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DETERMINATION OF PERFORMANCE AND ASSOCIATED ECONOMIC COSTS OF INDIRECT AIR-COOLING COMBINED WITH EVAPORATIVE COOLING FOR STORAGE OF TOMATOES IN SOUTH AFRICA

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ABSTRACT

Knowledge of the cost of a storage structure for fruits and vegetables is paramount as a decision tool when farmers consider the return on investment. The performance and economic analysis associated with using a solar-powered indirect air-cooling (IAC) combined with evaporative cooling (EC) storage structure for storage of green harvested tomatoes was investigated. This study investigated the effect of IAC+EC system and period of storage on the quality of tomatoes over a 28 day storage period. The construction, maintenance and operation costs of an IAC+EC system were also studied. Various quality attributes of tomatoes were investigated by monitoring the storage of green harvested tomato fruit over 28 days under both IAC+EC system and ambient conditions with data collated every seven days. Tomatoes stored under IAC+EC conditions had significantly ($P<0.01$) higher firmness, lower total soluble solids content, lower physiological weight loss and higher average percentage marketability than those under ambient conditions over the storage period. The tomatoes stored in the cold storage conditions were 28.1% more resistant to puncture; had 7,3% less total soluble solids content, had three times less physiological weight loss, than those stored under ambient conditions over the same period. The h° and L* values decreased progressively over the period of storage from 84% at day 0 to 48.31% and 50.43% at day28 under ambient and IAC+EC conditions, respectively. Tomatoes stored under IAC+EC conditions had a higher average percentage marketability (72.4%) than those under ambient conditions (40.9%) over the storage period. The cost of constructing a 53-m^3 IAC+EC system integrated with a solar photovoltaic system was US$8,680. The economic analysis that the payback period of the cooling system was less than two years. The results demonstrate that the IAC+EC system could be recommended for small-scale farmers in sub-Saharan Africa to maintain a better quality of produce if government and other funding agencies come on board.

Key words: marketability, payback period, postharvest losses, small-scale farming, air-cooling

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INTRODUCTION

In South Africa, most fruits and vegetables including tomatoes are produced in Limpopo province while most tropical and sub-tropical fruits are grown in Mpumalanga province [1]. These two provinces experience higher temperatures throughout the year which is a conducive environment for growth of fruits and vegetables. The sub-humid to humid high-lying areas of KwaZulu-Natal province are equally suitable for growing tomatoes, cauliflower, cabbage and carrots. The fruit and vegetables' sector in South Africa export prices and quantities have increased tremendously and continue to maintain an upward trend since 2010 and contributed US$5,13 billion in the 2020/21 farming season [2]. Statistics in South Africa indicate that fresh produce like tomatoes and onions have the highest annual yield quantity of 560, 418 t and 689, 777 t, respectively [1]

However, the major limitation to fresh produce production is the high postharvest losses (PHL) experienced by farmers. Postharvest loss reduction strategies are the panacea to improved income and food security for the over 200 million population that is currently facing food insecurity in sub-Saharan Africa (SSA) [3]. Fruit and vegetable producers in SSA experience high PHL estimated at 40-50% depending on commodity [4]. The high PHL largely occur due to lack of access to storage facilities and poor market access. In order to lower PHL, small-scale farmers (SSF) need amongst other options, to access and/or to adopt postharvest cold chain technologies that include appropriate storage facilities. With appropriate storage facilities, farmers are able to control environmental factors of temperature and relative humidity, which are the two main causal factors for physiological deterioration in fresh produce if left uncontrolled [5]. Where storage facilities are absent, SSF are forced to store fresh produce under sub-optimal conditions, which results in senescence that reduces marketability of the produce [6]. The quality of fruits and vegetables is influenced by sensory properties of flavor and marketability amongst others [7]. For SSF located in remote areas who cannot access conventional electricity grid, renewable energy can be considered as an option if the chosen storage structure requires energy input.

Most importantly, the costs associated with a chosen storage facility should be anticipated prior to ascertaining affordability and ensuring sustainability. For the storage of fresh produce, modern cooling methods like mechanical refrigeration, cold rooms, hydro-cooling, forced air-cooling, and vacuum cooling could be available. However, these cooling methods are not suitable for use by SSF because of high initial capital investments, high energy input, higher production volumes requirement that are required for economies of scale [8]. There are

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predominant costs for cold storage facilities which are construction, operation, and maintenance that have to be taken into consideration. Emily *et al.* [9] suggested that operating costs in cold storage systems are influenced by how energy-intensive they are. Energy demands, in turn, are influenced by the cost of the material used, the dimensions of the storage chamber, the gradient of temperature between the outside and inside. The other factors to consider are the specific heat capacity of the fresh produce to be stored and the rate at which the crop respires during storage.

A small-scale and owner-built cold room with a performance temperature range of 4ºC to 12ºC and energy consumption of 300 kWh and 180 kWh per day could cost US$5,000 to US$10,000 [10]. Larger refrigerated cold rooms with a similar temperature performance range and energy consumption of up to 1200 kWh per day cost between US$15,000 to US$30,000. If SSF would adopt pre-fabricated small-scale cold storage rooms, it would cost them over US$20,000 as a capital investment [11]. Once a cold storage facility has been installed, there are annual maintenance costs, which are estimated at 10 percent of the initial installation costs that need to be expensed according to Emana and Nigussie [12]. Maintaining storage facilities is important, for example, if cold rooms are properly maintained, their lifespan can be extended to 20 to 30 years. Budgeting for and carrying out maintenance, guarantees return on investment [13].

The cost of a storage system is important, as it helps the farmer to know which storage system to use for their produce after harvest. A low-cost storage system is an advantage to the farmer, as opposed to the costly ones. Currently, other options of cooling, are evaporative cooling technologies, which could best suit SSF because of their lower construction and maintenance costs. Evaporative cooling is regarded as efficient, economical, and has a potential energy saving of about 75% [14].

However, the evaporative cooling method is limited to arid areas. For this technology to be extended to hot and humid areas, indirect air-cooling by incorporating an indirect heat exchanger (IHE) is required before the air enters the psychometric unit. The incorporation of an IHE requires an external energy source like solar. This means that indirect aircooling combined with evaporative cooling (IAC+EC) could be the panacea to the fresh produce cooling challenges experienced by SSF. There is currently a research gap as there is limited investigation of an IAC+EC system for storage of fruits and vegetables. Performance characterization of such a system in terms of how it affects physical and chemical properties of stored fresh produce is required.

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Therefore, the design specifications of the IAC+EC system introduce fans and a water pump for ventilation and water reticulation respectively. The incorporation of an IHE, fans and water pump, requires a power source, which can be provided by a solar photovoltaic (SPV) system. A battery bank facility can be incorporated for the provision of energy overnight. Literature shows that research on IAC+EC system is limited and that no cost characterization has been done to date. Thus, the objective of this study is, therefore, to characterise the performance of an IAC+EC system and further determine the financial and maintenance costs of setting up an IAC+EC system that is powered by a SPV.

MATERIALS AND METHODS

To determine installation, operation, and maintenance costs for IAC+EC for cold storage of fruits and vegetables, the system was constructed and assembled at the Ukulinga research station at the University of KwaZulu Natal in Pietermaritzburg, in South Africa located at 30°24'S, 29°24'E at an altitude of 721m. Pietermaritzburg is predominantly hot and sub-humid. The average long-term minimum and maximum temperatures in September range from 10.0 - 17.1 ^{o}C and 12 - 27 ^{o}C respectively, while the relative humidity ranges from 61.1 – 68.1 %.

Description of the cold storage system

The IAC + EC system consisted of a 53m^3 storage chamber (with a storage capacity of four tones of tomato fruit), IHE, multiple cooling pads, water tank buried underground, 260W centrifugal water pump (Pedrollo PVm 55). The flooring of the storage chamber was concrete mortar. Figure 1 is a pictorial and schematic diagram of the system.

The inner dimensions of the storage chamber were 2.34 m height x 5.88m length x 3.88m width. The storage chamber had a zinc wall of 0.6m thickness, which was insulated by polyurethane in between the zintec layers. The dimensions of the IAC+EC storage chamber are premised on the quantity of tomatoes that SSF needs to store per unit between one harvest and the next transport to the market. Two fans facilitate air-flow, with constant speed and positive pressure. The first being a 30W fan (UF25GC12, AC 115 V, 50/60 Hz) mounted next to the IHE and a second 290W fan (308,7/6-6/P3HL/25/PA) mounted at the entrance to the chamber.

The system was solar photovoltaic powered and consisted of nine 330 W solar panels (44.80V, 8.69 A), 145VDC-60A solar charge controller (SANTAKUPS

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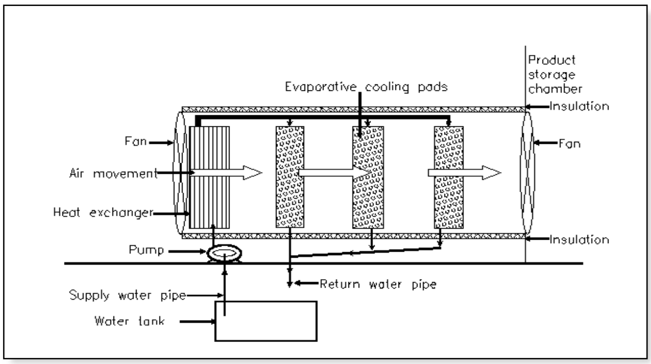
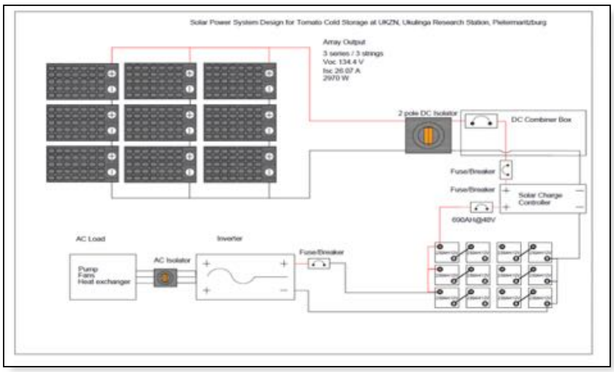
PC16-6015F) and 5kW-60A inverter (Sinowave, P11-LW5000NC48-C), as well as twelve 230 AH battery bank facilities. The array system consisted of three-string three-series solar panels, solar charge controller, inverter, and three string four-series batteries. This design arrangement of solar modules and batteries was able to power the cold storage system from the early morning of any day until 22.00 h at night when temperatures had dipped below 18^{o}C at which point the SPV system was switched off.

(A)



(B) Schematic diagram of storage chamber



(C) SPV system for the cooling

Figure 1: Storage chamber (A), Schematic diagram of chamber (B) and the SPV system (C)

The size of the storage chamber and the size of the available packing crates were used to determine the quantity of tomato product that could be stored per unit time. The cost of construction of the IAC+EC was a summation of individual costs of the storage chamber materials, psychometric unit (cooling pads, IHE, water reticulation

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system), SPV system, battery bank facility and electrical appliances (pump and fans). See detailed results on these in Table 5.

Quantity of tomatoes that can be stored per unit time in the storage chamber
The size of the IAC+EC storage chamber and the packing crates, venting space between the tomato layers and the bulk density of the tomatoes were used to determine the quantity of product that could be stored per unit time [15, 16]. The available packing crates used by farmers in Pietermaritzburg were plastic crates of dimensions; 0.500 m length x 0.300 m width x 0.230 mm height. The number of crates that could be contained in the storage chamber was determined by considering the inner dimensions for the storage chamber, which were 2.34 m height x 5.88 m length x 3.88 m width. In determining, the number of crates that could be stacked horizontally the following considerations were made:

(i) Packing space of 0.1m should be accommodated [15].

(ii) 0.9 m walkways to be left between the crates for ease of packing and unpacking by operators.

(iii) In the vertical stacking of the crates a spacing between crates of 0.025m should be left to enhance uniform air distribution [17].

(iv) The bottom crates are to be stacked on a 0.200m stand to minise transfer of diseases from the floor into the crates. A minimum distance of 0.5m left between the roof and the stacked crates to enhance uniform air distribution.

(v) Assume a bulk density of 694 $kg.m^{-3}$ for tomatoes [16].

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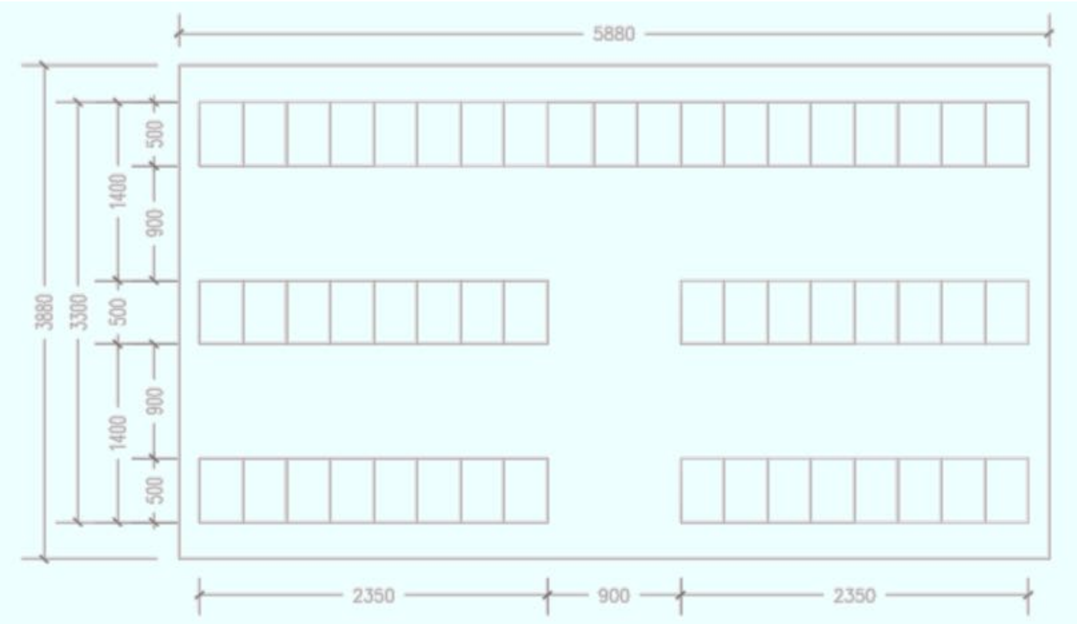

Figure 2: Schematic diagram showing the number of crates that can be stored on the floor of considering the storage chamber dimensions and the assumptions made

Total mass of tomatoes stored in storage chamber was calculated progressively using the equations 1 to 8 presented in Table 1 (adopted from Sibanda [18]). The storage capacity of the storage chamber was determined by first obtaining:

- The total number of crates stored horizontal (equation 3) was determined by the sum of the number of crates along the length of the storage chamber (equation 1) and the number of crates in the middle and along the storage chamber wall next to the door (equation 2).
- The total number of crates that can be stacked vertically. In the vertical stacking of the crates in the storage chamber, a spacing between crates of 0.025m was left according to Kim and Ferreira [17]. The height of stacking was determined using equation 4.
- The bottom crates were stacked on a 0.200m stand and a minimum distance of 0.5m was left between the roof and the stacked crates. Therefore, the total number of crates staked vertically was determined by using equation 5.
- The total number of crates that can be accommodated in the storage chamber is given by equation 6 which is a product of the number of crates stored horizontal and the number of crates stacked vertical. The product of mass of tomatoes stored in crate and the number of crates in the storage chamber determines the total mass that can be stored in the chamber. According to

Schurr [19] a space of 0.10m is left between the tomato layers when packing tomatoes in a crate. Therefore, equation 7 and 8 determine the volume and mass of tomatoes that can be stored in the storage chamber, respectively.

- If the bulk density of tomatoes is 694 kg.m^{-3} [16], mass of tomatoes per crate was calculated from equation 9.

Harvesting of tomatoes
Tomato Star 9037 cultivar was harvested at the green mature stage (at a farm 31km away in Pietermaritzburg) early in the morning into plastic crates were immediately loaded in a vehicle and transported to Ukulinga research station. The warm and dry season is the period when cooling intervention is most useful, and experiments were therefore, done between the dates 26 August 2018 to 22 September 2018. The environmental conditions of temperature and relative humidity in the storage chamber and under ambient were 14°C to 20°C, 87.8% to 97.4% and 20.0°C to 31.9°C, 46.6% to 80.7%, respectively, depending on the time of the day. Evaluation of the IAC+EC system was done through the determination of various characteristics and marketability of the tomato Star 9037 cultivar in storage over a 28-day period compared to ambient storage. The harvested tomatoes were stored in the IAC+ EC system and ambient conditions for a 28-days period and firmness, total soluble solids (TSS), colour, physiological weight loss (PWL), percentage marketability were monitored on a 7-days cycle.

Tomato Firmness (Puncture force)
In fresh farm produce, firmness is defined as the resistance to puncture [20]. The texture characteristics of tomato fruit in terms of firmness was determined through application of puncturing force on the surface using an Instron Universal Testing Machine (Model 3345) [21]. The tomatoes were mounted on a horizontal curved platform and a probe of diameter 2 mm was used to puncher the fruits. The probe drove into the tomato at a crosshead speed of 3 mm.s^{-1} to a depth of 7.5mm as described by Tolesa and Workneh [22]. The maximum force that was required to puncture the fruit was used as the exterior fruit firmness.

Colour of tomatoes
Changes in colour for fruits and vegetables determine the quality of the fresh produce and are associated with chlorophyll degradation and biosynthesis of lycopene. The tomato colour indicators were determined, using a digital CR-400 Chroma meter. This meter estimated the Hunter value L, a and b where according to Nath *et al.* [23], ‘a’ (‘+’ value 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 chromo meter was calibrated with a white paper before measurements were taken at day0, day7, day14, day21 and day28. Values for L*, a* and b* were measured at three equatorial positions (blossom end, stem-end and mid-way). These three values were averaged to obtain the overall values for L*, a* and b*. To determine changes in the colour of tomatoes, the L* value and the hue angle (h°) were measured. Using a* and b*, the hue angle (h°) for each tomato fruit was calculated from the equation 10 [24]:

$$\text{Hue angle} = \tan^{-1}\left(\frac{\text{b}}{\text{a}}\right) \tag{10}$$

Total Soluble Solids Content

After harvesting and during storage, the tomato fruit continues to ripen. During the ripening process, stored starch in the fruit transforms to sugars. As the ripening process, progresses further the sugar levels in the fruit increases. 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 total soluble solids (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 Tolesa *et al.* [25]. The 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.* [26].

Physiological weight loss (PWL)

The PWL is one of the methods that determines the quality of stored fresh produce like tomatoes [26]. Five sample tomatoes were weighed from each treatment (i.e for IAC+EC system and ambient conditions) using a scale (Teraoka, DIGI SM 300) at the start of the experiment on day 0 and this was repeated at seven-day intervals on days 7, 14, 21 and 28. The 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 at 7, 14, 21 and 28 days [27]. The equation 11, by Islam and Morimoto [26] was used to compute the percentage differential weight loss for each sample as percentage weight loss of the initial weight.

$$\%\text{Weight loss} = \frac{\text{Weight}_{(t=0)} - \text{Weight}_{(t=t)}}{\text{Weight}_{(t=0)}} \text{x}100 \tag{11}$$

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Where
$\text{Weight}_{(t=0)}$= average weight of sample at the start of experiment /interval and
$\text{Weight}_{(t=t)}$= average weight of the same sample of produce at t = t

Marketability of tomatoes
Tomato Star 9037 cultivar was harvested (at a farm 31km away in Pietermaritzburg) early in the morning into plastic crates at the mature green stage and were immediately loaded in a vehicle and transported to Ukulinga research station. Evaluation of the IAC+EC system was done through the determination of marketability of the tomato Star 9037 cultivar in storage over a 28-day period compared to ambient storage. The warm and dry season is the period when cooling intervention is most useful, and experiments were therefore, done between 26 August 2018 to 22 September 2018. The environmental conditions of temperature and relative humidity 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. The harvested tomatoes were stored in the IAC+ EC and ambient conditions for a 28-days period and firmness, total soluble solids (TSS), colour, physiological weight loss (PWL) percentage marketability was monitored on a 7-days cycle. The descriptive quality attribute of marketability of tomatoes was evaluated according to the scoring method of Awole *et al.* [28]. This method subjectively determines the quality attributes of tomatoes by observing the level of visible mould, colour changes, surface defects, decay, shriveling (dehydration) and shine. On the sampling day, five tomatoes were randomly selected from the IAC+EC system and ambient conditions and visual assessed. Awole *et al.* [28] method rated the tomatoes from 1 to 9, with 1 to 3 denoting 'unusable to unsalable' while scores ranging 5 to 9 denoted 'fair to excellent'. Only tomato fruits that attained rating of '5'and above were considered marketable. Percentage marketability was determined using the following equation 12:

$$\%\ \text{Marketability} = \frac{\text{Total no. of tomatoes receiving a rating of five and above}_{t=0}}{\text{Total no. of tomatoes at start of experiment}_{t=0}} \text{x}100\% \qquad (12)$$

The experimental design consisted of a combination of one tomato variety, two storage conditions (IAC+EC storage chamber, and ambient). Each storage condition was replicated three times (three crates). A total of 75 kg of tomatoes in six crates (12.5 kg of tomatoes per crate) were prepared for the experiment. Three crates of tomatoes were stored under IAC+EC conditions, while another three crates were stored under ambient conditions. In each replica, 25 tomatoes were marked and five were selected for quality attribute assessment of sensory (marketability) over five-storage periods of day 0, day 7, day 14, day 21, and day 28. Data were recorded on days 0, 7, 14, 21, and 28 from the start of the experiment (after storage), in order to determine percentage 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.

Economic considerations for the 53m^3 evaporative cooling storage
The costs of setting up storage facilities are determined prior to choosing the storage facility option. The predominant costs for storage facilities are construction, operation, and maintenance. In this study, the installation costs were obtained from enumerating the material used and labour to construct the IAC+EC system i.e. psychrometric unit, storage chamber and SPV system. The cost for the 53-m^3 storage structure was calculated for storage of the tomato fruit under the following assumption:

- The storage chamber is used for storage of 3,825 kg of tomatoes.
- The tomato fruit is stored in batches for a period of 28 days, which is the period that the tomatoes had the highest marketability. There after another full batch of tomatoes will be brought in and this will be repeated throughout the year.
- The marketability of the tomato fruit within 28 days is 71% and 46% for tomatoes stored in the IAC+EC and under ambient respectively.
- The cold storage structure is placed on the farmer's own premises and therefore there will be no rental expenses.
- No insurance and taxes are involved in the cold storage structure.

Payback period
The cost analysis of choosing a facility involves considering the payback which Newnan [29] defined as the investment of time required for an investment to equal the cost of the investment period. The payback period for this study was calculated using equation 13 by Wang *et al.* [30].

$$\text{Payback period (years)} = \frac{\text{Initial costs}}{\text{Cost savings per year}} \quad (13)$$

The operating costs are zero rated for comparison as the same farm workers will be used to operate the IAC+EC and are therefore no additional labour is required.

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The maintenance costs are assumed as 10% of the initial costs per annum according to Emana and Nigussie [31], equation 14.

$$\text{Mantenance costs } = 0.10 \text{ x initial costs} \tag{14}$$

RESULTS AND DISCUSSION

Quantity of tomatoes that can be stored a per unit time in the storage chamber

Table 2 presents the progressive calculations of the total mass of tomatoes stored in storage chamber using the equations 1 to 8 obtained in Table 1. Based on the computation in Table 2, the storage capacity of the chamber was found to be approximately 3,825 kg, which was the weight of tomatoes that could be stored per unit time. Indirect air-cooling combined with evaporative cooling systems require an energy input for driving the electrical components, which is usually supplied electrically. For areas where grid electricity is not available, and is unlikely to be available in the next few decades due to the huge financial outlays involved, one can develop a structure for SSF for temporary storage of about four tonnes of tomatoes. There are available trucks in South Africa to transport fresh produce once a week to markets, and therefore in a worst case scenario, farmers would need to temporarily store tomatoes for a maximum period of seven days between one harvest and the next.

Tomato Firmness

Firmness is the ultimate quality index influencing consumers in decision making at the time of selection of tomatoes to purchase or not. The effects of storage conditions and storage period on the firmness of the green-harvested tomato fruit were significant ($P<0.01$) as shown in Figure 3. The tomatoes stored in the cold storage conditions were 28.1% more resistant to puncture than those stored under ambient conditions over the 28-day period. The average firmness over the period for tomatoes stored under the IAC+EC system was 9.82 N mm^{-1}. Values of firmness greater than 8.46 N $mm.^{-1}$ indicates that tomatoes are very firm and suitable for retailing [32]. 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 fresh produce quality leading to an extended shelf life. These results agree with findings of Zakari *et al.* [33] who used an evaporative cooling system under dry and arid conditions and observed that tomatoes in the cooler had higher firmness values. The average firmness of tomatoes decreased significantly with storage period from day 0 to day 28. The longer the storage period, the longer enzymatic activity continues resulting in more tissue softening

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leading to reduced fruit firmness. Tolesa and Workneh [22] in their work, observed a similar decline in tomato firmness over storage a certain period.

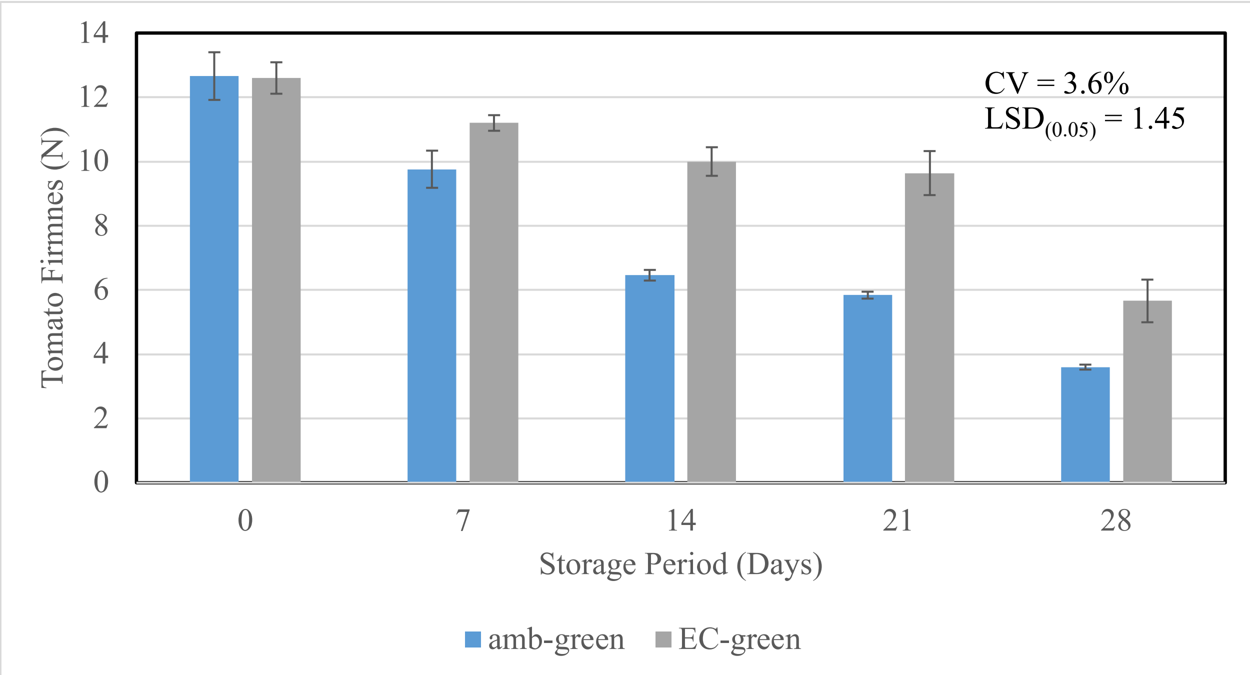

Figure 3: Tomato firmness under ambient conditions and IAC+EC

The decrease in firmness is attributed to physiological deterioration in tomato as the fruit continues to transpire, respire and further ripen.

Tomato fruit colour

Table 3 shows that both the h° and L* values were significantly (P<0.05) affected by storage condition and the storage period. The h° and L* values decreased progressively over the period of storage from 84% at day 0 to 48.31% and 50.43% at day 28 under ambient and IAC+EC conditions respectively. A decrease in both h° and L* values with storage period indicates progressive colour change from green or pink to red as the fruit ripens. Cherono *et al.* [34] had similar observation of colour changes with storage time. As the green-harvested tomato ripens, there is colour change from green to white through chlorophyll degradation, then white to red by carotenoid biosynthesis [35]. The lowest values coincide with time when the tomatoes have attained a deep red colour.

Total Soluble Solids Content

Table 4 presents the total soluble solids (TSS) of the green-harvested tomatoes subjected to either ambient conditions or IAC+EC storage conditions over 28 days. The storage conditions and the storage period significantly (P<0.01) had an influence on the TSS content. The tomatoes stored in the IAC+EC storage chamber had on average lower TSS content values compared to ambient conditions over the storage period. Lower TSS values imply a lower concentration of sugar. A general increasing trend in the TSS was observed but was most evident at ambient conditions, compared to the IAC+EC storage conditions. Lower TSS values imply a lower concentration of sugar. Similar findings were observed by Tolesa *et al.* [25] on the storage of mangoes.

At low temperature and high relative humidity storage conditions, the rate of increase of TSS content was slower, compared to storage at ambient conditions. The increased temperature and reduced relative humidity at ambient conditions is 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.

The two-way interactions between storage conditions and storage period significantly ($P \leq 0.05$) influenced the TSS accumulation (Figure 4).

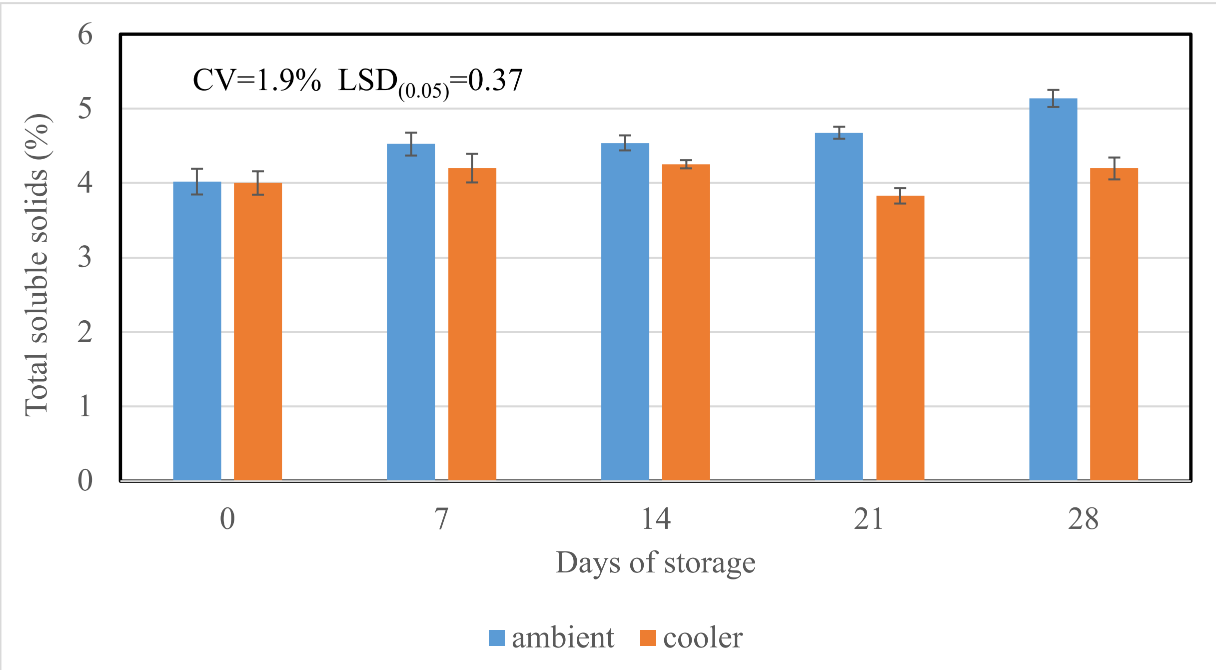

Figure 4: Percentage total soluble solids of green and pink harvested tomatoes

The TSS content increased with storage period both for the IAC+EC storage system and ambient conditions. This agrees with Tolesa and Workneh [22], that concluded that changes occur in sugar content during the development of tomato

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fruit increases progressively throughout the storage period as the fruit matures and ripens. This is normally associated with the first appearance of yellow pigment in the walls of the fruit at the breaker stage through to red. When tomatoes mature, the sugar levels increase, due to the metabolism of stored carbohydrates, lipids and proteins [36]. It is therefore very critical to adopt postharvest cooling technologies, such as IAC+EC to slow down respiration and ethylene production as a way of increasing the shelf life.

Physiological Weight Loss (PWL)

The PWL of green-harvested tomatoes subjected to storage conditions of either IAC+EC or ambient conditions and stored over a 28- day are presented in Figure 5. During the period of observation, the storage conditions and the storage period significantly (P<0.01) influenced PWL of stored tomatoes. The highest PWL was found in tomatoes stored under ambient conditions due to the considerably higher temperatures and lower relative humidity compared to the IAC+EC storage conditions over the 28 days storage period. Higher temperatures and lower relative humidity storage conditions induce a larger vapour pressure deficit between the fruit and the surrounding external environment. This creates a driving force for moisture loss from the fruit. These findings are consistent with reported observations by Islam and Morimoto [26].

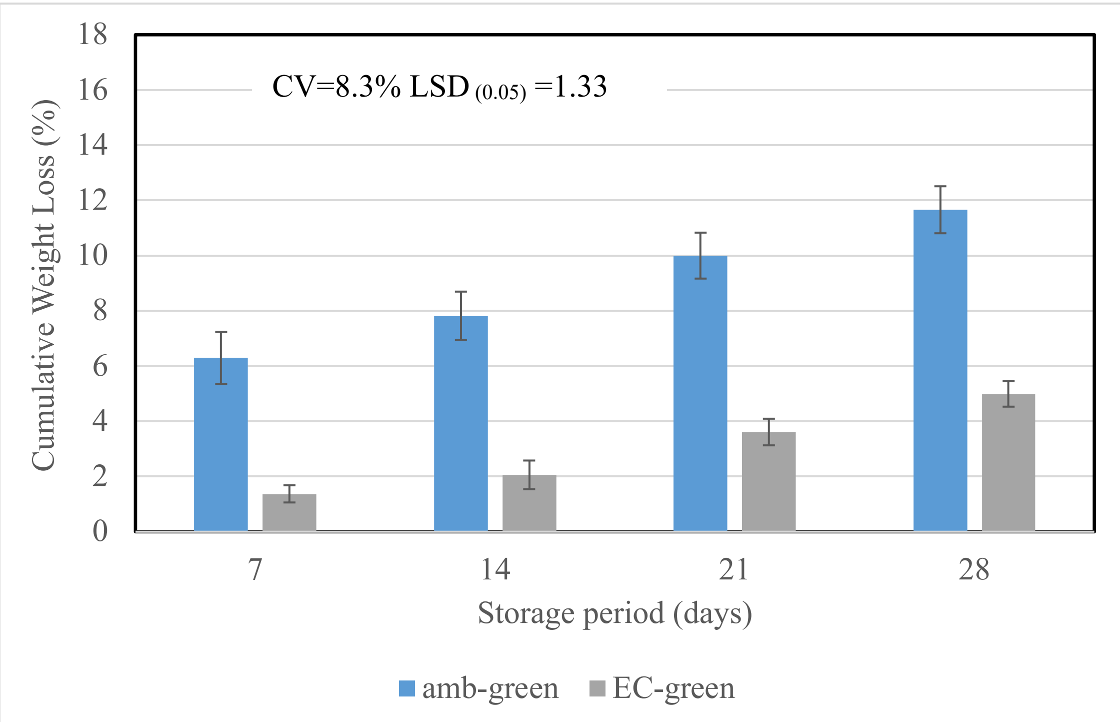

Figure 5: Physiological weight loss during storage period

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The 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. 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.* [34] in their research study had similar observations. Therefore, the use of IAC+EC system for preserving and improving the shelf life of tomatoes cannot be avoided.

Marketability

The percentage of marketability of tomatoes was at 100% on day 0 and decreased with storage period and was lowest at day 28. Tomatoes stored under IAC+EC conditions had a higher average percentage marketability (72.4%) than those under ambient conditions (40.9%) over the storage period (Figure 6). The higher percentage marketability for tomatoes under IAC+EC is attributable to the low temperature storage conditions of the storage chamber, which resulted in lower moisture losses.

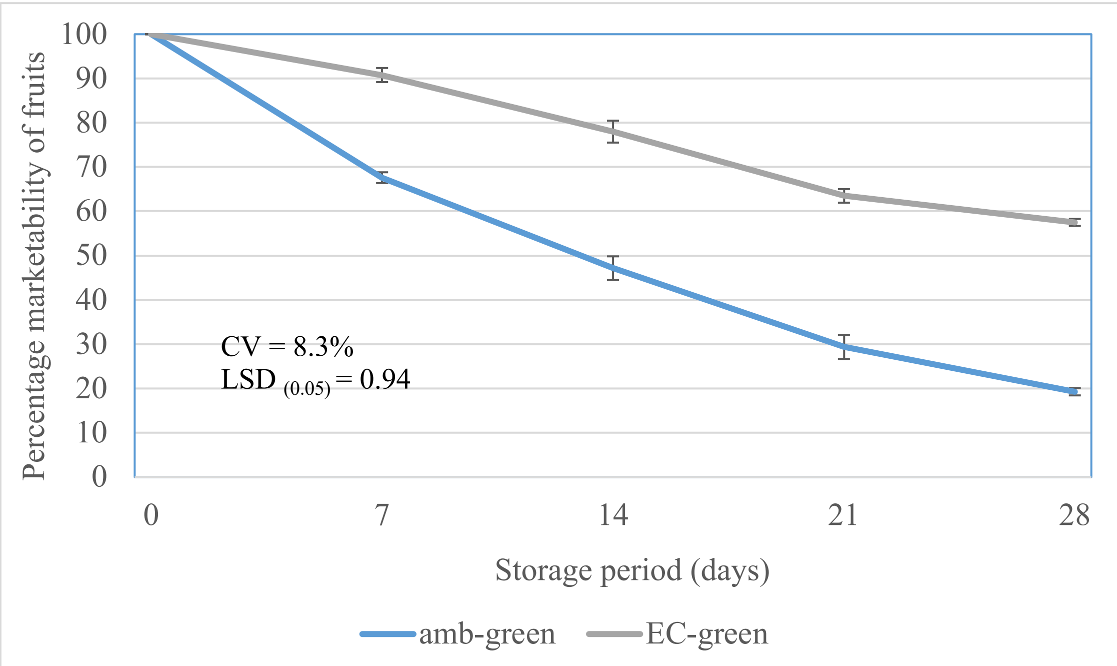

Figure 6: Percentage marketability of tomatoes during storage period

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 [37]. Marketability drastically decreased at ambient conditions from 100% to 47.2% by day 14 and could have decreased further if there were more days with high temperatures during the period of observation.

Figure 7: Visual observation of tomatoes stored under IAC+EC (A) versus tomatoes under ambient conditions (B) after three weeks

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 (Figure 7). 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 on day 28. Under IAC+EC, the tomatoes were at 63.5% and 57.5% marketability at day 21 and day 28 while for ambient conditions there was a sharp decline to 29.4% and 19.3% respectively. Marketability is expected to have been higher under the controlled conditions since Sibanda and Workneh [38] found that tomatoes stored in the IAC+EC system were 18.9% firmer, maintained a 10.5% lower concentration of sugars, increased the hue angle by 3%, and had 6.31% lower PWL than tomatoes stored under ambient conditions. Therefore, indirect air-cooling combined with evaporative cooling system preserved the organoleptic properties of the tomatoes.

Economic Evaluation

The cost of a solar photovoltaic powered IAC+EC system depends on the initial capital investment, operating and maintenance costs as alluded to by Sahdev *et al.* [28] for green house drying. The installation costs derived from the cost of material for construction are summarised in the Tables 5. The cost of installing a solar powered IAC+EC system are enumerated and summed in Table 5. The operating costs are zero rated for comparison as the same farm workers will be used to operate the IAC+EC and are therefore no additional labour. The maintenance costs are assumed as 10% of the initial costs per annum according to Emana and Nigussie [12].

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$$\text{Mantenance costs } = 0.10\text{xUS\$8,680} = \text{US\$868}$$

Payback period was calculated using equation 13. The capital cost of the cooler was US$8,680 and assuming that each SSF in Pietermaritzburg invests in one IAC+EC and that there are no risks of losses in the evaporative cooled storage. It should be noted that this cost could significantly reduce in countries where there are subsidies (for batteries and solar modules) for enterprises that incorporate use of renewable energy sources.

The storage chamber accommodates 3,825 kg of tomatoes and the marketability of the green-harvested fruit within 14 days is good 78% and 47% in the IAC+EC and under ambient respectively. There is a difference of 31% in marketability of tomatoes in IAC+EC and ambient conditions. If the 3,825 kg stored in the IAC+EC are sold in 14 days, then the farmer is able to store two batches per month totaling 7,625 kg. In 12 months, a farmer can store 91,500 kg under continuous production and are available for sale under 100% marketability. Fresh produce like tomatoes is available throughout the year. The computation for each produce depends on the number of months that fruit or vegetable is available per year. The difference for tomatoes available for sale per year as result of the use of cooler if the price of tomatoes is US$0.20 per kilogram:

$$\text{Savings per year } = 0.31\text{x}91500\text{x}0{,}2 = \text{US\$5,673}$$

The payback period is calculated from Wang *et al.* [29] equation 13:

$$\text{Payback period (years)} = \frac{8680}{5673} = 1.5$$

Small-scale farmers can adopt IAC+EC technology in hot and sub-humid to humid areas, as this should be viable as it takes 1.5 years to recoup the initial capital investment. For small-scale farmers that would grow tomatoes throughout the year this is a viable option and if seasonal a subsidy or complete funding from government and other agencies would be required. Wayua *et al.* [39] found payback periods of 1.2 years and 1.3 years in their research activities for evaporative cooling. A payback period of 1.5 years is regarded as viable [40]. A payback period of less than two years will further allow replacement of storage batteries as they generally have a much shorter life span (3 years) than the photo voltaic array as alluded to by Eltawil and Samuel [41]. The most important economic benefit of use of IAC+EC system is safeguarding against high PHL incurred by SSF if the produce is stored under ambient environmental conditions. Use of a SPV energy use safeguards against reliance on grid electricity, which is becoming expensive and unreliable in South Africa. In addition, the materials used for construction were locally sourced and are inexpensive. Further, the estimated potential benefits to consumers and producers are substantial considering the quantities that will reach the market and the effect on the price. Therefore, the use of IAC+EC system in fruit and vegetable production in hot and humid areas should be promoted as an alternative technology for SSF and emerging farmers. While mechanical refrigerators of the same capacity could be cheaper, but they require electricity, which is not available.

CONCLUSION

This study aimed at characterizing the IAC+EC system and assessing the marketability of tomatoes stored in such a system compared to storage under ambient conditions. The study further determined the construction and maintenance costs of establishing such a low cost cooling storage system for fruits and vegetables that uses renewable energy in Pietermaritzburg, South Africa. Results from the study revealed that IAC+EC system could be promoted as, applicable technology in areas with no access to grid electricity; proven low cost and acceptable among smallholder farmers. This is in a bid to try to reduce the PHL experienced by SSF. The study showed that tomatoes stored under the IAC+EC system were firmer and had lower TSS content and PWL compared to those stored under ambient conditions. The IAC+EC system increased shelf life of green-harvested tomatoes to 28 days with improved marketability. The cost to construct an IAC+EC system integrated with a solar photovoltaic system were US$8,680 with a 10% annual maintenance costs and the payback period was observed to be 1.5 years. A payback period of 1.5 years is regarded as economically worthwhile and viable as the solar photovoltaic powered IAC+EC safeguards SSF' reliance on ambient storage environment to mitigate PHL. This study recommends that government or other relevant stakeholders assist farmers to acquire such a technology to enhance their productivity, improve shelf life of their products and enhance marketability.

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Table 1: Determination of the total mass of tomatoes stored in storage chamber using progressive using the equations

Horizontal stacking	
No. of crates along the length of the SC (N1)	$= \frac{\text{Length of the chamber(m)}}{\text{Width of crates (m)}}$ (1)
No. of crates along N2	$= 2 \times \frac{\text{Length of the chamber (m)} - 0.90\text{ m}}{\text{Width of crates (m)}}$ (2)
The total no. of crates stored horizontal	$\text{N1} + \text{N2}$ (3)
Vertical stacking	
Height of stacking	$= \text{height of crate} + 0.025\text{m}$ (4)
No. of crates stacked vertically	$= \frac{\text{Height of storage (m)} - (0.2\text{ m} + \text{distance between roof and staked crates (m)})}{\text{Height of stacking}}$ (5)
Total crates stored in the SC	$= \text{No. of crates stored horizontal} \times \text{No. of crates stored vertical}$ (6)
Mass of tomatoes in the storage chamber	
Volume of tomatoes per crate in SC	$\text{Length of crate (m)} \times \text{Width of crate (m)} \times (\text{Height of crate (m)} - \text{spacing between tomato layers (m)})$ (7)
Mass per crate	$694\text{ kg.m}^{-3} \times \text{Vol occupied by tomatoes in one crate}$ (8)
Total mass of tomatoes in SC	$= \text{Mass per crate (kg)} \times \text{No. of crates}$ (9)

*SC storage chamber

**N2 is the number of crates in the middle and along the SC wall next to the door

(Table adopted from Sibanda, 2019)

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Table 2: Progressive calculations of the total mass of tomatoes stored in storage chamber

Horizontal stacking	
No. of crates along the length of the SC (N1)	$= \frac{5.88\ (\text{m})}{0.30\ (\text{m})} = 19\ \text{crates}$
No. of crates along N2	$= 2 \times \frac{5.88\ \text{m} - 0.90\ \text{m}}{0.30\ \text{m}} = 32\ \text{crates}$
The total no. of crates stored horizontal	$19 + 32 = 51\ \text{crates}$
Vertical stacking	
Height of stacking	$= 0.23\ \text{m} + 0.025\text{m} = 0.255\text{m}$
No. of crates stacked vertically	$= \frac{2.340\text{m} - (0.2\ \text{m} + 0.5\ (\text{m})}{0.255\text{m}}$
Total crates stored in the SC	$= 6\ \times 51 = 306\ \text{crates}$
Vol of tomatoes per crate in SC	$0.5\ (\text{m}) \times 0.28\ (\text{m}) \times \big(0.23\ (\text{m}) - 0.10\ (\text{m})\big) = 0.018\ \text{m}^3$
Mass per crate	$694\ \text{kg.}\,\text{m}^{-3}\ \times 0.018\text{m3} = 12.5\ \text{kg per crate}$
Total mass of tomatoes in SC	$= 12.5\text{kg per crate (kg)} \times 56\ \text{crates} =$ $3825\ \text{kg}$

*SC storage chamber
**N2 is the number of crates in the middle and along the SC wall next to the door

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Table 3: Changes in L values and hue angle of tomatoes subjected to treatments of storage conditions

			L values		
Treatment	**Day0**	**Day7**	**Day14**	**Day21**	**Day28**
Ambient	57.49[k]	46.16[h]	41.52[fg]	39.16[cdef]	34.12[a]
Cold storage	57.08[k]	46.71[h]	47.13[hi]	38.96[cde]	36.12[ab]
Storage (A)			<0.05		
Day (B)			<0.001		
A x B			<0.05		
$LSD_{0.05}$ = 1.168, CV (%) = 4.2, SE = 0.812					

			H values		
Treatment	**Day0**	**Day7**	**Day14**	**Day21**	**Day28**
ambient	84.68[d]	56.31[abc]	51.55[a]	52.91[a]	48.31[a]
Cold storage	84.78[d]	58.10[abc]	68.53[bc]	55.73[ab]	50.43[a]
Storage (A)			<0.05		
Day (B)			<0.001		
A x B			NS		
$LSD_{0.05}$ = 6.803, CV (%) = 9.2, SE = 3.416					

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Table 4: Changes in TSS (%) of tomatoes subjected to treatments of storage conditions and storage period

	Total Soluble Solids (%)				
Treatment	**Day0**	**Day7**	**Day14**	**Day21**	**Day28**
Ambient	3.848[ab]	4.446[bcdef]	4.472[cdef]	4.538d[ef]	4.980[fg]
Cooler	3.832[a]	4.068[abcd]	4.140[abcd]	4.162[abcd]	4.402[cde]
Significance level					
Storage (A)			<0.001		
Day (B)			<0.001		
A x B			<0.05		
$LSD_{0.05}$ = 0.0.163, CV (%) = 1.9, SE = 0.135					

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Table 5: Costs associated with establishment of solar photovoltaic and IAC+EC systems

Direct Costs	Unit price (US$)	Total costs (US$)
Solar modules (9 x 330 W)	253	3,036
Solar batteries (230 AH x 12)	284	3,408
Charge controller	300	300
Inverter	700	700
Indirect Heat exchanger	310	310
Water pump (0.26 kW)	80	80
Fan (x2)	146	292
250 L Water tank and Float	83	83
Water reticulation system	63	63
Charcoal for pads	40	40
Storage chamber insulating material	60	60
Storage chamber	400	400
Labour	667	667
Grand Total	US$8680	

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