiológica (%) durante un periodo de almacenamiento de 28 días para los tomates cosechados de color verde y rosa sometidos a condiciones ambientales y de IAC+EC (n = 5). Amb-green es el tomate cosechado de color verde, almacenado en condiciones ambientales; amb-pink es el tomate cosechado de color rosa, almacenado en condiciones ambientales; EC-green es el tomate cosechado de color verde, almacenado bajo condiciones IAC+EC; EC-pink es el tomate cosechado de color rosa, almacenado bajo condiciones IAC+EC.
further if there were more days with high temperatures during the period of observation. The sharp decline in marketability is because of excessive softening and shriveling caused by moisture loss, which is one of the factors leading to the PWL. Several tomatoes subjected to ambient conditions by day 21 experienced decay, shriveling and extreme softness and were discarded while those still in good condition were retained to be observed again in day 28. Under IAC+EC, the green harvested tomatoes were at 63.5% and 57.5% marketability at day 21 and day 28 while for pink harvested tomatoes there was a sharp decline from 50.1% marketability at day 21 to 28.1% at day 28. Postharvest practices such as IAC+EC are important in maintaining the quality and shelf life of fresh fruits since they slow down deteriorative metabolic processes such as respiration and transpiration resulting in preservation of the organoleptic properties of tomatoes for 21 days where at least 50% of them were still marketable.

Figure 5. Changes in cumulative percentage marketability of tomatoes over a 28-day storage period for tomatoes harvested green and pink and subjected to ambient and IAC+EC conditions (n = 5), where amb-green is green harvested tomatoes stored under ambient conditions, amb-pink is pink harvested tomatoes stored under ambient conditions, EC-green is green harvested tomatoes stored under IAC+EC conditions, EC-pink is pink harvested tomatoes stored under IAC+EC conditions.

4. Conclusion

This study was undertaken to determine the effects of postharvest storage environment, as well as tomato maturity stage at harvest and storage period on the postharvest quality of stored tomatoes. Integration between maturity stages, IAC+EC significantly contribute to the maintenance of tomato quality. The deductions from the study are that the physical, chemical, and subjective sensory quality parameters of tomatoes are largely dependent on maturity stage at harvest and storage environment as well as storage period. The IAC+EC system had a positive effect on the quality parameters, and this extended the shelf life of tomatoes compared to samples that were stored under ambient conditions. The unbridled ambient conditions accelerated the tomato fruit ripening process, which was most evident in the conversion of the skin color from green/pink to pink/red and the rapid reduction in firmness. This was more evident for pink harvested tomatoes, which on average were softer, had higher concentration of sugars higher PWL, and were less marketable. The best quality of tomatoes is obtained from less ripe fruits stored under IAC+EC. All tomato samples experienced a decrease in the measured quality attributes over the storage period of 28 days though the IAC+EC storage environment provided high quality of the fruit when compared to ambient condition on only the sampling dates. Consequently, the combinations of green maturity stage at harvesting and IAC+EC storage greatly extended the shelf life and improved the marketability of tomatoes. Therefore, a farmer can use a combination of tomatoes harvested at the green stage and IAC+EC to maintain a better quality of tomatoes and to extend their shelf life. Based on the results the IAC+EC system can be recommended for use by SSF in hot sub-humid to humid areas and the governments are encouraged to upscale this technology as this study has proven its efficacy.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Acedo, A. L. J. (1997). Storage life of vegetables in simple evaporative coolers. Tropical Science, 37, 169–175.

Anthon, G. E., LeStrange, M., & Barret, D. M. (2011). Changes in pH, acids, sugars and other quality parameters during extended vine holding of ripe processing tomatoes. Journal of Food Science Agriculture, 91(7), 1175–1181. doi:10.1002/jsfa.4312

Babaremu, K. O., Omodara, M. A., Fayomi, S. I., Okokpuije, I. P., & Oluwafemi, J. O. (2018). Design and optimization of an active evaporative cooling system. International Journal of Mechanical Engineering and Technology, 9(10), 1051–1061.

Baltazar, A., Aranda, J. I., & González-Aguilar, G. (2008). Bayesian classification of ripening stages of tomato fruit using acoustic impact and colorimeter sensor data. Computers and Electronics in Agriculture, 60, 113–121. doi:10.1016/j.compag.2007.07.005

Batu, A. (2004). Determination of acceptable firmness and colour values of tomatoes. Journal of Food Engineering, 61, 471–475. doi:10.1016/S0260-8774(03)00141-9

Beckles, D. M. (2012). Factors affecting the postharvest soluble solids and sugar content of tomato (Solanum lycopersicum L) fruit. Postharvest Biology and Technology, 63, 129–140. doi:10.1016/j.posthbio.2011.05.016

Caron, V. C., Tessmer, M. A., Mello, S. C., & Jacomino, A. P. (2013). Quality of mini tomatoes harvested at two maturity stages and kept chilled in three packages. Horticultura Brasileira, 31(2), 279–286. doi:10.1590/S0102-05362013000200017
