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The Influence of Indirect Air-Cooling Combined with Evaporative Cooling on Tomato Fruit Cooling Time and Temperature

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Abstract

This study developed a low cost and affordable to small-scale farmers' indirect air-cooling combined with evaporative cooling (IAC+EC) system for storage of fruit and vegetables under both arid and hot; and humid and hot climatic conditions. Field heat from freshly harvested produce should be immediately removed through cooling to the desired storage temperature. The aim of this study was to determine the effectiveness of IAC+EC system in terms of the cooling time requirement of the fresh tomato fruit. A fresh tomato cooling experiment to remove field heat during the summer month of September in Pietermaritzburg was conducted for 36 hours where the IAC+EC system was compared to storage under ambient conditions. The results showed that 16 hours was required to reduce the flesh temperature of tomatoes to 16.5°C while the flesh temperature for tomatoes under ambient conditions followed the ambient temperature profile with time of storage. The IAC+EC system reduced and maintained the microenvironment air temperature inside the coolers to 16.5°C - 19°C. The ambient temperature varied between 21 and 32°C. The results in this study are evidence that IAC+ EC system can be a choice for farmers, for cooling the fresh by reducing the field temperature after harvest.

Keywords: Small-scale farming; Field heat; Evaporative cooling; Flesh temperature.

1. Introduction

Tomato fruit is climacteric with a short shelf life of 2 to 3 weeks and exhibits high postharvest losses of 20-50% [1]. Tomatoes are living tissues that continue to transpire, respire and further ripen even after detachment from the mother plant [2]. High temperature and low relative humidity in a storage facility result in, excessive water loss from produce, firmness reduction and an undesirable shriveling appearing in fruits and vegetables [3]. Fresh produce require immediate cooling after harvesting to remove field heat, reduce flesh temperature, slow the ripening process, reduce physiological deterioration, maintain quality and extend shelf life [4-7]. Precooling of fresh produce should be rapid to ensure optimum storage temperature is achieved as quickly as possible after harvesting [8]**.** Once the fresh produce is under storage there should be even distribution of air blown through the crop to reduce the cooling time. The rate of cooling is a function of the temperature gradient of the cooling medium and cooling temperature-time studies for mechanical refrigerated cooling systems [9].

A number of modern day mechanical refrigerated cooling systems such as vacuum cooling and hydro cooling exists but are both capital and energy intensive [10]. Such systems require grid electricity which most small-scale farmers in sub-Saharan Africa in remote and dispersed populations have no access to. However, cheaper and environmental friendly methods like evaporative cooling can be used. Evaporative cooling is effective under hot and arid conditions and indirect air-cooling can be combined with evaporating cooling (IAC+EC) under hot and humid conditions because of inherent high relative humidity of the air. Indirect air-cooling is achieved through use of a suitable desiccation media before evaporative cooling by use of an indirect heat exchange, which is a focus of this study. The IAC+EC system for this study used a hybrid of solar modules and a battery bank to provide energy for the water pump, heat exchanger and fans to facilitate immediate cooling of fresh tomatoes after harvesting. No experimental studies have been published where cooling rates were measured on IAC+EC systems. The solar modules provided power from 06h00 to 18h00 while the battery bank provided energy after the sunshine period from 18h00 to 22h00 as it takes some time for the ambient air temperature to decrease substantially after sunset to 20^{o}C and below.

For this work, two tomato crates were placed on wooden pallets; one at the centre of the IAC+EC storage chamber while the other crate was under ambient conditions in the Food engineering laboratory. To determine the speed of cooling for each tomato fruit, both the ½ and the 7/8th cooling time equations were used [11]. This study seeks to determine the efficacy of IAC+EC in relation to the rate of cooling for fresh produce by investigating the temperature-time profile inside the IAC+EC systems for the tomato fruit. Hence, the objective of this study is to compare the cooling time and temperatures of the IAC+EC to ambient conditions.

2. Cooling Time Equations

In order to determine the time that is required to cool tomatoes from the field temperature to the optimum storage temperature, half-cooling time (Equation 1) and seven-eighths cooling time (Equation 2) methods were used.

$$Z = ln\left(\frac{0.5}{C}\right) \quad (1)$$

$$S = \ln\left(\frac{8j}{C}\right) \quad (2)$$

Where Z = half cooling time [hours]; S = seven eighths cooling time [hours],
C = cooling coefficient [dimensionless], and J = lag factor [dimensionless],
[12].

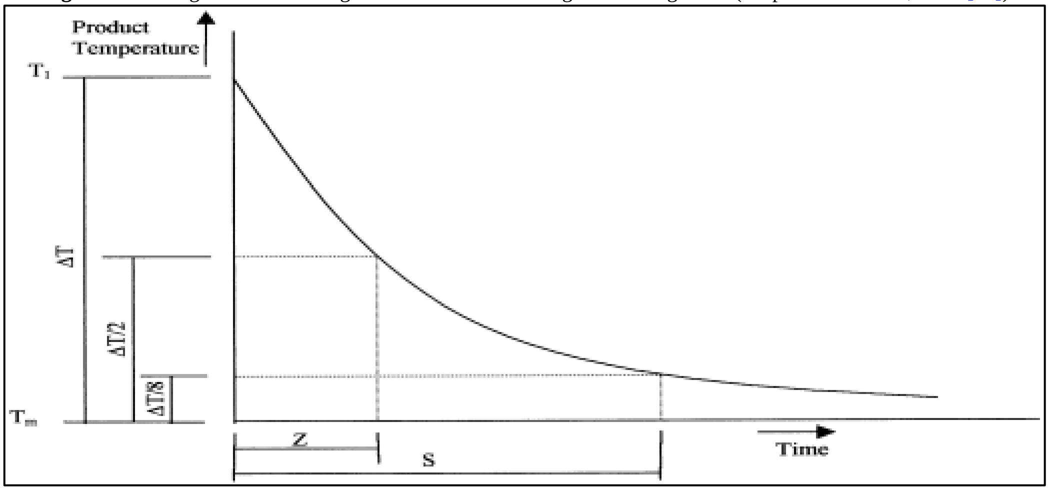
$$C = \ln\left(\frac{Y}{\theta}\right) \quad (3)$$

$$Y = \frac{T - T_m}{T_i - T_m} \quad (4)$$

Where Y = temperature ratio [°C]; T = temperature at any point in the product [°C];
T_m = temperature of cooling medium (air) [°C]; T_i = initial temperature [°C] and
C = cooling time or operating time [hours] [12].

The cooling time equations were used to derive the rate of cooling curves over time, which tend to follow the same basic curve of Wills, *et al.* [13] which diminishes exponentially as a logarithmic function. A typical cooling curve with constant air temperature and log-linear profile is shown in Figure 1.

Figure-1. Cooling curve illustrating the half and the seven eighths cooling times (adopted from Wills, *et al.* [13])

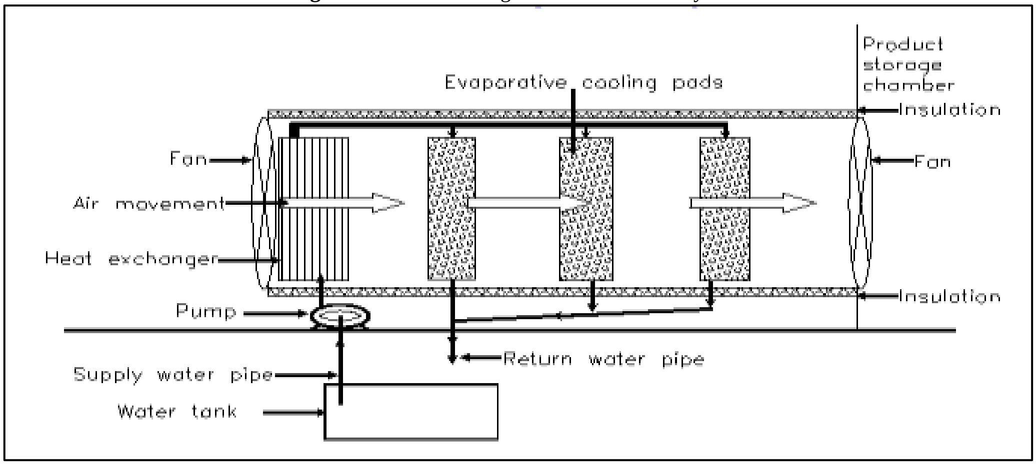


3. Methodology

3.1. Experimental Study Site

To determine the cooling time for the tomato fruit stored under IAC+EC system and ambient environmental conditions, a study was done in Pietermaritzburg (PMB), in South Africa. The IAC+EC system and ambient conditions were used to store tomatoes over a period 36 hours from 13h00 in the summer month of September 2019 to 01h00 of the third day.

Figure-2. Schematic diagram of the IAC+EC system



The IAC+EC system was constructed and assembled on site at Ukulinga research station at the University of KwaZulu Natal, in PMB. The site is located at 30°24'S, 29°24'E at an altitude of 721 m. Solar modules and a battery-bank facility to run, indirect heat exchanger (for indirect air-cooling), water pump for water reticulation and fans for ventilating the storage chamber powered the IAC + EC system. Figure 2 is a schematic diagram of the IAC+EC system. The solar modules provided power from 06h00 to 18h00 (12 hours) while the battery bank facility provided energy after sunshine period (18h00 to 22h00) as it takes time for ambient air temperature to decrease substantially after sunset. The IAC+EC system was switched off 4-hours into the night-time during which time the ambient temperature to dropped to 20^{o}C and below.

3.2. Harvesting and Storage of Tomatoes

Tomato Star 9037 cultivar was harvested into plastic crates from a nearby farm in PMB. Harvesting of the tomatoes was done before 11h00 (field temperature of 30^{o}C) and the tomatoes were immediately loaded in a car and transported to Ukulinga research station located 31 km away (29.67° S and 30.40° E, 840 m above sea level). The tomatoes were prepared on arrival for the experiment at room temperature. Visual inspection helped discard tomatoes with bruises and signs of infection from the fruits used as samples [14]. The selected tomatoes were packed and kept in two crates (12.5kg) under ambient conditions until the start of the experiment on the same day at 13h00 and at ambient temperature of 32^{o}C. One tomato crate was placed on wooden pallets at the centre of the IAC+EC storage chamber (18.4^{o}C) while the other crate was placed on wooden pallets under ambient conditions of (32^{o}C) in Food engineering laboratory at the start of the experiment. The crates of tomatoes were placed on wooden pallets to keep produce off the ground, reducing the likelihood of infection of tomatoes with soil borne diseases and mould as described by Obura, *et al.* [15].

3.3. Measurement of Storage Temperatures

Six (three for each storage condition) digital HOBOs (HOBO Prov2 Part No. U23-001) were located one at the centre, middle and exhaust end of the IAC+EC storage chamber and the Food engineering laboratory to capture hourly storage chamber and ambient temperatures respectively from 13h00 until the end of the experiment. To begin the experiment the doors of the IAC+EC storage chamber and Food engineering laboratory were closed and readings recorded hourly for the duration of 36 hours.

3.4. Determination of the Temperature Profile of Tomatoes

To determine the temperature profile of tomatoes stored inside the IAC+EC and under ambient storage conditions; Omega K-type thermocouples were used in conjunction with data loggers to collect hourly temperature at the geometric centre of three tomato fruits in each crate [9].

3.5. Determination of Temperature Profile using Cooling Curve Equations

3.5.1. Data Collection

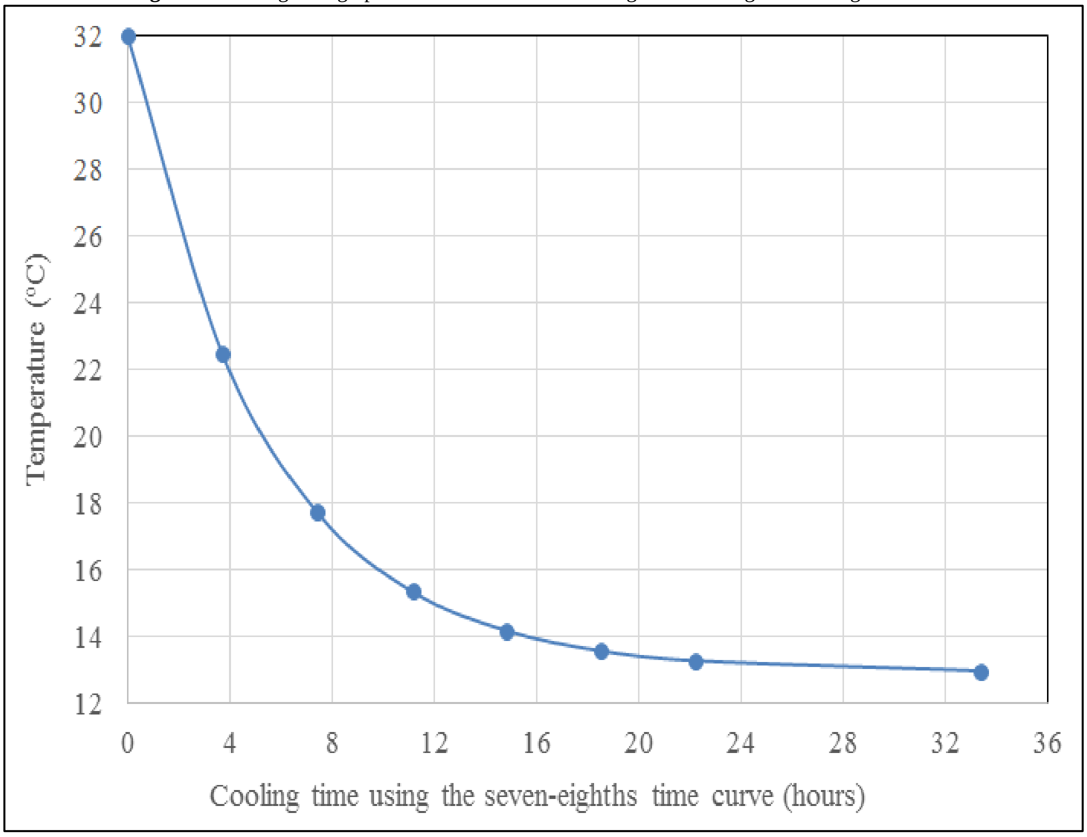
The experiment consisted of two cooling approaches, IAC+EC system and the control, which was ambient conditions. A comparison of cooling rate over time of the tomato fruit under the two storage conditions was done. The experimental data collection involved the hourly measurement of environmental parameters of temperature for the 36 hours of the experiment. In the period selected, there was a significant temperature gradient between IAC+EC and ambient storage conditions that would affect the metabolism rate in the tomato fruit resulting in varying cooling times graph. From 22h00 to 05h00, the average ambient temperatures in PMB is below 20^{o}C and the IAC+EC system was switched off during this period as tomatoes can tolerate temperatures between 13-21^{o}C for short periods. The temperature data obtained at the centre inlet, centre of the storage chamber and the centre of wall on the exhaust side was averaged and used for discussions. The experiment was mainly concerned with evaluating the cooling performance, in terms of the temperature reduction of cooling of the two cooling approaches. These temperature profiles were then contrasted with the half and seventh eights cooling curves developed by Henry and Bennett [16].

4. Results and Discussions

4.1. Cooling Time Using the Seventh-Eight Times

According to Thompson, *et al.* [17], cooling of tomatoes should take place within 16 hours otherwise, a marked deterioration in quality occurs after this period. The 7/8th cooling times were calculated for thermocouples set in the storage chamber of the IAC+EC system. In determining the time required to cool tomatoes from the field temperature to the optimum storage temperature, half-cooling time and seven-eighths cooling time methods as defined by Equations 1 to 4 were used with the following assumptions made that θ = 16 hours; $T = 15^oC$; $T_m = 14^oC$; $T_i = 32^oC$; and j = 1. From these assumptions and equations for half and seventh-eighth cooling times, the cooling time and the corresponding cooling temperature were calculated and are presented graphical in Figure 3 for tomatoes harvested at an ambient air temperature of 32^{o}C. The seven-eighths cooling time was found to be more practical because the temperature of the produce at seven-eighths is close enough to the target storage temperature [12]. The cooling time curve predicts that when warm tomatoes are cooled the rate of cooling will not be constant but will diminish exponentially as the temperature gradient reduces. The cooling curve follows a logarithmic function, with rapid cooling initially followed by a slower rate as alluded to by Prange [18].

Figure-3. Cooling time graph for harvested tomatoes using the seven-eighths cooling time curve



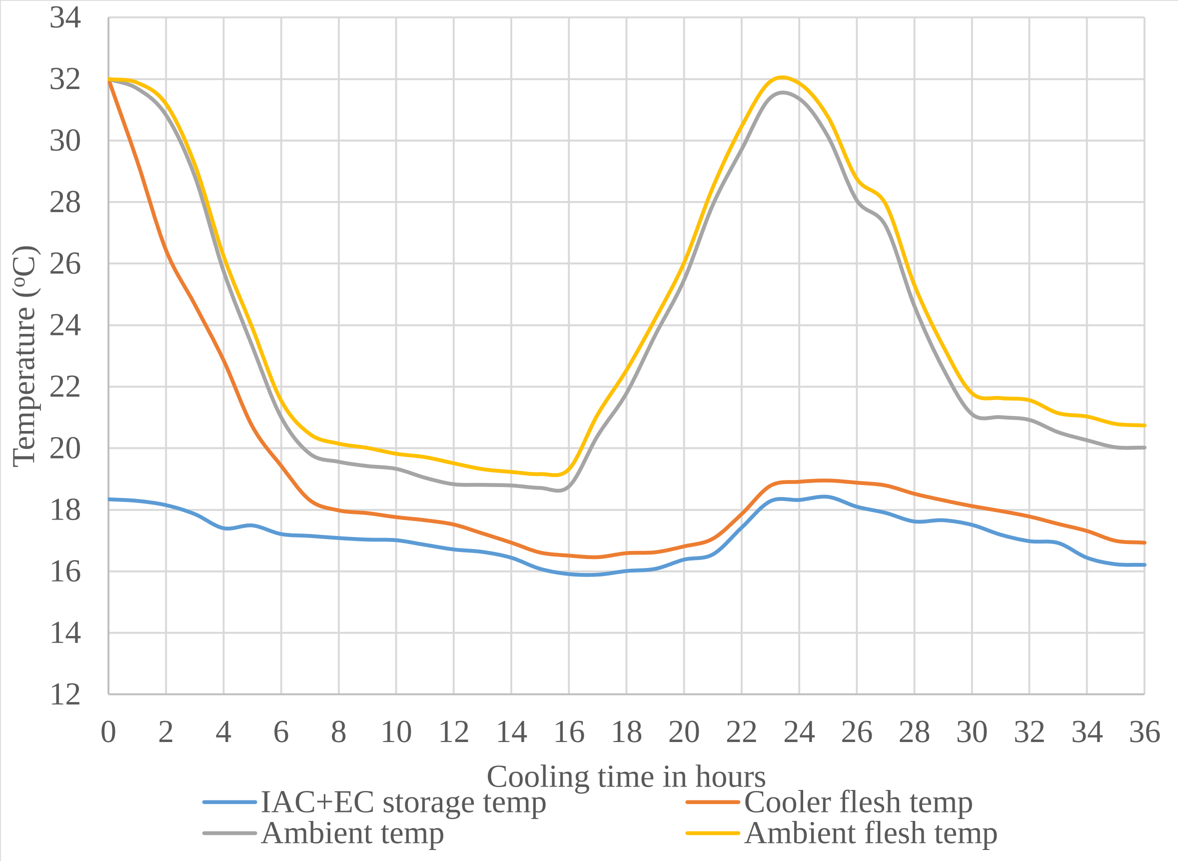
On the first day, the freshly harvested tomatoes are placed in the storage chamber and within 8 hours temperature drops below 18°C and at 16 hours, the fruit flesh temperature is 14 °C, which is within the optimum storage for tomatoes of 13°C. In the next 16 hours, temperature drops by a further 1°C. Therefore, it takes 32 hours for tomatoes to cool from 32°C to 13°C, which is the lowest optimum storage condition. This would provide a temperature gradient of 19°C. The initial tomato temperature drops rapidly especially for the first four hours of cooling and slows down as the product temperature approaches the target optimum recommended temperature. This is in line with observation by Thompson, *et al.* [19] that the rate of heat removed from fresh produce like tomatoes is a function of the temperature gradient of the product and the cooling medium. This means when packing tomatoes in the IAC+EC storage chamber in batches, it is possible that on the first day of stacking the tomato fruit' temperature drops from 32°C to 14°C within 16 hours and to 13°C on the next day within the next sixteen hours after which the next batch can be placed. This means that IAC+EC system is a viable cooling facility option for the immediate reduction of flesh temperature of harvested fresh produce for small-scale farmers in sub-Saharan Africa.

In the calculations, the seven-eighths cooling time gives more practical values as the temperature of the tomatoes at seven-eighths is close enough to the target storage temperature of 13°C. These equations help in predicting the cooling times and can help in planning especially with high value horticultural crops that need immediate pre-cooling [20]. Seven-eighths cooling times were used to evaluate cooling rates in this experiments as it is an industry standard and they are easy to calculate. However, the biggest limitation is that the equations assume constant air temperature throughout cooling while in reality temperature varies in the storage chamber.

4.2. Cooling Time of Tomatoes Loaded at Ambient Temperature

The IAC+EC system cooling operating time was 16 hours per day from 06h00 to 22h00. Figure 4 provides cooling time profile for tomatoes stored under both IAC+EC and ambient conditions monitored for 36 h from 13h00 to 01h00 on the third day. The results show that ambient temperature and the storage temperature fluctuated with the time of the day. The ambient and storage temperature varied between 32-19.1°C and 15.9 - 18.4°C respectively in the 36 hours of cooling. However, there was a significant temperature gradient between the ambient and storage chamber especially from 10h00 and 16h00 (coinciding with 21-26 hours of cooling), the hottest part of the day, was 10-12°C. This is comparable to the results obtained by Ndukwu, *et al.* [21] of gradients of up to 13°C during the same period of the day. The recommended storage temperature for tomatoes is 13-15°C and the values obtained in the storage chamber of the IAC+EC system are close to this. The significant temperature gradient between the storage chamber and ambient conditions provided an effective heat transfer between the stored tomatoes and the cooling pads. The average temperature distribution inside the storage chamber implied that the IAC+EC provided optimum temperature condition for the storage of most tropical and sub-tropical fruits and vegetables for most part of the day except between 12h00 and 15h00. Sibanda and Workneh [22] concluded that the IAC+EC is able to maintain the quality and shelf life of fresh fruits by slowing down deteriorative metabolic processes such as respiration and transpiration resulting in preservation of the organoleptic properties of tomatoes for 21days where at least 50% of them were still marketable.

Figure-4. Cooling time graph for harvested tomatoes and stored under IAC+EC and ambient conditions



The flesh temperature of the stored tomatoes in the IAC+EC storage chamber decreased from 32°C to 18°C within 8 hours and to 16.5°C in the next 8 hours. This shows that the rate of cooling is directly related to the temperature gradient between tomato fruit and the cooling medium as alluded to by Thompson, *et al.* [23]. Initial when the flesh temperature of the tomatoes was high temperature dropped rapidly in the first 8 hours than in the next 8 hours where the rate of cooling reduced significantly. Fast reduction of temperature to optimum storage conditions is important for slowing down physiological changes in fruits and vegetables for extension of shelf life after harvesting [20]. However, the tomato fruit flesh temperature rose again to 19°C coinciding with afternoon temperature of the following day and decreased again with decreasing storage temperature as evening approached to 16.9°C at 01h00 on the third day (36 hours). The tomato fruit flesh temperature under ambient temperatures was 21°C (after 8 hours) and 19.6°C (16 hours), rose to 31.4°C (24 hours) and later decreased to 20.8°C (36 hours).

While the IAC+EC system was able to reduce temperature to 16.5°C in the storage chamber, temperature increased by 2.4°C during the hottest part of the day as the rate of cooling did not follow a logarithmic function as cooling did not diminish exponentially. The seven-eighths cooling time curves are more practical for cooling system like mechanical refrigeration that are able to maintain storage temperature constant despite rises in outside temperatures. During the cooling tests, the IAC+EC storage air temperature was not constant but varied with time of the day by as much as 2.5°C during the course of the cooling. The IAC+EC system is limited in the extent that it can reduce temperature of the cooling medium (cold air) to wet bulb temperature of the air at the ambient condition [9]. In any case, even for modern day cooling technologies, it is extremely difficult to maintain constant air temperature as warm fresh produce is constantly being loaded into the storage chambers during operation. According to Anderson, *et al.* [11] variations in storage temperature of as little as 1°C, changes temperature for the 7/8th cooling time by 0.875°C. However, though the IAC+EC system did not achieve the optimum cooling temperature for tomato of 13°C, temperatures of 16.5°C were able to extend tomato life and improve marketability as reported by Sibanda and Workneh [10].

5. Conclusions

Immediate cooling of fruit and vegetables after harvest is important for handling, storage, marketing, and preservation of fresh produce along the cold chain. There are in existence simple, environmentally friendly, low energy input, low-cost and affordable postharvest technologies like IAC+EC system that can be implemented at farmer's level. Such technologies are affordable to small-scale farmers and can extend the shelf life of fresh produce for weeks as a short-term storage for 36 h of cooling. This paper compared the temperature-time series of tomato fruit cooling treatments by the selected IAC+EC and ambient cooling systems. The results showed that IAC+EC system reduced and maintained the micro-environment air temperature inside the coolers to 16 -19°C from about 32°C ambient air temperature. The results showed that 16 h was required to reduce the temperature of tomatoes using IAC+EC system to about 16°C. Variations in the storage chamber during cooling had a significant effect on cooling curve, which could not follow the calculated 7/8th cooling times for the tomato fruit. However, despite the small temperature variations, small-scale farmers can still use the IAC+EC system to remove field heat by reducing flesh temperature.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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