Performance evaluation of an indirect air cooling system combined with evaporative cooling

Sipho Sibanda a,*, Tilahun Seyoum Workneh b

a Agricultural Research Council, Institute for Agricultural Engineering, Pretoria, South Africa
b University of KwaZulu Natal, School of Engineering, Pietermaritzburg, South Africa

1. Introduction

Modern cooling technologies like mechanical refrigeration, hydro and vacuum cooling have been widely adopted for modification and control of the storage environment of high value-quality fresh produce in developed countries [1]. Such technologies when used in storage structures for fruit and vegetables (FV) help control temperature and relative humidity (RH) which are the two most important environmental factors that affect shelf life of fresh produce after harvest [2, 3]. However small scale farmers (SSF) in sub-Saharan Africa (SSA) cannot afford the high initial investment and maintenance costs of modern storage facilities available in the market [4, 5]. Furthermore, modern cooling technologies are energy intensive and this limits their availability to SSF located in remote areas with no access to grid electricity [6, 7]. However, evaporative cooling (EC) is another alternative and has an advantage in that research has proven it as a viable technology in SSA. Evaporative cooling has low initial investment; installation and maintenance costs compared to modern technologies and can be set up without a power grid source [1]. Evaporative cooling is efficient in maintaining temperature and RH at optimum levels for storage of FV. Evaporative cooling has a potential energy saving of about 75%; the structure can easily be constructed using available materials and comes at an appropriate scale in operation and economics [8, 9]. Evaporative cooling relies on velocity of natural wind through wetted pads to provide a cooling effect for preservation of organoleptic properties of food [10]. The EC systems studied so far are prototypes; with low storage capacity, environment specific and their effectiveness at a commercial scale and in other regions in SSA needs investigation [11]. Evaporative cooling...
removes room sensible heat, is effective in hot and arid areas but has limitations in hot and humid areas because of the inherent high RH of local air, which leads to low dry bulb temperature [12]. The extension of EC to such areas requires incorporating a suitable desiccation media (heat exchanger) or indirect air-cooling (IAC) before EC, which is a research focus for this study. A desiccation unit should help to bring the temperature in the storage chamber as close to the wet bulb temperature as possible. [13] alludes that IAC + EC systems have shown great potential of development and research opportunity for their perceived improved improved efficiency, high thermal performance and low energy use. It is therefore important to develop, evaluate the performance and determine the cooling efficiency of small-scale farming sized IAC + EC system as there is dearth of information. This work is a continuation of the work reported by [14]. To adopt an IAC + EC system, an energy source to power the heat exchanger (desiccation unit), fans and water pump for air and water circulation is required [15]. Solar energy is available in SSA in large quantities of 2 000 kWh m\(^{-2}\) per year with solar radiation of 4.5–6.5 kWh.m\(^{-2}\) for 6–7 h per day which is enough to power such a system [16]. To ensure energy is available at night a solar/battery hybrid system can be utilised where the battery bank stores energy during the day [17]. The objective of this study was limited to evaluating the effect of a small-scale farming sized IAC + EC system compared to ambient conditions in providing appropriate environmental conditions for the storage of FV under hot and sub-humid to humid conditions.

2. Materials and methods

The study was conducted at Ukulinga Research Station in Pietermaritzburg in South Africa (29.67° S and 30.40° E, at an altitude of 721) which is a research farm for the University of KwaZulu Natal.

2.1. Description of the indirect air cooling system combined with evaporative cooling

The IAC + EC system consisted of a storage chamber, indirect heat exchanger, multiple cooling pads, buried water tank, a water pump and two fans as shown in Figure 1. The sizing of the storage chamber premised on the requirement by SSF to temporarily store about four tons of tomatoes while they await transport to markets. The other requirements were the size of the available packing crates, venting space between the FV layers and the bulk density of the product [18, 19]. The evaporative cooler storage chamber had white coloured double-jacket walls and roof of 1 mm zintec (mild steel) on the outside and inside. The floor of the storage chamber was made of the same material and had the same height and thickness as the rest of the storage chamber.

The cooling load including heat of respiration, field heat, sensible heat from containers, heat leakages through walls and roof, heat through the floor, air change load and heat due to operators and lights were determined by [22] parallel to this manuscript. The ventilation rate and the sizes of the fan and heat exchanger were then determined from the value of the cooling load. A 1.76 kW indirect heat exchanger was incorporated in the design according to [23]. Three layers of vertically mounted charcoal granules direct cooling pads were mounted after the heat exchanger to ensure uniform flow of water and free flow of air [24]. A constant speed positive pressure fan (31/33 W, UF25GC12, AC 115 V, 50/60 Hz) was mounted next to the indirect heat exchanger and a second fan (290 W, 308.7/6/6-P/3/HL25/PA) was mounted at the entrance to the chamber to facilitate optimum airflow through the cooling unit and the storage chamber. Inside this storage chamber, the air picked up heat from the tomatoes and the warm air escaped from the storage chamber through six (100 mm-diameter) air vents positioned opposite the inlet, three at the bottom and three at the top [25].

The water distribution system continuously pumped water from an underground storage (supplied from the mains) using a 260 W (Pedrollo PVM 55) centrifugal pump placed at the surface as recommended by [26]. The circulation system pushed water from the underground storage tank, through the indirect heat exchanger and sprinkled water continuously over the vertically mounted cooling pads into the storage chamber. From the chamber, the water returned to the underground storage tank and ball valve float prevented the tank from over filling and flowing over. A collecting bath below the EC pads sloping at 5% was incorporated to allow water to flow freely to the bottom and return to the tank. The pump, fans and indirect heat exchanger connected direct to a hybrid of solar photovoltaic system and battery bank facility designed to power these electrical appliances. The array system consisted of a 3 string-3 series 330W solar modules with 44.80 V rated voltage and 8.69 A current, a 145 VDC-60 A (SANTAKUPS PC16-6015F) solar charge controller, 5 kW-60A (Sinowave, P11-LW5000NC48-C) inverter, 3 string-4 series 230 AH batteries. This translated to practical power output from the solar panels of 2 639 W against the design load for all electrical appliances of 2 310 W as determined by [14] in a parallel work to this manuscript.

2.2. Temperature and relative humidity measurements

The procedure by [27] was followed to select nine positions in the storage chamber. The other positions chosen were inside the psychometric unit and ambient conditions just outside the storage chamber (Figure 2). HOBOs (HOBO Prov2 Part No. U23-001) were then located in

![Figure 1. Schematic diagram of the psychometric unit and the storage chamber.](image-url)
these positions to measure temperature and relative humidity. The HOBO in psychometric unit captured the condition of the air going into the storage chamber with the door of the storage chamber closed. Temperature and RH readings were recorded hourly for 28 days during the month of September in 2018. The average psychometric unit, storage chamber and ambient temperature and RH were calculated from the 28 days' data separately for each time.

2.3. Cooling efficiency

The cooling efficiency ($\eta$) of the cooler, indicating the extent to which the dry bulb temperature of the cooled air approaches the wet bulb temperature of the ambient air was calculated as defined in Eq. (1) [28].

$$\eta = 100 \times \frac{T_{da} - T_{dc}}{T_{da} - T_{wa}}$$

(1)

where $\eta =$ cooling efficiency of EC unit (%);

$T_{da} =$ dry bulb temperature of ambient air entering the cooling unit ($^\circ$C);

$T_{dc} =$ dry bulb temperature of cooled air cooling leaving unit ($^\circ$C) and

$T_{wa} =$ wet bulb temperature of ambient air entering the cooling unit ($^\circ$C).

2.4. Data collection

The experiment consisted of two cooling approaches of IAC + EC and the control (ambient conditions). The experimental data collection involved the hourly measurement of temperature and RH between 05h00–22h00 of each day for the 28 days of the experiment. Eleven hot days with temperature above 26°C were selected and used for analysis. From 22h00–05h00, the average ambient temperature in area is below 20°C and the IAC + EC system was switched off during this period as tomatoes can tolerate temperatures of 13–21°C. GenStat Version 18 was used for the statistical analysis. Analysis of variance (ANOVA) by means of the GENSTAT statistical software, 18th edition, determined the differences. Duncan’s Multiple Range Test, with a significance level of 0.05 separated the means.

3. Results and discussions

3.1. Variation of temperature

Temperature is one of the most important factors requiring management at optimum conditions in the storage life of fresh produce [25]. Temperature was recorded from eleven data logger positions as shown in Figure 2. Figure 3 provides information on the average temperature recorded from these data logger positions over the eleven hot days; ambient (D-1), inside the psychometrics unit (after the last cooling pad) (D-2) and in the storage chamber (D-3 to D-11). There was a significant variation ($P < 0.001$) in temperature between ambient, psychometric unit and the storage chamber positions. The ambient temperature was on average 10.5°C and 9.5°C higher than inside the psychometric unit and the storage temperature respectively. A significant temperature gradient occurred between the storage chamber and ambient conditions that provided an effective heat transfer of the stored produce, cooling pad and a cold room. There was also a significant variation ($P < 0.001$) in temperature between the psychometric unit and the storage chamber. The lowest average temperature was obtained at the outlet of the psychometric unit (15.8°C), while the highest average temperature was observed at the left (16.9°C: D-9) and right side (16.9°C: D-10) of the roof at the exhaust end of the storage chamber.

When considering the conditions in storage chamber only, there was significant variation in temperature ($P < 0.001$) between the different data logger positions at the entrance, centre and exhaust end. The lowest temperature occurred near the inlet to the storage chamber (16.2°C).
while the highest temperature was at the exhaust end (16.9°C). The significant differences in temperature in relation to the position of sensors in the storage chamber could influence the quality of FV stored inside the IAC + EC storage chamber. The results observed in this study are in conformity with [29] who indicated that the temperature variations between sensors at the entry and exit of the storage chamber was about 2°C. Determining the ventilation rate to maintain a uniform air distribution in the storage chamber is important as it ensures that an optimal storage environment exists to maintain the physiological condition of fresh produce [30]. The average temperature distribution inside the storage chamber varied from 16.2°C to 16.9°C implying that the IAC + EC provided optimum temperature condition for the storage of most of the tropical and sub-tropical FV. The results also show that the IAC + EC under hot and sub-humid conditions can reduce the temperature to the same extent as EC alone in hot and arid conditions as evidenced by the work of [20]. In their work at an ambient temperature of 32°C, the EC system provided the storage conditions of 19.2°C. [11] obtained similar results where temperature drop of up 10°C was achieved when evaluating EC system of capacity of 0.6 m³ under hot and dry conditions where a jute bag was used as pad material.

Figure 3 shows the variation of average temperature per day in the 11 selected days for the four strategic data logger positions, in the psychometrics unit (after the last cooling pad) and 3 positions in the storage chamber (at inlet, centre and exhaust end). The ventilating fan at the entrance to the chamber forced the cold air coming from the last cooling pad in the psychometric unit into the chamber. The results showed a rise in temperature of 1°C inside the storage chamber between the air entering the storage chamber and the temperature recorded immediately after the inlet to the chamber. This could have possibly resulted due to air leaks into the storage chamber and air picking heat from the stored product.

There is less than 1°C difference in temperature between the air entering storage chamber and the air exiting the storage chamber at the exhaust end. This is attributable to the appropriate ventilation rate applied that provided a quick steady distribution of air throughout the storage chamber and the fact that the storage chamber was filled with sample tomatoes of 150 kg instead of 3825 kg. With a full to capacity storage chamber, it is possible that the temperature at the exhaust end can be higher as the air picks heat from stored produce.

Figure 4 shows the variation of average temperature per day in the 11 hottest days at Ukulinga Research Station in Pietermaritzburg.
Figure 5 shows the hourly characteristics of ambient air, the psychrometrics unit (after the last cooling pad) and three positions in the storage chamber (at inlet, centre and exhaust end). The temperature gradient from 10h00–16h00 the hottest part of the day, between the ambient and inlet to the storage chamber (D3) was 10–12°C. These values are comparable to the results obtained by [20] of gradients of up to 13°C during the same period of the day.

The study observed that psychometric unit, storage chamber and the ambient temperatures increased from 05h00–14h00 and thereafter the values started decreasing. The temperature decreased due to increasing incident solar radiation from morning until afternoon (14h00) and then decreased from then onwards towards evening and sunset as also confirmed by [31]. The IAC + EC system maintained an average temperature between 16°C and 21°C during the hottest time of the day (11h00 am to 14h00) where ambient temperatures ranged from 29°C to 32°C. The midday period is the critical time in which cooling of fresh produce is important to maintain quality [29]. This implies that the IAC + EC in particular is highly suitable for fresh produce pre-cooling and for short-term storage in hot and sub-humid to humid areas.

The ambient temperature flattened out from 19h00 and reached 20°C by 22h00 implying that the IAC + EC system can be designed to operate five hours into the night and be switched off until 05h00 of the following day as fresh produce like tomatoes can tolerate, for short periods temperatures of 13–21°C. Such an approach will reduce the number of solar panels and batteries required to power the IAC + EC systems and in turn reduce the capital investment in the facility. Reducing the capital costs will encourage a lot of SSF to venture into the lucrative fresh produce market. The aim of the current study was different from any previous research work as it sought to extend the principle of EC to hot and humid areas by addition of an IAC unit through incorporation of a heat exchanger for sensible cooling of air before EC. This study has shown that with the incorporation of such a deiscation unit in hot and humid areas, temperature in the storage chamber can be 16°C to 21°C during the hottest time of the day (11h00 am to 14h00) where ambient temperatures ranged from 29°C and 32°C.

3.2. Variation of relative humidity

RH is one of the most important factors requiring management at optimum conditions in the storage life of fresh produce [25]. Figure 6, shows that there was a significant variation (P < 0.001) in ambient, exit point of the psychometric unit and the storage chamber RH at various positions at entrance, centre and exhaust end.

The highest average RH was at the outlet of the psychometric unit (D-2) while the lowest average RH (65.7%) was at the ambient conditions (D-1). Inside the storage chamber the lowest average RH was at the exhaust end (D-10). There was significant variation in RH (P < 0.001) between the different data logger positions at the entrance, centre and exhaust end of the storage chamber. The highest RH of 93.8% occurred near the inlet to the storage chamber while the lowest value was at the exhaust end (89.6%). The results observed in this study show similar trends with [29] who indicated that the RH variations between sensors at the entry and exit of the storage chamber were about 12% C. The RH value of 93.8% was the maximum possible level of saturation of air by humidification for IAC + EC system as 100% RH is not achievable in a direct EC experiment [32]. To achieve 100% will require a cooling pad with a 100% efficiency and the contact time between air and water should be long enough to allow for 100% heat and mass transfer, which in reality does not happen [33].

Figure 7 depicts a similar scenario when observing the variation of RH in the eleven selected days for the four strategic data logger positions, in the psychrometrics unit (after the last cooling pad) and three positions in the storage chamber (at inlet, centre and exhaust end). Results showed a 2% drop in RH between the air entering the storage chamber and that recorded immediately after the inlet to the chamber. This resulted from air picking heat from the stored tomato fruit causing an increase in temperature. The IAC + EC system maintained the RH in the storage chamber constant and within the recommended levels of 85–95% throughout the period of observation. This is in sharp contrast with the ambient RH that fluctuated throughout the period well below the recommended storage levels.

Figure 8 shows that at 14h00, the ambient RH of 46.6% could be significantly (P < 0.001) brought to 90.9%, 88.6% and 87.8% RH at inlet, centre and exhaust positions by the effect of the IAC + EC. The small temperature increase after the psychometric unit into the inlet of the storage change resulted in a 2% drop in RH and a further reduction from 94.1% RH to 90.5% at the exit end of the storage chamber as air picks up heat from the produce. Observations are that RH decreased marginally with time of day in the storage chamber while ambient RH significantly decreased with time of the day and the lowest values occurred at midday and towards the afternoon. This was due to increase in temperature inside and outside the cooler, resulting in increased water holding capacity of the air in the storage chamber. [31] had a similar observation in their
study in evaluating the performance of a photovoltaic ventilated greenhouse where after 14h00, the RH increased as the ambient and storage temperatures decreased.

The RH inside the storage chamber was higher than ambient at any period of the day as the temperature inside the chamber was lower than the ambient during similar times. The general low ambient RH results in faster moisture removal from the wet surface of the FV [34]. This implies that during this period of the day, storage of fresh produce under ambient RH conditions leads to physiological deterioration in fresh produce quality. In the same period, for the IAC + EC system the RH inside the storage chamber was high due to humidification resultant from the indirect heat exchanger and the cooling pads providing a conducive environment suitable for extending the shelf life of FV.

The RH at entrance to the chamber was higher than the corresponding values obtained at the centre and exhaust end. This was due to increasing temperature at corresponding points due to cold air picking up heat from the tomatoes. The RH followed the same pattern at all four positions along the length of the day with a minimum of 87% at the exhaust end at 14h00. The maintenance of RH above 85% is important in maintaining weight, appearance, nutritional quality and flavour, while softening and juiciness of tomatoes are reduced [35]. The values of 85 > RH < 95 are ideally storage conditions for produce like avocados, bananas, cucumbers, mangoes, oranges, papaya, sweet potatoes and tomatoes [36]. The IAC + EC system increased ambient RH from 47% to 87–93%, which is in agreement with [14] that obtained values of 75–88%. However, the result of average ambient RH ranging from 44 to 65% between 10h00 and 17h00 was below that recommended by [37] and hence this will reduce the shelf life of fresh FV storage.

With such RH levels in the storage chamber, there will be minimal water loss from the tomatoes thus maintenance of saleable weight, appearance, nutritional quality and reduction in softening and juiciness as alluded to by [38]. This demonstrates that the use of IAC + EC significantly increases the storage chamber RH and thus prolonging the shelf life of tomatoes and many other fresh produce. The results of incorporating a heat exchanger in this study indicate that the EC system increased the relative humidity of the air when extended to hot and sub-humid to humid conditions, indicating reduction in physiological weight loss from FV as evidenced by the working of [14].
3.3. Cooling efficiency

The cooler efficiencies for the times 05h00 to 19h00 are shown in Table 1. From Table 1 the cooler efficiency ranged between 86.8% and 97%. Between 05h00 and 09h00, the efficiency was about 92–95% and achieved the highest efficiencies between 09h00–14h00, then declined to 86.8% by 18h00 before rising again. The cooling curve efficiency shows that higher cooling efficiency with higher temperature and lower RH of ambient air in the afternoon when the solar radiation is highest. The decline in efficiency is linkable to the increase in ambient dry bulb temperature as the solar radiation increases during the day and the results are within the findings by the study of [25] on direct evaporative cooling under hot and dry conditions.

The cooling efficiency of IAC + EC is affected by factors such as, type of cooling pad, pad design, thickness of pad, airflow rates and outside air temperature and RH [39]. The efficiency of the IAC + EC systems indicates that the Psychometric unit was on average 93.5% efficient in reducing the ambient temperature as it entered the indirect heat exchanger and the three layer cooling pads. These results are comparable to the direct EC experiments done by [11] and [21] who obtained efficiencies of 83% and 86% respectively. [26] obtained an average cooling efficiency of 67.2%. The variation in EC efficiencies by different researchers could be attributable to different materials used to construct the cooling system and the fact that the experiments possibly took place under different environmental conditions.

In this study, the combination of the indirect heat exchanger for indirect air-cooling and the EC produced reasonable reduction in ambient air temperature to a minimum temperature approaching ambient air wet bulb temperature. The higher cooling efficiency obtained in this study compared to [26] may be attributable to incorporation of suction and exhaust fans and an automatic water reticulation system from the tank to the pads and back. The results obtained in this experiment shows that IAC + EC can be utilised in coastal areas providing cooling efficiencies similar to those obtained in direct EC under dry and hot conditions.

Table 1. Temperature and cooler efficiencies.

| Time of the day | Dry bulb ambient air (°C) | Ambient relative humidity (%) | Wet bulb ambient air (°C) | Dry bulb cooled air (°C) | Cooler efficiency (%) |
|-----------------|---------------------------|-------------------------------|--------------------------|-------------------------|-----------------------|
| 05h00           | 18.82                     | 80.69                         | 12.60                    | 13.06                   | 92.6                  |
| 06h00           | 20.30                     | 78.27                         | 13.21                    | 13.62                   | 94.3                  |
| 07h00           | 21.74                     | 76.55                         | 14.68                    | 15.19                   | 94.2                  |
| 08h00           | 23.41                     | 73.93                         | 15.30                    | 15.81                   | 94.9                  |
| 09h00           | 25.23                     | 68.13                         | 16.61                    | 17.01                   | 96.4                  |
| 10h00           | 27.68                     | 64.34                         | 17.58                    | 17.98                   | 97.0                  |
| 11h00           | 29.66                     | 59.21                         | 16.72                    | 17.41                   | 95.3                  |
| 12h00           | 31.34                     | 54.14                         | 19.63                    | 20.11                   | 96.6                  |
| 13h00           | 31.98                     | 48.77                         | 19.90                    | 20.42                   | 96.7                  |
| 14h00           | 31.84                     | 46.55                         | 19.30                    | 19.94                   | 95.7                  |
| 15h00           | 30.39                     | 48.73                         | 17.92                    | 18.77                   | 93.8                  |
| 16h00           | 28.42                     | 52.71                         | 18.02                    | 18.83                   | 93.3                  |
| 17h00           | 25.45                     | 58.78                         | 16.31                    | 17.61                   | 86.8                  |
| 18h00           | 23.11                     | 63.39                         | 14.60                    | 15.82                   | 86.8                  |
| 19h00           | 20.75                     | 68.31                         | 13.33                    | 14.35                   | 87.2                  |
| Average         | 26.0                      | 41.0                          | 16.38                    | 16.99                   | 93.5                  |

Figure 8. Average relative humidity per day over the 11 hot days at Ukulinga Research Station in Pietermaritzburg.

4. Conclusion

The lack of cooling facilities and knowledge by SSF in SSA postharvest handling of fresh produce results in a significant amount of harvested FV decaying between the farmers’ field and the market. The environmental conditions provided by IAC + EC system significantly (P < 0.001) increased RH and decreased temperature which conditions are requisites for transportation and temporary storage of fresh produce.

In the IAC + EC system, the indirect heat exchanger helped significantly reduce the air temperature in the storage chamber while the EC unit increased the RH providing thermal comfort to fresh produce. Controlling the environmental factors within recommended levels in the storage chamber helps prevent the physiological weight loss in fresh produce and thus extending shelf life. The IAC + EC system under the hot and sub-humid to humid conditions performed to the same extent as the EC under dry and arid conditions where temperature is high and RH is low. This has tended to limit the application of EC but with the incorporation of an indirect heat exchanger extension to hot sub-humid to humid conditions is realised. These results clearly demonstrate that the IAC + EC system is useful in hot and sub-humid to humid climate for preservation of FV, especially during the hottest time of the day when cooling is most required. The results are more interesting as the study is a deviation from the norm where most studies have been carried out on miniature structures of less than 0.2 tons and in this experiment, the structure is 53 m³ with a 3.8 ton carrying capacity of tomatoes.

For future research studies some of the modifications and recommendations relating to the IAC + EC systems are:
1. To automate the power provision system so that once the temperature in the storage chamber falls below 20°C power supply is disconnected.
2. The storage chamber to be mobile for cold storage transportation of FV from the source to the market.
3. Use of surrounding air kinetic energy from a mobile storage transportation as a source of power for operation of the IAC + EC when in transit.

Declarations

Author contribution statement

Sipho Sibanda: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
Tilahun Seymour Workneh: Conceived and designed the experiments; Wrote the paper.

Funding statement

This work was supported by the Agricultural Research Council through the Economic Competitive Support Package of the National Treasury of South Africa.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] S.A. Oakanlawn, A.O. Oluronnisola, Development of passive evaporative cooling systems for tomatoes Part 1: construction material characterization, Agric. Eng. Intern.: CGI J. 19 (1) (2017) 178–186.
[2] S. Tyagi, S. Sahay, M. Imran, K. Rashmi, S.S. Mahesh, Pre-harvest factors influencing the postharvest quality of fruits: a review, J. Appl. Sci. Technol. 23 (4) (2017) 1–12. ISSN: 2233-0843.
[3] M.E. Saltveit, Respiratory metabolism, Postharvest Physiol. Biochem. Fruits Veg. 4 (2018) 73–91.
[4] O.W. Adeshi, J.C. Igbeke, T.O. Olarir, Performance evaluation of absorbent materials in evaporative cooling system for the storage of fruits and vegetables, Int. J. Food Eng. 5 (3) (2009) 1–14.
[5] M.C. Ndukwu, S.I. Manuwa, Review of research and application of evaporative cooling in preservation of fresh produce, Agric. Eng. Intern.: CGI J. 5 (7) (2014) 85–102.
[6] D.S. Kim, C.A.I. Ferreira, Solar refrigeration options – a state of the art review, Int. J. Refrig. 31 (2008) 3–15.
[7] M.K. Koor, U.N. Mutwiwa, G.M. Kituo, D.N. Sila, Effect of near infrared reflection and evaporative cooling on quality of mangoes, Agric. Eng. Intern.: CGI J. 19 (1) (2017) 162–168.
[8] O. Amer, R. Boukhanaouf, H.G. Ibrahim, A review of evaporative cooling technologies, Int J Environ. Sci. Dev. 6 (2) (2015) 111–117.
[9] D. Mizra, S. Ghosh, Evaporative cooling technologies for greenhouses: a comprehensive review, Agric. Eng. Intern.: CGI J. 20 (11) (2018) 1–14.
[10] O.V. Chijioke, Review on evaporative cooling systems, J. Greener Sci. Eng. Intern. Res. 7 (1) (2017) 1–20.
[11] M.D. Zakari, Y.S. Abubakar, Y.B. Muhammad, N.J. Shanono, N.M. Nasidi, M.S. Abubakar, A.I. Muhammad, I. Lawan, R.K. Ahmad, Design and construction of an evaporative cooling system for the storage of fresh tomatoes, Asian Res. Publish. Netw. (ARPN) J Eng. Appl. Sci. 11 (4) (2016) 2340–2348.
[12] S. Deora, E.I. Ekwe, B. Birch, An evaporative cooler for the storage of fresh fruits and vegetables, J. West Indian Eng. 38 (1) (2015) 86–95.
[13] N.J. Ogbuagu, I.A. Green, C.N. Anyanwu, J.I. Ume, Performance evaluation of a composite-paddled evaporative storage bin, Nigeria J. Technol. (NIJOTECH) 36 (1) (2017) 302–307.
[14] S. Sibanda, T.S. Workneh, Effects of indirect air-cooling combined with direct evaporative cooling on the quality of stored tomato fruit, CyTA – J. Food 17 (1) (2019) 603–612.
[15] S.M. Shaashid, L. El-Amin, Techno-economic evaluation of off-grid hybrid Photovoltaic–diesel–battery power systems for rural electrification in Saudi Arabia - a way forward for sustainable development, Renew. Sustain. Energy Rev. 13 (2009) 625–633.
[16] B.M. Olomiyese, O.D. Oyedum, P.E. Ugwueke, J.A. Ezenwor, A.G. Ibrahim, Solar energy for power generation: a review of solar radiation measurement processes and global solar radiation modelling techniques, J. Nigerian Solar Ener. 26 (2015) 1–8.
[17] GSES Solar-powered pumping in agriculture, in: A Guide to System Selection and Design, NSW Farmers, New South Wales, Australia, 2015.
[18] G.D. Sarvacos, A.E. Kostaropoulou, Handbook of Food Processing Equipment, Kluwer Academic, London, 2002.
[19] G. Sharan, K. Rawale, New packaging options for transporting tomatoes in India, ITDG Food Chain 29 (2009) 15–18.
[20] M.C. Ndukwu, S.I. Manuwa, O.J. Otokunibe, I.B. Oluwafarwa, Development of an active evaporative cooling system for short-term storage of fruits and vegetable in a tropical climate, Agric. Eng. Intern.: CGI J. 15 (4) (2013) 307–313.
[21] K.O. Babaremu, A.M. Omodara, S.I. Fayomi, P.O. Okopkujie, J.O. Oluwafemi, Design and optimization of an active evaporative cooling system, Int. J. Mech. Eng. Technol. 9 (10) (2018) 1051–1061.
[22] S. Sibanda, Development of a Solar Powered Indirect Air-Cooling Combined with Direct Evaporative Cooling System for Storage of Horticultural Crops in Hot and Humid Areas, PhD Thesis, University of KwaZulu Natal, Pietermaritzburg, South Africa, 2019.
[23] J.P. Holman, Heat Transfer, McGraw-Hill, Singapore, 1996.
[24] J.M. Ohura, N. Banadda, J. Wanyama, N. Riggundu, A critical review of selected appropriate traditional evaporative cooling as postharvest technologies in Eastern Africa, Agric. Eng. Intern.: CGI J. 17 (4) (2015) 327–336.
[25] M. Seweh, J.O. Darko, A. Addo, P.A. Asagadunga, S. Achibushe, Design, construction and evaluation of an evaporative cooler for sweet potatoes storage, Agric. Eng. Intern.: CGI J. 18 (2) (2016) 435–446.
[26] N. Nikozi, L.S. Muyaza, T.S. Workneh, A. Chimpango, Evaluating evaporative cooling system as an energy- free and cost- effective method for postharvest storage of tomatoes (Solanum lycopersicum L.) for smallholder farmers, Sci. Hort. 241 (2018) 131–143.
[27] S. Akdemir, S. Ozurt, F.O. Edis, E. Bal, CFD Modelling of two different cold stores ambient factors, IERI Procedia 5 (2013) 28–40.
[28] W.A. Olusunde, A.K. Aremu, P. Okoko, Computer simulation of evaporative cooling storage system performance, Agric. Eng. Intern.: CGI J. 18 (4) (2016) 280–292.
[29] G.N. Tolesa, T.S. Workneh, Influence of storage environment, maturity stage and pre-storage disinfection treatments on tomato fruit quality during winter in KwaZulu-Natal, South Africa, J. Food Sci. Technol. 54 (10) (2017) 3230–3242.
[30] M. Jnadi, S. Rifai, Experimental and numerical investigation of a dew-point cooling system for thermal comfort in buildings, J. Appl. Ener. 132 (2014) 524–535.
[31] M. Madhava, S. Kumar, D.B. Rao, D.D. Smith, H.V. Kumar, Performance evaluation of photovoltaic hybrid greenhouse dryer under no-load condition, Agric. Eng. Intern.: CGI J. 19 (2) (2017) 93–101.
[32] Y.M. Xuan, F. Xiao, X.F. Niu, X. Huang, S.W. Wang, Research and application of evaporative cooling in China: a review (I), Renew. Sustain. Energy Rev. 16 (2015) 3535–3546.
[33] S.I. Manuwa, S.O. Oley, Evaluation of pads and geometrical shapes for constructing evaporative cooling system, Mod. Appl. Sci. 6 (6) (2012) 45–53.
[34] S. Awole, K. Woldetsadik, T.S. Workneh, Yield and storability of green fruits from hot pepper cultivars (Capsicum spp.), Afr. J. Biotechnol. 10 (59) (2011) 12662–12670.
[35] A.L.D. Beseidya, V.K. Samuel, V. Beera, Evaporative cooling system for storage of fruits and vegetables – a review, J. Food Sci. Technol. 50 (3) (2013) 429–442.
[36] M.J. Cantwell, X. Nie, G. Hong, Impact of storage conditions on grape tomato quality, in: Sixth ISHS Postharvest Symposium, International Society of Horticultural Science, Antalya, Turkey, 2009.
[37] ASHRAE Handbook of Standards, American Society of Heating and Refrigeration and Air Conditioning, 1982.
[38] O. Laguerre, H.M. Hoang, D. Flick, Experimental investigation and modelling in the food cold chain: thermal and quality evolution, Trends Food Sci. Technol. 29 (2013) 87–97.
[39] C. Lertosjithamakorn, S. Rerngwongwitaya, S. Soponronnarit, Field experiments and economic evaluation of an evaporative cooling system in a silkworm-rearing house, Biosyst. Eng. 93 (2) (2006) 213–219.