DEVELOPMENT OF A SOLAR POWERED INDIRECT AIR COOLING COMBINED WITH DIRECT EVAPORATIVE COOLING SYSTEM FOR STORAGE OF FRUITS AND VEGETABLES IN SUB-SAHARAN AFRICA

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Bioresources Engineering, School of Engineering, College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The Agricultural Research Council (ARC) of the Republic of South Africa financially supported the research. The work is part of an ongoing research project funded by the National Treasury. The support funding is referred to "The Economic Competitive Support Package commonly called ECSP".

ABSTRACT

Maintaining fruit and vegetables' (F&V) quality requires optimal environmental conditions during transportation, storage and marketing. High ambient in excess of 30ºC and low relative humidity (RH) below 50% characterise most agro-ecological zones of Sub-Saharan Africa (SSA), which conditions create negative effect on F&V quality. Modern technologies like mechanical refrigeration, hydro and vacuum cooling have been widely adopted for the modification and control of the storage environment of high value-quality fresh produce in developed countries. Small-scale farmers (SSF) in SSA cannot afford the high installation and maintenance costs associated with such facilities. Low-cost evaporative cooling systems (EC) alone or combined with indirect air-cooling (IAC) provides alternative solutions to minimize postharvest losses (PHL) in small-scale farming.

The effectiveness of EC in providing optimum storage conditions of temperature and RH in dry and arid climates has been investigated and is well reported in published papers worldwide. However, the effectiveness of EC in hot and sub-humid to humid areas where the air needs sensible cooling before contact with water through indirect air cooling has not been well investigated and reported. Recent literature reviewed concludes that evaporative cooling coupled indirect air-cooling (IAC+EC) should be of particular research focus because of high potential thermal performance. Further, documented scientific information on performance of commercial scale IAC+EC of F&V storage systems is limited. IAC+EC requires incorporation of a suitable desiccation media as an indirect heat exchanger where electrical power is required. SSF in SSA could access this cheaper technology if solar energy can be utilised through solar photovoltaics (SPV) and dearth of information exists in actual performance of SPV powering IAC+EC which factors promoted this study. Thus, the primary aim of this study was to design and evaluate the effects of solar powered IAC+EC storage conditions on the physical, chemical and sensory quality parameters of the star 9037 tomato variety over the 28-day experimental period. Comparisons between tomatoes stored IAC+EC to those stored under ambient conditions was done.

A low cost SPV powered IAC+EC system with a storage chamber with a capacity 3.8 tonnes of tomatoes was designed and fabricated in Pietermaritzburg for study under a sample tomato load. The experimental set up consisted of SPV system, battery bank, electrical appliances, indirect heat exchanger, psychrometric unit, and 3.8 tonne storage chamber constructed and assembled on site.

In optimizing power from the SPV systems and battery bank to meet the demand load a three series-three strings solar panels rated 330 W with short circuit current and open circuit voltage of 8.69 A and 44.8 V, respectively, were used with a 48 V battery bank of twelve 230 AH batteries.

Based on the experiment data the SPV system produced 2639 W that is 90% of the calculated theoretical power output. The energy yield of 2639 W was 11% higher than the power required in running the electrical appliances for IAC+EC system. Tracking the SPV system under ambient conditions with an average daily generation during the period of the experiment, the power and PV array efficiencies were 81.2% and 15.1% respectively. The power output of modules increased with temperature of the module to 25℃ and declined thereafter. It was found that the solar array system can be used to power the IAC+EC at daytime during summer season, and the excess power, stored in the battery ran the system until 22h00 at night when temperatures are low enough for storage of tomatoes and SPV system was then switched off.

There were significant variations ($P<0.001$) between storage and ambient conditions. The temperature inside the cooler was on average 7℃-16℃ lower and the average RH was 28% to 47% higher than ambient conditions. The cooler efficiency varied from 86.8% to 96.7%. The IAC+EC tested in Pietermaritzburg was found to perform at the same level as EC under dry and arid conditions. The solar powered IAC+EC tested in this study has benefits in providing optimum conditions for fresh produce and in reducing losses as well as being a low-cost technology that can be a candidate for implementation in hot and to humid areas in SSA. The effect of two storage conditions on total soluble solids, tomato firmness, colour, physiological weight loss (PWL) and marketability of tomatoes was investigated. The storage conditions and the storage period significantly ($P\leq0.001$) affected the evaluated quality parameters. Low temperature IAC+EC storage offered the greatest benefit in maintaining high marketability, reduced PWL and delayed the peak in respiration, compared to ambient conditions. Tomatoes stored under ambient conditions exhibited increased rates of ripening, which was evident in increased PWL, reduced firmness, redness in skin colour, rapid increase in TSS. The green harvested tomatoes combined with IAC+EC provided favourable conditions in maintaining lower PWL, higher marketability, higher moisture content which are indicative of delayed ripening. The findings show that cold storage improved the shelf life to three weeks and preserving the quality of tomatoes during short and extended storage durations compared to storage under ambient conditions.

DECLARATION ON PLAGIARISM

I, Sipho Sibanda, declare that:

(i) The research reported in this dissertation, except where otherwise indicated, is my original work.

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Prof TS Workneh

DECLARATION ON PUBLICATIONS

This section outlines the sections in this dissertation that have been presented/submitted to a conference, and submitted to peer-reviewed international journals for publication. The research reported is based on the data I collected from the various experiments. I designed the experiments, collected, analysed the data, and wrote the presentation and the manuscripts. This work was done under the supervision, guidance and review of my supervisor; Prof TS Workneh. The * indicates the corresponding author.

Chapter 2

Sibanda, S, Workneh TS and Mugodo, K. 2016. Postharvest storage for fruit and vegetables appropriate for use by small-scale farmers in South Africa. Oral presentation. Proceedings of an ASABE Global Initiative Conference entitled Engineering and Technology Innovation for Global Food Security, Stellenbosch, South Africa (24-27 October 2016).

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Chapter 5

Sibanda, S, Workneh TS and Mugodo, K. 2017. Development of a solar battery powered evaporative cooling system for small-scale farmers. Poster presentation. Proceedings of Third International Conference on Global Food Security, Cape Town, South Africa, 03-06 December 2017. *Book of Abstracts, 16.*

Chapter 3

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SUPERVISORS' APPROVAL

Subject to the regulations of the School of Engineering, I the supervisors of the candidate, consent to the submission of this dissertation for examination.

Supervisor: ________________________ Date: ……. / ……. / 2019

Prof TS Workneh

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A	Amperes	79
AC	Alternating Current	78
AAC	Amps of Alternating Current	103
ADC	Amps of Direct Current	103
AGRA	Africa Agriculture	1
AH	Ampere Hour	79
ANOVA	Analysis of Variance	129
ARC	Agricultural Research Council	127
ASHRAE	American Society of Heating, Refrigerating and Air-condition Engineers	3
C_p	Specific Heat	81
CV	Coefficient of variance	93
DAFF	Department of Agriculture, Forestry & Fishiries	18
DC	Direct Current	78
DEC	Direct Evaporative Cooling	4
EC	Evaporative cooling	3
F	Perimeter heat loss factor	82
F&V	Fruit and vegetables	1
FAO	Food and Agriculture Organisation	1
GSES	Global Sustainable Energy Solutions	74
LSD	Least Significant dDfference	165
h	Enthalpy of air in the storage chamber	82
Ha	Hectares	19
h_a	Enthalpy of ambient air	82
HP	Horse Power	39
IAC	Indirect air cooling	4
IEA	International Energy Agency	41

Abbreviation/Symbol	Meaning	Page
IPAP	Industrial Policy Action Plan	73
IRENA	International Renewable Energy Agency	42
I_{sc}	Short Circuit Current	72
kWh	Kilowatt Hour	5
m_a	Mass of air entering the chamber	82
MJ	Mega Joules	49
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m_w	Mass of water condensing in the chamber	82
NDP	National Dvelopment Policy	73
OECD	Organisation for Economic Cooperation Development	19
P	Storage chamber perimeter	82
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PHL	Postharvest Losses	1
PMB	Pietermaritzburg	75
PV	Photovoltaic	72
PWL	Physiological weight loss	151
Q	Heat ($kJ.Kg^{-1}$)	81
R	Rand	22
RH	Relative humidity	1
SAWS	South African Weather Services	127
SAYB	South African Year Book	1
SPV	Solar Photo Voltaic	43
SSF	Small-Scale Farmers/Farming	1
SSA	Sub-Saharan Africa	1
STC	Standard Test Condition	79
T	Temperature	82
TSS	Total Soluble Sugars	152
UNDP	United Nations Development Programme	20

Abbreviation/Symbol	Meaning	Page
USA	United States of America	38
USD	United States Dollars	40
US$	United States Dollars	40
VAC	Volts of Alternating Current	102
V	Volts/Voltage	79
VDC	Volts of Direct Current	72
V_{oc}	Open Circuit Voltage	72
W	Watts	36
η	Efficiency	84

1 INTRODUCTION

1.1 Introduction to Postharvest Factors and Cooling Technologies

Agriculture is the mainstay of Sub-Saharan African (SSA) economies with about 80% of the population directly or indirectly dependent on agriculture for employment and livelihood (Shah *et al.,* 2008; AGRA, 2017; Taylor, 2017). Commercial agriculture in South Africa contributes 2.5% to the gross domestic product and another 12% through value addition from related manufacturing and processing and 7% to formal employment (SAYB, 2017). The crops grown in tropical and sub-tropical climates of SSA include field and horticultural crops.

Small-scale farmers (SSF) have an increased interest in the production of fresh produce because of a shift in consumer demand to fruit and vegetables (F&V) and higher returns (Njaya, 2014; Pereira, 2014; Miller *et al.,* 2017). South Africa's F&V export prices and quantities have increased tremendously and continue to maintain an upward trend since 2010 and contributing R76 967 million by the 2017/18 farming season (SAYB, 2018). Statistics in South Africa indicate that fresh produce like tomatoes and onions have the highest annual yield quantity of 560 418 t, 689 777 t respectively (Shabalala and Mosima, 2002; SAYB, 2016; SAYB, 2017). The downward side of fresh produce production in SSA is the huge postharvest losses (PHL), which can be as high as 30-50% (Kitinoja *et al.,* 2011; van Gogh *et al.*, 2013; FAO, 2014; Victor, 2014; Affognon *et al.,* 2015). In countries like South Africa, PHL are estimated at 30-50% for F&V depending on commodity (Mashau *et al.*, 2012). For example, losses in tomatoes are 10-30% of the total production (Etebu *et al.*, 2013; Sibomana *et al.,* 2016). The sustainable development goal (SDG 12.3) requires that by 2030 countries should halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including PHL. Therefore, research on postharvest interventions through development of innovative technologies that reduce PHL in SSA are a priority (Kitinoja *et al.*, 2011; Stathers, 2017).

SSF in SSA could potentially produce 80% of the F&V if the PHL experienced before the fresh produce reaches the consumer were mitigated (Murthy, 2009; Arah *et al.,* 2015). Reducing PHL of fresh produce as sustainable way of growing the horticultural industry in SSA involves the development of technologies for manipulation of storage environmental factors of temperature and relative humidity (RH) (Thompson *et al*., 2002; Alamu *et al*., 2010; Awole *et al*., 2011; Azene *et al.,* 2011; Arah *et al.,* 2015; Misra and Ghosh, 2018). Decreasing temperature and increasing RH helps maintain high quality in fresh produce by providing optimal storage conditions that delay the onset of ripening and senescence (Yahia, 2002; Kader, 2003; Perez *et al*., 2004; Workneh and Woldetsadik 2004; Mashau *et al*., 2012; Pereira, 2014; Chijioke, 2017; Sibomana *et al.,* 2017). Fresh produce has high moisture content which makesF&V liable to spoilage and as living entities continue to transpire, respire and further ripen after harvest (Wills *et al*., 1989; Workneh, 2010; Seweh *et al,* 2016; Gupta and Dubey, 2018; Sitorus *et al.,* 2018).

When temperature is too low and RH is too high, fresh produce can suffer from chilling injury or the proliferation of microorganisms (Maftoonazad and Ramaswamy, 2008; Okanlawon and Olorunnisola, 2017). When the converse occurs, promotion of excessive water loss from produce occurs, firmness reduces and an undesirable shriveling appears (Paull, 1999; Singh *et al.,* 2014). To avoid these two scenarios, immediate cooling of F&V is required after harvest especially when harvesting fresh produce at high temperatures or at an advanced stage of maturity (Rudnick and Nowak, 1990; Paull, 1999; Brosnan and Sun, 2001; Gupta and Dubey, 2018). Cooling of fresh produce allows for market rescheduling and improves the export conditions by allowing continuous supply of quality product during off-season (Chopra *et al.,* 2003; Jain, 2007; Nunes, *et al*., 2009; Paul *et al*., 2010; Shitanda et al., 2011; Okanlawon and Olorunnisola, 2017).

Sub-optimal environmental conditions during temporary storage and transportation are prevalent for SSF in SSA because of unavailability of cooling facilities (Jain, 2007; Etebu *et al.,* 2013; Sibomana *et al.,* 2016; Cherono *et al.,* 2018). Because of lack of investment in postharvest infrastructure SSF are compelled to immediately sale their fresh produce in some instances at distressed prices to the local market soon after harvest to avoid any spoilage (Kebede, 1991; Verna and Josh, 2000; Rayaguru *et al.,* 2010; Obura *et al.,* 2015; Cherono and Workneh, 2018). None ownership of cooling facilities relates to the fact that SSF in SSA own land holdings which are no more than 1.5 ha resulting in smaller output that does not justify investment in capital-intensive postharvest technological interventions (Makeham and Malcolm, 1986; Du Plessis *et al.,* 2002; Backeberg, 2006; Denison and Manona, 2007; Seweh *et al*., 2016).

There is a need to search for appropriate methods for SSF to reduce PHL during temporary storage and transportation so that the produce can reach better-priced markets at relatively suitable environmental conditions (Wills *et al*., 1998; Mandal *et al.,* 2010; Gustavsson *et al.,* 2011; Seweh *et al.,* 2016). Modern cooling technologies such as mechanical refrigeration, forced air cooling, hydro-cooling and vacuum cooling can be utilised to reduce the temperature of the micro-environment of F&V to between -1 and 13℃ (Thompson *et al*., 2002; Paull and Duarte, 2011; Yahia, 2011). These modern cooling technologies are utilised in developed countries to extend shelf life and to minimise PHL (Tefera *et al.,* 2007; ASHRAE, 2011; Ambaw *et al.*, 2013; Sibomana *et al.,* 2016). However, the capital cost involved, expertise of operation required, energy requirements to operate modern cooling technologies are a serious constraint for SSF in SSA making unfeasible their adoption (Roy and Pal, 1994; Samira *et al.,* 2011; Seweh *et al.,* 2016).

Some SSF in SSA are located in remote rural areas with no access to grid electricity in contrast to large-scale commercial farmers that have economies of scale, financial muscle and access to grid electricity (Backeberg, 2006; Kim and Ferreira, 2008; Korir *et al.,* 2017). Studies have revealed that conventional electric-powered mechanical cooling systems could not be of much use in rural areas of SSA because of non-availability of energy sources (Jain 2007; Tefera *et al.,* 2007; Kim and Ferreira, 2008; Basediya *et al.,* 2013; Korir *et al.,* 2017). This, therefore, renders it difficult to install and operate mechanical modern-day cooling technologies for SSF; implying alternative low-cost cooling systems need to be sought (Workneh and Woldetsadik, 2004; Okanlawon and Olorunnisola, 2017). Therefore, the focus of this study ensures use of low-cost cooling technologies with no or less energy demand in the preservation of fresh produce for extended periods in a marketable state (Quick, 1998; Prusky, 2011; Basediya *et al*., 2013; Manaf *et al*., 2018).

Evaporative cooling systems (EC) could be the solution to SSF challenges of PHL as a short to medium term storage facility of F&V. It is reliable, efficient and economical for temperature reduction and increasing RH (Jha and Chopra, 2006; Vala *et al.,* 2014), is a tried and tested method (Odesola and Onyebuchi, 2009; Liberty *et al.,* 2013), is environmentally friendly (Camargo, 2007; Okanlawon and Olorunnisola, 2017) and does not require special skills to operate (Vala *et al.,* 2014; Chijioke, 2017). EC is an appropriate low-cost cooling system; has a potential energy saving of 75% compared to mechanical refrigeration; and can be assembled from local available material in South Africa or any country (Datta *et al.,* 1987; Jain, 2007; Odesola and Onyebuchi, 2009; Deoraj *et al.,* 2015; Yahaya and Akande, 2018). Therefore, evaporative cooling (EC) can address PHL in fresh produce suffered by SSF in SSA if affordable energy sources can be accessed to power the cooling system can be utilised. Understanding the performance of EC in controlling the microenvironment is critical for its characterization as a low-cost cooling technology with potential utilization at a commercial scale.

EC is a physical phenomenon where evaporation of a liquid, into surrounding air, cools an object or a liquid with which it is in contact (Kitinoja and Thompson, 2010; Workneh, 2010; Olosunde *et al.,* 2016). Evaporation of water produces a considerable cooling effect and the faster the evaporation the greater is the cooling (Basediya *et al.,* 2013; Shahzad *et al*., 2018). The results of the research done to date demonstrates that EC can reduce temperatures below ambient with a depression reaching 12°C and RH above 90% and thus showing potential for preservation of fresh produce (Tolesa and Workneh, 2017). Two types of EC methods exist, direct evaporative cooling (EC) and indirect air-cooling (IAC). In IAC, the air first passes through the heat exchanger as opposed to passing straight to the humidifier as is the case with direct EC (Chaudhari *et al.,* 2015; Gómez-Castro *et al*., 2018).

EC system adds moisture to the cool air and is effective in hot and dry conditions of arid or semi-arid climates like in SSA (Thompson *et al*., 2002; Samira *et al*., 2011; Xuan *et al*., 2012; Hao *et al*., 2013; Chijioke, 2017; Fong and Lee, 2018). Most of the work done to date on EC in SSA are prototypes and has been limited to testing the technology on cooling small quantities of produce (Ndukwu and Manuwa, 2014; Yahaya and Akande, 2018). The research work on EC in developed countries and Asia has focused on cooling buildings (comfort cooling) and most research publications are from temperate regions that markedly differ from tropical climates found in SSA (Manuwa and Odey, 2012; Yahaya and Akande, 2018). EC is ideally for hot and dry conditions and cannot be applied in hot and sub-humid to humid areas. Therefore, its use has been limited to conditions in which it is applicable. In SSA work on EC has been limited to West Africa, North Africa and East Africa with little or no work done in Southern Africa (Anyanwu, 2004; Ahmed *et al.,* 2011; Samira *et al.,* 2011; Ndukwu *et al*., 2013). Performance of EC varies with agro-climatic conditions (regions) as evidenced by a report by Thipe *et al.* (2017) and therefore, performance of EC with a focus in Southern Africa needs investigation. Further, the studies done to date have been with miniature structures of less than 0.2 tonnes that do not mimic the SSF conditions in SSA where up to 4 tonnes storage chamber might needed (Mashau *et al.,* 2012; Ndukwu and Manuwa, 2014). Because of requirements of high temperature and low RH, EC has limitations in humid conditions and therefore, there is a need to seek an alternative for such conditions. IAC as a principle has been proposed by researchers working on green-houses and this potentially can be extended to preservation of F&V.

IAC system sensible cools the air without any moisture addition and the expectation is it should work better in hot and humid regions if coupled with EC (Kapilan *et al.,* 2016). The literature review by Misra and Ghosh (2018) showed that IAC alone had not been applied in a greenhouse and it has not been used for cooling the microenvironment in storage of fresh produce under practical conditions. There is no literature on IAC coupled with EC i.e. IAC+EC for the preservation of F&V; many of the work on this technology are for comfort cooling, production process in metallurgical shops, cooling automobile engines and tractor cabins (Ndukwu and Manuwa, 2014). There is currently dearth of information on the performance of IAC+EC for the preservation of F&V and this study proposes that it be investigated. This potentially, provides an opportunity to develop and characterise an IAC+EC for hot and sub-humid to humid conditions that are subject to high temperature and RH prevalent in coastal areas of SSA, which is innovation in terms of developing cooling facilities for fresh produce. The review by Manaf *et al.* (2018) identified IAC+EC as an encouraging system, yet research into its use is still at an initial stage and needs further investigation. Manaf *et al.* (2018) also alluded that IAC+EC have high potential for use in hot and humid weather.

As a cheap and convenient key measure to decreasing the deterioration of fresh produce, IAC + EC integrated with alternative sources of energy other than grid, electricity would be critical in reducing energy consumption during the cooling process as alluded to by Mahmood *et al.* (2016). Possible options are the clean energy sources like solar energy that have no pressure of concerns on global warming with significant carbon emissions (James and James, 2011). Misra and Ghosh (2018) in their recommendations for further research on EC allude to the application of renewable energy (solar and geothermal) for IAC+EC. From the literature available, there is no evidence of background work in SSA of application of renewable energy as a power source for IAC+EC. Since the majority of areas in SSA, receive an average of 5.5 kWh.m^{-2} of solar irradiation then it implies that the use of solar energy is feasible (Fluri, 2009). The research gap in SA is that there is limited investigation on SSF producing F&V research, development and performance characterization on utilisation of solar energy and IAC+EC of fresh produce. This could assist in improving the marketability of F&V.

1.2 Summary for the Introduction

F&V production in the sub-tropical regions occur where the air is dry and warm and fresh produce has high moisture content (Sitorus *et al.,* 2018). Such environmental conditions result in SSF in SSA experiencing high PHL. There is therefore, a need to ensure a significant percentage of this production does not spoil through sub-optimal environment but reaches both the domestic and international market in a palatable state. High air temperature and low RH negatively affects the physiologically state of F&V. Optimum storage conditions are key and to maintain fruit quality during storage and transportation. Studies need to be conducted to develop low cost appropriate cooling technologies that ensure optimal conditions are maintained inside storage containers especially for use by SSF. Mechanical refrigeration already exists but is expensive and has high-energy demands and hence the need to develop technologies that have low energy requirements (Okanlawon and Olorunnisola, 2017).

It is therefore necessary to develop and test a simple low energy input technology powered by solar energy, appropriate, in-expensive cooling method like EC to attain optimum storage conditions for F&V. EC is well researched and documented and is applicable in dry and hot conditions but has functional limitations in hot and humid conditions. For EC to be extended to hot and humid areas IAC has to be combined with EC. Literature shows that a lot of work relating to IAC+EC is yet to be done. More scope of further research remains, to characterise IAC+EC in hot and sub-humid to humid tropics. The design specifications of the energy source of IAC+EC system will introduce fans for ventilation and water pump for water reticulation and an indirect heat exchanger to increase efficacy of the cooling system. Introduction of air and water circulation systems will require determination of storage size, sizing of the psychrometric unit and water reticulation and ventilation systems. Hence, this study was devoted to characterization and performance evaluation of a solar photovoltaic IAC+EC in terms of microenvironment temperature reduction and increasing RH in the storage chamber towards the optimal recommended storage conditions. The study evaluated the influence of the low-cost IAC+EC storage system on the tomato fruit in coastal areas with a sub-humid to humid climate and compared temperature and RH variations within the cooling unit, storage chamber and ambient air conditions. The overall aim of this study was to to design, construct and evaluate the performance of a solar powered IAC+EC unit; to evaluate the changes in the quality of IAC+EC stored tomatoes under sub-humid to humid conditions.

The specific objectives of this study were to:

1. To develop and evaluate a solar energy powered IAC+EC system for storage of tomato fruit.
2. To evaluate the performance of IAC+EC in terms of cooling efficiency, an increase in RH and a decrease in temperature under hot and sub-humid conditions.
3. To assess the physical, chemical and quality changes of tomato fruit stored in the IAC+EC system compared to ambient conditions.

1.3 Outline of Dissertation

This dissertation is organised into six chapters.

Chapter 1	Provides a general overview of the study detailing its justification and the objectives. The chapter discusses challenges faced by small-scale farmers in preservation of fresh produce after harvest. Evaporative cooling is identified as an ideally cooling method for small-scale farmers with no capital to invest in expensive systems that also require intensive energy supply. Evaporative cooling has been limited to dry and arid areas and its efficacy in sub-humid to humid areas need to be investigated. In hot and humid areas, indirect air-cooling is required in combination with evaporative cooling. Indirect air-cooling coupled with evaporative has not been well investigated. Therefore, this study proposes characterisation of indirect air-cooling coupled with evaporative for fruit and vegetables storage in hot and sub-humid to humid regions.
Chapter 2	Details an overview of the horticultural industry and its challenges. It reviews the factors influencing the shelf life of fruit and vegetables. It discusses the factors affecting postharvest losses in fruit and vegetables. This chapter considers available modern-day cooling technologies and their inherent challenges as to why small-scale farmers cannot adopt them and finally presents fresh produce cooling options for small-scale farmers. The chapter considers evaporative cooling as an option for fresh produce storage and further considers combination of indirect air-cooling and evaporative cooling. Indirect air-cooling coupled with evaporative cooling is

identified as an option for hot and sub-humid to humid areas requiring extensive investigation as it provides a potential of high thermal performance. The chapter concludes by considering renewable energy options available to power indirect air-cooling with evaporative cooling options for remote and scattered farmers that cannot be connected to the national greed.

Chapter 3 Focuses on development of a solar photovoltaic array system powering an indirect air-cooling in combination with evaporative cooling system for fresh produce. The chapter considers the design requirements to set up a solar photovoltaic system for indirect air-cooling, cooling load and energy requirements for electrical appliances like water pump and fans, battery bank capacity and sizing and optimisation of solar modules, charge controller and inverter. The chapter evaluates the performance of the solar photovoltaic system, determines and compares the theoretical power output to the actual power output. Variation of current and voltage with time of the day and ambient and module temperatures are considered. The chapter provides information on the charging and discharging curves of the bank facility. The chapter concludes by looking at the systems efficiencies and the economic evaluation of the solar photovoltaic system.

Chapter 4 This chapter overall investigated the performance of a combination indirect air cooling with evaporative cooling system in temperature reduction and RH increase in the storage for provision of optimal storage conditions for fruit and vegetables. The theoretical design of the system was derived from the design considerations that sized the storage chamber and cooling unit, cooling pad size and design, sizing and selection of water pump, determination of cooling load and the ventilation rate, sizing of fan. The chapter compares the results obtained in this study for indirect air-cooling combined with evaporative cooling under sub-humid conditions with results from literature of evaporative cooling systems in dry and arid conditions. The chapter concludes by providing evidence that indirect air-cooling is effective in areas with high humidity.

Chapter 5 Presents the effect on indirect air-cooling combined with evaporative cooling on the physical, chemical and sensory properties of tomatoes. The effects of this system on the quality of stored tomatoes are evaluated. The influence of storage environment on different factors, such as the fruit maturity stage, the storage period and storage conditions were investigated on tomato fruit quality during summer in KwaZulu-Natal, South Africa. The chapter compares the physical, chemical and sensory fresh produce results obtained in this study under sub-humid conditions with results from literature of evaporative cooling systems in dry and arid conditions of similar produce.

Chapter 6 This is the conclusion and recommendation chapter of this study. It highlights the major findings of this work and makes recommendations arising from the study.

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2 LITERATURE REVIEW

2.1 Introduction

The aim of this review is to identify the causes of postharvest losses (PHL) in fruit and vegetables (F&V) in relation to small-scale farming in sub-Saharan Africa (SSA). The reduction of PHL can improve food security at household level. Farmers involved in small-scale production of fresh produce experience high PHL due to physiological deterioration associated with technical, biological and environmental factors. If these factors could be contained, then sufficient supplies of fresh produce would reach the consumer thus improving both household income and nutritional status. This article details the PHL experienced by farmers during harvesting and packaging, on-farm temporary storage and transportation, and then considers research into cold chain technologies; their benefits and costs. There are existing and available modern cooling technologies but these are capital intensive and require electricity, which is not always available to small-scale farmers (SSF). This review explores several cooling technologies and recommends direct evaporative cooling (EC) for dry and arid climates and EC combined with indirect air-cooling (IAC+EC) for hot and sub-humid to humid conditions. Many research studies are required on IAC+EC for preservation of F&V as there is dearth of performance information. The review also considers alternative power sources for cooling technologies and their integration with IAC+EC in a bid to minimise losses experienced by SSF in SSA. Low-cost and adequate cooling technologies are unavailable to the average SSF. However, there is scope for EC, which is simple and cheaper technology. Solar and wind energy can be used to power fan, if forced air IAC+EC is required.

2.2 Potential of Fruit and Vegetables in SSA

SSA has potential for tropical F&V production, which is further supported by the annual increases in price and quantities produced in the last five to ten years (Ruel *et al*., 2005; DAFF, 2017). Two distinct farming production levels, large-scale commercial agriculture and small-scale farming characterize the horticultural sector in SSA. In large-scale commercial farming, farmers own large tracts of land and have the financial capability to invest in irrigation, agricultural inputs, skilled management, and agricultural infrastructure for crop production including postharvest operations

(Schalkwyk *et al*., 2012). SSF on the other hand on average own land holdings of less than 1.5 ha and are characterized by low output and very little investment in infrastructure for production (Baloyi, 2010; Salami *et al*., 2010; Tscharntke *et al*., 2015; Rahiel *et al.,* 2018). Despite these setbacks, SSF contribute approximately 80% of all F&V all fresh produce in SSA including South Africa (OECD/FAO, 2016; SAYB, 2017). The challenges faced by SSF in SSA according to Salami *et al.* (2010), Mpandeli and Maponya (2014) and Arah *et al*. (2016) relate to:

i. Security of tenure as the land is in most instances state owned;
ii. Limited access to credit because of lack of collateral and/or credit history;
iii. Farmers having to fund agricultural activities from either money generated from off-farm activities, or remittances from family members from off-farm employment;
iv. Spending on agriculture by most African countries is less than 6% of total expenditure since 1980 and less than 1% of commercial lending goes to agriculture with most of this funding large-scale commercial farming.

Furthermore, the fact that most SSF are located in remote areas with no access to grid electricity compounded by poor road infrastructure connecting them to major towns hinders growth and productivity (Kim and Ferreira, 2008; Korir *et al.,* 2017). SSF in many instances are forced to sale their produce at the farm gate at depressed prices or to intermediaries that offer them low prices rendering their enterprises unprofitable (Obura *et al.,* 2015; Seweh *et al.,* 2016).

High PHL in F&V characterise small-scale farming, which reduce the amount of farm fresh produce for both household consumption and sale (Baloyi, 2010; Kader, 2010; Rahiel *et al.,* 2018). As a result, the horticultural industry has not been significantly contributing to the economies of the SSA countries. Appropriate post-harvest technologies for SSF in SSA have not been developed or adopted for the handling of perishable commodities (Baloyi, 2010; Saran *et al*., 2012; Kasso and Bekele, 2018). The unavailability of appropriate postharvest facilities for SSF in South Africa for packaging, temporary storage and transportation, threatens food security in the country (Cherono and Workneh, 2018; Rahiel *et al.,* 2018). The traditional peddling of fresh produce at farm gate at low prices to avoid PHL is not a lasting solution as it ultimately undermines sustenance (Sibomana *et al*., 2017). Figure 2.1 shows the supply chain process of fresh produce for SSF and large-scale growers. SSF harvest their fresh produce and sale directly at farm gate for local consumption or intermediatories while large scale growers transport harvested fresh produce first for washing and packaging in packing houses before distribution to processing industries and fresh produce markets (Sibomana et al. 2016)

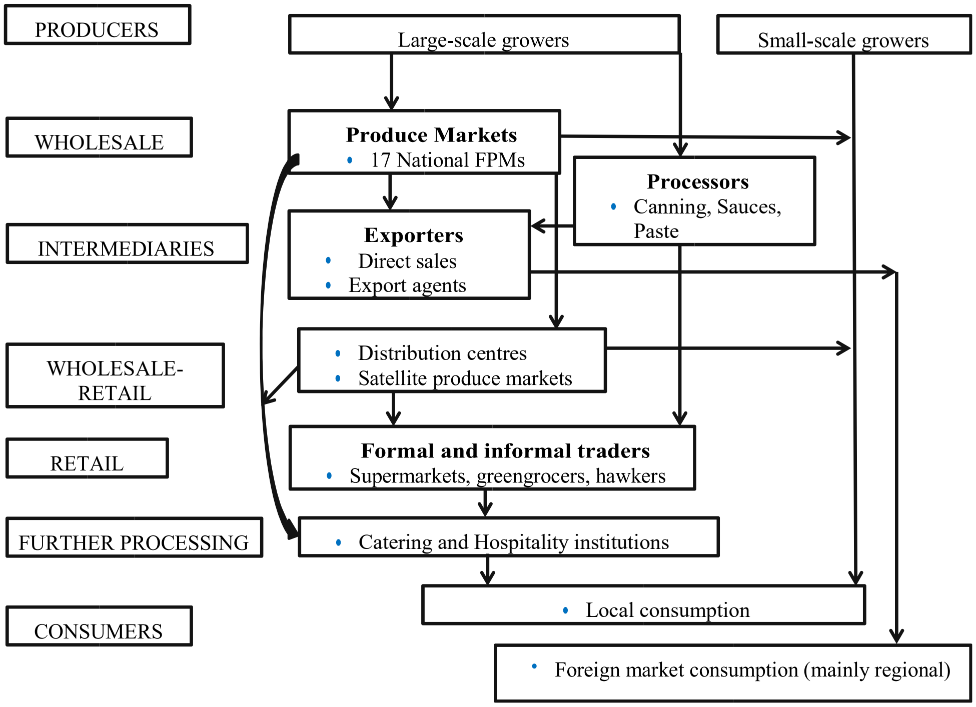

Figure 2.1 The supply value chain in South Africa for fresh produce (adapted from Directorate Marketing 2013).

Although there are a number of modern cooling technologies developed and imported into the region, SSF have not been able to adopt and utilise such facilities as they are both capital and energy intensive (Workneh and Woldetsadik, 2004; Ejeta, 2009; Baloyi, 2010; Rayaguru *et al*., 2010; Seweh *et al.,* 2016). The adoption of these cooling technologies, however, has largely relied on the scale of production (Caleb *et al*., 2011; Prusky, 2011). For instance, large-scale farmers in SSA have access to various cooling technologies, thus have maintained their dominance on national fresh producers' market (Tigist *et al*., 2011; Sibomana *et al.,* 2016). Despite the numerous researches on both production and postharvest handling of commodities in the region, there is less adoption or application of the research results to solve the post-harvest handling problems under SSA conditions particularly for small scale farming (Saran *et al*., 2012). Therefore, to discuss low cost cooling technologies this review has found it necessary to explore causes mainly related to postharvest physiology of crops since cooling applies to slowing down respiration and ethylene production and extent of losses. This will lead to consideration of cooling technologies as a major issue of this review. The review also explores alternative renewable energy options available for possible integration with low-cost technologies to preserve F&V that SSF can access.

2.3 Overview of the Horticultural Industry in SSA

Over a thousand species of F&V, consisting of different morphology and composition, are known to exist within the region (Obura *et al.,* 2015). In excess of 950 million people consume F&V as food in SSA (Husain *et al.,* 2016). Recently, there has been an expansion in fruit production that include mangoes, bananas, citrus, avocado, papaya, pineapple, grape, apple, pear, guava and peach. Another area of high production growth has been in vegetables, that include tomatoes, cabbages, onions, sweet pepper; French beans, pea, lentil, leek, chilies, okra, garlic, ginger, carrot, turnip, mushroom, lettuce, spinach and other local leafy vegetables (Ngowi *et al*., 2007; Banjaw, 2017). In South Africa most F&V are grown in Limpopo province while most tropical and sub-tropical fruits are grown in Mpumalanga province (SAYB, 2018). The humid low-lying coastal belt of KwaZulu-Natal province is suitable for banana production while vegetables like tomatoes, cauliflower, cabbage, carrots, etc are found in the high-lying areas of the province. The climate of most of KwaZulu-Natal province is not really suitable for large-scale commercial production of onions (Katundu *et al.,* 2010; DAFF, 2016).

F&V provide the much-needed nutritional value to the population and a number of countries within the region heavily rely on this primary commodity for revenue through the bulk export of raw or processed fresh produce (OECD/FAO, 2016; Cherono and Workneh, 2018). Involvement in production of F&V is an important source of income for SSF and this sub-sector provides rural households with job opportunities throughout the value chain. There exist competing needs for local country consumption and export of fresh produce that needs to be satisfied (Banjaw, 2017). Moreover, the population in SSA is likely to double by the year 2045, so a more sustainable approach to preserving fresh produce will be required to meet future food demand (UNDP, 2012).

The increasing population and shifts in consumer demand have resulted in an exponential demand and price hikes for fresh F&V in SSA (Workneh, 2007; Ntombela, 2012; Pereira, 2014; SAYB, 2015). For example, the demand has seen annual price increases in F&V of 7% in South Africa (SAYB, 2016) and increased fresh produce production quantities from 2010 to 2015 as shown in

Table 2.1. Such a scenario improves farmers' living conditions including health and income and improves food security at household level in the villages (Workneh, 2007; Bourne, 2009). An increasing demand for fresh produce at the right prices is likely to move SSF from subsistence to commercial scale production (Workneh, 2010).

Table 2.1 Vegetable production per (1000 ton) in South Africa and the average prices at major fresh produce markets for 2010 and 2015 (adopted from DAFF 2016)

	Vegetables production (1000 t)		Average price at major fresh produce market (R/tonne)	
	2010	2015	2010	2015
Potatoes	1 955	2 423	2 598	3 222
Tomatoes	575	539	4 233	8 310
Pumpkins	234	256	1 737	1 805
Green mealies	339	373	8 260	13 726
Onions	489	675	2 573	2 802
Sweet potatoes	60	63	1 977	3 699
Green peas	17	9	17 960	37 012
Beetroot	67	78	2 763	3 050
Caiuliflower	25	13	3 777	7 752
Cabbage	141	146	2 573	1 963
Carrots	151	201	3 251	2 132
Green Beans	23	25	5 634	1 917
Lettuce	-	-	3 338	5 950

One of the major challenges constraining rural households from attaining commercial farming status is the quality deterioration that result in PHL experienced in the production cycle of fresh produce (Sibomana *et al*., 2016). It is essential that the quality of fresh produce be maintained throughout the value chain as quality has a significant relationship with customer satisfaction (Ngcobo, 2013; Senthikumar *et al.,* 2015). The quality of fresh produce can be maintained through provision of optimum storage conditions, which varies with crop type and depends on intended use, the level of quality required for the purpose, distance and time to market (Watkins, 2006; Toivonen, 2007; James and Zikankuba, 2017; Kyriacou and Rouphel, 2018).

2.4 Postharvest Losses

PHL are the qualitative and quantitave losses in a given produce during harvest or along the value chain of a post-harvest system. Although a recent report by the World Bank (World Bank, 2011) indicated that an estimated US$ 4 billion worthy of grains alone is lost through PHL in SSA, the entire F&V supply chain might be facing similar challenges (Affognon *et al*., 2015). Since F&V are categorised as perishable commodities, which are susceptibility to physiological deterioration in the supply chain (Ngcobo *et al*., 2012; Pathare *et al*., 2012; Deoraj *et al.,* 2015; Macheka *et al.,* 2017). Physiological deterioration is the main root cause of PHL in the tropical and sub-tropical regions SSA (Macheka *et al.,* 2017). PHL have the potential to discourage farmers venturing into production and marketing of fresh produce, and thus affecting the availability and consumption of F&V in urban areas (Workneh, 2007; Azene *et al*., 2011; Affognon *et al.,* 2015). Efforts to reduce PHL are paramount, particularly if economically feasible as this is of great significance to farmers and consumers alike (Johnson and Sangchote, 1994; Saquet *et al.,* 2016; Rahiel *et al.,* 2018).

Reducing PHL, as an important component of food security, has potential to lower food prices to vulnerable communities in the region (Ogbuagu *et al.,* 2017). In this food-scarce part of the world, F&V that do not reach the intended market are a significant waste of resources (Ngcobo *et al*. 2012; Kasso and Bekele, 2018). A survey carried out by Mashau *et al.* (2012) in the Tshakuma fruit market, in Limpopo province of South Africa showed that fresh fruit like bananas, oranges, avocados, paw-paws and tomatoes, experience deterioration in both quality and quantity of 43.3% mainly due to over-ripening. This means sellers at this market lose almost half of their potential income. In the 2011 production of tomatoes the supply chain experienced loss of produce estimated at 10.2% (US$22.03m) in South Africa, 13.4% (US$180.9m) in Nigeria and 10.1% (US$19.99m) in Kenya because of inadequate storage or transportation (Sibomana *et al*., 2017).

PHL in the supply chain of fresh produce in SSA, are difficult to estimate as there is limited official data from different countries and there is no standard methodology to estimate them (Adeoye *et al*., 2009; Affognon *et al.,* 2015; Sibomana *et al*., 2016; Sheahan and Barrett, 2017). PHL in F&V in the region are estimated to be over 50% though there are varying estimates from crop to crop and country to country (Kader, 2005; FAO, 2008; Kader, 2010; Mashau *et al*., 2012; Deoraj *et al.,* 2015; Niewiara, 2016). Table 2.2 provides examples of estimated percentage PHL for F&V for selected countries in East Africa, Central Africa, West Africa and Southern Africa.

Table 2.2 Postharvest losses in fruits and vegetables for selected countries in Sub-Saharan Africa

Sub-region	Country	Estimated Postharvest Losses (%)	References
East Africa	Ethiopia	50	FAO 2005
Central Africa	Rwanda	30-80 depending on product	Kitinoja *et al*. (2010)
West Africa	Ghana	30-80 depending on product	Kitinoja *et al*. (2010)
Southern Africa	Swaziland	20-50 depending on product	Masarirambi *et al*. (2010); Mashau *et al*. (2012)

These high losses shown in the Table 2.2 are a precursor to food insecurity for Sub-Saharan communities. Small scale farming exporters of F&V in region have complained of PHL experienced during short periods of storage before (i.e. awaiting transportation) and during transportation to markets and proposes that reduction of these should be a research priority (Workneh and Woldetsadik, 2004; Tigist *et al*., 2011; Kenghe *et al.,* 2017; Sibomana *et al.,* 2016).

2.5 Causes of Postharvest Losses

Maintenance of fresh produce quality requires precise application of optimum cold chain conditions from harvest, grading, packaging, storage and transportation to the consumer (Tanner and Smale, 2005; Zude, 2009; Sibomana *et al*., 2016). The optimum fresh produce conditions vary according to the intended use and the targeted market; either consumption at household level, local country consumption or export and the distance to the destination (Brosnan and Sun, 2001; Toivonen, 2007; Sood *et al.,* 2011; Kyriacou and Rouphel, 2018). It is important, therefore, to understand the correlation between PHL and increased fresh produce prices resultant from a constraint output market because of spoilage.

PHL may occur due to factors like environmental (Mandal *et al*., 2010; Rayaguru *et al*., 2010; Workneh, 2010; Tyagi *et al.,* 2017), biological and chemical, physiological (Joas and Lechaudel, 2008; Tyagi *et al.,* 2017), as well as technical factors (Kader, 2010; Gebru and Belew, 2015). The main environmental factors that result in significant PHL in F&V are temperature and RH (Getinet *et al.,* 2008; Workneh and Osthoff, 2010; Prusky, 2011; Misra and Ghosh. 2018). The biological and chemical factors arise because F&V are prone to microbial contamination during growth, harvest and postharvest operations (Ambaw *et al*., 2013a; Kasso and Bekele, 2018). Three main types of microorganisms that affect quality of fresh produce during transportation and storage are bacteria, yeast and mould (Alexandre *et al*., 2011; Marriott *et al*., 2018).

Physiological deterioration of fresh produce happens since F&V are living tissues that continue to transpire, respire and further ripen even after detachment from the mother plant during harvesting (Brosnan and Sun, 2001; Ngcobo *et al*., 2012; Hagos, 2014; Jedermann *et al.,* 2017; Misra and Ghosh, 2018). This process continues throughout the life of fresh produce. As the anaerobic process continues, respiration increases further with more heat generation either inside or outside the fruit (Irtwange, 2006; Rahiel *et al.,* 2018). This sustained respiration in fresh produce means decreased food value, associated with loss of flavor, loss of salable weight (through loss of moisture) and more rapid deterioration (Paull and Duarte, 2011; Ait-Oubahou, 2013; Sitorus *et al.,* 2018).

The technical factors that affect fresh produce quality are mainly associated with mechanical damage or injury to F&V, lack of skilled labour in handling of fresh commodities and prolonged storage time (Wilson et *al*., 1999; Parfitt *et al*., 2010; Prusky, 2011; Paull and Duarte, 2011; Beckles, 2012; Gebru and Belew, 2015). Controlling these factors provides improved efficiency of broader value chains and systems in fresh produce. On the other hand, social factors relate to trends such as urbanization, where many people from rural areas move to large cities causing a high demand for F&V in urban centres, thus increasing the need for more efficient supply-chain systems (Parfitt *et al*., 2010; Kasso and Bekele, 2018). The critical issue in all this is that, the effects of the mentioned factors are not receiving the required attention at various control points such as harvesting, packaging, on-farm temporary storage and transportation to the market resulting in high PHL in the fresh produce supply chain.

2.5.1 Losses during Harvesting and Packaging

Harvest-labour especially for SSF should be skilled to know when to harvest the produce, as it is an essential requirement of industrial postharvest handling (Beckles, 2012; Banjaw, 2017). Fresh produce should be harvested during the coolest part of the day, either very early in the morning or late afternoon (Botondi *et al*., 2003; Bachmann and Earles 2014; Arah *et al.,* 2015; Tyagi *et al.,* 2017). In developing labour skills, harvesters should be trained in handling the crop carefully to avoid injury; harvesting dry whenever possible and at proper maturity; handling each produce no more than is necessary and avoiding careless handling e.g. dropping F&V (Tijskens, 2007; Kitinoja *et al*., 2010; Prusky 2011; Mulualem *et al.,* 2015; Cherono *et al.,* 2018). To mitigate losses due to technical factors of wrong timing of harvest and improper handling during harvesting, farmers must practice good harvesting practices that will not result in injury to fresh produce (Zenebe *et al.,* 2015; Sibomana *et al*., 2016).

van Zeebroeck *et al.* (2007) and Banjaw (2017) describe mechanical damage as pausing a challenge to the quality of fresh produce and having a potential to reduce the value of F&V. According to Basediya *et al.* (2013), mechanical injury due to impact resultant from dropping or tossing fresh produce during harvesting can cause splitting of fruit and internal bruising. Impact damage is detrimental and its effect is not just limited to visual aspects but can also cause a risk of fungal and bacterial contamination (Aba *et al.,* 2012; Fadiji *et al*., 2016). Inappropriate packaging or containers and over or under packaging of containers also can result in mechanical injury to F&V (Wilson *et al*., 1999; Aharoni, 2004; Adeoye *et al*., 2009; Prusky, 2011; Mashau *et al*., 2012; Ngcobo *et al*., 2012; Kasso and Bekele, 2018). Packaging should ensure produce is loaded into convenient units for handling during distribution, storage and marketing (Wills *et al*., 1998; Kasso and Bekele, 2018). However, many SSF in production of tomatoes utilise traditional baskets as packaging material (Kereth *et al*., 2013; Ugonna *et al*., 2015). For SSF in South Africa and Ethiopia producing fresh produce for urban markets are using plastic crates (Mashau *et al*., 2012; Kasso and Bekele, 2018).

Whenever fresh produce is loaded in baskets or plastic crates, it applies a static load on itself (Adeoye *et al*., 2009; Arah *et al.,* 2015). The static load result in excessive pressure applied in the lower part of the packaging material thus causing deformation of the produce at the bottom, which may result in bruising and breakage leading to decay development (Sirisomboon *et al*., 2012; Ugonna *et al*., 2015). This scenario obtains when baskets are used or there is over-packaging (Sibomana *et al*., 2016). In under-packaging, the movement of fresh produce in the container is high resulting in collision/friction that damages the fruit (Çakmak *et al.,* 2010; Arah *et al.,* 2015). In some instances, these plastic crates have rough internal surfaces, which can injure fruit or vegetables by contact (Sibomana *et al*., 2016).

Another cause of losses during harvesting and packaging is due to physiological deterioration of fresh produce since F&V are living tissues that transpire, respire and further ripen during the period of harvesting and packaging. The respiration rate of a product strongly determines its transit and postharvest life (Sinha *et al*., 2011; Yahia, 2011; Tyagi *et al.,* 2017). The higher the temperature at harvest, the higher the respiration rate will be hence fresh produce in the tropical and sub-tropical regions in SSA have a reduced shelf life (Workneh and Woldetsadik, 2004; Tefera *et al*., 2007; Sandhya, 2010; Gupta and Dubey, 2018).

2.5.2 Losses during on-Farm Storage and Transportation

Although not ideal for perishable produce quality, sometimes F&V are stored at the farm gate for some period until either transport to the market is available or local buyers purchase the produce for consumption or resale (Singh *et al.,* 2010; Kasso and Bekele, 2018). Losses during on-farm storage and transportation is a major contributor to the total PHL encountered by SSF in SSA fresh produce supply chain (Emana and Gebremedhim, 2007; Buzby *et al.,* 2014; Kiaya, 2014; Cherono and Workneh, 2018). Often the transport and local markets are without temperature-controlled environmental conditions (Kitinoja and Thompson, 2010; FAO, 2016; Cherono *et al,* 2018).

In circumstances where storage (on-farm) and transportation facilities have sub-optimum environmental conditions, the ripening of F&V continues resulting in further physiological deterioration (Opara *et al*., 2011; Yahia, 2011; Maliwichi *et al*., 2014; Saltveit, 2018). Physiological, chemical and enzymatic changes are speeded when fresh produce is subjected to high ambient temperature and low RH during temporary storage and transportation at the back of trucks (Choudhury, 2005; Nunes *et al*., 2009; Fadeyibi and Osunde, 2011; Paull and Duarte, 2011;

Ogbuagu *et al.,* 2017). The ambient temperatures in SSA can be 7℃ - 20℃ higher than the recommended 15℃ for tomatoes (Kitinoja and AlHassan, 2012; Sibomana *et al*., 2017).

When temperature and RH are unregulated, fruit physiological deterioration and senescence accelerates as fruit rot organisms spread rapidly at warm storage temperatures and low RH (Gharezi *et al*., 2012; Ambaw *et al*., 2013a; Chijioke, 2017). High temperature and low RH can result in a significant loss of nutritional value, decreased returns due to poor produce quality (wilting, shriveling), loss of saleable weight and in many cases the whole fruit or vegetable is lost (Joas and Lechaudel, 2008; Odesola and Onyebuchi, 2009; Gupta and Dubey, 2018).

Temperature management after harvest is fundamental in minimizing PHL and maintaining nutrients like vitamins of F&V (Prusky, 2011; Pathare *et al*., 2012; Misra and Ghosh, 2018). The sub-tropical climate obtaining in most countries in East and Southern Africa which is characterized by high temperature, increases the rate of microbial changes and in turn activates enzymatic reactions in produce (Brosnan and Sun, 2001; Workneh, 2010; James and Zikankuba, 2017). Respiration rate, metabolic processes and ethylene biosynthesis of some fruit increase with room temperature within a given range (Workneh, 2010; Wills and Golding, 2016). Respiration rates can double, triple or even quadruple with every increase in temperature (Zagory and Kader, 1988; Mansuri, 2015; Saltveit, 2018).

Therefore, the storage of F&V at low temperature immediately after harvesting will reduce the rate of decomposition and microbial spoilage (Ito *et al.,* 1988; Workneh and Osthoff, 2010; Senthilkumar *et al.,* 2015; Saltveit, 2018). Fresh produce shelf life can double by reducing temperature from 10℃ to 5℃ (Sun and Zheng, 2006). Typically, the storage temperature of F&V is 0℃ to 12℃ and most tropical and subtropical fruits require high temperatures of 5℃ to 13℃ according to (FAO, 2003; Paull and Duarte, 2011) and as shown in Table 2.3.

RH is another important aspect considered during storage and transportation of F&V (Paull and Duarte, 2011; Prusky, 2011; Seweh *et al.,* 2016). Occurrence of higher humidity during temporary storage and transportation of fresh produce reduces water loss, thus maintaining produce weight, appearance, nutritional quality and flavour, while wilting, softening and juiciness are reduced (Kobiler *et al*., 2010; Basediya *et al.,* 2013; Laguerre *et al*., 2013; James and Zikankuba, 2017; Yousuf *et al*., 2018). According to Cantwell *et al*. (2009) and Nabi *et al*. (2017), the recommended storage RH for most horticultural crops is between 70 to 95%. Table 2.3 provides a summary of recommended storage RH for selected F&V. Most fresh produce under smallholder production is stored at RH levels lower than recommended resulting in excessive moisture loss (Singh *et al.*, 2014; Banjaw, 2017). Subsequently, the F&V suffer wilting, shriveling and dryness resulting from small moisture losses of 3-6% (Nunes *et al.*, 2009). These changes in the produce affect marketability or economic value especially if F&V are sold by weight (Paull and Duarte, 2011; Yahia, 2011; Rahman *et al.*, 2016).

Table 2.3 Optimum temperatures and relative humidity of selected vegetables

Product	Optimum Temperature	Optimum Relative Humidity (%)	References
Broccoli	0 ℃	90-95	Snowdon, (1992); Flores Gutiérrez, (2000)
Cabbage	0 ℃	90-95	FAO (1989)
Lettuce	0 ℃	90-95	Flores Gutiérrez, (2000)
Carrots	0 ℃	90-95	Prusky, (2011)
Tomatoes	12-15 ℃	≥ 85	Beckles, (2012)
Guava	5-10 ℃	90	Basediya *et al.,* (2013)
Mango	12 ℃	85-90	Shitanda et *al.,* (2011)
Potatoes	5-15 ℃	90	Wilson *et al*., (1999)
Onions	1-2 ℃	70-75	Byczynski (1997);
Garlic	0 ℃	70-75	Byczynski (1997);
Banana (green)	13-14 ℃	90-95	Hardenburg *et al*., (1986)
Cucumber	10-13 ℃	95	Flores Gutiérrez, (2000)

The other important moist air property closely linked to RH is the vapour pressure. The difference in vapour pressure between the ambient air and the intercellular spaces of living plant tissue governs the migration of moisture and the rate of moisture transfer in fresh commodity storage (Deirdre, 2015). Weight loss from perishable commodities is high if surrounding air temperature, flesh moisture content and temperature are high as vapour pressure increases as flesh temperature and moisture content increases. Moisture movements either in the form of vapour or liquid takes place within the product to a surface and evaporates from a surface provided the humidity ratio is high around the stored product (Becker and Fricke, 1996; Wills and Golding, 2016). Thus, under poor postharvest management conditions of storage or in transit perishable commodities lose excessively large weight due to existence of large vapour pressure deficit (Workneh, 2010; Kritzinger *et al*., 2018).

Among other key contributors to high PHL in fresh produce is demographic and socio-economic characteristics of smallholder F&V producers (Affognon *et al.,* 2015). SSF have to travel to cities to sell their fresh produce and due to lack of transport; farmers keep F&V over long periods at the farm gate awaiting transportation to markets resulting in further mechanical damage (Kader, 2003; Wakholi *et al.,* 2015; Nabi *et al*., 2017). When this waiting period at the farm gate is prolonged, there is further mechanical damage to produce due to over handling (Knee and Miller, 2002; Sibomana *et al.,* 2016; Cherono *et al.,* 2018). The damaged F&V allow easy penetration of microbial population into the tissue (Fadeyibi and Osunde, 2011; El-Ramady *et al.,* 2015). This increases chances of decay and growth of micro-organisms (Johnson *et al.,* 1997; Pinto *et al.,* 2004; Rajan and Anandan, 2018). As packaged produce applies static load on itself the degree of deformation on F&V will depend on the period the static load is applied (Idah *et al* 2007; Sirisomboon *et al*., 2012). The longer the period the greater the deformation and stress effected on the produce. The stress effected on the produce will also depend on the ripeness of produce, as it ripens the same static load will inflict more internal flesh damage (Mashau *et al*., 2012; Sibomana *et al*., 2016). The injury to produce increases if it is loaded at the back of trucks in rough road conditions because of vibration forces experienced (Fadeyibi and Osunde, 2011; Kereth *et al*., 2013; Bradbury *et al*., 2017). For SSF in SSA trucks that pick-up produce is not regular and if a farmer misses the truck on a certain day it can take up to a week before there is transport to pick up his F&V to the market (Mashau *et al*., 2012). To eliminate this challenge, it is required that the duration between harvest and arrival at the markets be minimized.

If mechanical damage took place during harvesting and packaging, the F&V will be prone to microbial contamination during storage and transportation (Ambaw *et al*., 2013b; Tzia *et al.,* 2016). Microbial decay accounts for about 15% of the postharvest decay in F&V (Workneh and Osthoff, 2010; Wills and Golding, 2016). Microbial decay is influenced by air, soil, poor sanitation, environmental factors and moisture content of crops (Rahiel *et al.,* 2018). Although Workneh and

Osthoff (2010) alluded to the fact that most microorganisms cannot grow under acidic conditions of pH values less than 4.5, fungal growth still causes about two thirds of spoilage of F&V. This is because fungi are much more tolerant to pH values below 4.5. Vegetables have pH values above 4.5 and near neutrality, and such levels create favourable conditions for many microorganisms such as bacteria, yeast and fungi. Often, bacteria would have a competitive advantage in vegetables because it grows faster than the fungi or yeast. Microbiological effect should be minimized to avoid consumer's risks as fresh produce can be eaten uncooked or minimally processed (Sagoo *et al*., 2003; Beckles, 2012; Arah *et al.,* 2015).

2.6 Research into Cold Chain Technologies: Costs and Benefits

The maintenance of market quality of fresh produce through management of a cold chain is key to the success of the horticultural industry, it is therefore, not only necessary to cool the product down but to do so as quickly as possible after harvest (Paull, 1999; Senthilkumar *et al.,* 2015; Saltveit, 2018). A cold chain is a temperature-controlled supply chain, which consists of uninterrupted range of systems that monitor or maintain produce at a given temperature and keeps history (Wills and Golding, 2016). According to Prusky (2011), the requirements for maintaining quality and safety of horticultural perishables through the supply chain from harvest to consumption are the same in developing and developed countries. For SSF in F&V production in SSA, the challenges are beyond whether cooling technologies exist or not as there are other factors like volume to be cooled per day, harvest temperature versus recommended storage temperature, capital and operating costs come into play (Kitinoja and Thompson, 2010; Azene *et al*., 2011; Vala *et al.,* 2014). To invest in modern cooling technologies, SSF have to consider the cost-benefit analysis as to whether there will be an increased financial benefit associated with the chosen technology (Ejeta, 2009; Faris, 2016). Availability of electricity is one of the critical factors to consider as an energy input to power cooling technologies (Kitinoja *et al*., 2011; Seweh *et al.,* 2016).

Possible areas of consideration should allow low energy cool storage facilities so that fresh produce reaches markets at recommended storage conditions (Kader, 2005; Chaudhari *et al*., 2015; Sekyere *et al.,* 2016). Achieving this would ensure that both the supply of fresh produce and the shelf life would improve significantly in SSA.

Kitinoja and Thompson (2010) have previously reviewed pre-cooling systems for small-scale producers. These authors and broader literature have described various methods for preservation of fresh F&V immediately after harvest. These cooling methods include among others, mechanical refrigeration, hydro-cooling, vacuum cooling, forced air-cooling and evaporative cooling (EC) (Senthilkumar *et al.,* 2015). Mechanical refrigeration, forced air-cooling, vacuum cooling, hydro-cooling and EC of fresh produce have previously been described in detail by reviews that include Brosnan and Sun (2001); Thompson *et al.* (1998) and Senthilkumar *et al.* (2015), who placed emphasis to the different performance parameters of various cooling methods. The following publications discuss the different pre-cooling methods, Boyette *et al.* 1994; Singh-Negi and Kumar-Roy, 2000; Brosnan and Sun, 2001; Wang and Sun, 2001; Jiro, 2002; Zhang and Sun, 2006; Zheng and Sun, 2006; James *et al.* 2009; ASHRAE, 2011; James and James, 2011; Ambaw *et al.* 2013a, b; Senthilkumar *et al.* 2015; Misra and Ghosh, 2018.

2.6.1 Mechanical Refrigeration

Mechanical refrigeration refers to the process where heat absorption takes place at one point and heat dispersion at the other (Zou *et al*., 2006; Moureh *et al*., 2009; Sunmonu *et al.,* 2014). This is achieved through circulation of a refrigerant through the system by a compressor picking heat through the evaporator inside the fresh produce space and dissipating it through the condenser on the outside (Zou *et al*., 2006; Hera *et al*., 2007a; Vala *et al.,* 2014; Rajan and Anandan, 2018. The compressor can be powered through an electric motor. The refrigeration system is energy intensive as electricity power is consumed throughout the whole cold chain (Hera *et al*., 2007b; Fernandes *et al.,* 2018). This in turn leads to high product cost since unit energy costs make part of the unit cost for production of a given produce (Swain *et al*., 2009; Seweh *et al.,* 2016). However, where there is a ready and cheaper supply of electricity mechanical refrigeration is the most reliable cooling technology (Kitinoja and Thompson, 2010; Sekyere *et al.,* 2016).

2.6.2 Hydro-Cooling

Hydro-cooling is a fast, uniform cooling process of removing field heat from freshly harvested F&V by bathing them in chilled water or running cold water over it (Vigneault *et al*., 2009;

Prusky, 2011; Gomez-Lopez, 2012; Senthilkumar *et al,* 2015; Chen *et al*., 2016). Since the produce will be at higher temperature immediately after harvest the heat movement takes place from the produce to the water and hence leading to cooling of produce (Rennie *et al*., 2003; Wills and Golding, 2016). This process is an efficient way to remove heat as it uses water which removes heat at least five times faster than air (Bachmann and Earles, 2014). The use of water also provides another benefit as water serves as a means of cleaning at the same time. Hydro-cooling reduces water loss, the rates of microbiological and biochemical changes in order to prevent spoilage and maintain quality and increase shelf life (Gustavsson *et al*., 2011; Fernandes *et al.,* 2018). Hydro-cooling has limitations as it is only appropriate for commodities that tolerate wetting like carrots, peaches, asparagus, cherries etc. and is not appropriate for berries, potatoes to be stored, sweet potatoes, bulb onions, garlic, or other commodities that cannot tolerate wetting (Kitinoja and Thompson, 2010; Bachmann and Earles, 2014; Chen *et al*., 2016).

2.6.3 Vacuum Cooling

Vacuum cooling is a rapid EC method for porous and moist foods to meet the special cooling requirements (Zhang and Sun, 2006; Senthilkumar *et al.,* 2015; Chen *et al*., 2016). It is achieved by the evaporation of moisture from the surface and within the produce (Sun and Zheng, 2006; Deng *et al.,* 2011). The evaporation is encouraged and made more efficient by reducing the pressure to the point where boiling of water takes place at low temperature (Rennie *et al*., 2001; Vonasek and Nitin, 2016.). The difference between vacuum cooling and conventional refrigeration is that for the former, the effect is achieved by blowing cold air or other cold medium over the product and the later describes direct transfer of heat from a produce (Rennie *et al*., 2003; Wills and Golding, 2016). Speed and efficiency are the two features of vacuum cooling, which are unsurpassed by any conventional cooling method, especially when cooling boxed or palletised products (Sun and Wang, 2004; Rajan and Anandan, 2018). The speed and efficiency of vacuum cooling relate to the ratio between its evaporation surface and the mass of produce (Prusky, 2011). Cooling time, in order of 30 minutes ensures that strict cooling requirements for safety and quality of foods can be met (Brosnan and Sun, 2001). Vacuum cooling is ideally for any product, which has free water, and the product structure is not be damaged by the removal of such water.

2.6.4 Evaporative Cooling

EC or humidification of surrounding air in F&V storage involves the use of principles of moist air properties or psychometrics (Workneh, 2007; Chijioke, 2017). In EC, temperature drops considerably and humidity increases to the suitable level for short–term on farm storage or transportation of perishables (Jha and Kudas Aleskha, 2006; Misra and Ghosh, 2018). EC provide cool air with a temperature 1-2℃ above wet bulb temperature of ambient air by forcing hot dry air over a wetted pad (Chaudhari *et al*., 2015). The water in the pad evaporates, removing heat (sensible heat) from the air while adding moisture and thus producing a considerable cooling effect (La Roche, 2012; Basediya *et al*., 2013; Kapilan *et al.,* 2017). The heat in fresh produce transfers to the surrounding cool air. The air rises by natural convection in the process giving off the absorbed heat. As a result, EC can provide a storage environment for most tropical and sub-tropical F&V. Figure 2.2 illustrates the process of EC where the ambient temperature reduces from t_1 to t_2. The evaporation and addition of moisture utilises energy from the air thus increasing its water content from w_1 to w_2. A constant wet bulb line represents the process (Xichun *et al.,* 2008).

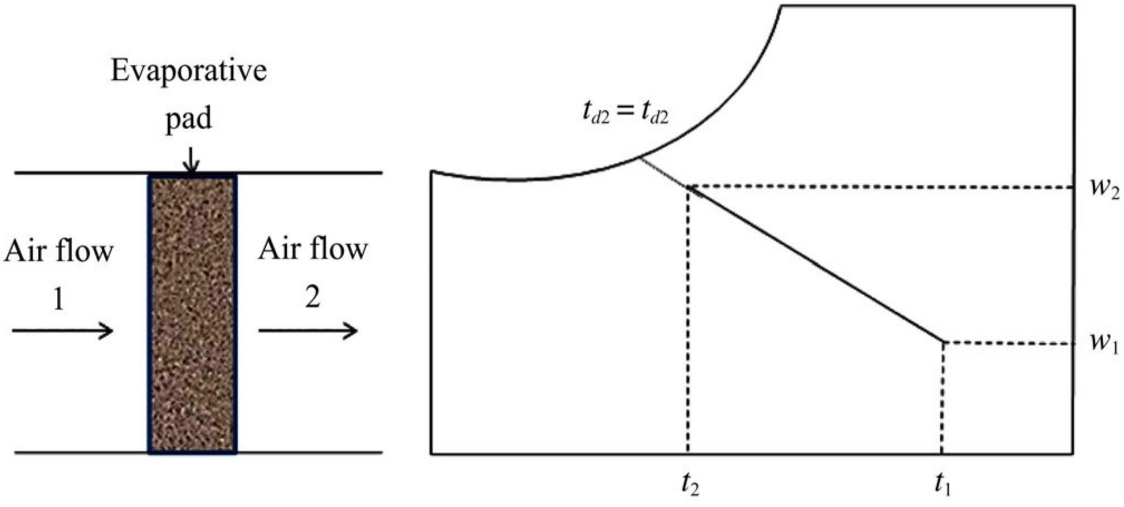

Figure 2.2 Illustration of evaporative cooling (Adopted from Akton, 2009)

EC is regarded as a low-cost system requiring no electricity input in a passive system or just an electric fan in a forced air system (Kitinoja and Thompson, 2010; Tigist *et al*., 2011; Chijioke, 2017). EC has achieved a favourable environment in storage structures for F&V where shelf life of some fresh produce like apples, tomatoes, bananas, mangoes, potatoes and pumpkins has been increased by factors of 1.3-5 at the same time exhibiting good appearance (Xuan *et al*., 2012; Hao *et al*., 2013; Chaudhari *et al*., 2015; Tolesa and Workneh, 2017). In the work done by Anyanwu (2004) the evaporative cooler increased the shelf life of tomatoes by a factor of three above open-air storage values. Figure 2.3 shows visual observation of tomatoes stored under EC when compared to those stored under ambient conditions after three weeks.

Figure 2.3 Visual observation of tomatoes stored under EC (A) versus tomatoes under ambient conditions (B) after three weeks.

There are two types of evaporative coolers, direct and indirect air-cooling (Duan *et al.,* 2012; Xuan *et al.,* 2012; Ahmad and Rahman, 2017). The two are similar except that in the indirect air-cooling, the air first passes through the heat exchanger as opposed to passing straight to the humidifier as is the case with direct cooling (Chaudhari *et al.,* 2015). In direct EC systems, there are two types i.e. natural ventilated (passive) and forced air-cooling (active). A natural or passive ventilated system uses natural air circulation to drive air into the cooling chamber while in a forced air system fans or blowers drive the ambient air through the wet pad (Ndukwu *et al.,* 2013; Ahmad and Rahman, 2017). The fans or blowers increase the airflow rate over the wet surface improving the cooling efficiency. In passive system, a lot of water is lost, as this system does not incorporate water recirculation mechanism. A passive system results in poor air circulation and compromised heat and mass transfer systems. Therefore, an active system involving fans and pump for water circulation is preferred.

Modern cooling technologies like, mechanical refrigeration, vacuum cooling and hydro-cooling could be used in SSA depending on, the type of fresh produce, the rate of cooling required, energy consumption requirements, level of production, availability of funds to purchase the technology and availability of energy (James and Zikankuba, 2017). Regrettable most SSF in SSA are located in areas where there is no grid electricity for driving these modern cooling technologies. There are also issues related to, the cost of modern cooling technologies, performance of modern cooling technologies, economies of scale and relevance to small-scale production under SSA conditions as discussed in the next section.

2.7 Selection of Suitable Cooling Technology for Different Fruit and Vegetables

Where there is, uninterrupted electricity supply, investment capital is not limited to cover purchase and cost of installation, availability of technical skills to maintain and run the facility, mechanical refrigeration would be the ideally cooling system (Basediya *et al.,* 2013; Okanlawon and Olorunnisola, 2017). However, mechanical refrigeration is not suitable for several F&V; for example, banana, plantain, tomato etc. cannot be stored in the domestic refrigerator for a long period as these fruits are susceptible to chilling injury (Ndukwu, 2011; Banjaw, 2017). The selection of suitable cooling technologies for specific crop usually depend on the different performance characteristics and parameters as described in Table 2.4.

Hydro-cooling, is achieved in a short space of time and the method is suitable for leafy produce and because the produce is bathed in water, prevention of loss of moisture from the product is ensured (Wang and Sun 2001; Thompson *et al.,* 1998; Elansari and Siddiqui, 2016). The limitations with hydro-cooling are its low energy efficiency and that requirement of containers that are water resistant which otherwise might cause cross decay contamination (Vigneault *et al.,* 2000; Senthilkumar *et al.,* 2015). The application of hydro-cooling by SSF is limited by its unsuitability to cooling of root and grass crops and vegetables like tomatoes, apples and pepper as they have a thick cuticle (Wang and Sun, 2001).

Forced air-cooling could be applicable to SSF but its limitation is that it requires a definite stacking pattern, hence use of skilled operators to achieve the required loading pattern to ensure satisfactory cooling rates (Arfin and Chau, 1988; Han *et al*., 2017).

Table 2.4 Summary of advantages, disadvantages and characteristics of different cooling technologies.

Cooling technology	**Advantages**	**Disadvantages**	**Performance of cooling technology**	**References**
Evaporative cooling	Low capital cost; high energy efficient; environmental benign; low weight loss; slow deterioration in quality; suitable for rural application; requires no special skill to operate; can be made from locally available materials; and easy to maintain.	Requires a constant water supply; no humidification, and high dew point; condition decreases the cooling capability; mineral deposits leading to pad and interior damage	Can maintain temperatures at 10-15℃ below ambient; Can achieve relative humidity of 90%; Can increase shelf life from 3 days to 15 days. Typical cooling time is 40-100 hours in passive cooling and 20-100 hours in fan-ventilated systems.	Anyanwu (2004) Dadhich *et al.* (2008) Tigist *et al* (2011) Basediya *et al.* (2013) Chaudhari *et al.* (2015) Chijioke (2017) Adewale & Olorunnisola, (2017) Puran and Isaac (2017) Rajan and Anandan (2018)
Hydro-cooling	Rapid cooling; prevents loss of moisture during cooling; cools and cleans the produce at the same time; and simple and effective pre-cooling method; High energy efficient.	Not uniform may leave “hot spots”; not suitable for: leafy produce; products that do not tolerate wetting; products that can be damaged by falling water; water left on surface can lead to fungus growth or discoloration; capital cost is relatively high;	Cooling can be achieved in 20-30 minutes; Water removes heat about 15 times faster than air at typical flow rates and temperature difference; Refrigeration capacity of 1.4 kW cool 500 kg produce per hour to achieve 11℃ depression;	Boyette *et al*. (1994) Lambrinos *et al.* (1997) Brosnan and Sun (2001) Rennie *et al.* (2001) Rennie *et al.* (2003) Prusky (2011) Senthilkumar *et al.* 2015; Puran & Isaac, 2017 Rajan & Anandan 2018

Cooling technology	**Advantages**	**Disadvantages**	**Performance of cooling technology**	**References**
		the equipment is not portable.		
Forced-air cooling	Faster cooling than conventional cooling; most common for cooling of flowers; and most common cooling method for produce sensitive to exposure to water; the potential for produce decay contamination is low; the equipment is portable depending on size; Capital cost is low.	Lowest energy efficiency; rapid cooling is required; forced air cooling is costlier when rapid cooling is required; and stacking pattern requires skilled operators	Doubling air velocity reduces pre-cooling time 2- 6-fold; Doubling air-flow rate from can shorten pre-cooling time by 30-40%; typical cooling times 1-10 hours	Baird *et al*. (1988) Han *et al*. (2017) Thompson and Chen (1988) Rudnicki and Nowak (1990) Brosnan and Sun (2001) Kader (2002), Tassou *et al*. (2010) Ambaw *et al*. (2013a) Takayuki *et al*. (2014) Senthilkumar *et al*. (2015) Zhao *et al*. (2016) Puran and Isaac (2017) Rajan and Anandan (2018)
Vacuum cooling	Rapid cooling achievable; distinct advantage over other cooling methods; cooling can achieve uniform cooling; gives highest energy efficiency; and hygienic since air only goes to the vacuum chamber; No potential for	Very capital cost; limited application to large growers; causes weight loss in the produce; only suited for produce with a high surface to volume ratio; works best only for produce like lettuce; cabbage, mushroom	Rapid cooling; method and can achieve temperatures of 1°C; Can increase shelf life from 3-5 days at ambient temperature to 14 days when combined with cold storage at 1°C; For every 5.5°C reduction in	Kim *et al*. (1995) Artes and Martinez (1996) Ito *et al*. (1998) Brosnan and Sun (2001) Rennie *et al*. (2001) Rennie *et al*. (2003), Sun and Zheng (2006) Feng *et al*. (2012) Ambaw *et al*. (2013b) Senthilkumar *et al*. (2015) Puran and Isaac (2017)

Cooling technology	Advantages	Disadvantages	Performance of cooling technology	References
	decay contamination; equipment is portable.		temperature there is 1% weight loss;	Rajan and Anandan (2018)

While vacuum cooling is a rapid cooling technology, it is only suitable for fresh produce with a high ratio of surface to volume and is unsuitable for oranges, tomatoes and apples (McDonald and Sun, 2000; Senthilkumar *et al.,* 2015). Any cooling method unsuitable for tomatoes would be unattractive as this fruit is a major commodity grown by SSF in a number of countries in the region (Mashau *et al*., 2012). Another limiting factor of the use of hydro-cooling and vacuum cooling by SSF is that both are pre-cooling methods, refrigeration is still required thereafter between the farm and the market.

The construction and operating costs of different cooling technologies vary from relatively low to high depending on the level of farm management (Kitinoja *et al.,* 2011; Siddiqi and Ali, 2016). Sometimes farmers ignore the cost of cooling technique during selection of technology as they transfer the cost to consumers making selling price of the produce higher especially in developed countries where there are good marketing systems (Boyette *et al.,* 1994; Rahiel *et al.,* 2018).

In developing countries where intermediaries set prices at farm gate, SSF may find themselves selling their produce below the production costs. Both vacuum cooling and hydro-cooling are regarded as expensive methods (Table 2.5) and therefore need to be operated for relatively longer periods in a year to justify an investment (Ryall and Pentzer, 1982; Boyette *et al.,* 1994; Deoraj *et al.,* 2015). Brosnan and Sun (2001) concluded that since vacuum chamber system for vacuum cooling is expensive then this technology is only feasible for large growers that produce large volumes of fresh produce throughout the year. Unfortunately, SSF in SSA do not have sufficient volumes of fresh produce to warrant the use of vacuum and hydro cooling throughout the year (Kitinoja *et al.,* 2011). As a result, these two cooling methods are limited for products for which they are much faster and more convenient (Ryall and Pentzer, 1982; Senthilkumar *et al.,* 2015).

A small scale commercial mechanical refrigeration system with a capacity of one tonne complete and ready for use in the USA will costs about US$7 000 for 3.5 kW (Kitinoja and Thompson, 2010). This cost is way above what most SSF in region can afford for a cooling capacity of one tonne. From Table 2.5 it is possible to construct an EC system of 1-2 MT at US$1 300 at an energy use per MT of 0.7 kWh compared to hydro-cooling whose costs while it varies is still higher than EC and would require more than 100 kWh per MT. The energy costs to cool 1 MT of tropical F&V using EC is $0.14 compared to $22-30 per MT to pre-cool cherries.

Table 2.5 Properties and costs of selected pre-cooling technologies

Cooling Technology	**Purchase Price (USD)**	**Suitable crops**	**Typical Size or capacity**	**Energy User per MT (kWh)**	**Cost per MT at an electricity rate of $/kWh**	**References**
Evaporative forced-air cooling (0.1 HP fan) to 13℃	$400	Tropical fruits and vegetables	0.5 MT	0.7	$0.14	Kitinoja & Thompson (2010) Rayaguru *et al.* (2010) Basediya *et al.* (2013) Chijioke (2017)
Evaporative forced-air cooling (0.5 HP fan to 13℃	$1 300	Tropical fruits and vegetables	1 to 2 MT	0.7	$0.14	Kitinoja & Thompson (2010) Rayaguru *et al.* (2010) Basediya *et al*. (2013) Rajan & Anandan (2018)
Vacuum cooling to 1 ℃	Varies	Produce with high surface to volume ratio	Suitable for large growers	*	*	Kim *et al.* (1995) Brosnan and Sun (2001) Elansari & Siddiqui (2016)
Hydro-cooling immersion type to 0 to 2℃	Varies	Cherries	3 MT cooled in 1 hour	110 to 150	$22 to 30	Thompson *et al*. (1998) Brosnan and Sun (2001) Kitinoja & Thompson (2010) Siddiqi & Ali (2016)

Cooling Technology	**Purchase Price (USD)**	**Suitable crops**	**Typical Size or capacity**	**Energy User per MT (kWh)**	**Cost per MT at an electricity rate of $/kWh**	**References**
Portable forced-air cooling (1 HP) fan in existing cold room to 2℃	$1 600	All crops	3 MT cooled in 4 to 6 hours	55	$11.00	Kitinoja and Thompson (2010) Zhao *et al*. (2016) Rajan & Anandan (2018)
Portable forced-air cooling (1 HP) fan in existing cold room to 13℃	$1 600	All crops	3 MT cooled in 2 to 4 hours	35	$7.00	Zhang and Sun (2006) Zhao *et al*. (2016) Rajan & Anandan (2018)

*Values not found in literature

EC provides a solution, as the technology has low initial investment, low installation and maintenance costs and in a passive system can be established without electricity (Sahdev *et al*., 2016). EC presents itself as an appropriate cooling technology for small-scale farming of fresh produce in SSA as it is appropriate for sub-tropical and tropical F&V, the volumes for cooling per farmer per unit time are not huge and the storage temperature is around 15℃. Chaudhari *et al.* (2015) reviewed the work done on EC from 1987 to 2010 and concluded that since this system is not harmful to environment, has low initial costs, can be constructed from local available material what is left is finding relevant and cheap energy sources for its upscaling.

2.8 Relevance of Evaporative Cooling to SSF in SSA

EC is an adiabatic cooling process where the air temperature decreases without change in its total heat content when dry air passes over or through wet surfaces (Chijioke, 2017). During adiabatic cooling of air, its temperature decreases while the air absorbs moisture from wet surface (Olosunde *et al.,* 2016). The humidity ratio of the air increases also increases. The heat content of the air remains the same even after passing a wet EC pad, although the air temperature decreases. The main aim of EC is to increase humidity ratio, vapour pressure and RH and decrease temperature. EC is relevant to SSF as the principle of operation is simple, can be easily constructed from local available materials (storage, cooling chamber, water tank, cooling pad media) and the components that require maintenance like the motor, extraction fan and heat exchanger can be repaired at low cost (Deoraj *et al*., 2015; Ogbuagu *et al.,* 2017). The system uses a cheap and environment friendly refrigerant water (Okanlawon and Olorunnisola, 2017).

Literature shows studies on EC in SSA Dzivama, 2000; Anyanwu, 2004; Olosunde, 2006; Olosunde *et al*. 2009; Ahmed *et al*. 2011; Taye and Olorunisola, 2011; Samira *et al*. 2011; Liberty *et al*. 2013; Ndukwu *et al*. 2013; Deoraj *et al*. 2015 and Adewela and Olorunnisola, 2017. A number of studies have shown the attractiveness in the use of evaporative coolers by SSF in Africa as unveiled by the increased research productivity through publications from authors in different countries: Anyanwu (2004) in Nigeria; Ahmed *et al*. (2011) in Sudan, Samira *et al*. (2011) in Ethiopia. The results of use of EC have demonstrated that coolers can maintain cooling spaces at temperatures below ambient with a depression reaching 12°C (Anyanwu, 2004). In EC cooling, lies the solution for SSF in finding a method appropriate that could alleviate storage challenges, reduce losses and improve food security at household level (Mordi and Olorunda, 2003; Ogbuagu *et al.,* 2017).

Therefore, EC is as an appropriate cooling technology for small-scale farming of fresh produce in SSA in alleviating storage challenges and reducing fresh PHL as;

i. it is appropriate for sub-tropical and tropical F&V,

ii. the volumes for cooling per farmer per unit time are not huge normal less than 5 tonnes,

iii. the storage temperature for tropical and sub-tropical F&V is around 15℃ and RH is 85-95%**.**

As EC only removes room sensible heat, it works best in hot and dry climate prevalent in SSA and is not suited for sub-humid to humid areas like coastal regions with moderate to high RH of 70-85% (Ahmed *et al.,* 2011; Basediya *et al.,* 2013; Cuce and Riffat, 2016; Ahmad and Rahman, 2017; Chijioke, 2017). The efficiency of an evaporative cooler depends on the original humidity of the surrounding air and the efficiency of evaporative surface (Jradi and Riffat, 2014). Therefore, the extension of EC to such areas by incorporating suitable desiccation media i.e. indirect heat exchanger where indirect air-cooling will take place before evaporative cooling (IAC+EC) is a possible research area. Despite perceived favourable results so far, the IAC+EC technology remains at development stage (Buker and Riffat, 2015).

Therefore, more focused research and contribution needs investigation for the development of this technology. Literature studied and confirmation by Misra and Ghosh (2018) reveals that indirect air cooling has not been used in both greenhouse cooling of fresh produce storage. Incorporation of heat exchanger will require additional accessories like a water pump for water reticulation and fans for ventilating the storage chamber. The review by Manaf *et al*. (2018) identified IAC+EC is an encouraging system, yet research into its use is still at an initial stage and needs further investigation. Manaf *et al*. (2018) also alluded that IAC+EC have high potential for use in hot and humid weather.

The use of an indirect heat exchanger, water pump and fan(s) will require energy. Should IAC+EC be required the energy requirements are low and the cooling technology is energy efficient. Therefore, a possibility exists to integrate IAC+EC with use of alternative energy for example wind or solar energy (Manaf *et al*., 2018). Fossil fuels could power the cooling methods but these contribute to greenhouse gas emissions (Best *et al*., 2012; Goel and Sharma, 2017).

2.9 Renewable Energy Use in Postharvest Handling of Fresh Produce

Renewable energy technologies have a high adaptation rate in many industries due to climate mitigation, ability to enter foreign markets because of green processes, green consumer requirements and improved corporate images of industries that use clean energy (OECD/IEA and IRENA, 2017). Besides conventional energy sources there is an option of energy provision from natural energy sources that include among others solar and wind energy (Szabo *et al*., 2011; Tyagi *et al*., 2012; Mentis *et al*., 2015; Oliveira and Trindade, 2018). The role of renewable energy along the different stages of food supply chain by providing requisite energy supplies especially for powering the fresh produce cold chain is important (Toshwinal and Karale, 2013; Chaudhari *et al*., 2015; Damerau *et al*., 2016). The role is more pronounced for remote, dispersed populations with low and scattered energy demands (Cecelski, 2000). Both solar and wind energy represents the largest source of renewable energy supply compared to solid biomass, biogas, hydro and geothermal sources (Tyagi *et al*., 2012; Goel and Sharma, 2017).

The consumption of fossil fuel is the major contributor to the greenhouse gases emitted to the atmosphere thus causing global warming (Schneider *et al*., 2000; Demirbas, 2006; Hassan and Mohamad, 2012; Nakumuryango and Inglesi-Lotz, 2016; Goel and Sharma, 2017). Biomass is combusted for heating and cooking and is convertible into electricity (David *et al*., 2002; Nunes *et al*., 2016). Direct combustion of biomass produces steam, which turns turbines that drive generators, producing electricity (Ayhan, 2006; Rolin and Porte-Agel, 2018). The cost of producing 1 kW of electricity from wood biomass is US$0,058. Biomass combustion releases different chemical pollutants, including fourteen carcinogens into the atmosphere (Alfheim and Ramdahl, 1986; Godish, 1991; Nunes *et al*., 2016). Grid electrification is expensive and yet other sources of energy can meet all the energy requirements (Deveci *et al*., 2015; Khare *et al*., 2016). Senol (2012) and Lewis (2016) recognises the need to promote alternative energy supply especially for increased productivity and for income generation.

Wind energy or power is the production of electricity by turning blades on a wind turbine (Ayhan, 2006; Foxon, 2018; Rolin and Porte-Agel, 2018). An advantage of wind turbines over other renewable energy sources is that they can produce electricity whenever the wind blows (both during the day and at night). Wind energy can be utilised if the annual energy available is at an average speed of 5 $m.s^{-1}$, and is 490 $MJ.m^{-2}$ of surface perpendicular to the wind flux (Mentis, 2013). According to Archer and Jacobson (2005) and Mentis *et al*. (2015), while Africa has an abundance of wind energy, in some areas it is seasonally while in coastal regions is available throughout the year. Solar energy seems to be the most viable alternative to fossil fuels as it is clean and renewable since it comes from the sun (Sontake and Kalamkar, 2016; Goel and Sharma, 2017). Solar energy is the largest source of renewable energy supply, compared to solid biomass, biogas, hydro, wind etc. and is available in most areas of SSA throughout the year with values in excess of 2 000 kWh m^{-2} (Heimiller, 2005; Best *et al*., 2012; Davis and MacKay, 2013; Kabir *et al*., 2018). In this region, the average solar radiation ranges between 4.5 $kWh.m\text{-}^{2}$ – 6.5 $kWh.m\text{-}^{2}$ for an average of 6 -7 hours (Fluri, 2009; Baurzhan and Jenkins, 2016). This according to Saïdou *et al*. (2013) and Saxena *et al*. (2013) is enough solar radiation that is convertible to electricity.

2.9.1 Solar Power

There has been application of solar energy in generating solar thermal or directly conversion to electricity through photovoltaic cells (Hassan and Mohamad, 2012; Foxon, 2018). According to Best *et al*. (2012), the use of solar energy for refrigeration purposes in the Agro-industry has a potential in developing countries. Abu-Hamdeh and Al-Muhtaseb (2010) stressed that there is a potential energy saving of 40-50% when using solar driven air conditioning systems instead of conventional systems. Feasibility studies of this technology when carried out in Mexico and the Mediterranean area showed that it is possible to obtain temperatures as low as -2℃ for air-cooled systems using solar energy as a source (Ayadi *et al*., 2008). There has been application of solar energy in solar refrigeration technologies i.e. solar electric and solar thermal (Kim and Ferreira, 2008). In the solar electric system, conversion of solar energy to electricity is by use of solar photovoltaic (SPV) cells that operate a vapour-compression refrigeration technology.

There is a lot of research work currently being carried out for absorption-based refrigeration and air conditioning systems that use solar energy (Liu and Wang, 2004; Balaras *et al*., 2007; Helm *et al*., 2009; Said *et al*., 2012; Shirazi *et al*., 2016). The numerous reviews found in literature is evidence in support of solar-based refrigeration (Wang *et al*., 2011; Best *et al*., 2012; Khan and Arsalan, 2016). Solar energy has also been integrated with EC by many researchers for cooling of buildings (Tiwari and Jain, 2001; Maerefat and Haghighi, 2010; Naticchia *et al*., 2010; Finocchiaro *et al*., 2012; Hands *et al*., 2016; Sahlot and Riffat 2016; Manaf *et al*., 2018). Naticchia *et al*. (2010) exploited both air ventilation and heat exchange by use of porous insulating material as an absorption matrix. Maerefat and Haghighi (2010) integrated a solar system employing a solar chimney with EC cavity. This integrated system enhanced passive cooling and natural ventilation in a solar house, and the numerical experiments showed that daytime temperatures significantly reduced at a poor solar intensity of 200 $W.m^{-2}$ and high ambient temperature of 40℃. Finocchiaro *et al*. (2012) employed a solar energy assisted desiccant and EC system for building air conditioning. In this system, solar energy regenerated a desiccant material that dehumidifies moist air by vapour adsorption. The resultant dry and warm air was then cooled in a sensible heat exchange and then in an evaporative cooler. Hands *et al.* (2016) used a two-rotor intercooled desiccant arrangement to maximize dehumidification and provided solar energy for precooling and preheating only. When the ambient conditions were suitable, the solar driven desiccant cooling system met 35% of the total building cooling load.

Because of research work, there have been reasons for focusing on the potential of converting solar energy through photovoltaic systems for use in agriculture production (Ekren *et al*., 2011; Mujahid *et al*., 2015). This could be a basis for sustainable agricultural production at village level in SSA The challenge is for researchers to find means of dramatically reducing the cost per solar panel to deliver cheaper energy to SSF. It is believed that this has been achieved to a certain extent as the price of renewable energy from solar has dropped in the last decade from US$0,18 kWh to just US$0,03 kWh (OECD/IEA and IRENA 2017).

2.9.2 Wind Energy

Wind power has versatility of uses worldwide that include home power, water-pumping applications, running mills and other machines (Twidell and Weir, 1986; Goudarzi and Zhu, 2013). There is scope also to extend the use of wind power to agricultural produce processing and energy driven farming activities (Crawford *et al*., 2009; Hossain *et al.,* 2016). A wind turbine operating at an ideal location can run at maximum 30% efficiency. A 500-kW turbine at this efficiency can yield an energy output of 1,3 million kW (e) per year at an estimated cost of US$0,007 per kWh (e) (David *et al*., 2002). To date, there is no available literature showing harnessing of wind energy for cooling purposes of fresh produce. As a result, there exists a research scope in the utilisation of wind energy to support cheaper and less energy intensive cooling methods for fresh produce like EC (Chaudhari *et al*., 2015; Hossain *et al.,* 2016). Integration of wind energy with EC could be the panacea in the reduction of PHL experienced by SSF producing F&V in SSA. When envisaging a wind-powered system for cooling fresh produce, batteries are required for backup storage of electricity, as wind does not blow all the times.

2.9.3 Relevance of Solar Energy in Cooling of Fresh Produce.

Best *et al*. (2012) estimates that energy demand for cooling processes and greenhouse gas emissions will increase by 60% by 2030 compared to 2000 levels. Kim and Ferriera (2008) have recognised that there are energy requirements for agriculture in rural areas addressed by using alternative sources of energy other than grid electricity. Efforts in planning and provision of the additional power requirements with clean energy need to be in place. In Africa, there are more opportunities to use solar energy because much of the continent has limited access to electricity (Szabo *et al*., 2011; Power *et al.,* 2016).

Therefore, the high-energy demands on existing power sources and global warming threats provides impetus for research towards technological alternatives (Hassan and Mohamad, 2012). Among these technologies, solar energy is the most appropriate for adaptation with cooling methods for fresh produce, as the resource is available throughout the year (Best *et al*., 2012). A lot of research in this regard has been taking place.

Fan *et al*. (2007) and Bataineh and Taamneh (2016) reviewed the research on solar absorption and adsorption refrigeration technologies. From this review, there is a conclusion that solar power sorption technologies may possible be used for refrigeration, air-conditioning applications and ice making. Other solar sorption's are still at research study level and are not fully developed. Other issues that still need addressing with sorption refrigeration systems regards enhancement of the heat and mass transfer to improve performance (Chindambaram *et al*., 2011). As a result, most of the systems are at the stage of demonstration and prototyping (Fan *et al*., 2007; Chindambaram *et al*., 2011; Ahmad and Rahman, 2017). While the prospect of developing an environmentally friendly and low energy demand, solar power sorption systems are good the cost of the refrigeration system represents a large percentage of the cost, which will limit its use among SSF (Otanicar *et al*., 2012; Zhai *et al*., 2011; Faris, 2016).

The use of solar energy for EC in all the cases has been limited to buildings and this provides an opportunity for the extension of the same principles to the preservation of fresh produce (Ahmad and Rahman, 2017). The use of solar energy to power electrical appliances for EC like heat exchanger, water pump and fan is very limited and literature was not found providing evidence that solar energy has been used for IAC+EC for fresh produce. This confirmed by Jani *et al.* (2018) who alludes that there is no wide historical background for commercial application of solar energy for in IAC+EC.

EC technology if used with forced air requires lower energy to operate water pump and fans while it is effective in providing cold and humid air to the storage chamber. The use of SPV energy to operate low-cost cooling technologies for F&V has a high potential. Hence, an integrated approach of IAC+EC and solar energy as a source of power could be highly suitable for SSF that are engaged on production of F&V in SSA. This will play a pivotal role in ensuring food security at household level and a reliable family sustenance through income obtained from sales. With the advent of re-distribution of land in South Africa, there will be emerging SSF in F&V production with no access cooling facilities and integrated approach of EC and solar energy will fill the gap.

2.10 Discussions

All categories of farmers' experience high PHL in SSA, but for SSF as they lack appropriate low-cost post-harvest cooling technologies the challenge is more pronounced. The deterioration in quality of F&V is largely due to factors such as technical, biological and chemical, and as well as environmental aspects. These factors affect fresh produce quality from harvesting, packaging, temporary storage at the farm through to transportation to markets.

Training of harvesters, use of appropriate packaging material like plastic crates and ensuring that appropriate transportation containers are used addresses issues related to technical factors. This would significantly eliminate the exposure to mechanical damage, which is the main cause of physiological deterioration and bacterial contamination. Biological process of metabolism such as respiration, transpiration and biosynthesis cause fresh produce deterioration through moisture loss, which may lead to senescence. The physiological deterioration due to biological processes is compounded by environmental factors that can result in a significant loss of nutritional value.

Harnessing of biological process is through the control and management of environmental factors of temperature and RH.

This review identified a number of conventional cooling technologies available in the market such as forced-air cooling, vacuum cooling, hydro-cooling and mechanical refrigeration. The different conventional cooling technologies have inherent challenges in their application by SSF in SSA. Hydro-cooling is not suited for leafy produce and SSF require a technology that is able to cool all vegetable types, leafy, root and grass. Forced-air cooling is a specialized technology, requiring skilled operators who SSF do not always have. Forced air-cooling is more expensive than other cooling methods when rapid cooling is required. In the case of vacuum cooling beside the cost, requires sustained higher volumes throughout the year, which demand only large-scale growers with economies of scale of growing high cash value crops can satisfy. Literature also revealed that the conventional cooling technologies are both capital and energy intensive. SSF have no access to capital to purchase and install conventional cooling technologies and even if they did, they would still need to surmount the challenge of energy required for these technologies, as most of these farmers are in remote areas with no access to grid electricity.

Further, this review also recognizes that EC is a simple and cheap method compared to conventional cooling technologies. EC is regarded as economical and does not necessarily need external power source as it relies on velocity of natural wind through wetted pads. EC is ideally, for both pre-cooling and cooling and its use increases shelf life of fresh produce. EC has had a big impact in cooling of buildings in Asia and has been practiced by some SSF in SSA. EC premises on removal of sensible heat, which makes it relatively efficient under hot and dry climates obtaining in SSA but has limitations in hot and sub-humid to humid areas obtaining in coastal regions. EC has been tested at laboratory scale in dry and arid areas and the results are encouraging. For sub-humid to humid areas, IAC coupled with EC could work, but no work-studies on such a cooling system has been done for either greenhouse cooling or storage of fresh produce.

Conventional cooling technologies are energy intensive. Grid electricity is not available in remote and isolated areas in SSA, while use of fossil fuels has limitation in that they emit greenhouse gases. The alternative then is the use of renewable energy sources like solar, which is abundant in SSA. As a result, there exists a research scope in the utilisation of solar energy to support IAC+EC of fresh produce for hot and sub-humid to humid areas. This integrated system could be very useful to SSF in SSA producing F&V in ensuring that they rise from high PHL incurring farmers to profitable farmers who are able obtain returns enough to sustain their families.

2.11 Conclusions

Literature shows that the introduction of appropriate cooling technologies for SSF will ensure provision of cold chain systems that minimize PHL from harvesting to consumption by end user of fresh produce. The training of harvesters and ensuring the use of appropriate transportation containers are important to reduce the effect of technical factors on PHL. Biological processes play a key role in aggravating PHL if not properly controlled by maintaining environmental factors of temperature and RH at recommended storage levels as per specific requirement of each crop. However, this review showed that in developing countries like SSA there is lack of proper cold chain storage facilities. Hence, there is need to develop or adopt appropriate low-cost cold chain facilities aiming at cooling of fresh produce for SSF. This is the only way SSF can rise from subsistence farming to commercial fresh produce production. The two most limiting factors for the adoption of advanced cooling by SSF is the initial capital cost and the energy demands, since conventional cooling technologies are energy intensive. The alternative, then, is the use of an integrated system that involves solar energy source combined with a low-cost cooling technology.

Based on the brief survey of literature, it is observed that a lot of research has been done on EC for comfort cooling at prototype scale for fresh produce preservation. EC is suitable for hot and dry regions where it is very much effective in providing a suitable microclimate inside buildings or storages as the process relies on removal of sensible heat. The application of EC in sub-humid to humid areas has limitation as presence of high RH leads to low dry bulb temperature. Selection of appropriate EC system depends mainly on local environmental conditions and performance varies from one to the other. More scope of research remains to be carried out in the hot and humid tropic and subtropics. Extension of EC as a principle to humid areas requires inclusion of a heat exchanger for IAC, which is a concept that is not previously documented for cooling the microenvironment in storage of fresh produce. The incorporation of heat exchanger and other electrical appliances for IAC require energy, which can be supplied by solar energy for SSF with no access to grid electricity. This provides an opportunity for the use of solar energy to power a heat exchanger for sensible cooling of air; water pump for water reticulation; fan to ventilate the IAC+EC.

The availability of literature pertaining to the integration of solar energy and IAC+EC, particularly in South Africa, is limited. Innovative and convenient technologies of provision of a cold chain for F&V after harvest are required to reduce losses that occur when fresh produce is stored under ambient conditions. It is envisaged that by developing a low-cost cooling technology for hot and humid areas in coastal regions a larger export market can be created, as well as providing small-scale farmers with a niche in this export arena. The integrated system of IAC+EC with solar energy will reduce PHL thus increasing the quantity of fresh produce that will reach the consumer. IAC+EC systems still need development and characterization especially in Southern Africa where minimal research has been done on EC in general. IAC+EC systems have shown great potential of development and research opportunity for their perceived improved efficiency, high thermal performance and low energy use. From the conclusions made above, the proposition is carrying out a study to develop and characterise a solar powered IAC+EC system for temporary storage and transportation of F&V with a specific focus on sub-humid to humid areas in Southern Africa.

In conclusion, there is still a lack of available research in IAC+EC systems and their performance under hot and sub-humid to humid weather. The use of renewable energy in IAC+EC system powered by solar still needs investigation in hot and humid country where solar power can be harvested year-round.

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3 ASSESSMENT OF SOLAR ENERGY SYSTEM INTEGRATED WITH INDIRECT AIR COOLING COMBINED WITH DIRECT EVAPORATIVE COOLING

Abstract

In this study, a solar photovoltaic (SPV) system generating power to run a 53 m^3 storage for indirect air-cooling combined with evaporating cooling (IAC+EC) for providing a cool environment for storage of tomatoes was evaluated based on actual performance. The experimental set up consisted of nine 330 W solar modules, twelve 230 AH batteries for battery bank facility, 145 VDC (60 A) solar charge controller, 5 kW (125A) inverter, electrical appliances of 290 W ventilation fan and 260 W water pump, psychrometric unit, and 3.8 tonne tomato storage chamber constructed and assembled on site. The psychrometric unit consisted of three-cooling pad layer and 1 760 W indirect heat exchanger. The modules had a short circuit current (I_{sc}) and open circuit voltage (V_{oc}) of 8.69 A and 44.8 V respectively and were arranged in a three series-three strings and were used in conjunction with a three string-48V system bank facility. The performance evaluation of the system was done under no-load and sample-load, with full recirculation of air inside the cold storage chamber using solar array module yield and efficiencies of the photovoltaic array, inverter, battery and solar charge controller. Based on the experiment data the SPV system produced 2639 W that is 90% of the calculated theoretical power output. The energy yield of 2 639 W was 11% higher than the power required in running the electrical appliances for IAC+EC system. Tracking the SPV system under ambient conditions with an average daily generation during the period of the experiment, the power and photovoltaic (PV) array efficiencies were 81.2% and 15.1% respectively. The power output of modules increased with temperature of the module to 24°C and declined thereafter. The power generated by the SPV system depended on the climatic variables, such as solar irradiance availability and ambient temperature at the site and the time of the day. It was found that the solar array system can be used to power the IAC+EC at daytime during summer season, and the excess power, which was stored in the battery, could run the system until 22h00 at night when temperatures were low enough for storage of tomatoes and SPV system was then switched off. SPV systems can run IAC+EC, which is ideally for small-scale farmers that are not connected to the national grid as it has low initial capital investment of R 130 190 with a payback period of 1.9 years for a 53 m^3 storage structure.

3.1 Introduction

Small-scale farmers (SSF) in South Africa have identified the need to access appropriate small-scale low-cost postharvest technologies for long-term storage of fresh produce to maintain quality and extend shelf life (Baiphethi and Jacobs, 2009; Mashau *et al.,* 2012; NDP, 2012; IPAP, 2013; DAFF, 2016; SAYB, 2016). Facilities like mechanical refrigeration, hydro-cooling, forced air-cooling and vacuum cooling exists but are expensive to SSF because of high initial capital investments, high energy input, higher production volumes for economies of scale (Tefera *et al.,* 2007; Baloyi, 2010; Paull and Duarte, 2011; Prusky, 2011; Yahaya and Akande, 2018). Literature reveals that there is currently no available modernized cooling technology accessible to SSF in SSA for storage of their fresh produce (Ntombela, 2012; Mashau *et al.,* 2012; Manaf *et al*., 2018). This study considers adoption of evaporative cooling system (EC) which is best suited for SSF as the initial capital and running costs are low and the technology is efficient, economical and has a potential energy saving of about 75% (Workneh, 2010; Ndukwu *et al.,* 2013; Rajan and Anandan, 2018). EC functions by the removal of sensible heat and therefore works best in hot and dry climate prevalent in SSA. For EC to be extended to areas, which are hot and sub-humid to humid indirect air cooling (IAC) has to be considered to be able considerable reduce air temperature before the air enters the evaporative cooling unit. IAC in addition to EC will be referred as IAC+EC in this chapter. For IAC to be feasible an indirect heat exchanger is incorporated and the energy requirements can be supplied by solar energy. Misra and Ghosh (2018) in their recommendations for further research on EC allude to further investigation on the use of solar and geothermal for IAC. Therefore, the integration of IAC+EC with solar energy is a new research focus whose results will provide a cooling facility to SSF in remote areas of SSA with no access to grid electricity.

Use of solar energy has increased in importance in the recent past as an alternative energy source as prices of grid electricity and fossil fuels escalate (Young, 2013; Damerau *et al*., 2016; Yahyaoui *et al*., 2016; Goel and Sharma, 2017). The use of solar energy in SSA has been limited for domestic (Chow, 2010) with limited extension to water pumping systems as documented by publications of Chandel *et al*. (2015) and Sontake and Kalamkar (2016). The use of solar energy for commercial fresh produce cooling and storage is still unutilized and undocumented, even though there could be clear advantages, of low generating costs, suitability for remote areas and being environmentally friendly (Rehman and Al-Hadhrami, 2010; Parida *et al*., 2011; Deveci *et al*., 2015; Sontake and

Kalamkar, 2016). In literature, there is no information on the integration of IAC+EC with solar energy that provides the energy requirements derived from actual performance data for a specific size of a cooler of storage chamber. In South Africa, the average solar radiation is 4.5–6.5 $kWh.m^{-2}$ for 6 -7 hours (Heimiller, 2005; Fluri, 2009; Best *et al*., 2012; Davis and MacKay, 2013). This according to Saxena *et al*. (2013) is enough solar radiation to run a Photovoltaic (PV) system for rural applications. Solar Photovoltaic (SPV) is an attractive solution providing autonomous fruit and vegetables (F&V) storage system in remote areas or dispersed populations. The SPV system provides the autonomous installation with the needed energy, optimal sized in relation to intermittent climatic parameters of solar radiation and the ambient temperature (Yahyaoui, 2016; Yahyaoui *et al*., 2016). For F&V cooling, the removal of heat to achieve optimum storage conditions, the size of PV modules surface and accessories like charge controller and inverter, the battery bank capacity are critical (Khatib *et al*., 2013a; Chandel *et al*., 2015; Kazem *et al*., 2017). The battery bank is to import/export energy depending on need for applications that operate during both day and night as this study proposes (Kazem *et al*., 2014).

Though there are arguments that SPV systems are expensive, such systems should find application for SSF in remote, isolated, dispersed populations or in rugged terrain where it is un-economical to stretch the utility grid (Shaahid and El-Amin, 2009; Khatib *et al.,* 2013b; Khare *et al.,* 2016). SPV systems are modular, low maintenance, easy and quick to install. It is easy to expand SPV systems, as demand increase to generate power where it is required without the need for transmission line (Olomiyesan *et al.,* 2015). In South Africa with the pending land re-distribution exercises, new commercial SSF will emerge with an additional burden on the national grid for more energy requirements that can be met by use of solar energy. The prices of solar panels and batteries is decreasing year after year (Gopal *et al.,* 2013; GSES, 2015; Foxon, 2018). As prices fall, farmers will afford to buy more solar panels and batteries thus motivating farmers to migrate to high value fresh produce and adopt solar powered EC systems. The expected decline in prices of accessories, the non-availability of studies in energy requirements, and performance assessment of SPV powered IAC+EC systems under South Africa conditions have motivated this study. If the installation of solar powered IAC+EC is successful, this will feel the gap in South Africa that could be created by the land re-distribution with no supporting fresh produce cooling infrastructure.

There has been testing of SPV in powering miniature-evaporating coolers of capacities less than a 0.2 tonnes in other countries (Eltawil and Samuel, 2007; Razak *et al.,* 2007; Duffie and Beckman, 2013; Foxon, 2018). There is need to conduct studies that will fully mimic the temporary storage requirements of SSF and provide evidence of the efficacy of solar energy in such instances. Currently, there is no literature and data of a cooperation, which used solar energy to power any IAC+EC system for small-scale cold storage of F&V in SSA. For this to happen, one can consider a stand-alone solar powered system with a battery storage facility as SPV systems have a sunshine dependent output that does not necessarily match with the load on a 24-hour cycle. There is no study on the use of solar energy–battery hybrid to power a water pump, indirect heat exchanger and fan for IAC+EC. As a result, a hybrid system of solar/battery system is recommended by this study. To solve this problem and encourage commercial SSF to adopt solar energy as their main source of power, a demonstration unit was designed and constructed in order to motivate them to adopt solar power, as it is a sustainable and renewable. This study also will provide data on the performance of SPV in powering a 3.8 tonne sized storage chamber for tomatoes.
The objective of this study is to:

1. Construction of a small-scale IAC+EC system of 3.8 tonnes storage capacity for tomatoes.

2. Designing, installation and performance evaluation of solar-battery system.

3. Evaluating the performance of SPV-battery based IAC+EC system.

3.2 Materials and Methods

This section presents the methodology followed in design, fabrication of solar photovoltaic (SPV) powered IAC+EC system to attain favourable conditions for tomato storage under different operating conditions.

3.2.1 Design Specifications

The design of the cooling unit provides the optimum storage temperature and relative humidity (RH) for tomatoes in Pietermaritzburg (PMB) in KwaZulu Natal province. The design and construction of the evaporative cooler premises on the PMB environmental requirements and considerations with the following specifications:

(a) The SPV should provide energy to drive water pump, heat exchanger and fans. The following will be considered:

  - The design-cooling load to produce the required power for the IAC+EC system will be determined. The cooling load will determine the ventilation rate (fan rating and size) for the storage chamber.
  - The electrical load considering all appliances (pump, heat exchanger and fans) will be calculated and this will determine the amount of power required per hour to run the SPV system.
  - Solar panel configurations will be obtained from the total energy required.
  - From the amount of power required per hour to run the system, the battery bank facility will be determined.
  - A short-circuit configurations from the solar panels will be used to calculate the solar charge controller rating and also taking into considerations the numbers of strings. The solar charge controller will be rated at or above the amperage and voltage requirements of the solar array system.

(b) The input rating of the inverter size will be at least 25% greater than the cooling and application loads as the inverter size should be larger than the load size.

(c) The IAC+EC unit had to be able to maintain the temperature inside the storage chamber at the wet bulb temperature of the prevailing ambient air conditions.

3.2.2 Factors Affecting Performance of the SPV

The efficiency factor of PV modules influences the performance ratio of the PV system. The higher the efficiency of PV modules, the higher the performance value (with corresponding higher solar irradiation at the location). The efficiency of solar energy conversion for solar cells is 15-19% and is dependent on whether the solar module is monocrystalline, polycrystalline or thin-films type (Huang *et al.*, 2013). Monocrystalline modules have the highest energy conversion efficiency;

polycrystalline modules are in between, whilst thin-films are least expensive and least efficient in comparison (GSES, 2015; Bai *et al.*, 2016). Monocrystalline modules were chosen for this study to ensure we get the highest possible amount of energy from the available solar radiation, the highest efficiency and least cost from the permutations of the solar array system.

Factors affecting module output

For solar arrays to produce maximum power output, they must be at an optimal tilt angle to trap maximum radiation (Gunerhan and Hepbasli, 2007; Tripathy *et al.*, 2017). According to Morales (2010) the optimum tilt angle correlates with latitude and is considered being equal to the latitude or latitude ± 15^{o} (+ for winter and – for summer). Asowata *et al*. (2012) and Stanciu *and* Stanciu (2014) in their work in nine locations in South Africa recommend that the optimum tilt angle for a fixed solar collector should be the same as the latitude of the location. The optimal tilt angle depends on the season and the latitude of the area (Kaddoura *et al*., 2016). For higher power output, incorporation of solar trackers allows automatic adjusting of the collector tilt angle of solar arrays to, follow the sun's change in elevation during the day and always face the sun (GSES, 2015; Pedro *et al.,* 2016). In this study, no solar tracking device was available and to determine, the optimum tilt angle historical data for the selected area will be used as provided by Schulze *et al*. (1999).

The other factors of consideration are power dissipation, stagnation, conduction losses, efficiency factors of the inverter and controller and differences in solar cell technologies of the modules (Sun *et al.,* 2016). The aggregate sun-oriented radiation received at a given geographical location varies depending on the length of the insolation on a specific day and the power of sunlight-based vitality (Honsberg and Bowden, 2016; See Appendix 7.2 and Figure 7.4). Variations also arise because of latitude and the day or time of the year (Morales, 2010; Tripathy *et al.*, 2017). All the factors are considered in Appendix 7.3 and for this study; the solar radiation values recorded by over 50 years and captured in the South African Atlas 18 of Agro-hydrology will be used.

3.2.3 Installation of SPV System

The experiments were carried out at Ukulinga research station which is a research station for the University of KwaZulu Natal in PMB in South Africa (30º24'S, 29º24'E). The experimental set up consisted of SPV panels, battery bank facility, charge controller and inverter, and evaporative cooling unit, storage chamber constructed and assembled on site (Eltawil and Samuel, 2007). The cooling unit consisted of indirect heat exchanger (M14-20, 8874 BTU/Hr) (see Appendix 7.1 and Appendix 7.9) with performance rating of 1760 W and three-layer charcoal granules cooling pads. A 31/33 W (UF25GC12, AC 115 V, 50/60 Hz) constant speed positive pressure fan was connected to the indirect heat exchanger to facilitate airflow across the heat exchanger. A 290 W fan was directly mounted at the entrance of the storage chamber 0.5 m above the floor to ventilate the storage chamber 3.6 m. s^{-1}.

The solar array system consisted of 9 x 330 W modules (2.01 m x 1.02 m, SETSOLAR manufacturer) installed and fixed on one rectangular metal manual tilt-frame and mounted facing south on an inclined angle of tilt = -15° as recommended by Strnadel *et al* (2013) and Ronoh (2017). Inclining modules prevents accumulation of dust on their surface and contributes to a natural cooling effect according Li *et al*. (2005). To avoid shading on the PV modules, panels were positioned away from trees and buildings that could throw shadows resulting in modules absorbing less solar irradiation than normal and thus affecting the efficiency of the system (Ramaprabha and Mathur, 2009). The panels were dusted and dirty was removed from the surface to ensure no soiling according to Sun *et al*. (2016).

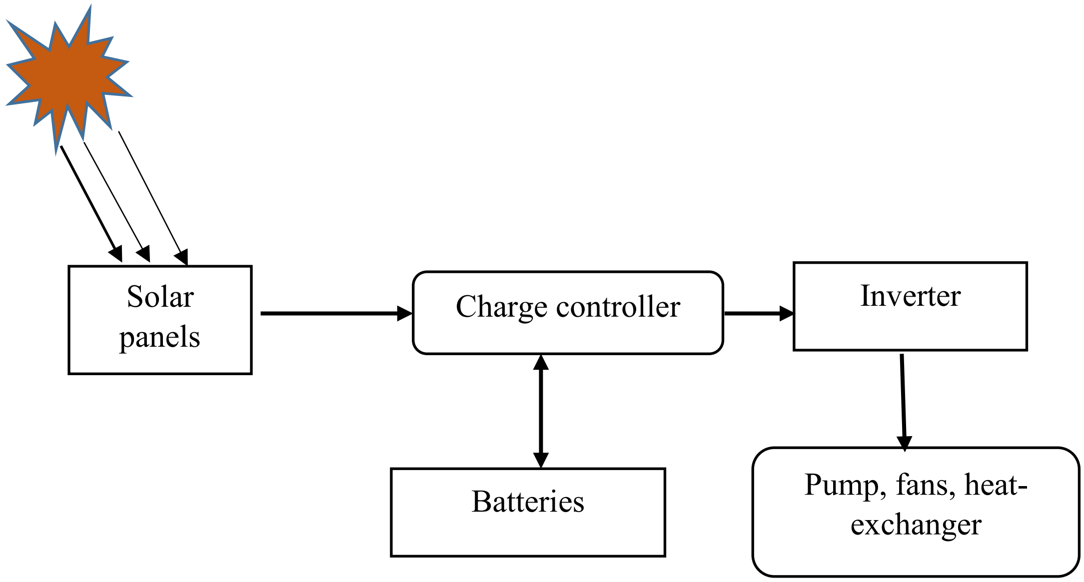

Figure 3.1 Schematic diagram of the solar energy process flow

The manually operated frame allowed tilting to angle of tilt = -15° that resulted in optimum power output. The modules were at 2 m distance from the storage chamber. The circuit output voltage of each module at the point of peak power output is 44.80 V and short circuit current is about 8.69 A. The above values were at the specified standard test conditions (STC) of 1000 $W.m^{-2}$ solar radiation at 25°C cell operating temperature and an air mass of 1.5. Under field conditions, the output power is normally less than the rated peak power. The power generated from the SPV modules was transmitted to the solar charge controller prior to charging the solar batteries and the inverter converted DC to AC. Figure 3.1 is a schematic layout of the solar system and also shows how the rest of the components were connected.

The solar charge controller (SANTAKUPS, PC16-6015F) ensured constant voltage and current to the load from the batteries according to Deveci *et al.* (2015). The solar charge controller had maximum input ratings of 60 A current and DC voltage of 145 VDC. A 5-kW inverter (125 A Sinowave, P11-LW5000NC48-C) with rated efficiency of 85% was chosen as its characteristics match the system in terms of voltage input, AC power output, efficiency, frequency and voltage regulation as described by Chandel *et al.* (2015). Twelve fully charged 230 AH batteries (Gel) with a 90% efficiency arranged as a three-string 48V system were utilised to start the experiments and this temporarily stored energy generated by solar panels for overnight use. The distance between the battery and the inverter was made as short as possible. The wiring chosen ensured that the voltage loss of the PV system and batteries was less than 0.5% (Eltawil and Samuel, 2007; Saxena *et al.*, 2013). Cable wiring and sizing kept loss of energy as minimal as possible and prevented overheating. A multi-meter (Fluke 381) measured both open circuit voltage and current, voltage and current under location and at different positions. Thermocouples connected to data loggers measured the PV module temperatures at hour intervals as module temperature influences the performance of solar systems (Sun *et al.*, 2016). The solar radiation data from the South African Weather Services was used. The various heat load in the storage chamber were calculated using the standard equations as discussed in section 3.2.4 and the cooling capacity together with the load from electrical appliances (fan, heat exchanger and water pump) was used to size the solar array system. The solar array system was sized and modules arranged to produce sufficient voltage and current to power the electrical appliances and ventilate the storage chamber to the required environmental conditions.

3.2.4 Determination of the Cooling Load

The cooled and humidified air from the cooling pads is required to remove the total heat load in the evaporative cooler and is proportional to the mass of produce that is loaded at a time (Studman, 1990). The cooling load is made of the following critical heat sources from the cooler (i) heat of respiration (ii) sensible heat of containers (iii) field heat load (ASHRAE, 1998; Prasad, 1999; Eltawil and Samuel, 2007). The other heat losses important but smaller in magnitude are (i) heat gain through the wall (ii) air-change heat load during the opening of the storage chamber door and (iii) miscellaneous heat load gains from lights, fan and labourers during stacking and removal of tomatoes from the storage chamber (Arora, 2000; Thompson, 2004; Eltawil and Samuel, 2007).

A cooler packed to its maximum capacity takes longer to reduce the temperature of the stored products. Loading a cold storage in batches allows the batches to reach the recommended target temperature in a shorter period. Three loading capacities of the storage chamber of filling the storage chamber to, full capacity, half-capacity and one-third capacity was considered in this study. This was in consideration of the amount of tomatoes that a SSF in SSA might be harvesting daily. The various heat load above was calculated using the standard equations in literature as obtaining in Table 3.1.

Table 3.1 Formulae used to calculate the cooling load

Heat Type	**kJ. Kg^{-1} 1**	**Equation**
Heat of respiration	$Q = m \times h$	m = mass of tomatoes to be cooled [kg]; h = heat transfer coefficient of product [J. kg^{-1} = 543 J. kg^{-1}]; (Fellows, 2000; ASHRAE, 2002).
Field heat	$Q = \frac{m \times c_p(T_2 - T_1)}{3600 \times n}$	m = mass of tomatoes to be cooled, kg; c_p = Specific heat of tomatoe , k J. kg^{-1}; n = operation time, [hours]; T_2 = Storage temperature of products °C; T_1 = Initial product in crates temperature, °C; (Arora and Domkundwar, 1999; ASHRAE, 2001)

Heat Type	**kJ. Kg^{-1} 1**	**Equation**
Sensible heat from containers	$Q = \frac{m \times c_p(T_2 - T_1)}{3600 \times n}$	m = mass of product to be cooled [kg]; c_p = Specific heat of crates[KJ. kg^{-1}]; n = operation time [hours]; T_2 = Storage temperature of tomatoes[°C]; T_1 = Initial tomatoes temperature [°C]. (ASHRAE, 2001 and Fellows, 2000).
Heat leakages through walls, roofs	$Q = \frac{k \times A(T_2 - T_1)}{x}$ (Fellows, 2000; ASHRAE, 2002)	m = mass of product to be cooled, [kg]; c_p = Specific heat of tomatoe [kJ. kg^{-1}]; n = operation time [hours]; T_2 = Storage temperature of products [°C] and T_1 = Initial product in crates temperature [°C].
Heat loss through the floor	$Q_f = FP(T_o - T_i)$	F = perimeter heat loss factor [W.m^{-1}. K^{-1}] and P = storage chamber perimeter [m]. (Albright, 1990).
Air-change load	$P_a = m_a(h_a - h) + m_w C_{pw}(T_a - T)$ (ASHRAE, 2002)	P_a = air change load [W]; m_a = mass of air entering the chamber/hr [kg. s^{-1}]; h_a = enthalpy of ambient air [kJ.kg^{-1}]; m_w = mass of water condensing in chamber/hr [kg]; h = enthalpy of air in the storage chamber [kJ.kg^{-1}]; C_{pw} = specific heat capacity of water [kJ.kg^{-1}. ºC^{-1}]; T_a = ambient air temperature [°C] and T = air temperature inside the chamber [°C].
Operators and lights	$Q_{O\&L} = \frac{Q}{3600 \times n}$	Q = Total amount of heat that lights and operators release in the chamber [kW], and n = number of hours per day [hours]. (Fellows, 2000)

Using the formulae, the amount of heat load to be removed when the storage chamber is filled with tomatoes to full capacity is 8 220 W and when filled to one-third capacity is 4 252 W (see Table 7.5 and Table 7.6 in Appendix 7.5). When the tomatoes have cooled to the required storage temperature, part of the cooling is no longer necessary. Less cooling is required to maintain the required temperature in the store and the cooling system can operate for a shorter period or the cooling capacity can be reduced.

According to Thompson (2004), the design load is calculated as:

$$Design\ load\ = 1.1\ \times Actual\ load \tag{3.1}$$

Therefore, $Design\ load\ = 1.1\ \times 4252\ W\ = 4677\ W$

From the cooling load of 4677 W the required ventilation rate for the storage chamber is 0.234 m^{-3}. s^{-1} requiring a 308,7/6-6/P3HL/25/PA @1.440 min^{-1} fan which provides an air-flow rate of 0.278 m^{-3}. s^{-1} at static pressure of 68.27 Pa with a power rating of 290 W and air velocity of 3.6 m. s^{-1} (Appendix 7.6).

3.2.5 Design Load Including Appliances

The designed solar array system accommodates the cooling load in the storage chamber and the appliances that include a heat exchanger with fan, second fan ventilating the storage chamber and water pump and operates for 5 hours into the night.

$\text{Total load (w)} = 1760 + 290 + 260 = 2310\ W$

The power required in a day here referred to as the daily (w-h) is calculated from the equation

$$\text{Daily (w} - \text{h)} = \text{Total Power Consumption} \times \text{Operating Hours} \times \text{Loss factor} \tag{3.2}$$

Therefore, $\text{Daily (w} - \text{h)} = 2310 \times 5 \times 1.2 = 13860\ W$

The allowable battery discharge is limited at a minimum of 50% to prolong their shelf life. Therefore, the daily watt-hours at 50 % discharge doubles to obtain the system capacity using the following equation that divides the daily (w-h) by 0.5.

$$50\%\ \text{depth of depletion of the battery} = \frac{\text{Watt Hours/day}}{0.5} \tag{3.3}$$

$$\text{50\% depth of depletion of the battery} = \frac{13860}{0.5} = 27720 \text{ Wh}$$

$$\text{Power produced/h} = \frac{\text{Total Power Consumption} \times \text{Operating Hours} \times \text{Loss factor}}{\text{Sunshine hours}} \qquad (3.4)$$

$$\frac{\text{Power produced}}{\text{hour}} = \frac{27720}{6.7} = 4137.3 \text{ W. h} - 1$$

Therefore, this system will produce 4 137.3 W. h^{-1} to cool 3 825 kg of tomatoes.

3.2.6 Determination of Bank Capacity

The battery capacity was determined with reference to the electrical appliances' specifications for the daily watt-hours at 50% discharge and this is in accordance with Linden (2002) as given in equation (3.5). The required battery size bank to store / supply required amp-hours is;

$$\text{Battery Bank Capacity} = \frac{\text{System Capacity}}{\text{System Voltage}} \qquad (3.5)$$

Therefore, the battery bank capacity using a 48V system $= \frac{27720}{48} = 577\ AH$

The battery bank capacity is 577 AH using a 48-V system and available battery in the market is a 230 AH with a 90% efficiency. The number of batteries required to run the system with 3 825 kg of tomatoes is

$$\text{Number of strings of 48V system} = \frac{\text{Battery Bank Capacity}}{\text{AH of battery}} = \frac{527}{230} = 2.5 \sim 3$$

Therefore, the total number of batteries is $4 \times 3 = 12\ batteries$

3.2.7 Determination of Charging Battery to Full Capacity

The time required to fully charge the batteries is important as it helps understand how long it takes to fully-charge the batteries to run the system during non-effective sunlight periods. The charging time to fully-charge the batteries is defined by equation 3.6:

$$Q_t = \frac{C'}{I_C} \qquad (3.6)$$

Where, Q_t = charging time (hours); C' = battery capacity (AH) and $C' = 1.4 \times C$;

I_C = charge current of the battery (A) and,

$I_C = 10\% \times C$; Where, C = rated capacity of the battery (Ah) = 230 AH;

- $I_C = 10\% \times 230A = 23A$ and $C' = 1.4 \times 230 = 322\ AH$
- $Q_t = \frac{322}{23} = 14\ hours$

Therefore, the charging time to full capacity when the battery has been discharged to 50% depletion is 14 hours.

3.2.8 Design of the Charge Controller

The solar array system should produce sufficient current and voltage to the cooling load and associated applications and according to Eltawil and Samuel (2007). To achieve this the system can be connected either in parallel or in series or a combination of both. When solar panels are in series, the voltage is increased and when in parallel the current is increased (Smith, 1976). The best option to achieve the power requirements for this study is having three solar panels in series of three strings, considering the inverter and charge controller sizes. The charge controller controls the charging and discharging of the battery by providing a constant current and voltage to the load from batteries (Deveci *et al.,* 2015). For the power requirements of this study the available charge controller is a TriStar solar charge controller (t 60) with a maximum rated input current of 60 A and DC voltage of 145 VDC.

The input power to the solar charge controller is given by equation 3.7

$$P_{out} = \eta_{controller} \times P_{in} \tag{3.7}$$

Where

Pout = power output from inverter (W);

η_{c} = efficiency of the charge controller from the supplier (90%) and

P_{in} = power input to the charge controller.

3.2.9 Design of the Inverter

The inverter powers the equipment (pump, fans and heat exchanger) that may require 2-3 times the running wattage power; therefore, the inverter of the system was sized to be more than the actual power requirement of the whole system. An inverter of 5 kW, 48 V with a 125 A-fuse was used. The input power to the inverter system is output power from the charge controller (equation 3.8). The output power can be calculated by incorporating the efficiency of the inverter.

$$P_{out} = \eta_I \times P_{in} \tag{3.8}$$

Where

P_{out} = power output from inverter (W); η_I = efficiency of the inverter from the supplier (90%) and

P_{in} = power input to the inverter.

3.2.10 Solar Panels Specifications

The solar panels available in the market that were used are monocrystalline solar modules with the specifications summarized in Table 3.2.

Table 3.2 Electrical characteristic of the solar modules

Description	**Measurement**	**Units**
Nominal Power (P_{max})	350	W
Rated Voltage (V_{mpp})	36.6	V
Rated Current (I_{mpp})	8.2	A
Short Circuit Current (I_{sc})	8.7	A
Open Circuit Voltage (V_{oc})	44.8	V
Minimum Power	330	W
Quantity	9	-

The specifications are from the manufacturer at nominal operating cell temperature with an insolation of 1000 W. m^{-2}, the cell temperature at 25℃ and air mass at 1.5.

3.2.11 Optimisation of the Number of Modules for the SPV System

The optimization of the hybrid SPV system considering the number and sizes of modules and batteries will require a balance between the system voltage and current that will supply the required power (Erdinc and Uzunoglu, 2012). A number of combinations need to considered, series, parallel and combination of both in different permutations as recommended by Goel and Sharma (2017). A parallel connection with two panels in series will provide the following scenario;

The output voltage will be: $Output\ voltage = 3 \times 44.8\ VDC = 134.4\ VDC$

The output current will be: $Output\ current = 3 \times 8.7\ A = 26.1\ A$

Total power output: $Power_{\ output} = 134.4 \times 26.1 = 3507.8\ W$

Hence, the solar array system was a three-series-three-strings i.e. consisting of three solar modules in series and parallel to other two sets (Figure 3.2). In each set, the modules were connected in series and the sets were connected in parallel to each other. This arrangement was ideally for the system, as it did not overload the available solar charge controller.

$$Ic\ rating = N \times Isc$$

$$Ic\ rating = 3 \times 8.7 = 26.1\ A$$

The average monthly power output (P_{out}) from the optimal solar radiation was calculated using equation 3.9.

$$P_{out} = \eta_{panel} \times G \times A_{panel} \times N_{panels} \tag{3.9}$$

Where

P_{out} = average monthly power output (W);

η_{panel} = overall PV module efficiency (=0.1522);

N_{panels} = number of PV modules (9);

A_{panel} = area of the module, m^2 = 2.01m x 1.02m = 2.0502 m^2 and

G = solar radiation ($W.m^{-2}$).

The energy produced at the minimum solar radiation was calculated from Equation 3.10.

$$E_{produced} = \frac{P_{out} \times D_1}{N_{panels} \times A_{panel}} \tag{3.10}$$

$E_{produced}$ = energy produce on a day length D_l ($Wh.\ m^{-2}$) and

D_l = average monthly day length (hours);

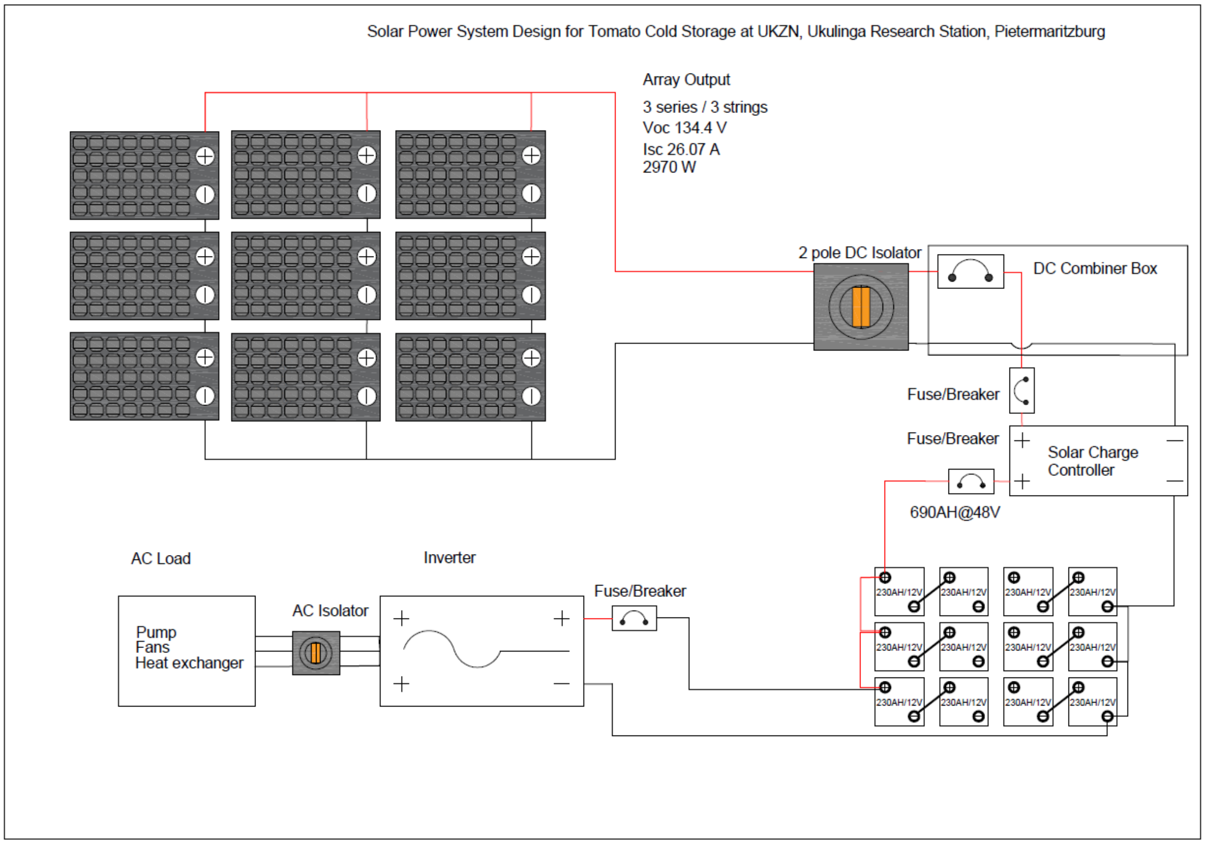

Figure 3.2 Solar Photovoltaic system for the evaporative cooling system

3.2.12 Optimisation of Power Output from the Solar Panels

Tilt angle of a solar panel impacts on the solar radiation incident on a surface. To optimize the power output from the solar panels, different tilt angles of the panels were taken into consideration in this study. Solar insolation is a function of latitude and tilt angle of the panel according to Honsberg and Bowden (2016) and equation 3.11 shows the relationship.

$$S_h = S_i \times \mathrm{Sin}\,\alpha \tag{3.11}$$

Where

S_h = horizontal solar radiation (W. m^{-2});

S_i = incident solar radiation (W. m^{-2}) and;

α = elevation angle (^{0}).

The solar radiation on the module at the module tilt angle (β) was calculated from the incident solar radiation (Honsberg and Bowden, 2016).

$$S_{module} = S_i\, Sin(\alpha + \beta) \tag{3.12}$$

Where β = solar module tilt angle (^{0}) and S_{module} = solar module radiation (W. m^{-2}).

To optimize the power output from the solar panels, different tilt angles of the panels were taken into consideration in this study. Solar insolation is calculated from equation 3.11

$$S_h = S_i \times \mathrm{Sin}\,\alpha$$

Therefore,

$$S_i = \frac{S_h}{\mathrm{Sin}\,\alpha}$$

In order to optimise solar radiation the tilt angle was varied with ± 46^0 to the latitude of PMB. For the months of June and September considering tilt angles of (i) tilt = horizontal plane (ii) tilt =+15^0, tilt = latitude and tilt = -15^0. The experiments in this study were conducted during the last week of August into the third week of September, however solar radiation data for June was also considered as it is the month that PMB receives the least radiation.

3.2.13 Performance Evaluation

The solar radiation values recorded by Schulze *et al*. (1999) over 50 years' and captured in the South African Atlas 18 of Agro-hydrology and climatology for PMB were extracted to obtain the average solar radiation for each month at different tilt angles. The solar radiation data at Ukulinga Research Station for selected 11 days during the experiment where the maximum temperatures were above 27°C was obtained from the South African Weather Services (SAWS). On the first day of the experiment, the battery bank facility powered the SPV system under load conditions while connected to the charge controller until the system cut off. The following day the batteries were charged under load conditions from 08h00 to 17h00 and the system was then discharged from 17h00 until 10h00 under load conditions. As the batteries were charging, the voltage was recorded from the charge controller at 30 minutes' intervals from 08h00 to 17h00 during the charging period and during the discharge period when the SPV was using power stored in the battery bank facility. On the days of the experiment, the solar modules supplied the energy requirements during the day from 08h00 to 17h00 and thereafter the battery bank supplied energy until 22h00 when the system was switched off. By 22h00, the temperature had fallen below 20°C. A voltage greater than the battery voltage was applied to the system causing current to flow through the battery in the reverse direction to that when the battery is supplying current and in this way the battery was charged. The rate of charge or current that flowed depended on the difference between the battery voltage and the voltage that the solar panels supplied. The series voltage of the system of 44.8 V was capable of producing over 50 volts in the 48V-battery system thus ensuring that the batteries fully charge. The charge controller ensured that the batteries were not over charged otherwise they would be damaged.

During evaluation, there were five positions (Figure 3.3) identified to evaluate the performance of the solar array system. A Fluke 381 multi-meter measured both open circuit voltage and current, voltage and current under location and different positions.

For position 1, the simultaneous readings of current and voltage were measured using a multi-meter at the exit point of the panels and at the entrance point of the solar charge controller.

The test procedures to be followed are:

The power output tests were done by measuring both the voltage and current at different points and these values were used to calculate the power output using the Ohm's Law.

(a) Measurements at position 1 of the system (the input side of the solar charge controller). The voltage and current measured at this point were used to calculate solar modules power output and was compared with the theoretical calculation of the power output from the solar modules;

(b) Position 2 measures both voltage and current at the exit of the charge controller and the input of the inverter. The difference in the readings obtained from position 1 and 2 determines the efficiency of the charge controller;

(c) Position 3 read voltage and current to and from the batteries, and

(d) Position 4 read current and voltage between the inverter and heat exchanger, pump and fans. The power difference between position 2 and 4 determines the inverter efficiency, which will be compared to the manufacturer's efficiency. Measurements at this point also provides how much power the appliances draw.

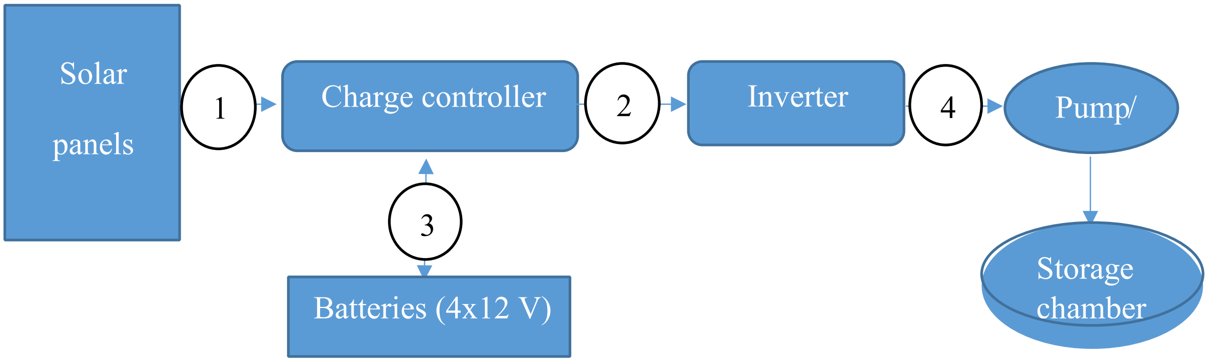

Figure 3.3 Schematic diagram showing points of measurements of current and voltage

3.2.14 Payback Evaluation

The costs of establishing storage facilities should be determined prior to choosing the storage facility unless there are no options because of extenuating circumstances like choice of renewable energy because SSF are located in remote, dispersed areas with no access to grid electricity. The predominant costs for storage facilities are construction, operation and maintenance (Emily *et al.*, 2015; Sahdev *et al.*, 2016). 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 analysis of choosing a facility involves considering the payback which Newnan (2002) defined as the investment of time required for the project of an investment to equal the cost of the investment period. The payback period for this study was calculated using the equation by Workneh (2010) and Wang *et al*. (2015):

$$Payback\ period\ (years) = \frac{Initial\ costs}{Cost\ savings\ per\ year} \qquad 3.11$$

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. The maintenance costs are assumed as 10% of the initial costs per annum according to Emana and Nigussie (2011).

$$Mantenance\ costs\ = 0.10\ x\ initial\ costs \qquad 3.12$$

3.3 Results and Discussions

3.3.1 Theoretical Power and Energy

The performance of SPV systems depends on the tilt angle and orientation of the array. In studying, the effect of insolation on modules a solar tracking device helps in adjusting the position of the solar panels so that the highest possible energy output obtains compared to a fixed PV system. This necessitates that installations of the modules be at an optimal tilt angle that maximizes the solar radiation captured by PV panels. In the absence of a tracker for this study, data obtained by Schulze *et al*. (1999) over 50 years who used four positions of solar radiation at horizontal, tilt = $+15^0$, tilt =latitude and tilt $=-15^0$ to measure solar radiation received in different areas in South Africa was used. The solar radiation data at different tilt angles data for PMB is summarised in Tables 7.1 to Table 7.4 in Appendix 7.3. This data is utilised for calculating the optimum power and energy output from the SPV in Ukulinga research station (in PMB). Table 3.3 is a summary of the solar radiation at different tilt angles and the solar radiation at optimised solar radiation taken over a period of 50 years extracted from Schulze *et al*. (1999). The average optimum solar radiation received in PMB in June and September are 539.93 $W.m^{-2}$ at tilt = $+15^0$ and 1 168.66 $W.m^{-2}$ at tilt = -15^0 respectively as shown in Table 3.3. A fixed optimum tilt angle equal to -15^0 latitude for September was used for PMB as provided by Schulze *et al*. (1999) as he did a more detailed work covering the whole of South Africa than Asowata *et al*. (2012) and Stanciu *and* Stanciu (2014) who recommended one fixed tilt angle equal to the latitude of the area. Table 3.3 shows that the value for tilt $=-15^0$ is higher than the value for tilt =latitude for the month of September in PMB.

Table 3.3 Summary of solar radiation at different tilt angles (Adopted from Schulze *et al.,* 1999).

	Radiation in W. m^{-2} at different tilts					
Month	**Horizontal**	**Tilt = +15**	**Tilt = Lat**	**Tilt = -15**	**Optimal radiation**	**Optimal power**
Jan	1 032.41	1 032.59	1 127.00	1 144.61	1 144.61	3 214.48
Feb	873.02	897.27	928.93	897.27	928.93	2 608.77
Mar	807.69	725.68	711.03	647.93	807.69	2 268.29
Apr	692.43	545.70	513.90	447.07	692.43	1 944.60
May	540.94	402.29	373.12	318.52	540.94	1 519.16
June	485.23	539.93	508.72	442.83	539.93	1 516.32
July	534.98	631.07	619.84	566.36	631.07	1 772.27
Aug	600.69	840.92	873.06	845.70	873.06	2 451.87
Sept	754.56	1 041.68	1 144.16	1 168.66	1 168.66	3 282.02
Oct	873.66	1 487.48	1 712.79	1 821.37	1 821.37	5 115.06
Nov	1 170.63	1 646.56	1 928.77	2 079.54	2 079.54	5 840.11
Dec	1 263.89	1 318.96	1 524.50	1 626.15	1 626.15	4 566.82

Probability of exceedance is the chance of an event occurring in a given period. In this case, the probability shows the percentage of the working period in which a given solar irradiance is exceeded and this helps assess the viability of stand-alone SPV systems at a particular location. At 20% of the time in each month there is a higher radiation received in PMB than in 50% and 80% of the time i.e. in September there is a 50% chance to receive 1 092.71 W.m^{-2} and 80% chance to receive 998.94 W.m^{-2}. As the exceedance probability increases, the amount of radiation received decreases. Relatively lower percentages are recorded at high irradiance levels and the converse is true. The high irradiance levels, which are associated with a direct beam component, that is spread more widely with very small individual frequency percentages. For the purpose of calculation of a

50%, exceedance probability is used as it was closer to the values obtained during the period of the experiment.

Table 3.4 Probability of exceedance of a monthly solar radiation (Adopted from Schulze *et al*., 1999).

Month	**CV**	**Exceedance Probability Solar radiation (W.m^{-2})**		
		20%	50%	80%
Jan	7.00	1 365.74	1 296.30	1 203.70
Feb	6.00	1 212.52	1 150.79	1 080.25
Mar	6.00	1 051.28	1 004.27	957.26
April	5.00	845.41	809.18	764.90
May	5.00	646.93	614.04	570.18
June	15.10	559.07	530.94	502.81
July	6.00	579.56	548.70	517.83
August	6.00	798.33	756.67	715.00
September	8.00	1 149.90	1 092.71	998.94
October	8.00	1 241.04	1 173.84	1 075.27
November	8.00	1 453.37	1 369.05	1 254.96
December	7.00	1 416.67	1 337.96	1 240.74

From equation 3.9 and solar radiation data from Table 3.4, the theoretical power output is;

$P_{out} = 0.1522 \times 530.94 \times 2.0502 \times 9 = 1491.1\ W$, for the month of June and for the month of September, $P_{out} = 0.1522 \times 1092.71 \times 2.0502 \times 9 = 3068.7\ W$

Therefore, the incident solar radiation calculated for June 2017 and September 2017 where 530.94 W. m^{-2} producing a module power of 1 491W at tilt = +15^0 and 1 092.71 W. m^{-2} producing a module power of 3 068.7 W at tilt = -15^0. The theoretical power output in September is very significant and from Table 3.4 the theoretical power output for November will even be higher as the area receives more solar irradiation in the month. In November, the theoretical power output is high and coincides with higher cooling loads as the ambient temperature is also relatively higher. This is the reason why most of the large-scale SPV systems are built in arid and semi-arid areas, where the solar insolation levels are high (Sayyah *et al*., 2014). However, caution has to be taken as high ambient temperature affects performance of the SPV system due to high cell temperature (Rao *et al.,* 2014; Ronoh, 2017).

From equation 3.10 and Table 3.4, the theoretical energy output is given as:

$E_{produced} = \frac{1491\times 7.90}{9\times 2.0502} = 638.4\ \mathrm{Wh.m^{-2}}$ for June and

$E_{produced} = \frac{3068.7\times 6.70}{9\times 2.0502} = 1098.9\ \mathrm{Wh.m^{-2}}$ for September.

The design shows that the expected power output is 638.4 Wh. m^{-2} and 1 114.39 Wh. m^{-2} respectively for the months of June and September at 50% probability of exceedance for PMB. The theoretical power and energy are low in June because solar insolation levels are low. To generate adequate energy under such circumstances would require more solar modules and this would increase the cost of installation of SPV. The sizing of stand-alone SPV considers meeting electrical loads requirements with lowest average daily solar insolation on the array surface usually during winter months. To ensure optimization of the solar insolation a switch could be incorporated to the system coupling the electrical load (pump, fans and heat exchanger) to the PV array directly when the storage battery is fully charged. Optimising the system is important, as the cost of installation is reduced allowing utilisation of SPV by emerging farmers in low cost cooling technologies like IAC+EC (Chandel *et al.,* 2015; Goel and Sharma, 2017). However, the temperatures are also generally low in winter (June), and in most cases, the maximum temperatures are 16°C-20°C. Under such conditions for tomatoes and many tropical and sub-tropical F&V in SSA, either no cooling or minimal cooling will be required during short periods as alluded to by Kitinoja and AlHassan (2012) and Punja *et al*. (2016).

From equation 3.7 the output power from the charge controller is:

Therefore, $P_{out} = 0.9 \times 1491 = 1341.9\ W$ in June and $P_{out} = 0.9 \times 3068.7 = 2761.8\ W$ in September. From equation 3.8 the output power of the inverter is:

Therefore, $P_{out} = 0.9 \times 1341.9 = 1207.71\,W$ in June and $P_{out} = 0.9 \times 2761.8 = 2485.6\,W$ in September.

This means that the power available to run the electrical components during the period of the experiment is 2 485.6 W. The inverter converts VDC to 220 Volts, hence, the current that should flow to the electrical components can be obtained from Ohm's law:

$$I_{appliances} = \frac{2485.6}{220} = 11.3\text{ A}$$

3.3.2 PV Module and Theoretical Power Output

Ambient air temperature and solar radiation outside the IAC+EC system around the SPV system was studied, clear and, sunny days were selected for the experiment. It was observed that ambient temperatures and solar radiation were low in the morning and increased from 08h00 to between 12h00 to 14h00 and thereafter decreased towards 18h00 (Figure 3.4).

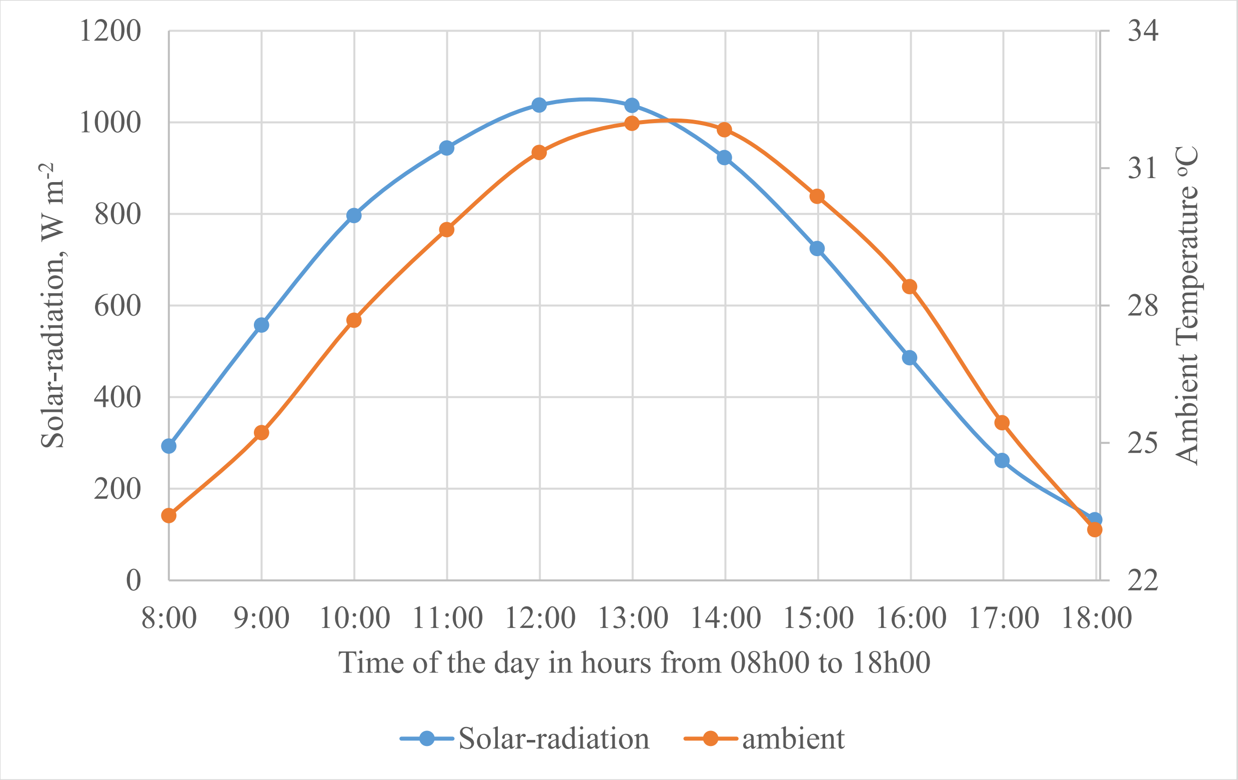

Figure 3.4 Variation of solar radiation and ambient temperature at Ukulinga research station in Pietermartitzburg.

Ambient temperature increased due to increasing incident solar radiation from morning until afternoon 13h00-14h00 and then decreasing from then onwards towards evening and sunset as also confirmed by Madhava *et al*. (2017). The average insolation values rose from 293.4 W.m^{-2} at 08h00 in the morning to 1 037.6 W.m^{-2} at mid-day. A similar trend was observed by Eltawil and Samuel (2007). At any location like PMB, the length of the path the radiation takes from source to ground level varies with time of the day as the spectrum of the radiation changes through each day because of the changing absorption and scattering path length (Ronoh, 2017). The graph relates to data obtained on a clear day where the solar insolation increases from early morning to a peak at midday and then decreases to zero at night. The peak is achieved at midday as the sun is overhead and its path length is shortened. At midday, less solar radiation is scattered or absorbed by atmospheric mediums, and more direct radiation reaches the modules compared to any other time of the day and Olomiyesan *et al*. (2015) complements these results.

Figure 3.5 shows the variation of the practical PV and the theoretical solar irradiance with solar radiation during the period of study from 08h00 to 18h00. The practical PV module output P_{module} and the theoretical power output from the solar irradiance $P_{irridance}$ increased with solar radiation to a peak between 12h00 and 14h00 and decreased thereafter as shown in Figure 3.5. The measured results from the present study agree with findings of Li *et al*. (2005). The solar irradiance received and practical power output had very similar trends with the maximum and minimum values at the same hours during the selected 11 clear and sunny days. This shows that the amount of electricity generated by SPV system is largely depended on the availability of the solar energy at a particular location as corroborated by Li *et al*. (2005). From Table 3.3 the highest average solar radiation received in PMB over 50 years in the month of September is 1 168.66 W.m^{-2} providing an optimal power of 3 282 W compared to 1 092.7 W.m^{-2} (Table 3.4) producing 3 068.7 W at 50% probability of exceedance. The average peak solar radiation during the period of the experiment in August and September was 1 037.6 W.m^{-2} providing an optimal power of 2 639.1 W.

The practical power output of 2 639.1 W when using equations 3.2–3.4 translates 4 726.7 W.h^{-1} actual energy produced by the solar modules and to be stored by batteries in order to cool the 3.8 tonnes of tomatoes from 17h00 to 22h00. To cool one tonne of tomatoes, using IAC+EC requires 1 200 W.h^{-1}. The value of 1 200 W.h^{-1} compares to the value of 700 W.h^{-1} for forced air evaporative cooling of tropical F&V using a 0.1 HP mentioned by Kitinoja and Thompson (2010). The difference in power requirements can be attributable to the additional indirect heat exchanger that was incorporated in this experiment. The power requirements a solar powered IAC+EC system are low when compared hydro-cooling (immersion type) to 0 to 2℃ or hydro-cooling (shower type) to 7℃ where the energy required to cool 1 metric tonne of produce is 35-150 kWh.

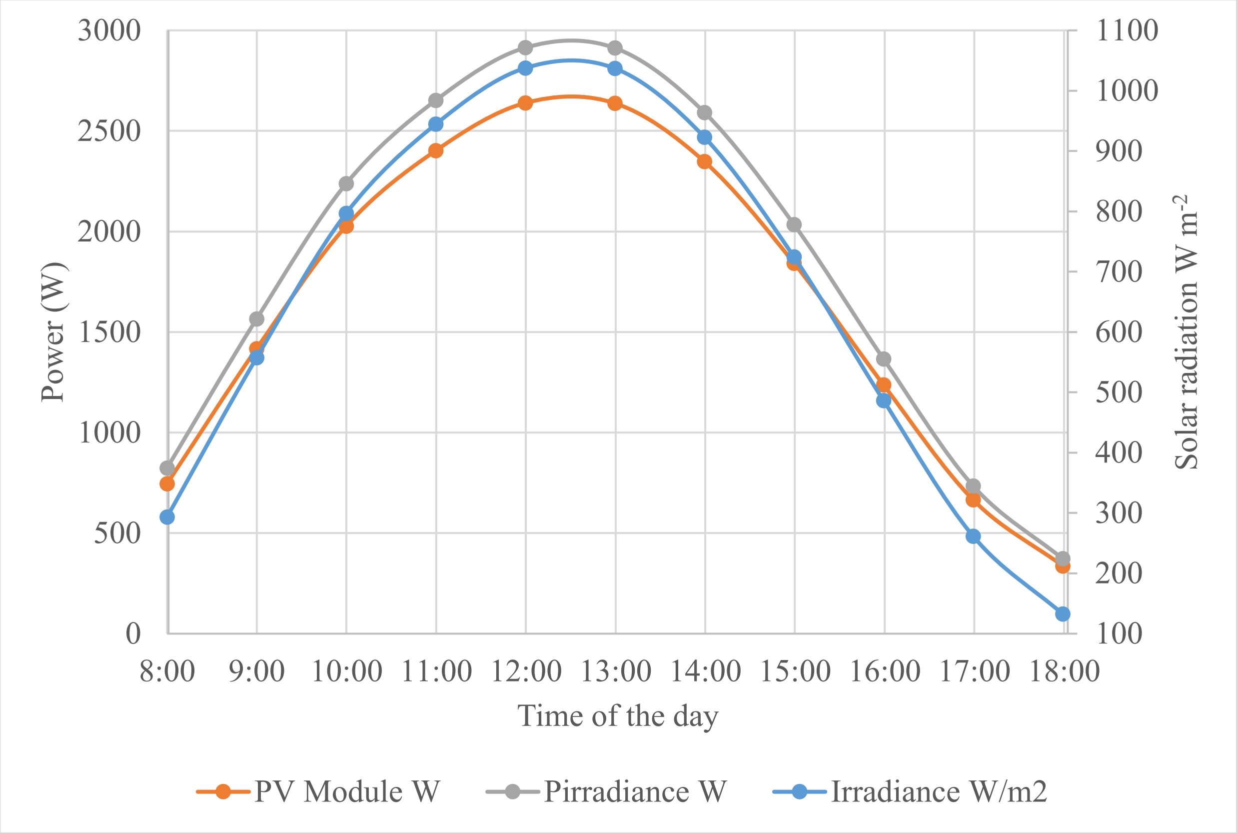

Figure 3.5 Variation of module power and solar radiation with time for SPV system at Ulukinga Research Station in Pietermaritzburg.

The theoretical power output from the solar irradiance $P_{irridance}$ was determined and compared with the actual power output to establish how much power SPV P_{module} can produce in the month of September in PMB. Figure 3.5 shows that the practical power output (P_{module}) from the solar panels of a peak of 2 639 W was 10% less than the theoretical power output ($P_{irridance}$) of 2 914 W during the period of the experiment. However, the practical power output of 2 639 W is 11% higher the design load for electrical appliances of 2 310 W. The difference between the theoretical and the practical power output is attributable to the efficiency of the solar panels of 15.4%, which was lower end of the rated solar panel efficiency of 15-19%. The other contributors are environmental factors of module temperature, soiling material accumulating on the module surfaces, resistance in the wiring and connections and in some instances, modules of the same type have slight differences in electrical characteristics. The solar modules need regular cleaning as soiling, is regarded as one of the significant contributors to reduction of the power output of SPV systems as it reduces the solar radiation reaching the surface of modules as alluded to by Ghazi *et al*. (2014). When modules are soiled, the dust particles deposited on the surface absorb and scatter the incoming incident light and this might have contributed to the reduction of the P_{module} value (Sayyah *et al*., 2014).

The power output increased with module temperature (Figure 3.6) until about 25℃, which coincided with the highest ambient temperature at midday.

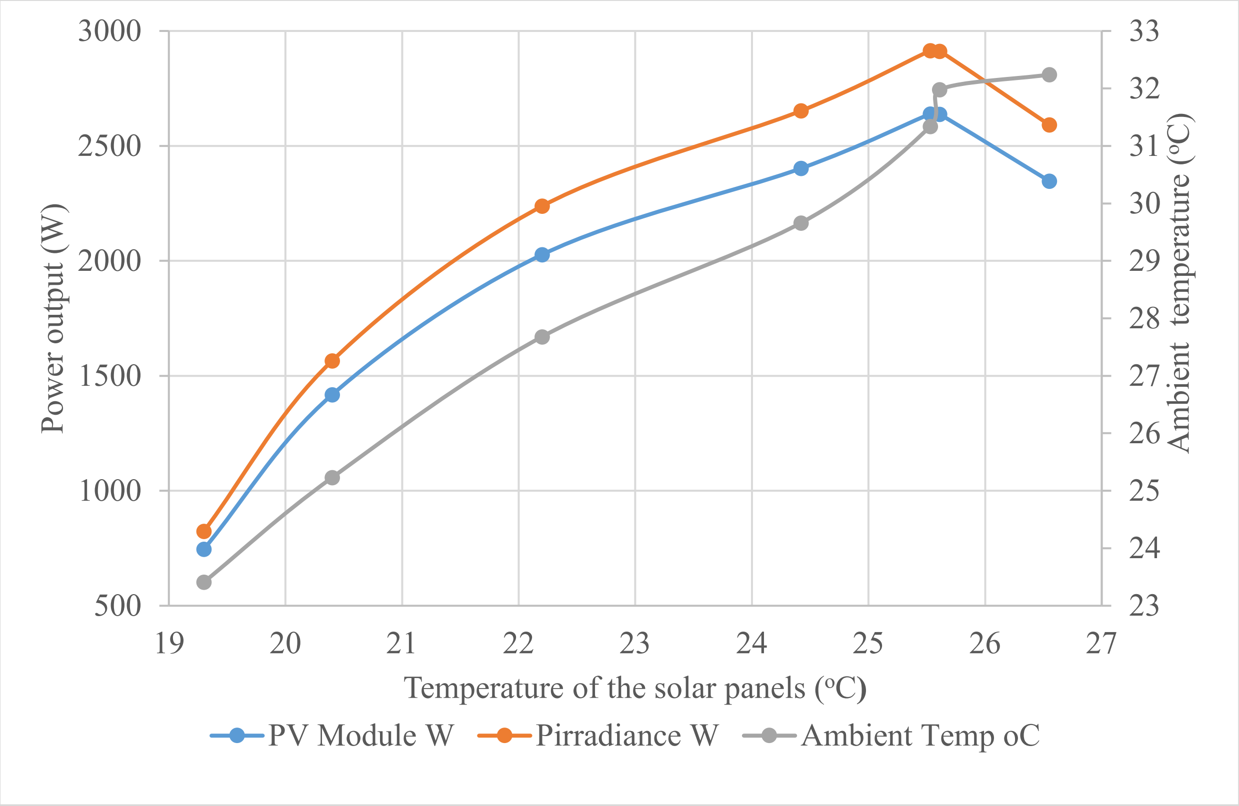

Figure 3.6 Variation of power output with temperature of the solar panels at Ukulinga Research Station in Pietermaritzburg.

The power output declined after 25℃ module temperature. This corroborates the work done by Bai *et al*. (2016) which showed that though solar panels are designed to operate in the presence of the sun, high heat reduce panels' capacity to generate power. When the module surface temperature increases beyond a certain level, the atoms in the material vibrate resulting in a reduction in the conductance of the electron traveling through the electrical component (Olcan, 2015). Many standard grade solar panels may produce 1% less electricity for every 9.44℃ temperature above 25℃ (Bai *et al.,* 2016).

The maximum power of the solar array system was achieved at 31℃-33℃ ambient temperature, which coincided with optimum solar panel temperature of 25℃. Similar results were obtained by Ya'acob *et al*. (2014) who had the highest generated power data at 32.5℃–34.5℃ ambient temperature. The PV module output voltage remained static with ambient temperature (Table 3.5), which indirectly affected the temperature of solar panels. The PV module output voltage also did not change with changes in insolation on the selected days, as the weather was sunny and clear.

Table 3.5 Variation of current and voltage with time of the day, ambient and module temperature.

Time of the day	Panel Temp℃	Ambient Temp℃	Voltage (V)	Current (A)	Irradiance W. m^{-2}
08h00	18.82	23.41	130.09	5.73	293.4
09h00	19.88	25.23	130.83	10.83	557.4
10h00	21.70	27.68	131.01	15.47	796.9
11h00	23.92	29.66	131.62	18.25	944.5
12h00	25.03	31.34	131.67	20.04	1 037.6
13h00	25.11	31.98	131.33	20.08	1 036.9
14h00	25.05	31.84	131.16	17.90	922.9
15h00	22.98	30.39	130.85	14.08	724.4
16h00	21.99	28.42	130.64	9.47	486.3
17h00	20.94	25.45	130.21	5.11	261.6
18h00	20.22	23.11	129.38	2.61	132.6

This could be attributable to the fact that module output voltage cannot increase beyond certain limit of photons equivalent to energy gap as explained by Shaltout *et al*. (1995). On the selected days, the short circuit current increased with insolation due to the increase in the number of photons generating the current. Increased solar panel temperature increases the kinetic energy of the photons resulting in increased current. The increased PV module temperature arose from high insolation heating and high ambient temperature. Ramamurthy *et al*. (1992) made similar observations.

Solar energy is one of the major sources of renewable energies available in SSA and SPV are currently utilised in many agricultural applications. For this study the SPV system of 9 modules (3-series 3 string) of 330 W each and a battery bank (12 x 230 AH) was able to supply the appliances with the needed electrical power and provided sufficient energy to charge the battery bank. Optimal sizing of SPV systems in order to supply load demand is important because of high capital investment costs and benefits of preservation of fresh produce in the case of solar energy powered IAC+EC systems.

3.3.3 Charging and Discharging of the Battery Bank Facility

Figure 3.7 shows the charging-discharging curve for the battery bank for the SPV powering the IAC+EC system. The system voltage rose from 43.8 V at 08h00 to peak at just above 50 V on both days. On the selected days, the system voltage increased from 08h00 to 14h00 with increase in module power output and increase in insolation. The batteries began to discharge from 17h00 when insolation was lower as the sun approached the west to set. The batteries powered the IAC+EC unit with all appliances from 17h00 to 22h00. The SPV system powering the IAC+EC was switched off from this time, as the temperatures were on average lower than 20℃, which is temporarily fine for storage of tomatoes.

The energy supply from the solar panel charged the batteries for overnight operation of the IAC+EC system. The battery bank facility was rightly sized and provided enough power for the electrical appliances until 22h00. The battery bank reliability to supply the required energy depended on accommodating fluctuations, which are considered as independent, then the energy requirements of discharge and charge events can be considered independently. The achieved components' size allowed the load to be supplied during the requested cooling duration, the battery bank to operate safely, and provided energy for the next five hours into the night during which period the temperatures will have dropped to 20°C and lower. The power was switched off at 22h00, as the ambient temperature by this time was 20°C and below and fresh produce such as tomatoes can tolerate temperatures of 13-21°C for short periods (Kitinoja and AlHassan, 2012; Punja *et al.*, 2016). This implies that the IAC+EC system can be designed to operate five hours into the night and then be switched off until 09h00 when ambient temperatures begin to rise above 20°C (section 4.3.3). Such an approach allowed reduction of the number of solar panels and batteries required to power the IAC+EC systems and thus in turn reduced the capital investment in the facility.

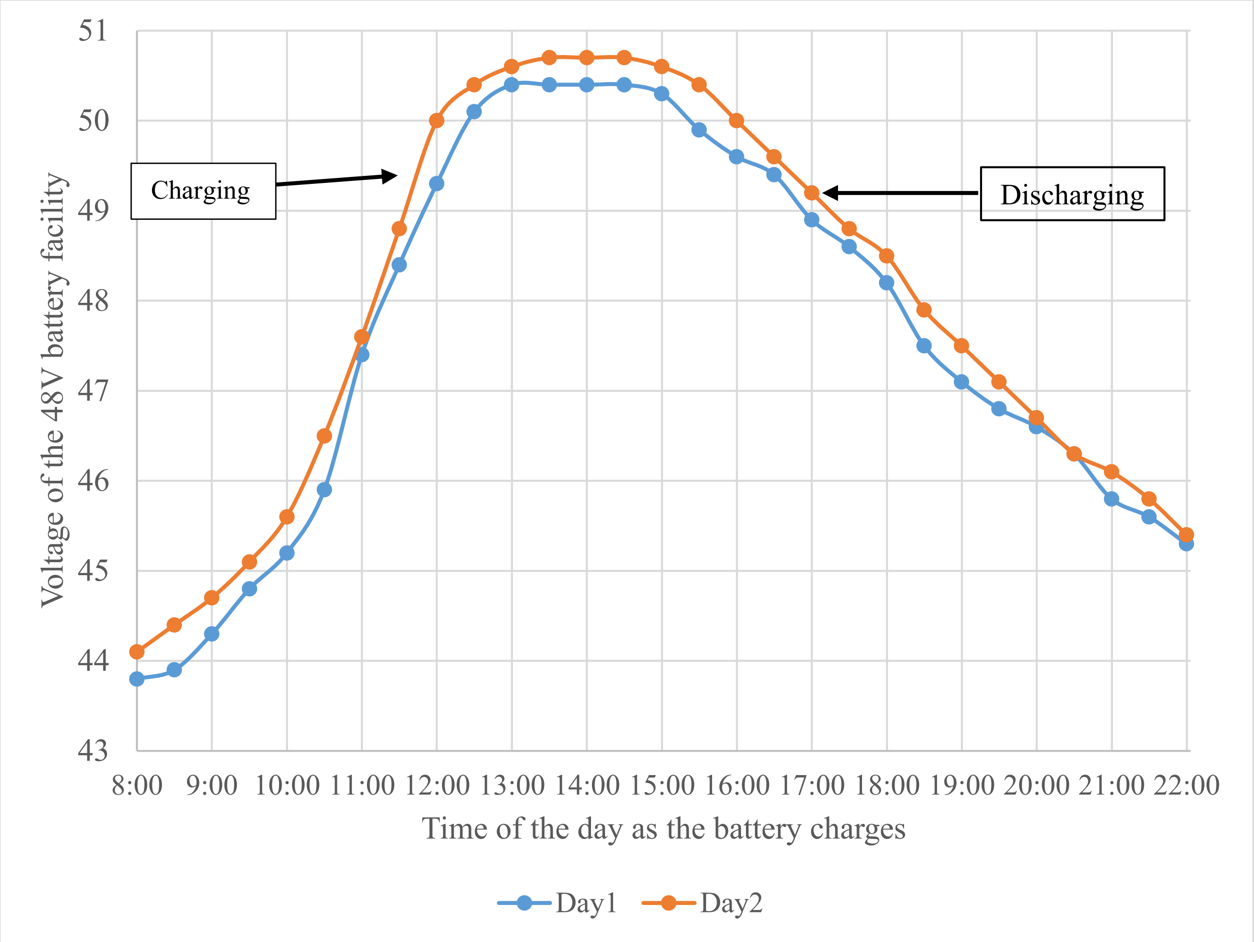

Figure 3.7 Charging and discharging curve for SPV battery bank

3.3.4 Performance Evaluation of the Electrical Components of the Design

During evaluation, there were four major tests to evaluate the performance and assess the electrical components of the design for the 3-string 3-series solar module system and three-string 48 V battery system. At point 1 (refer to Figure 3.3), voltage and current were measured at the exit point of the solar modules and at the entrance point of the solar charge controller to determine the voltage drop through the PV cables.

For measurements taken at the exit point of solar modules, the voltage was 129.1V while the reading at the entrance point of the charge controller were 127.3V. Therefore,

$$V_{drop}\,(\%) = \frac{129.1 - 127.3}{127.3} \times 100\% = 1.4\%$$

This practical voltage drops as calculated provides reasonable efficiency of operation occurrence as the voltage drop is less than 3% as defined by Early *et al.* (2014).

For the measurements taken at position 1 (Figure 3.3), the input side of the solar charge controller the voltage was 127.3V and the current was 20.1 A and using Ohms law

$$P = VI = 127.3V \times 20.1A = 2558.7\,W$$

Therefore, the power input to the charge controller was 2 558.7 W.

For the measurements at position 3, the average current supplied by the solar to the batteries was measured to be 18.01 A and the voltage was 127.3 Vdc.

For the measurements at position 2, the exit of the charge controller and the input of the inverter the measured current and voltage were 19.5 A and 125.4 V

$$P = VI = 125.4V \times 19.5A = 2445.3\,W$$

The inverter converted DC to AC, the AC current and voltage measured between the inverter and the load at position 4 was 19.87 AAC and 205 VAC respectively. And from Ohms law

$$P = VI = 205V \times 19.2A = 3936\,W$$

To convert the AC power to DC power to compare with supplied power we use the formula

$$VDC = 0.636VAC = 3936 \times 0.636 = 2503.3\,W$$

Hence, the power supplied is enough to run the electrical appliances that include the heat exchanger, water pump and fan.

The current drawn by the load from the batteries through the inverter was measured to be 19.4 ADC and the voltage was also measured to be 129.1 VDC.

$P = VI = 129V \times 22.8A = 2941.2\ W$

Therefore, the DC power of 2 941.2 W.

3.3.5 Efficiencies of the Designed System

The solar panel efficiency is calculated from the relationship between current and the voltage measured between the solar panels and the charge controller and theoretical power output of the solar panels.

$$\eta_{solar\ panel} = \frac{P_{measured}}{G \times A \times N} \times 100\% = \frac{2941}{1037.6 \times 2.0502 \times 9} \times 100\% = 15.4\%$$

The efficiency of the solar panels was 15.4% as solar cells have a threshold photon energy corresponding to the particular energy band gap below which electricity conversion does not take place. Photons of longer wavelength do not generate electron–hole pairs but only dissipate their energy as heat in the cell. However, most common PV module converts 4–17% as explained by Chow (2010) of the incoming solar radiation into electricity. The efficiency of 15.4% is within the monocrystalline efficiency of 15-19%. The reasons why a low-end efficiency was obtained could be that solar modules work best when module temperature is below 25°C. Higher ambient temperatures of above 32°C increase the module temperatures and that could cause a slight increase in current as the semiconductor properties of solar cells to shift, resulting in a much larger decrease in voltage as alluded to by Bai *et al. (*2016). Some solar panels may produce as much as 1% less electricity for every -9.44°C temperature above 25°C. The other reason why there is a variation could be that the annual peak accumulated output is calculated using the PV module efficiency under a reference sunlight of irradiance 1 000 W.m^{-2} with a solar cell temperature of 25°C. In reality, solar radiation at a location varies with the weather condition; season and time of day, as a result the technical information provided for STC might not occur in practice.

The efficiency of the charge controller is obtained from the relationship of input and output power into and out of the charge controller.

$$\eta_{solar\ charge\ controller} = \frac{18.01 \times 127.3}{127.3 \times 20.1} \times 100 = 89.6\%$$

The efficiency of the inverter is obtained from the relationship of input and output power into and out of the inverter.

$$\eta_{Inverter} = \frac{19.2 \times 205 \times 0.636}{129 \times 22.8} \times 100 = 85.1\%$$

The inverter efficiency of 85.1% corresponds to the manufacturer's specification of 85% under STC and small variations are expected as explained by Early *et al* (2014).

The relation of the voltage and current to and from the batteries determine the efficiency of the batteries.

$$\eta_{Battery} = \frac{2941.2}{3282.6} \times 100 = 89.6\%$$

The battery efficiency of 89.6% corresponds to the manufacturer's specification of 90% under STC and small variations are expected as explained by Early *et al.* (2014). For the charge controller, inverter and battery variations are expected due to stochastic conditions of the area as alluded to by Ya'acob *et al.* (2014).

$$\eta_{Overall\ system\ efficiency} = \frac{2558.7}{2941} \times 100 = 87\%$$

The value of an overall system efficiency of 87% is comparable to the value of 85% obtained by Ya'acob *et al.* (2014) in their work where they carried out a comparative study of three types of grid connected photovoltaic systems based on actual performance.

3.3.6 Economic Evaluation

The cost of a SPV powered IAC+EC system depends on the initial capital investment, operating and maintenance costs as alluded to by Sahdev *et al.* (2016) for green house drying. The installation costs derived from the cost of material for construction are summarised in the Tables 3.6. The cost of installing a solar powered IAC+EC system are enumerated and summed in Table 3.6. 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 (2011).

$$Mantenance\ costs\ = 0.10xR130190 = R13{,}019$$

Payback period was calculated using equation 3.11. The capital cost of the cooler was R 130 190 and assuming that each SSF in PMB invests in one IAC+EC and that there are no risks of losses in the evaporative cooled storage.

Table 3.6 Costs associated with establishment of SPV and IAC+EC systems

Direct Costs	**Unit price (R)**	**Total costs (R)**
Solar panels (9 x 330 W)	3 800	34 200
Solar batteries (230 AH x 12)	4 250	51 000
Charge controller	4 490	4 490
Inverter	10 500	10 500
Heat exchanger (1)	4 650	4 650
Water pump (0.26 kW)	1 200	1 200
Fan (x2)	2 200	4 400
Water tank and Float (250 litres)	1 250	1 250
Water circulation system	950	950
Charcoal for pads	650	650
Insulating material	900	900
Storage chamber	6 000	6 000
Labour	10 000	10 000

Grand Total	**R130 190**

The storage chamber accommodates 3 825 kg of tomatoes and the marketability of the fruit within 14 days is good at 64% and 39% for pink harvested tomatoes in the IAC+EC and under ambient respectively; 78% and 47% for green harvested tomatoes in the IAC+EC and under ambient respectively (section 5.3.2). There is an average difference of 28% 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. The difference for tomatoes available for sale in per year as result of the use of cooler if the price of tomatoes is R 3 per kg.

$$Savings\ per\ year\ = 0.28x91500x3 = R76{,}860$$

The payback period is calculated from Workneh (2010) equation:

$$Payback\ period\ (years) = \frac{143209}{76860} = 1.86$$

SSF can adopt IAC+EC technology in hot and sub-humid to humid areas, as this should be viable as it takes 1.9 years to recoup the initial capital investment. Workneh (2010) and Wayua *et al.* (2012) found payback periods of 1.2 years and 1.3 years in their research activities for EC. The most important economic benefit of use of IAC+EC is safeguarding against high PHL incurred by SSF if the produce is stored under ambient environmental conditions. In addition, the materials used for construction were locally sourced and are inexpensive. Therefore, the use of IAC+EC in F&V 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.

3.4 Conclusion

The use of SPV systems is increasing as installations costs are decreasing and the application is finding expression in remote and isolated communities and in new farming setting ups of small-scale farmers with no access to cooling facilities. Electricity supply is of great concern, as it is inadequate and in SSA, not everyone is connected to the national grid in the near future. This has turned interest to renewable energy sources like solar as a means of bridging the energy gap and providing environmentally friendly energy. In this study, a SPV system IAC+EC is evaluated based on actual performance. This experiment explored the possibility of integrating of solar energy to power IAC+EC targeting SFF in remote areas with no access to grid electricity.

Most of the literature does not give actual figures of energy required by different cooling systems, it mostly states which cooling systems are more energy intensive to others. Energy required to operate modern cooling systems are greater than the energy required to operate IAC+EC. The SPV systems used in the study supplied energy during the critical period of the day when temperatures are high from 08h00 to 22h00. To cool one tonne of tomatoes, using IAC+EC requires 1 200 $W.h^{-1}$ and the batteries had to store 4 726.7 $W.h^{-1}$ to provide energy for the 3.8 tonne storage chamber to cool tomatoes from 17h00 to 22h00 when the IAC+EC system was switched off. The efficiency of the solar panels was 15.4% and the overall systems efficiency was 88%. The energy to power an IAC+EC system relates to the size of the solar array required to provide the energy and the cost of the system. The study also concludes that combinations of the solar array system can be used to power the cooling system at daytime during summer season and the excess energy can be stored in the battery to run the system for another five hours into the night. A bigger and expensive system is required to run all-nighttime. The cost to construct an IAC+EC system integrated with a SPV system were R 130 190 with a 10% annual maintenance costs and the payback period was observed to be 1.9 years. A payback period of 1.9 years is regarded as economically viable as the SPV powered IAC+EC safeguards SSF reliance on ambient storage environment to mitigate PHL.

Therefore, where grid electricity or other commercial energy sources are unavailable and solar energy is available, IAC+EC is a viable alternative to these more complex and costlier modern-day cooling systems. This shows that stand alone SPV systems have an expression in rural, dispersed and remote areas where grid electricity supply may not be readily accessible. Integrated solar and indirect EC is an attractive alternative for SSF with no access to cooling technologies in developing countries especially African countries, where issues of land re-distribution are topical and there will be a significant small-scale commercial in these remote areas, which require cooling facilities for their fresh produce.

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4 PERFOMANCE OF INDIRECT AIR COOLING COMBINED WITH DIRECT EVAPORATIVE COOLING SYSTEMS

Abstract

The aim of this study was to explore influence of indirect air-cooling (IAC) through a heat exchanger before air enters the evaporative cooling unit (IAC+EC) for cooling the microenvironment and increasing relative humidity (RH) in the storage chamber for hot and sub-humid to humid regions. The other objective was to carry out a quantitative performance evaluation study of small-scale farmer sized temporary storage for fresh produce in terms of provision of an optimum microenvironment of temperature and RH. A low cost solar photovoltaic (SPV) powered IAC+EC system consisting of SPV system, battery bank, electrical appliances, IAC unit, evaporative cooling unit, and 3.8 tonne storage chamber (53 m^3) was constructed and assembled at Ukulinga research center at the University of KwaZulu Natal in Pietermaritzburg. The EC system incorporated a suitable desiccation media (heat exchanger) for IAC. Performance evaluation was conducted under conditions storage of 150 kg sample tomatoes. The performance of the IAC+EC was evaluated based on the temperature and the RH measured hourly from 05h00 to 22h00. Temperature and RH were measured in various positions in the storage chamber, at the entrance to the storage chamber and outside the storage structure to give the ambient conditions. There were significant variations ($P<0.001$) in temperature and RH between storage and ambient conditions. The temperature inside the storage chamber was on average 7°C-16°C lower while the average RH was 13%-41% higher than ambient conditions. Temperature and RH at the exhaust end of the IAC+EC storage chamber were 16.40 °C and 88.9% compared to 30.9°C and 47.6% under ambient conditions, which can enhance the shelf life of fruit and vegetables (F&V) of moderate respiration rates. The temperature after the last cooling pad rose by 0.75°C at the fan to 15.73°C at the entrance to the storage chamber while RH decreased by 2% to 93.8%. Inside the storage chamber, the temperature varied between 15.7°C and 16.4°C and the RH varied between 93.8% and 89.6% at different locations respectively. The cooler efficiency varied from 88.04% to 95.6%. The IAC+EC was found to perform at the same level as evaporative cooling under dry and arid conditions. The solar powered IAC+EC tested in this study has benefits in providing optimum conditions for fresh produce and in reducing losses as well as being a low-cost technology that can be utilised in hot in sub-humid to humid areas in sub-Saharan Africa.

4.1 Introduction

The World Bank (World Bank, 2011) reports grains and fresh produce worth more than US$ 4 billion of is lost through postharvest losses (PHL) in Sub-Saharan Africa (SSA). The entire fruit and vegetables (F&V) supply chain faces even more dire challenges resultant from high PHL estimated at 26.4% (FAO, 2013; Affognon *et al.,* 2015). In SSA during the period of glut, F&V not immediately consumed or sold rot away in the farms or else small-scale farmers (SSF) dispose of to intermediaries at low and unprofitable prices (Kiggundu *et al.,* 2016; Korir *et al.,* 2017).

SSF in the Embo area of KwaZulu-Natal in South Africa claim to miss premium market prices for their organic potatoes due to amongst other factors lack of proper storage facilities (Katundu *et al.,* 2010). Modern cooling technologies like mechanical refrigeration, hydro and vacuum cooling have been widely adopted for the modification and control of the storage environment of high value-quality fresh produce in developed countries (Jensen, 2002; Waaijenberg, 2004; van Henten *et al*., 2006; Okanlawon and Olorunnisola, 2017). Availing such facilities to SSF could assist in the reduction of PHL through control of temperature and RH, which are the two most important environmental factors that affect shelf life of F&V (Tyagi *et al.,* 2017; Saltveit, 2018).

SSF in SSA cannot afford the high installation and maintenance costs of modern storage facilities available in the market (Adebisi *et al.,* 2009; Ndukwu and Manuwa, 2014). Furthermore, modern cooling technologies are energy intensive limiting availability to SSF located in remote areas with no access to grid electricity (Kim and Ferreira, 2008; Chaudhari *et al.,* 2015; Korir *et al.,* 2017). However, evaporative cooling (EC) has low initial investment, installation and maintenance costs compared to modern technologies and can be set up without a power grid source (Tigist *et al.,* 2011; Okanlawon and Olorunnisola, 2017). EC has a potential energy saving of about 75% and relies on velocity of natural wind through wetted pads to provide a cooling effect for preservation of organoleptic properties of food (Amer *et al.,* 2015; Misra and Ghosh, 2018). EC is a technology that can succeed in use by SSF in SSA as it can easily be constructed using available materials, comes at an appropriate scale in operation and economics, can have more than one use (year-round utility) (Liberty *et al.,* 2014; Tabrez and Chaurasia, 2014; Chijioke, 2017). These are the critical reasons why this study is focusing on EC as a panacea to reducing PHL for SSF in SSA.

Most of the research in EC in developed countries and Asia has focused on EC of buildings as opposed to cooling fresh agricultural produce. Literature shows many laboratory scale studies on EC in SSA as summarised by Ndukwu and Manuwa (2014) where the technology has achieved maintaining cooling spaces at temperatures below ambient with a depression reaching 12°C and RH above 90%. The EC systems studied so far are prototypes; with low storage capacity and environment specific and their effectiveness at a commercial scale and in other regions in SSA needs investigation (Abbouda and Almuhanna, 2012; Zakari *et al.,* 2016).

The current research has been limited to east Africa, West Africa and North Africa with few studies done in the Southern African (Ndukwu *et al.,* 2013). EC removes room sensible heat, is effective in hot and arid areas, and has limitations in hot and humid areas because of the inherent high RH of local air, which leads to low dry bulb temperature (Deoraj *et al.,* 2015). 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. Performance of EC systems varies with climatic conditions (regions) as evidenced by a report by Thipe *et al.* (2017) where in greenhouse EC, fan-pad ventilation performed better than natural ventilation in Southern African regions, while in the tropical and Mediterranean climates, the reverse was true. There is need to develop and test and characterise IAC coupled with evaporative cooling system (IAC+EC) in southern Africa sized big enough to mimic the quantities of fresh produce that a SSF requires to cool per unit time. Literature review done for EC for preservation of fresh produce and greenhouse application shows that IAC+EC has not been applied for such purposes as corroborated by Misra and Ghosh (2018). Ogbuagu *et al.* (2017) alludes that IAC+EC systems have shown great potential of development and research opportunity for their perceived improved efficiency, high thermal performance and low energy use. Therefore, this study proposes use of an IAC+EC with three-layer charcoal granule cooling pads. The IAC+EC system will require an energy source to power the heat exchanger, fans and water pump for air and water circulation (Razak *et al.,* 2007; Shaahid and El-Amin 2009).

Integrating IAC+EC with solar energy is critical for SSF with no access to grid electricity in remote areas or in rugged terrain where it is un-economical to stretch the utility grid (Kim and Ferriera, 2008; Szabo *et al.,* 2011; Parida *et al.,* 2011; Hassan and Mohamad, 2012; Chaudhari *et al.,* 2015; Kazem *et al.,* 2017). Solar energy is available in quantities of 2 000 kWh m^{-2} per year with solar radiation of 4.5 – 6.5 kWh.$m-^{2}$ for 6 -7 hours per day in SSA which is enough for conversion to electricity for applications like EC needs (Rehman and Al-Hadhrami, 2010; Best *et al.,* 2012; Davis and MacKay, 2013; Saxena *et al.,* 2013; Olomiyesan *et al.,* 2015). To ensure energy is available at night a solar/battery hybrid system can be utilised where the battery bank stores energy during the day (GSES, 2015). Integration of solar/battery facilities and provision of SSF sized IAC+EC system is a new phenomenon proposed in this study for use in areas without access to grid electricity and along coastal areas with hot and sub-humid to humid conditions.

The phenomenon of commercial exploitation of IAC+EC system for storage of fresh produce under hot and sub-humid to humid conditions is untapped in Southern Africa and requires profiling and evaluation. To solve this problem and encourage adaptation of low-cost cooling methods a SSF sized demonstration able to store about 4 tonnes of tomatoes was designed and constructed. Therefore, the objective of this study is to evaluate the performance of SSF sized IAC+EC system for storage of fresh produce under hot and sub-humid to humid conditions in South Africa.

4.2 Materials and Methods

4.2.1 Design Information and Specifications

The cooling unit design provided the optimum storage temperature and RH for the selected fresh produce for KwaZulu Natal province and specifically PMB, which is predominantly hot and sub-humid. The average long-term minimum and maximum temperatures in September range from 10.0 - 17.1 °C and 12 - 27 °C respectively, while the relative humidity ranges from 61.1 – 68.1 % (Schulze and Maharaj, 2007). The following factors should be taken into cognisance:

- in the IAC+EC system, the ambient air conditions limit the lowest temperature attained and that;
- the IAC+EC system can only cool to the wet bulb temperature of the ambient air temperature (ASHRAE Handbook, 2004).
- mature green (breaker stage) and pink tomatoes require a storage temperature varying between 13°C and 21°C and RH of 90 to 95% (Thompson *et al.,* 1998).

4.2.2 Design Considerations and Specifications for the Cooler

The following design considerations were made:

1. The IAC+EC storage chamber size to mimic quantities of fresh produce that a SSF' in SSA requires to cold store at a unit time.
2. The IAC+EC constructed from local available material.
3. Incorporation of a water re-circulation system supplying a constant water flow rate.
4. Incorporation of forced air-circulation system to supply a constant ventilation rate.
5. Incorporation of a desiccation media system for indirect cooling of air before EC.

Based on the above-mentioned considerations, the design and construction of IAC+EC system had the following specifications:

1. The IAC+EC unit to maintain the temperature inside the storage chamber at the wet bulb temperature of the prevailing ambient air conditions.
2. The IAC+EC unit to maintain the RH in the storage chamber at 80 - 95%.
3. The cooling pads had to be available in South Africa and made from relatively cheap material.
4. The fan attached to the indirect heat exchanger to provide airflow velocities of 2.0 -2.2 m.s^{-1} across the cooling pads.
5. The fan at the entrance to the storage chamber to provide airflow velocities ranging between 3 - 4.0 m. s^{-1} to maximize the efficiency of the IAC+EC.
6. The solar array system to power the heat exchanger, fans and the pump.

4.2.3 Sizing of the Storage Chamber

The sizing of the storage chamber was based on the requirement to store about 3.8 tonnes of tomatoes using packing crates found in PMB of sizes 500 mm long × 300 mm wide × 230 mm high with each crate holding about 12.5 kg of tomatoes. The packing of crates left at least 5% venting with a spacing of 100 mm between the tomato layers to allow adequate airflow according to Schuur (1988) and Sarvacos and Kostaropolous (2002). A provision of 0.9-metre walkways in between the crates for ease of packing and unpacking. The vertical stacking of tomatoes in the crates inside the storage chamber ensured a spacing of 25 mm between the crates according to Kim and Ferreira (2008). This arrangement accommodated 3 825 kg of tomatoes assuming a bulk density of tomatoes is 694 kg.m^{-3} according to Sharan and Rawale (2009) as detailed in Appendix 7.3. Three hundred and six crates (51 stacked to 6) of 12.5 kg tomatoes can packed in the storage chamber as shown in Figure 4.1. Appendix 7.3 provides a pictorial image of the storage chamber.

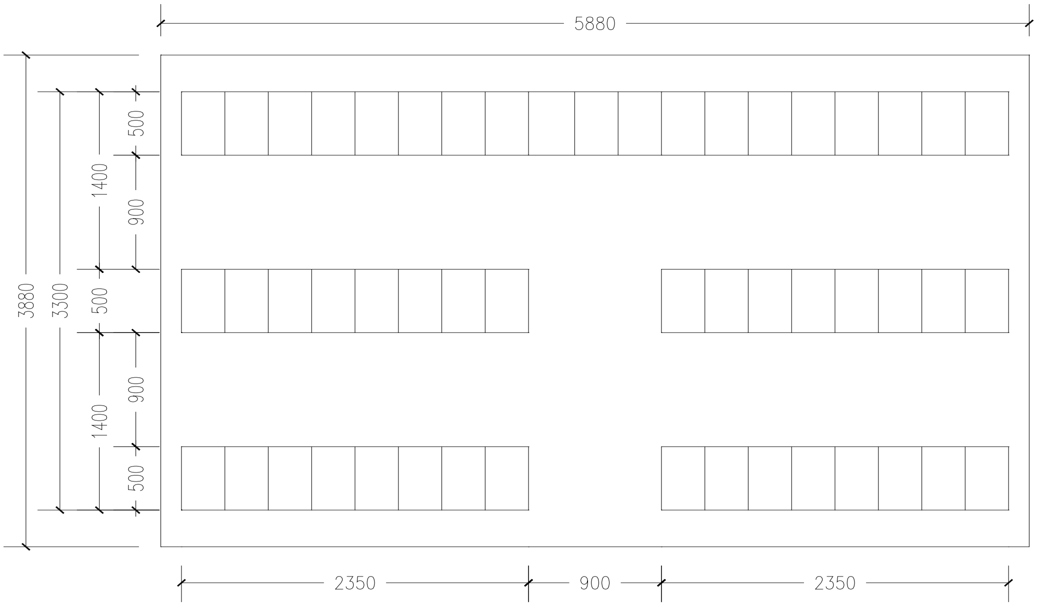

Figure 4.1 Storage chamber floor plan showing arrangement of crates

4.2.4 Sizing of the Psychrometric Unit

Heat exchanger

A heat exchanger was chosen according to Holman (1989) in Appendix 7.9 for substantial temperature reduction effect and a minimal increase in RH for hot and sub-humid to humid climatic regions.

Air circulation

The required ventilation rate ensured that a continuous heat removal process obtains as described by Hellickson and Walker (1983) and Grubinger and Sanford (2015) to produce airflow across the indirect heat exchanger and cooling pads and to enhance evaporation in the chamber. Two fans were used, one fan attached to the heat exchanger to facilitate airflow in the psychrometric unit and another at the entrance to the chamber to ventilate the chamber as proposed by Babaremu *et al.* (2018).

Air circulation across the cooling unit

A 31/33 W (UF25GC12, AC 115 V, 50/60 Hz) constant speed positive pressure fan with a flow rate of 0.25 $m^3. s^{-1}$ was bought with the heat exchanger and supplied air across the psychrometric unit consisting of the heat exchanger and cooling pads at constant speed of 2.1 $m. s^{-1}$ (Table 7.8 and Appendix 7.9). This fan was able to overcome a maximum pressure drop of 50 Pa across the heat exchanger and 130 Pa across each cooling pad as prescribed by Thompson *et al*. (1998) and Gunhan *et al*. (2007).

Air circulation across the storage chamber

Introduction of cold air into the storage chamber facilitates warm air to escape from the storage chamber through exhaust holes and for this to happen a 290 W (308,7/6-6/P3HL/25/PA) fan was installed at the inlet/entrance to the storage chamber just after the cooling pads. The selection of the fan derived from the required ventilation rate of 0.234 $m^3. s^{-1}$ (Appendix 7.6) calculated from the total cooling load (Appendix 7.5). The selected fan was the closest found in PMB with an airflow rate of 0.278 $m^3. s^{-1}$ and air velocity of 3.6 $m. s^{-1}$ at a static pressure of 68.27 Pa and Figure 7.5 shows its performance curve.

Pad design

The cooling pad was made of charcoal granules to provide a very porous structure able to hold water (Obura *et al.,* 2015). Charcoal is locally available, relatively cheap and achieves cooling efficiency of up to 92% (Workneh and Woldetsadik, 2004; Getinet *et al.,* 2008). Standard equations were used in calculating the pad area, thickness and volume as determined by Gupta *et al*. (1995) as shown in Appendix 7.7. The charcoal cooling pads were vertically mounted to allow uniform flow of water, free flow of air and achievement of maximum capillarity and evaporation (Gunhan *et al.,* 2007). Based on literature from Gunhan *et al*. (2007) and Liao *et al*. (1998) a design air velocity of 2.1 $m. s^{-1}$ from the fan attached to the heat exchanger facilitated air velocity across the cooling pads.

4.2.5 Water Distribution System

Selection of pump

A water pump is required to deliver water to the EC pads. Centrifugal pumps handle small discharges and small heads (Hamill, 1995) such as required for this IAC+EC unit of 0.115 $m^3.hr^{-1}$and 2.5 m total head (Table 7.7 in Appendix 7.8). The net positive suction head at which cavitation was likely to be avoided in the pump was determined. These values were incorporated in the determination of the pump power requirements as described by Burger *et al*. (2003). Subsequently, the selected pump from the local market was a Pedrollo PVm 55 centrifugal pump supplied complete with a 260 W pump, this was the smallest available pump that could supply the small flow rate required, and Figure 7.6 shows its performance curve.

Water distribution bath

The distribution bath is a small reservoir that serve the purpose of wetting the EC pads, which was determined based on the dimensions of the cooling pads. The distribution bath of 1mm galvanized iron sheet had dimensions of 0.390 m × 0.160 m × 0.05 m. The required mass flow rate of water to be evaporated in each 1.2 mm hole was also determined. This velocity was low enough to allow water to drip down the pad by gravity and enhance capillary action, which allow for the maximum wetted area.

4.2.6 Description of the storage chamber and psychrometric unit

The IAC+EC system consisted of a storage chamber, indirect heat exchanger, multiple cooling pads, buried water tank, a water pump and two fans (Figure 4.2 and Appendix 7.1) as described by Chen *et al*. (2010). Figure 4.2 shows a schematic diagram of the IAC+EC. The evaporative cooler storage chamber had double-jacket walls and roof of 1mm zintec (mild steel) on the outside and on the inside to reduce heat transfer by conduction. The flooring of the storage chamber was concrete mortar.

The inner dimensions of the unit were 2 340 mm high x 5 880 mm long x 3 880 mm wide to hold a capacity of 3.8 tonnes of tomatoes in a 53 m^3 storage volume. The cooler was a cuboid to provide a wider surface for circulation of air (Ndukwu *et al.*, 2013). The cooler had a 60 mm zinc wall thickness with 58 mm polyurethane insulation in between the zintec layers to prevent heat exchange

(Babaremu *et al.,* 2018). The door (90cm wide) to the storage chamber was made of the same material and had the same height and thickness as the rest of the storage chamber. The outside of the walls and roof were white colored to increase the reflectivity of the material and decrease the rate of absorption of heat (Babaremu *et al.,* 2018). Figure 4.2 is a schematic diagram of psychometric unit and in summary the Fan on the left blows ambient air through indirect heat exchanger and three pads while the fan on the right forces the air through the room.

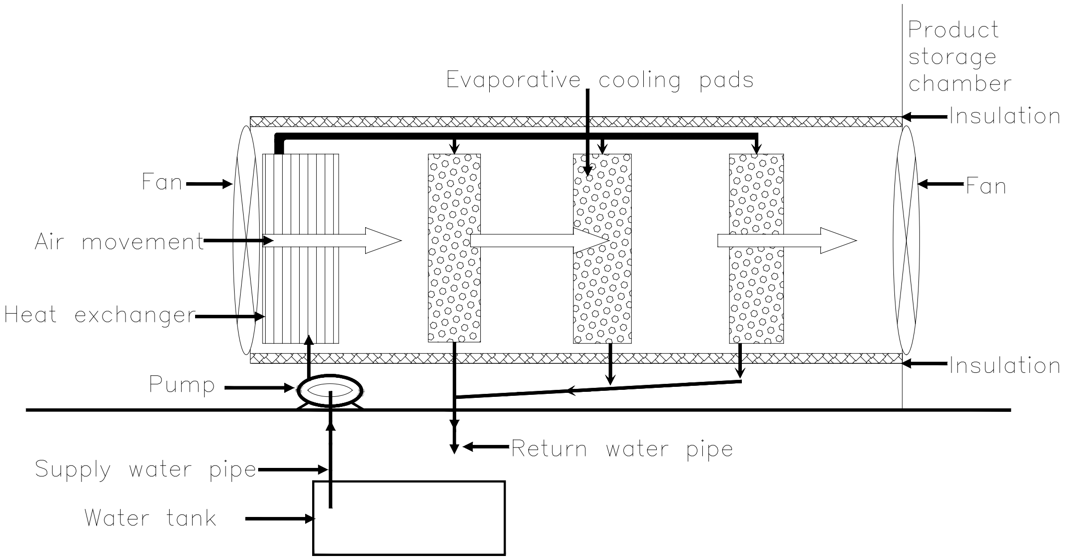

Figure 4.2 Schematic diagram of the psychrometric unit and the storage chamber

Incorporation of an indirect heat exchanger brought the temperature as close to the wet bulb temperature by indirect cooling of the air before coming into contact with water. After the heat exchanger, were three layers of vertically mounted charcoal granules cooling pads primarily mounted so, as the area in Ukulinga research station is not dusty. Through forced convection, a 31/33 W (UF25GC12, AC 115 V, 50/60 Hz) constant speed positive pressure fan purchased mounted next to the indirect heat exchanger facilitated optimum airflow at 2.1 m. s^{-1} velocity by forcing air through the heat exchanger and the three layers of cooling pads into the storage chamber. A 290 W (308,7/6-6/P3HL/25/PA) fan pushed the air coming from the cooling unit into the storage chamber at an airflow rate of 0.278 m^3. s^{-1} and air velocity of 3.6 m. s^{-1}. 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 (exhaust) vents. These air vents were opposite the inlet, three at the bottom and three at the top and they facilitated continuous heat removal as described by Seweh *et al*. (2016).

The water distribution system was designed so that, water continuously pumped from an underground storage (supplied from the mains) using a 260 W Pedrollo PVm 55 centrifugal pump placed at the surface as recommended by Nkolisa *et al*. (2018). An underground tank maintained the water temperature as low as possible and created a temperature gradient between the air stream and the water stream in the heat exchanger thus facilitating heat transfer. The circulation system pushed water from the underground storage tank, through the indirect heat exchanger and sprinkled water continuously over the vertical mounted IAC+EC pads into the storage chamber, and thus increasing RH and decreasing temperature (Babaremu *et al.,* 2018). 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% allowed water to flow freely to the bottom and return to the tank (von Zabeltitz and Baudoin, 1999). The pump, fans and indirect heat exchanger were connected to SPV array system consisting of a 3 string-3 series 330W (SETSOLAR, PC 16-6015F) solar modules with 44.80 V rated voltage and 8.69 A current, solar charge controller (SANTAKUPS PC16-6015F) of ratings 60 A and 145 VDC, inverter (5 kW (60A), P11-LW5000NC48-C), twelve 230 AH battery recharged.

4.2.7 Harvesting of Tomatoes and Cooling Times

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 31.5°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 (Getinet *et al.,* 2011). The selected tomatoes were packed and kept in crates under ambient conditions until the start of the experiment on the same day at 14h00 (ambient temperature of 31°C). The half-cooling time and seven-eighths cooling time were used for the determination of cooling time of tomatoes from the field temperature to the optimum storage temperature as in Equation 4.1 to 4.4. The seven-eighths cooling time is more practical as the temperature of the produce at seven-eighths is close enough to the target storage temperature according to Brosnan and Sun (2001).

$$Z = ln\left(\frac{0.5}{C}\right) \tag{4.1}$$

$$S = \ln\left(\frac{8j}{C}\right) \tag{4.2}$$

Where Z = half cooling time [hours]; S = seven eighths cooling time [hours],

C = cooling coefficient [dimensionless], and J = lag factor [dimensionless],

(Brosnan and Sun, 2001).

$$C = \ln\left(\frac{Y}{\theta}\right) \tag{4.3}$$

$$Y = \frac{T - T_m}{T_i - T_m} \tag{4.4}$$

Where Y = temperature ratio [℃]; T = temperature at any point in the product [℃];

T_m = temperature of cooling medium (air) [℃]; T_i = initial temperature [℃] and

C = cooling time or operating time [hours] (Brosnan and Sun, 2001).

At the start of the experiment, the crated 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.* (2015). The tomatoes were then kept under ambient conditions and cooling environment.

4.2.8 Temperature and Relative Humidity Measurements

The procedure by Ho *et al*. (2010) and Akdemir *et al*. (2013) was followed to select nine positions (Figure 4.3) including centre and boundary environmental conditions of temperature and RH in the storage chamber to determine the performance of the IAC+EC system. The boundary conditions were:

- Temperature and RH at inlet and exhaust ends of the storage chamber.
- Temperature and RH on the ground floor and ceiling of the storage chamber:
- Temperature and RH on the surface of left and right walls of the storage chamber.

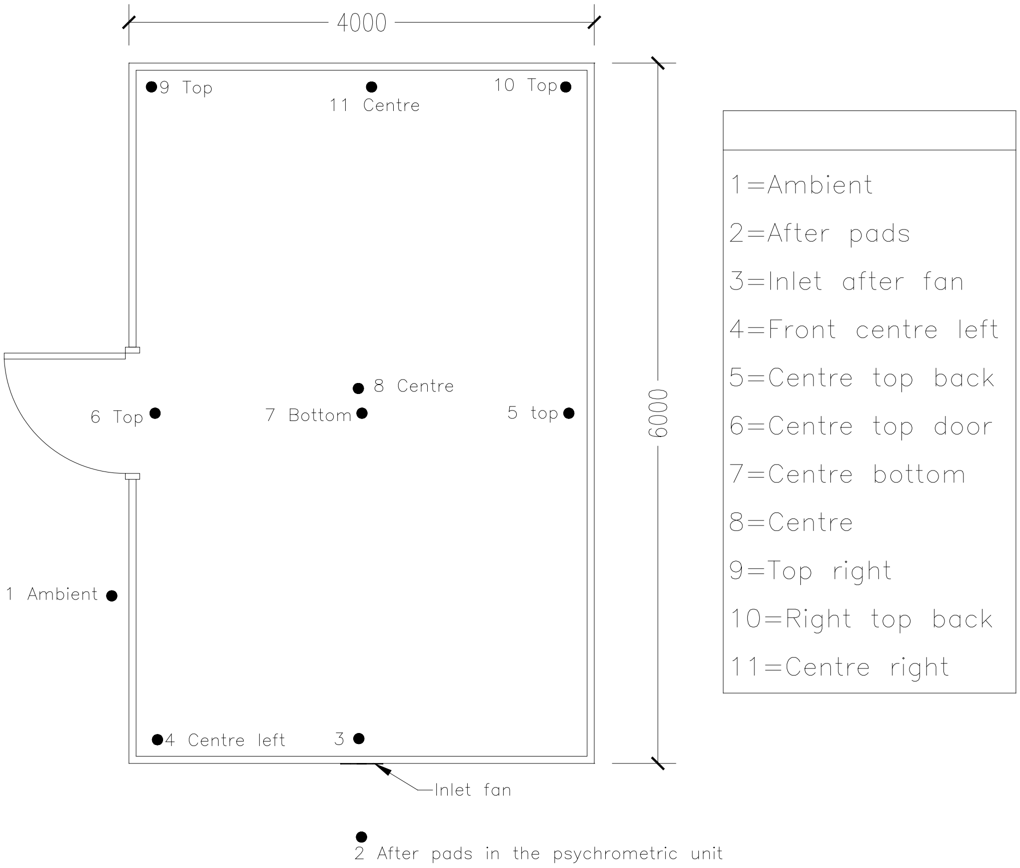

Figure 4.3 Position of the data loggers

Digital HOBOs (HOBO Prov2 Part No. U23-001) were located in nine different positions in the storage chamber capturing the different cooler environments as shown in Figure 4.3. One

HOBO was located inside the psychrometric unit after the last cooling pad to capture the condition of the air going into the storage chamber. Another HOBO captured the ambient conditions.

The digital HOBOs measured air temperature and RH at different positions in the storage stage, after the cooling pads in psychrometric unit of air supplied to the storage chamber and ambient conditions. The door of the storage chamber was closed and readings recorded hourly throughout the day from day0 to day 28 i.e. from 25 August 2017 to 22 September 2017. The average psychrometric unit, storage chamber and ambient temperature and RH were calculated from the 28 days' data separately for each time. Ambient air temperature data was obtained from ARC-SAWS weather station located within Ukulinga research station. The air velocity measurements were taken inside the psychrometric unit, at the inlet to the storage chamber and along the same symmetry line in equal distances at the centre, exit side of the storage and were recorded every hour using an anemometer (Lutran 4201) for one day from 08h00 to 16h00. Experiments were carried out throughout the period with the daytime powered by the solar array and the nighttime by the batteries. Days where the maximum temperature was above 26℃ were isolated for analysis.

4.2.9 Cooling Efficiency

The cooling efficiency (η) 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 Equation 4.5 (Olosunde *et al*., 2016). The cooling efficiency (η) equation is a widely used index for evaluating the performance of direct EC media (Xuan *et al.,* 2012). The cooling efficiency of the IAC+EC system indicates the extent to which the dry bulb temperature of the cooled air approaches the wet bulb temperature of the ambient air as calculated using Equation 4.5 (ASHRAE Handbook, 2004; Lertsatitthanakorn *et al.,* 2006; Olosunde *et al.,* 2016).

$$\eta = 100 \times \frac{T_{da} - T_{dc}}{T_{da} - T_{wa}} \tag{4.5}$$

Where η = cooling efficiency of EC unit (%);

T_{da} = dry bulb temperature of ambient air entering the cooling unit (°C);

T_{dc} = dry bulb temperature of cooled air-cooling leaving unit (°C) and

T_{wa} = wet bulb temperature of ambient air entering the cooling unit (°C).

4.2.10 Data Collection

The experiment consisted of two cooling approaches, IAC+EC and the control, which was ambient conditions. A comparison of storage and outside temperatures and RH was done. The experimental data collection involved the hourly measurement throughout the day of environmental parameters of temperature and RH for the 28 days of the experiment. However, data for 11 hot days with temperature above 26℃ were selected and used for analysis. In the selected 11 days there was a significant temperature and relative humidity gradient between ambient and cold storage conditions that would affect the metabolism rate between the two storage conditions. Of the selected days, data collated between 05h00 to 22h00 of each day was used for analysis. From 22h00 to 05h00, the average ambient temperatures in PMB is below 20℃ and the IAC+EC system was switch off during this period as tomatoes can tolerate temperatures between 13-21 ℃. The data obtained at the centre inlet, centre of the storage chamber and the centre of wall on the exhaust side was used for analysis and discussions. The experiment was mainly concerned with evaluating the cooling performance, in terms of the temperature reduction, RH change and efficiency of cooling of the two cooling approaches. 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.

4.3 Results and Discussions

4.3.1 Cooling Time of Tomatoes Loaded at Ambient Temperature

According to Thompson et *al*. (2001), cooling of tomatoes should take place within 16 hours otherwise, a marked deterioration in quality occurs after this period. The IAC+EC system for this study used a hybrid of solar module and a battery bank facility to provide energy for the water pump, heat exchanger and fans. The battery bank facility provided energy for five hours after the sunshine period as it takes some time for the ambient air temperature to decrease substantially after sunset. As a result, the cooler was switched off 5-hours into the night time to allow the ambient temperature to cool down to 20°C and below.

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 4.1 to 4.4 were used with the following assumptions made that $\theta = 16$ hours; $T = 15$°C; $T_m = 14$°C; $T_i = 32$°C; 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 in Figure 4.4, which shows the cooling time graph for tomatoes harvested at an ambient air temperature of 32°C. From Figure 4.4, it took 33 hours for tomatoes to cool from 32°C to 13°C, which is the lowest optimum storage condition. This provided a temperature gradient of 19°C.

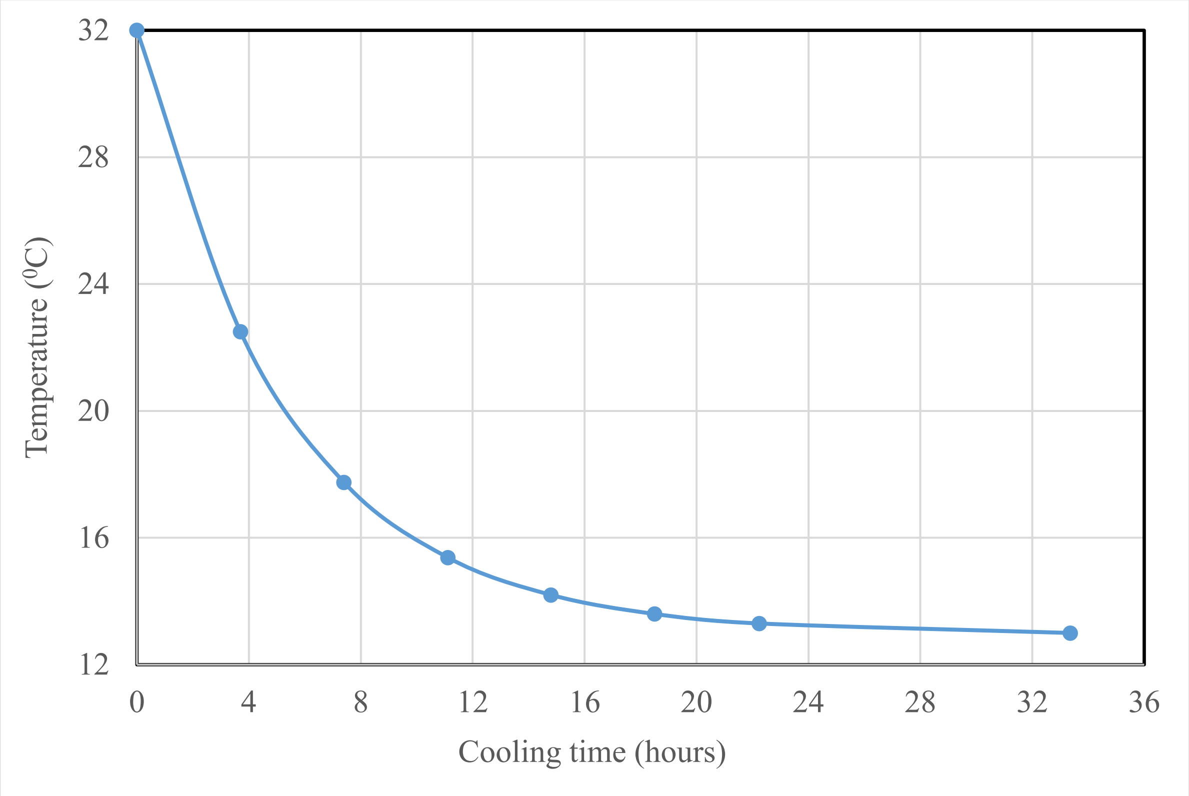

Figure 4.4 Cooling time graph for harvested tomatoes in the IAC+EC storage chamber at Ukulinga Research Station in Pietermaritzburg.

On the first day the freshly harvested tomatoes are placed in the storage chamber and within 16 hours, the fruit flesh temperature drops from 32℃ to 14℃, which is within the optimum storage for tomatoes of 13℃. In the next 16 hours temperature dropped by a further 1℃. The initial tomato temperature dropped rapidly especially for the first four hours of cooling and slowed down as the product temperature approached the target optimum recommended temperature. This is in line with observation by Thompson *et al*. (1998) that the rate of heat removed from fresh produce like tomatoes is directly influenced by 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℃ to 14℃ within 16 hours and to 13℃ on the next day within the next sixteen hours after which the next batch can be placed. This means that IAC+EC is a viable cooling facility option for the immediate reduction of flesh temperature of harvested fresh produce for SSF in SSA. In the calculations the seven-eighths cooling time gave more practical values as the temperature of the tomatoes at seven-eighths was close enough to the target storage temperature as corroborated by Brosnan and Sun (2001).

4.3.2 Variation of Temperature

Temperature inside the psychometric unit and storage chamber were studied on eleven clear, sunny days during the period end-August to end-September 2017 where the maximum temperature was above 26°C. Temperature is one of the most important factors that needing management at optimum conditions in the storage life of fresh produce like tomatoes (Arah *et al.,* 2015; Seweh *et al,* 2016). Temperature was recorded from eleven positions as shown in Figure 4.5.

The initial results and discussions consider all the nine positions in the chamber but there is then a special focus on environmental conditions pertaining to the inlet to the chamber, centre of the chamber and the centre of the exhaust end. Figure 4.5 provides information on the average temperature recorded over the eleven days from the eleven data logger positions that includes ambient obtained from SAWS station (D-1), one psychometrics unit position after the last cooling pad (D-2) and nine storage positions (D-3 to D-11). There was a significant variation (P<0.001) between ambient and the psychometrics unit position and the nine storage chamber temperatures. The ambient temperature was on average 10.5℃ and 9.5℃ higher than the last cooling pad temperature and the average storage temperature respectively. A significant temperature gradient between the storage temperature and ambient temperature provides 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 temperature. The lowest average temperature was obtained at the outlet of the psychometric unit (15.77°C), while the highest average temperature was observed at the left (16.92°C: D-9) and right side (16.93°C: D-10) of the roof at the exhaust end of the storage chamber.

Figure 4.5 Average temperature for the sensors over the 11 hottest days at Ukulinga Research Station in Pietermaritzburg.

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 was recorded near the inlet to the storage chamber (16.2°C) while the highest temperature was observed at the exhaust end (16.9°C). The significant differences in temperature in relation to the position of sensor in the storage chamber could influence the quality of F&V stored inside the IAC+EC storage chamber. Determining the ventilation rate to maintain a uniform air distribution throughout the storage chamber is important as it ensures that optimal storage environment is provided to maintain the physiological condition of fresh produce (Jradi and Riffat, 2014; Tolesa and Workneh, 2017). 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 F&V. The results show that IAC+EC under hot and sub-humid conditions of PMB can reduce the temperature to the same extend as EC alone in hot and arid conditions as evidenced by the work of Ndukwu *et al.* (2013). In their work at an ambient temperature of 32℃, the EC system provided the storage conditions of 19.2 ℃. Zakari *et al*. (2016) obtained similar results where temperature drop of up 10℃ was achieved when evaluating EC system of capacity of 0.6 m^3 under hot and dry conditions where they used jute bag as pad material.

Figure 4.6 depicts a similar scenario when observing the variation of average temperature per day in the 11 selected days for the four strategic data logger positions; in the psychometrics unit just after the last cooling pad and storage chamber (at inlet, centre and exhaust end). The cold air coming from the last cooling pad in the psychrometric unit was forced into the chamber by the ventilating fan at the entrance to the chamber.

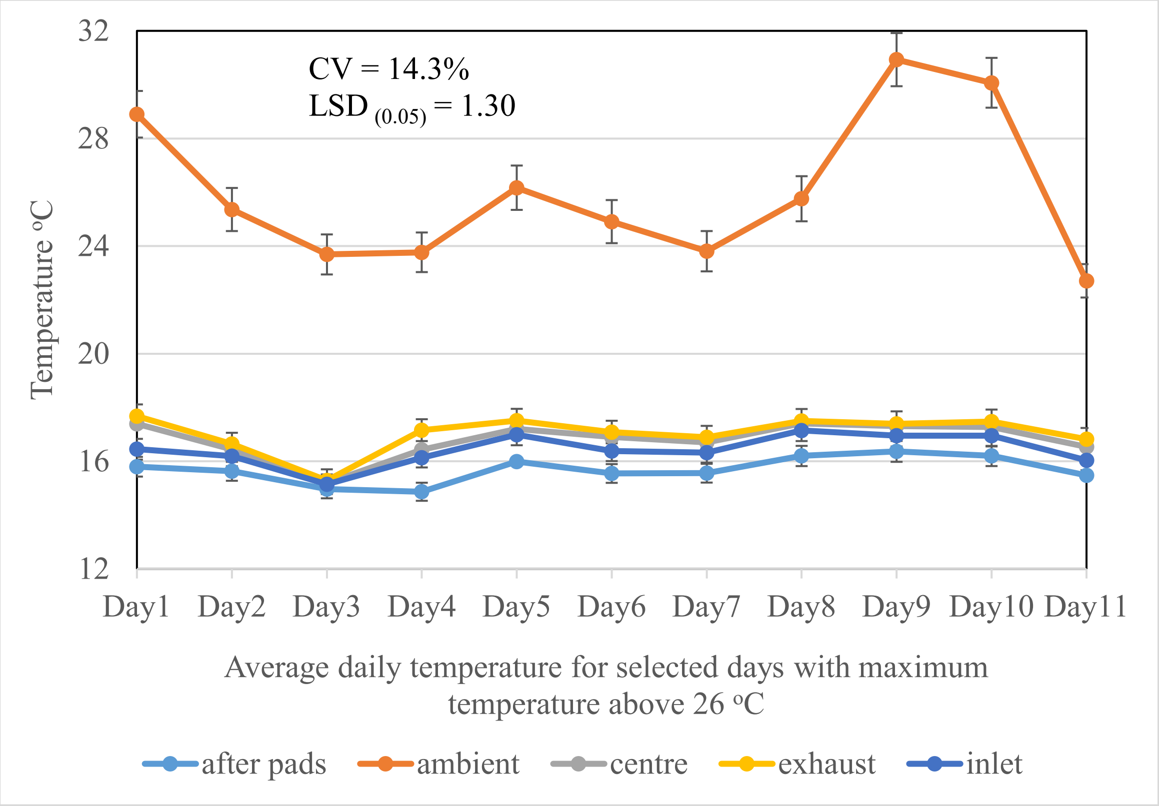

Figure 4.6 Average temperature per day over the 11 hot days at Ukulinga research station in Pietermaritzburg.

A 1°C temperature rise was observed 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 tomato fruit. 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 provides 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 3 825 kg. It is possible that the temperature at the exhaust end can be high when the storage chamber is filled to capacity as the air picks heat from stored produce.

Figure 4.7 shows the hourly characteristics of ambient air and exit to the psychometric unit, cooler air at the inlet, centre and exhaust positions of the cooler.

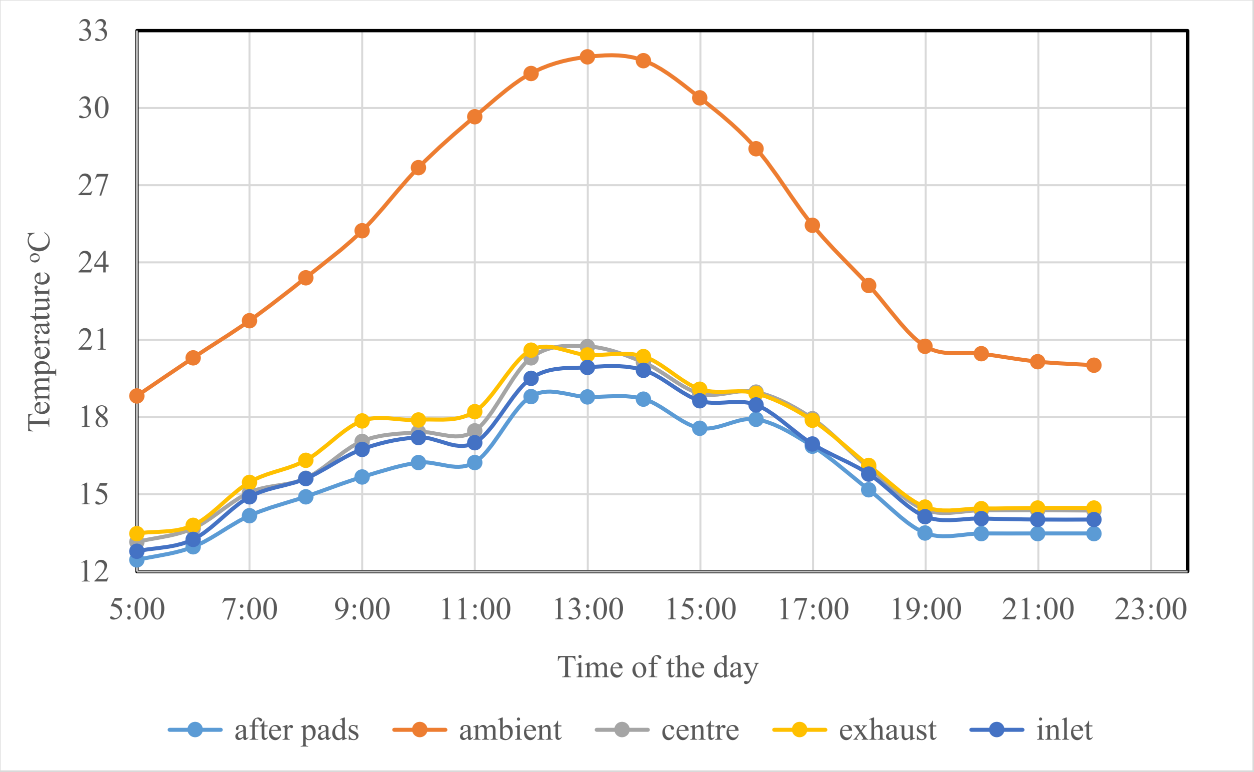

Figure 4.7 The effect of IAC+EC on temperature during daytime at Ukulinga research station in Pietermaritzburg.

The temperature gradient between the ambient and at inlet to the storage chamber (D3) from 10h00 and 16h00, the hottest part of the day, was 10 - 12°C, which is comparable to the results obtained by Ndukwu *et al*. (2013) of gradients of up to 13℃ during the same period of the day. It was observed that psychometric unit, storage chamber and the ambient temperatures increased from 05h00 until between 13h00 to 14h00 and thereafter starting decreasing to about 26℃ at 17h00. The temperature decreased due to increasing incident solar radiation from morning until afternoon 13h00-14h00 and then decreasing from then onwards towards evening and sunset as also confirmed by Madhava *et al*. (2017). The period from 05h00 to 17h00-18h00 is the time during which cooling is important for F&V to reduce physiological activities and to maintain freshness (Getinet *et al.,* 2008). This implies that the EC technology in general and 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 maximum temperature gradient between the storage chamber and ambient was found between 09h00 and 17h00 and this is the period that cooling for fresh produce is required. Anyanwu (2004) and Tolesa and Workneh (2017) made similar observations.

The ambient temperature flattened out from 19h00 and reached 20℃ 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℃. Such an approach will reduce the number of solar panels and batteries required to power the IAC+EC systems and thus will in turn reduce the capital investment in the facility and encourage a lot of SSF to venture into the lucrative fresh produce market.

From the Figure 3.4 in section 3.3.2 at 13h00, the ambient air temperature could be significantly ($P<0.001$) dropped down by 11-13℃ by the effect of IAC+EC at the inlet, centre and exhaust positions of the cooler. The IAC+EC system maintained an average temperature between 16℃ and 21℃ during the hottest time of the day (11h00 am to 14h00) where ambient temperatures ranged from 29℃ and 32℃. The midday period is the critical time in which cooling of fresh produce is important to maintain quality (Tolesa and Workneh, 2017). Controlling temperature within optimum levels is necessary especially in the sub-tropical climate obtaining in most countries in East and Southern Africa characterized by high temperature, to reduce the rate of microbial changes and in turn activates enzymatic reactions in produce (Brosnan and Sun 2001). The average hourly ambient air temperature rose significantly from 18℃ at 05h00 to a maximum average of 30 ℃ and 32℃ between midday and 14h00 and dropped to 20℃ and below after 19h00 while the storage chamber conditions were maintained at 13 to 16℃ during the same period, which agrees with

Tolesa and Workneh (2017). The IAC+EC system achieved temperature of 13 to 16 ℃ and this agrees with that reported, by ASHRAE (1982) and Zakari *et al*. (2016) that obtained 13 to 21℃ and 13.75 to 14.75℃ respectively. This is moderately acceptable. However, the ambient temperature greater than 23℃ are well above that recommended by ASHRAE (1982) of 13 to 21℃ lead to deterioration and thereby reduce the shelf life of fresh F&V storage.

By design, cooling systems like EC significantly reduce ambient air temperature to a safe storage temperature range for tomatoes according Thompson *et al*. (1998). The temperature inside the storage chamber was lower than ambient at any period of the day while temperatures in the storage chamber varied in a narrow range. Therefore, the mean air properties of temperature in the evaporative cooler are more suitable for storage of tomatoes than the mean ambient air properties. It is critical that there is no deviation in provision of optimum storage temperature either too low or too high as such conditions can result in either chilling injury or physiological disorders for fresh produce stored in cold storage (de Castro *et al* 2005; El-Refaie and Kaseb, 2009; Rajan and Anandan, 2018).

Thus, it is clear that the IAC+EC is able to reduce temperature to appropriate storage level for a number of tropical and sub-tropical F&V and therefore such facilities need to be installed for SSF throughout the humid and sub-humid tropical regions in order to promote F&V production. EC would be used to solve the problem associated with cooling F&V.

4.3.3 Variation of Relative Humidity

RH of the IAC+EC system were studied on eleven clear, sunny days where the maximum temperature was above 26℃. RH was recorded from eleven positions as shown in Figure 4.8. The initial results and discussions consider all the nine positions in the chamber but there is then a special focus on environmental conditions pertaining to the inlet to the storage chamber, centre of the chamber and the centre of the exhaust end.

Figure 4.8 shows that there was a significant variation ($P<0.001$) in ambient, exit point of the psychrometric unit and the storage chamber RH at various positions at entrance, centre and exhaust. The highest average RH was obtained at the outlet of the psychometric unit (D-2), the lowest average RH was at the ambient (D-1) and inside the storage chamber the lowest average RH was at the exhaust end (D-10). The average ambient RH was 65.37%.

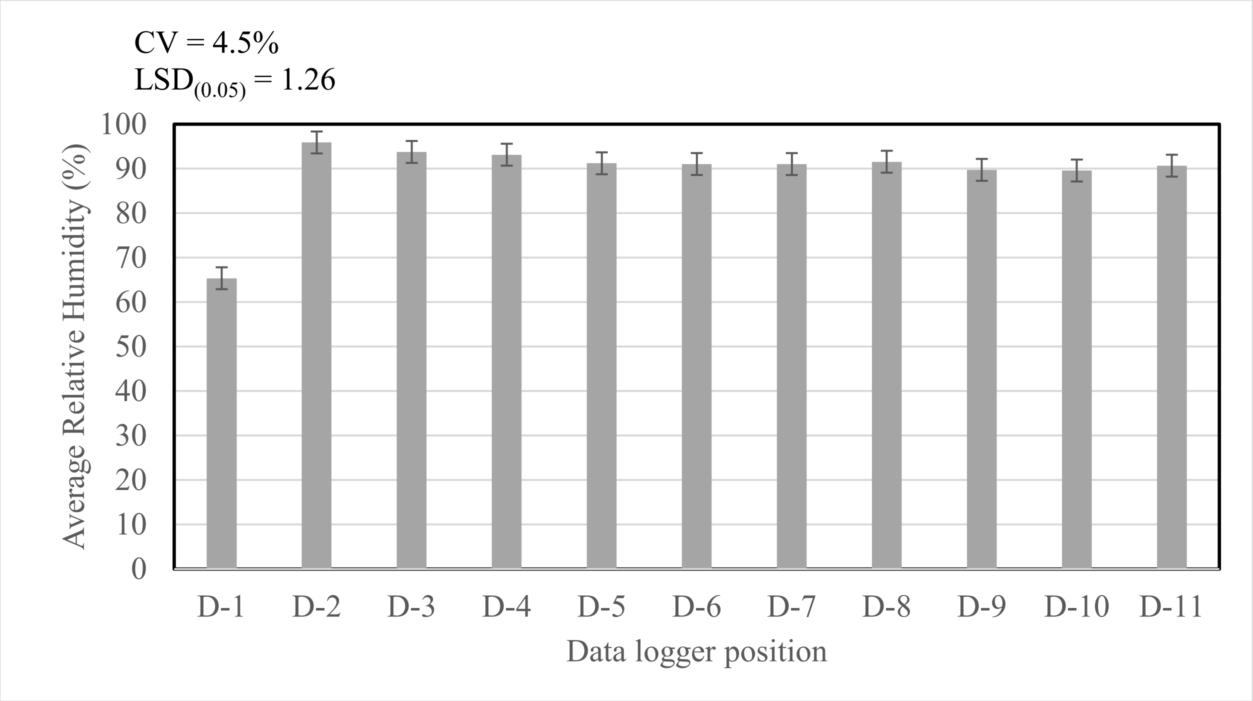

Figure 4.8 Variation of relative humidity in the IAC+EC unit and storage chamber at Ukulinga research station in Pietermaritzburg

It was also observed that 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% was recorded near the inlet to the chamber while the lowest RH inside the storage chamber was observed at the exhaust end. The RH in the storage chamber ranged from 89.6% – 93.8%, which was the maximum possible level of saturation of air by humidification for IAC+EC as 100% RH is not achievable because 100% saturation is impossible as alluded to by Xuan *et al*. (2012) in a direct evaporative cooling experiment. 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 (Manuwa and Odey, 2012).

Figure 4.9 depicts a similar scenario when observing the variation of RH in the eleven selected days for the four strategic data logger positions; in the psychometrics unit just after the last cooling pad and storage chamber (at inlet, centre and exhaust end). The cold air coming from the last cooling pad, next to the storage chamber inlet, centre of the chamber and centre of the exhaust end. A two percent RH drop was recorded inside the storage chamber between the air entering the storage chamber and the RH 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.

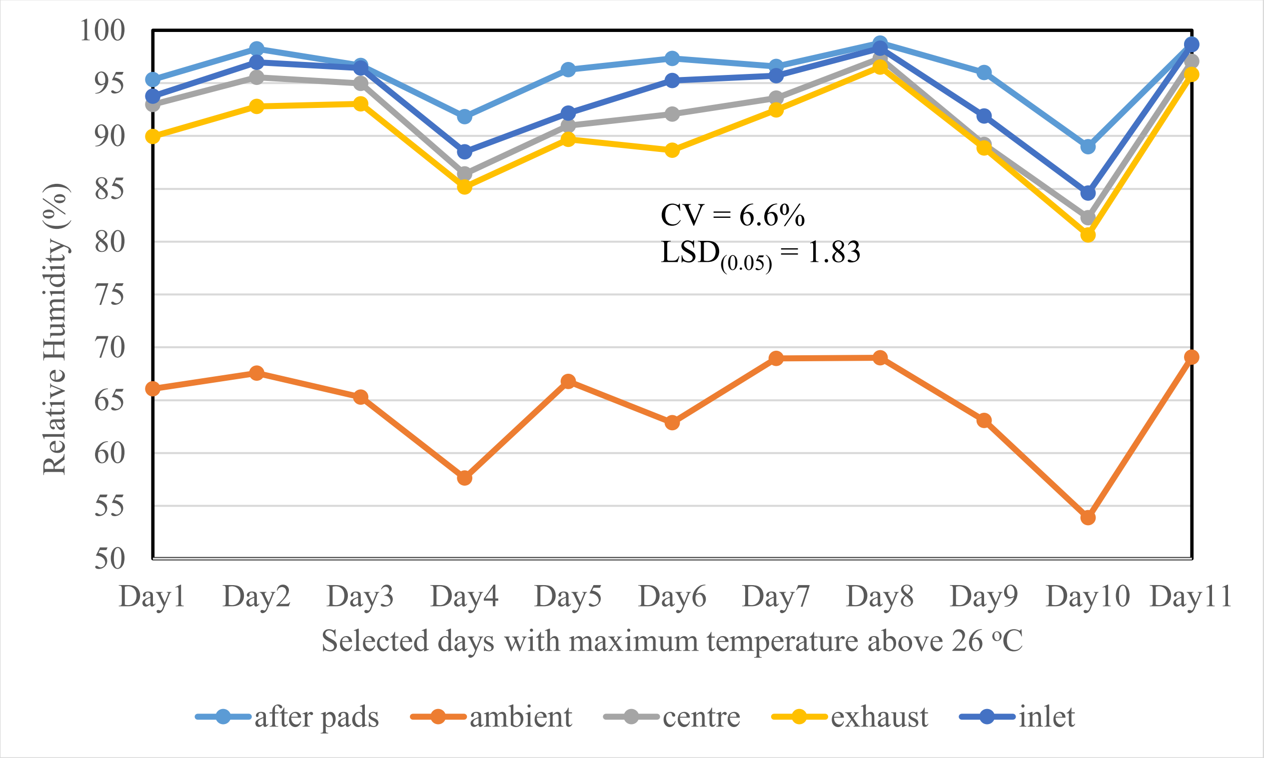

Figure 4.9 Average relative humidity per day over the 11 hot days at Ukulinga research station in Pietermaritzburg.

At the same time from Figure 4.10 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 increases after the psychometric unit into the inlet of the storage change resulted into 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 decreased with time of the day was found to be very low values 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 cooler. Madhava *et al*. (2017) had a similar observation in their study in evaluating the performance of a photovoltaic ventilated greenhouse. During the period after 14h00, the RH increased as the ambient and storage temperatures decreased.

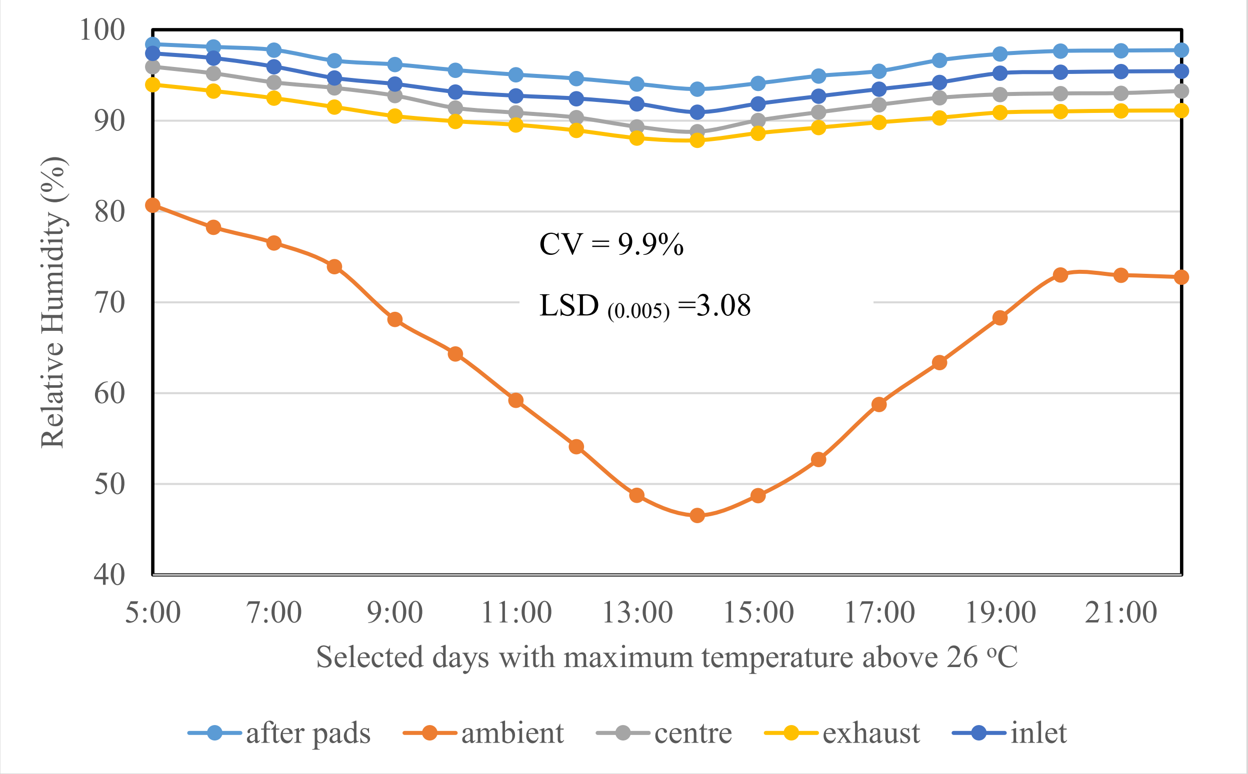

Figure 4.10 Average relative humidity per day over the 11 hot days at Ukulinga research station in Pietermaritzburg.

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 at any period of the day. The general low ambient RH results in faster removal moisture from the wet surface of the F&V (Awole *et al.,* 2011). This implies that during this period of the day, cooling of fresh produce under ambient RH conditions leads to physiological deterioration of 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 F&V.

The RH at entrance was always higher than the corresponding times at the centre and exhaust end. This was due to increasing temperatures 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 (Basediya *et al.,* 2013). The values of 85>RH<95 are ideally storage conditions for produce like avocados, bananas, cucumbers, mangoes, oranges, papaya, sweet potatoes and tomatoes (ASHRAE, 1982; Cantwell *et al*., 2009). The IAC+EC system increased ambient RH from 47% to 87 to 93%, which closely agrees with that reported by ASHRAE (1982) and Zakari *et al*. (2016) that obtained 75 to 88%. However, the result of average ambient RH ranging from 44 to 65% between 10h00 and 17h00 was below that recommended by ASHRAE (1982) and hence this will reduce the shelf life of fresh F&V 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 Kobiler *et al*. (2010) and Laguerre *et al*. (2013). 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 produces.

4.3.4 Cooling Efficiency

The period from 05h00 to 19h00 during the evaluation period was considered to determine cooling efficiency. The cooler efficiencies for 05h00 to 19h00 are shown in Table 4.1. From Table 4.1 the cooler efficiency ranged between 86.8% and 97%. Between 05h00 and 09h00, the efficiency was about 92-95% and was rising in the period achieving highest efficiencies between 09h00 to 14h00, then declining thereafter to 86.8% by 18h00, and started rising from there. The cooling curve efficiency shows that higher cooling efficiency obtains with higher temperature and lower RH of ambient air in the afternoon when the solar irradiation is highest. This is desirable state as the cooling load is highest at the time that the solar photovoltaic is providing the highest power as corroborated by Ndukwu *et al*. (2013). The decline in efficiency is linkable to the increase in ambient dry bulb temperature as the solar radiation increased during the day and the results are within the findings by the study of Seweh *et al*. (2016) 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 (Lertsatitthanakorn *et al*., 2006).

Table 4.1 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

The efficiency of the cooling for IAC+EC systems as shown in Table 4.1 indicates that the Psychrometric 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 evaporative cooling experiments done by Zakari *et al*. (2016) and Babaremu *et al*. (2018) who obtained efficiencies of 83% and 86% respectively. The results imply that the combination of the indirect heat exchanger for indirect air-cooling and the evaporative cooling produces reasonable reduction in ambient air temperature to a minimum temperature approaching ambient air wet bulb temperature. At these prevailing hot and sub-humid conditions, the cooler was able to preserve freshly harvested tomatoes for more than 21 days. 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 evaporative cooling under dry and hot conditions.

4.4 Conclusions

The lack of cooling facilities and knowledge by SSF in SSA postharvest handling of fresh produce results in a significant amount of harvested F&V decaying between the farmers' field and the market. To alleviate this challenge, a low-cost, IAC+EC storage system was developed for SSF in hot and sub-humid to humid areas. 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. EC offers an advantage over mechanical refrigerating systems, which decrease both temperature and RH at the same time with high-energy consumption while IAC+ EC decrease temperature by 7-16℃ and increased RH by 13-41% with a considerable low amount of energy. In addition, IAC+ EC is more suitable for storage of F&V that do not require very low temperature (below 12℃) . The storage chamber environmental conditions were hardly influenced by external solar radiation conditions whilst the ambient conditions were. The IAC+EC was able to maintain temperatures of 20℃ and below during the midday hours which is the hottest part of the day where cooling is required. The ambient air temperature increased from an average of 18.8 ℃ at 05h00 in response to increasing solar radiation and the peak of 32.0 ℃ coincided with peak solar radiation at mid-day (13h00). The temperature gradient ranged from

7℃ to 16℃ between the IAC+EC system and the ambient conditions. Low temperature inhibits ethylene production through reducing the enzymatic activities of the tomato fruit and thus prolonging the shelf life. Similarly, RH reduced with increasing solar radiation. The lowest RH levels were in the middle of the day, coinciding with peak solar radiation. The RH gradient ranged from 13% to 43% between the IAC+EC storage chamber and ambient conditions. The increase in the temperature and reduction in RH under ambient conditions increases the water holding capacity of the ambient air hence would increase moisture loss from fresh produce resulting in wilting and shriveling. It is therefore important to reduce temperature and increase RH from midday to late afternoon.

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 i.e. the moisture content of the air thus 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 RH in for the IAC+EC was within the recommended range of most tropical and sub-tropical F&V for the storage. The benefit of the indirect heat exchanger and multiple charcoal cooling pads in the reduction of temperature was exploited in helping to maintain the high RH.

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, it can be extended to sub-humid to humid conditions. These results clearly demonstrate that the IAC+EC system is useful in the study area of hot and sub-humid to humid climate for preservation of F&V, especially during the hottest time of the day when cooling is most needed. 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 tonnes and in this experiment, the structure is 53 m^3 with a 3.8 tonne carrying capacity of tomatoes. The results on IAC+EC system recommends and pave way for adaptation by SSF as the system's energy requirements were supplied by SPV systems thus availing a suitable cooling structure for farmers in isolated, dispersed and remote areas. It is expected that EC in general and IAC+EC in particular will provide relief to SSF in coastal areas that will emerge from the pending land re-distribution in South Africa as the current facilities and available grid electricity might not suffice curter for new needs.

The work presented in this chapter is important because there is a scarcity of quantitative characterization of the performance of low-cost IAC+EC technology for cooling the microenvironment in the storage in order to maintain the quality of fresh produce, which can be used by SSF, emerging farmers' and cooperatives. This work has also contributed to improving the understanding of the effect of low-cost IAC+EC technology in provision of a microenvironment for storage of F&V under hot and sub-humid to humid conditions in Southern Africa. This study characterised IAC+EC and clearly demonstrated that the cooling system could maintain the inside environmental conditions of air temperature and RH approximately constant and at recommended levels for tomatoes and most tropical and sub-tropical F&V. This work has therefore, contributed to improving the understanding of the effect of low-cost IAC+EC technology on temperature reduction and RH increase under hot and sub-humid to humid conditions in Southern Africa. IAC+EC is therefore, recommended for storage tropical and sub-tropical F&V as it can increase their shelf life.

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5 EFFECTS OF INDIRECT AIR COOLING COMBINED WITH DIRECT EVAPORATIVE COOLING ON THE QUALITY OF STORED TOMATO FRUIT

Abstract

Low-cost cooling systems either as direct evaporative cooling for dry and arid climates or combined indirect air cooling and evaporative cooling (IAC+EC) for hot and sub-humid to humid climates can provide an optimum storage environment in small-scale farming. A 53 m^3 solar powered evaporative cooler for temporary storage of tomato fruit was developed to improve the shelf life of tomatoes for small-scale farmers (SSF) in Southern Africa by reducing indoor temperature and increasing RH. This study aimed at investigating the effect of IAC+EC, maturity stage at harvesting and period of storage on the quality of tomatoes. The effect of these factors on total soluble solids (TTS), tomato firmness, colour, physiological weight loss (PWL) and marketability of tomatoes (*star 9037*) was investigated by monitoring the storage of green and pink maturity stage harvested fruit over 28 days under both IAC+EC and ambient conditions with data collated every seven days. Storage condition, maturity stage at harvesting and the storage period had significant effect (<0.001) on the overall quality of tomatoes. The tomatoes stored in the IAC+EC system were 18.9% firmer, maintained 10.5% lower concentration of sugars, increased the hue angle by 3%, had 6.31% lower PWL and were 24.8% more marketability than tomatoes stored under ambient conditions. The tomatoes harvested at the green stage were 20.2% firmer, had 6.6% lower TSS content, increased the hue angle by 4.9%, had a 3.1% lower PWL and were 11.6% more marketable than the pink harvested tomatoes. As the period of storage of tomatoes increased from zero to 28 days' firmness decreased from 11.2 N to 4.3 N, TSS content increased from 4.0 to 4.7%, the hue angle decreased by 27.2%, PWL increased from zero to 10.4% and marketability decreased to 29.5%. The testing of the IAC+EC shows that the fresh tomato fruit can be stored under hot and sub-humid environment for an average of 21 days with negligible changes in weight, color, firmness and rotting as compared to ambient condition. SSF and farmers that will emerge from land re-distribution in South Africa can adopt the use IAC+EC system for the storage of fresh tomatoes as this increases the shelf life of tomatoes.

5.1 Introduction

Tomato is a widely consumed vegetable in the world with a global annual production estimated at 1.60 million metric tonnes (Tigist *et al.,* 2011; Bergougnox, 2014). In South Africa, the tomato is the second most important vegetable after potatoes grown by both small and large-scale farmers with a gross income of over USD 210 million (Directorate Marketing 2013; FAOSTAT 2014). Limpopo province grows 75% of the total production (DAFF, 2014a, b; Sibomana *et al.,* 2016).

Tomato fruit is climacteric with a short shelf life of 2 to 3 weeks and exhibits high postharvest losses (PHL) of 20-50% and requires immediate cooling after harvesting to slow the ripening process and maintain quality (FAOSTAT 2014; Affognon *et al.,* 2015; Wang *et al,* 2016; Macheka *et al.,* 2017; Saltveit, 2018). Hence, the selection of the tomato as experimental fruit for this study. A reduction in PHL is crucial for increasing market participation, improving the welfare of tomato growers and increasing food availability (DAFF, 2013; Adepoju, 2014; Sibomana *et al.,* 2016). Appropriate postharvest technologies for fresh tomato fruit that provide optimum conditions of low temperature of 10 ℃ to 15℃ and high relative humidity (RH) of 85-95% from the time of harvesting, storage and transportation to the market are indispensable (Tshiala and Olwoch, 2012; Ait-Oubahou, 2013; Chijioke, 2017; Babaremu *et al.,* 2018).

The quality of fresh tomatoes is determined by considering parameters classified into physical, chemical, biochemical and sensory properties (Garg and Cheema, 2011; Baldwin *et al.,* 2015). The physical properties are firmness (Pinheiro *et al.,* 2013; Vinha *et al.,* 2013; Thipe, 2014), skin colour (Gonçalves *et al.,* 2007) and physiological moisture loss (Shahnawaz *et al.,* 2012). The main chemical properties are total soluble solids (Beckles, 2012), citric acid and pH (Babitha and Kiranmayi, 2010). The sensory properties of tomatoes include flavour and marketability (Beckles, 2012; Haile, 2018). The balance of sugar content and acidity influences the flavour of tomatoes (Garcia and Barrett, 2006). TSS are a measure for tomato quality (Anthon *et al.,* 2011). The TSS is a refractometric index that indicates the percentage proportion of dissolved solids in a solution expressed as °Brix (Abd Allah *et al.,* 2011; Anthon *et al.,* 2011; Saad *et al*., 2016). TSS (°Brix) are one of physical and chemical parameters used as an index of determining tomato ripening. The colour of the tomato is the first external characteristic that determines both consumer acceptance and ripeness (Goncalves *et al.,* 2007; Pinheiro *et al.,* 2015). The determination of skin colour of produce assists in determining the maturity stage of produce immediately after harvest.

Modern day cooling systems like mechanical refrigeration, hydro-cooling and vacuum cooling delay or halt the deterioration in F&V qualities of colour, firmness, soluble sugar content and pH (Brosnan and Sun, 2001; Wang and Sun, 2001; Zheng and Sun, 2006; James *et al.,* 2009). However, modern cooling technologies require high throughput operations and besides have high installation and maintenance costs and high energy input normally from the grid which SSF in most remote areas in SSA have no access to (Cecelski, 2000; Kim and Ferreira, 2008; Ejeta, 2009; Katundu *et al.,* 2010; Rayaguru *et al.,* 2010; Ndukwu and Manuwa, 2014; Wills and Golding, 2016).

Evaporative cooling (EC) has a potential of adoption by SSF because of low, initial investment requirements, installation and maintenance costs, and energy requirements (Kitinoja and Thompson, 2010; Tigist *et al.,* 2011; Fernandes *et al.,* 2018). Most of the research in EC in the developed countries has focused on cooling buildings as opposed to cooling fresh agricultural produce (Ndukwu *et al.,* 2013; Deoraj *et al.,* 2015). The evaporative cooling systems studied so far in sub-Saharan Africa (SSA) for preservation of F&V are prototypes with low storage capacity. A lot of this work has been having been limited to west and east Africa; the technology might not perform accordingly if extended southern Africa as alluded by Thipe *et al*. (2017). EC works best in hot and dry conditions as it relies on removal of sensible heat and for it to be extended to hot and humid regions will require that the air be indirectly cooled by incorporation of desiccation medium before evaporative cooling (Misra and Ghosh, 2018). Use of indirect air-cooling combined with evaporative cooling (IAC+EC) in for provision of cool environment for storage of fresh produce is undocumented and a new research focus (Manaf *et al*., 2018).

Use of IAC+EC would require an indirect heat exchanger, water pump for water circulation, fans to blow the ambient air into the system and this requires energy that can be supplied by solar (Ndukwu *et al.,* 2013; Rahiel *et al.,* 2018). An investigation into the efficacy of IAC+EC on the ability to maintain quality or extend shelf life of tomatoes is required as recommended by Ogbuagu *et al*. (2017). The performance of the IAC+EC is putting to test the recommendations of Amer *et al*. (2015); Deoraj *et al*. (2015); Ogbuagu *et al*. (2017) and Misra and Ghosh (2018) who realised the potential of the system. This study seeks to provide performance data on the efficacy of solar-powered IAC+EC for preservation of F&V quality under hot and humid conditions. Therefore, the objective of this study was to determine the quality and shelf life extension of tomatoes through evaluation of changes in physical, chemical changes and sensory qualities of tomato variety harvested at two maturity stages and stored under a IAC+EC and ambient conditions.

5.2 Materials and Methods

5.2.1 Design Information and Specifications

The design of the IAC+EC provided the optimum storage temperature and RH for the tomato fruit for KwaZulu Natal province. Ambient air conditions limited the lowest temperature attained in the IAC+EC as it can only cool to the wet bulb temperature of the ambient air temperature (ASHRAE Handbook, 2004). The IAC+EC had to be able to maintain the temperature inside the storage chamber at the wet bulb temperature of the prevailing ambient air conditions and maintain the RH in the storage chamber at 80 - 95%.

5.2.2 Description of IAC+EC system

The IAC+EC consisted of a storage chamber, indirect heat exchanger, multiple charcoal cooling pads, buried water tank, a pump and two fans and Figure 5.1 shows a schematic diagram of the system. The evaporative cooler storage chamber had white double-jacket walls and roof of 1 mm zintec (mild steel) on the outside and on the inside and a floor of concrete mortar. The inner dimensions of the unit were 2 340 mm high x 5 880 mm long x 3 880 mm wide to hold a capacity of 3.8 tonnes. The cooler had a 60mm zinc wall thickness with 58 mm polyurethane insulation in between the zintec layers. The door for access into the storage chamber was made of the same material as the rest of the storage chamber. It had the same height as the storage chamber with a thickness of 900 mm and thickness of 60 mm. The indirect heat exchanger was included for sensible cooling of the air before coming into contact with water as it passes through the pads for adiabatic cooling. The material selected for cooling pad was charcoal and the pads were vertically mounted. Six exhaust vents opposite the inlet, three at the bottom and three at the top, provided for air outlet from the system into the atmosphere. The water continuously pumped from an underground storage using a 0.26 kW Pedrollo PVm 55 centrifugal pump placed at the surface. The water circulated throughout the cooling system (through the heat exchanger and sprinkled water on the EC pads) and a return valve released it back to the storage tank.

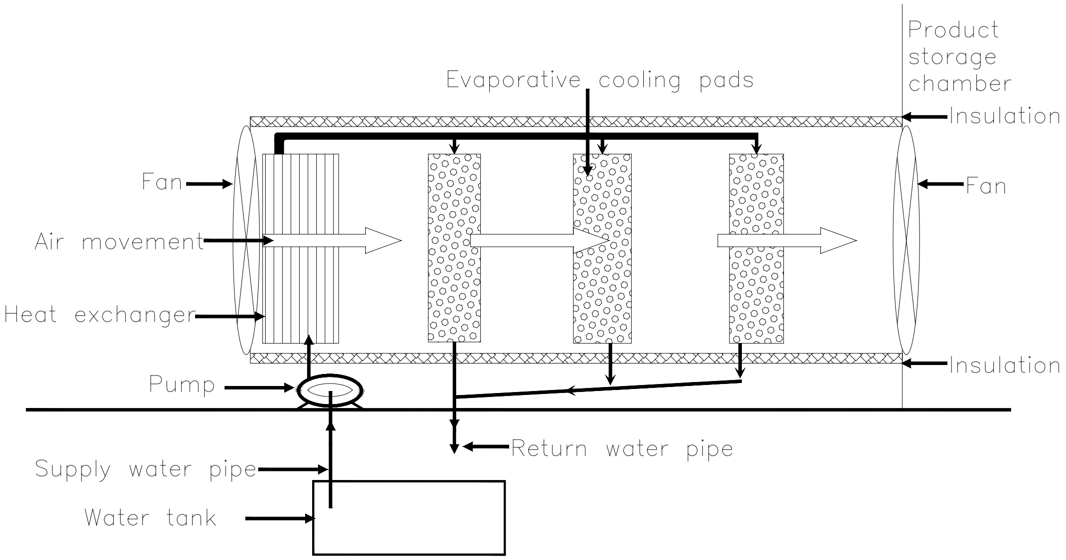

Figure 5.1 Schematic diagram of the evaporative cooling unit

A 0.29 kW (308,7/6-6/P3HL/25/PA) drove air into the storage chamber at an airflow rate of 0,278 $m^3. s^{-1}$ and air velocity of 3.6 $m. s^{-1}$. Connected to a SPV system consisting of a 145 VDC (60 A) charge controller, 5 kW (60 A) inverter, 12 x 230 AH batteries recharged by 9 x 330 W solar panels were water pump, fans and 1,8 kW indirect heat exchanger.

5.2.3 Performance Assessment

Evaluation of the cooler performance through determination of physical and chemical properties and marketability of the tomatoes in storage over a 28-day period was undertaken. The warm and dry season is the period when cooling intervention are most useful and experiments were therefore done during this time. For the fullest advantage of harnessing the IAC+EC effect, the cooler was located in an area with good ventilation. The experimental procedures focused on the IAC+EC performance within 7 days' cycle period over a 28-days duration. Investigations of patterns of tomato quality changes in both the storage chamber and under ambient conditions were undertaken. The shelf lives and quality attributes of the tomato fruit i.e. firmness; physiological weight loss and colour were evaluated between the fruit stored in the IAC+EC storage chamber against ambient conditions.

5.2.4 Sample Preparation

Tomato Star 9037 cultivar was harvested into plastic crates at physiologically matured and ripen stage with half at green and the other at pink mature stage from a nearby farm in PMB. Harvesting of the tomatoes was done early in morning before 10h00 and the tomatoes were immediately loaded in a vehicle and transported to Ukulinga research station located 31 km away (29.67° S and 30.40° E, at an altitude of 721). The tomatoes were visual inspected to discard those with bruises and signs of infection from the fruit used as samples (Getinet *et al.,* 2011; Saad *et al*., 2016). Selection of tomatoes which were uniform, unblemished, having similar size and colour was done and these were washed under a running tap to remove any dirt or soil particles and to reduce microbial population on the surface (Nath *et al.,* 2012). After washing, the tomatoes were surface dried with a soft clean cloth, which was free from contaminating materials and then the fruit was subdivided into plastic crates. The crates were then stored under room temperature in food processing laboratory and under IAC+EC conditions in the storage chamber in three replications. The crates were stacked on a 200 mm stand to prevent any transfer of desease from the ground to the tomatoes (FAO, 2011). A sample from each treatment and replication was analyzed periodical for physical and chemical properties, and sensory qualities as summarized in the Table 5.1.

Table 5.1 Summarised produce quality attributes that were measured

Quality attributes		**Reference**
Physical properties	Texture or firmness	Kassim *et al.* (2013)
	Colour	Batu, 2004; Kassim *et al.* (2013)
Chemical properties	Physiological weight loss	Workneh *et al.* (2009); Kassim (2013)
	Total soluble solids	Beckles (2012)
Sensory qualities	Percentage marketability	Nath *et al.* (2012)

5.2.5 Research Methodology

The experimental design used in the study consisted of a factorial combination of one tomato variety, two storage conditions (IAC+EC storage chamber and ambient), two maturity stages at harvesting (green-breaker stage and pink). Figure 5.2 shows the experimental design. Each storage condition-maturity stage was replicated three times (three crates). In each replica, 25 tomatoes were marked and five were selected for physical and chemical measurements over five-storage periods of day0, day7, day14, day21 and day28.

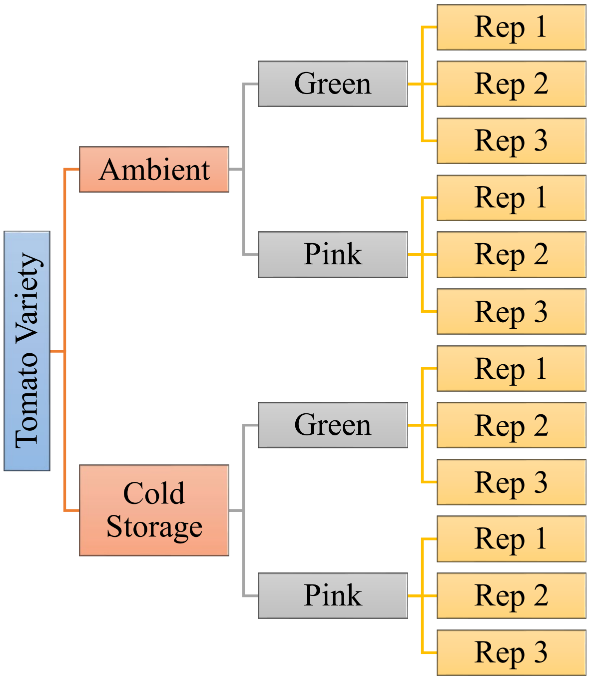

Figure 5.2 Experimental design

A total of 150 kg (12.5 kg of tomatoes per crate x 12 crates) of tomatoes were prepared for storage under IAC combined three-layer charcoal granules pads EC conditions and ambient conditions. The 150 kg tomatoes consisted of 75 kg of pink colour stage and 75 kg green colour stage harvested fruits. Each one of the two-maturity stage harvested tomatoes of 75 kg were subdivided into two lots of 37.5 kg (12.5 kg of three replications of each storage condition and maturity stage at harvesting) in preparation for storage IAC+EC and ambient conditions. Assessment of five sampled tomatoes for quality attributes of physical properties (firmness and colour), chemical properties (physiological weight loss and TSS) and marketability on days 0, 7, 14, 21 and 28 of storage was undertaken.

5.2.6 Physical Properties

5.2.6.1 Firmness (Puncture force)

In fruit and vegetables, firmness can be defined as the resistance to puncture, which is a mechanical property of the fruit according to Singh and Reddy (2006). The texture characteristics of tomato fruit in terms of firmness was determined through puncturing the surface using an Instron Universal Testing Machine (Model 3345) in combination with the Instron Bluehill 2 Version 2.25 software as described by Sirisomboon *et al*. (2012). A probe of diameter 2 mm punched tomatoes mounted horizontal on a curved platform (to ensure stability during the compression test). The probe attached to a load cell drove into the tomato at a crosshead speed of 3 $mm.s^{-1}$ to travel to a depth of 7.5 mm according to the procedure used by Tolesa and Workneh (2017). The maximum force required to puncture the fruit is the exterior fruit firmness as described by Aguilar-Mendez *et al*. (2008).

5.2.6.2 Colour

Changes in colour are a criterion for quality determination and are associated with chlorophyll degradation and biosynthesis of lycopene (Nino-Medina *et al.,* 2013). The tomato colour indicators were determined, using a digital CR-400 Chroma meter during the storage period. The CR-400 and estimated Hunter value L, a and b where according to Nath *et al*. (2012), ‘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. Each sampled tomato was measured for L*, a* and b* at three equatorial positions (blossom end, stem-end and mid-way), which were averaged to determine the overall values for L*, a* and b* using the procedure by Cherono *et al*. (2018). The changes in the colour of tomatoes were measured in terms of the L* value and the hue angle (h°), as these are important quality parameters used as a measure for market value of produce. Using a* and b*, the hue angle (h^o) for each tomato fruit was calculated from the equation (Saad *et al*., 2016)

$$Hue\ angle = tan^{-1}\left(\frac{b}{a}\right) \qquad (5.2)$$

5.2.7 Chemical Properties

5.2.7.1 Physiological weight loss

PWL is one method amongst others that determines the quality of stored tomatoes (Islam and Morimoto, 2016). Weighed five samples of the stored tomatoes from each treatment using a scale (Teraoka, DIGI SM 300) at the start of the experiment and on seven-day intervals at days 7, 14, 21 and 28. PWL was calculated as cumulative percentage weight loss based on the initial tomato sample weight (before storage) and loss in weight recorded at the time of sampling at 7, 14, 21 and 28 days during storage (Nath *et al.,* 2012; Caron *et al.,* 2013). The following formula used by Islam and Morimoto (2016) computed the percentage differential weight loss for each sample per each interval as percentage weight loss of the initial weight.

$$\%\text{Weight loss} = \frac{\text{Weight}_{(t=0)} - \text{Weight}_{(t=t)}}{\text{Weight}_{(t=0)}} \text{x}100 \qquad (5.3)$$

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

The percentage cumulative weight loss was determined by summing the respective physiological weight losses (Getinet *et al.,* 2008; Awole *et al.,* 2011).

5.2.7.2 Total Soluble Solids

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 (Ross *et al.,* 2010). 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 (Ranganna, 1995). A clean cloth then sieved the puree into a small container and the puree was used for estimation of TSS. The TSS were determined using an RFM 340^+ digital refractometer (± 0.1% Brix) by placing a few drops of the puree on the prism (Getinet *et al.,* 2008; Maftoonazad and Ramaswamy, 2008). TSS measurements were taken at day0, day7, day14, day21 and day28. Between samples, the prism was cleaned with distilled water using a soft clean cloth according to Saad *et al.* (2016)

5.2.8 Percentage Marketability

The marketability of tomatoes, which is a descriptive quality attribute, was evaluated according to the scoring method used by Mohammed *et al*. (1999) and Awole *et al*. (2011). Descriptive quality attributes were determined subjectively, based on observing the level of visible mould, colour, surface defects, decay, shriveling (dehydration) and shine (Tefera *et al.,* 2007; Workneh *et al.,* 2012). On the sampling day, five tomatoes were randomly selected from each treatment and visual assessed. Based on a rating, with 1 being 'unusable', 3 being 'unsalable', 5 being 'fair', 7 being 'good' and 9 being 'excellent', fruits were evaluated. Tomatoes that received a rating of '5' and above were considered marketable, while those receiving a rating less than '5' were considered unmarketable. Damaged, decayed or overripe tomatoes which were considered unmarketable were removed from the stored samples (Cherono *et al.,* 2018). The percentage of the marketable fruit was calculated from the relationship between the number of fruits receiving a rating of five and above over the total number of fruits.

$$\%\ \text{Marketability} = \frac{\text{Total no. of tomatoes receiving a rating of five and above}_{t=0}}{\text{Total no. of tomatoes at start of experiment}_{t=0}} \text{x}100\% \quad (5.4)$$

5.2.9 Data Collection and Analysis

Data were recorded on days 0, 7, 14, 21 and 28 from the start of the experiment (after storage), in order to determine the change in the tomato quality (Arzate-Vazquez *et al.,* 2011). On each sampling date, samples from the marked tomatoes were selected randomly from each treatment for quality analysis. The following parameters evaluated the change in the quality of the tomatoes: physical properties; texture/firmness and skin colour: chemical properties; PWL and TSS: sensory qualities; marketability. Analysis of variance (ANOVA) by means of the GENSTAT statistical software, 18th edition determined the differences between treatments. Duncan's Multiple Range Test operated by the Least Significant Difference test (L.S.D.) with a significance level of 0.05 separated the means.

5.3 Results and Discussions

5.3.1 Tomato Firmness

Firmness is the ultimate quality index influencing consumers' in decision making at the time of selection of tomatoes to purchase or not (Thipe, 2014; Salveit, 2018). For tomatoes in transit or under storage, the increase in temperature may lead to the loss of firmness due to the activation of enzymes responsible for cell wall degradation (Tolesa and Workneh, 2017). Hence, the control of temperature during storage of fresh produce is very important. The firmness of tomatoes is determined by using a deformation test (Batu, 2004). The effects of storage conditions, maturity stage at harvesting and storage period on the firmness of the tomatoes were significant ($P<0.001$) as shown in Figure 5.3.

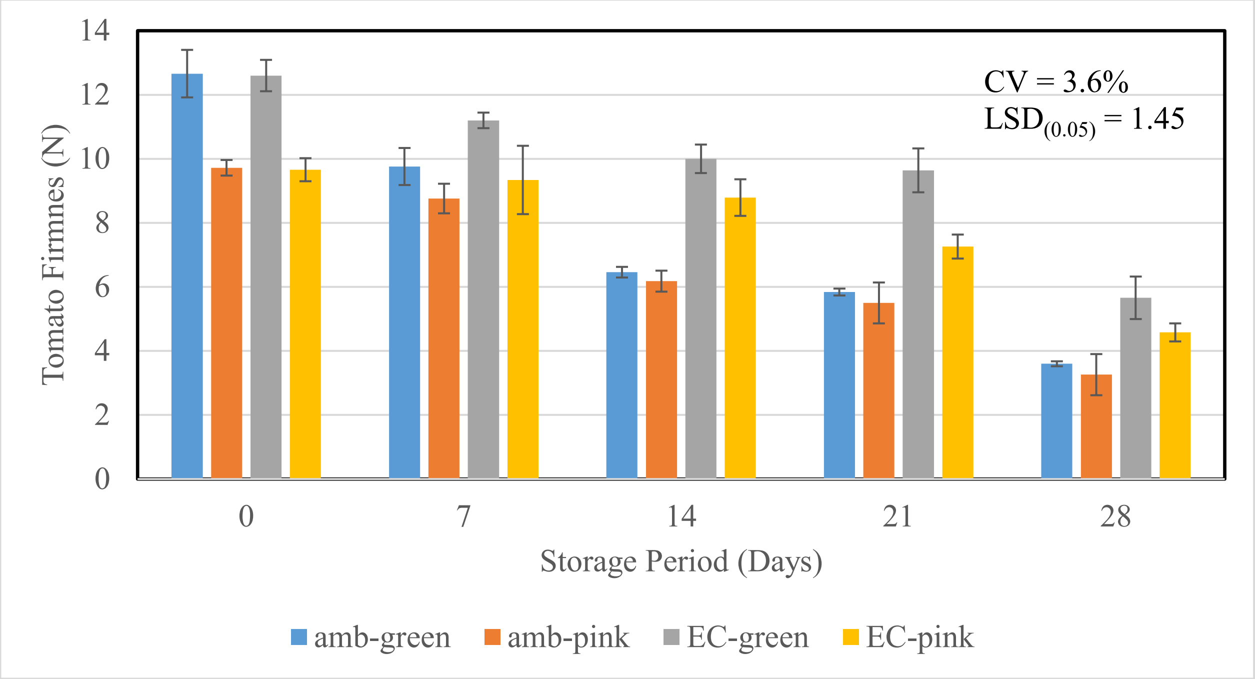

Figure 5.3. Tomato firmness under ambient conditions and IAC+EC

The tomatoes stored in the IAC+EC storage chamber were 18.9% more resistant to puncture, with 8.84 N, compared to those stored under ambient conditions with 7.17 N, which are averages over the 28-day period. A firmness value of greater than 8.46 N mm.$^{-1}$ indicates that tomatoes are very firm and suitable for supermarket shelves (Batu, 2004). The result indicates that IAC+EC kept the tomato structure intact and firm under the hot and humid conditions, which might contribute to the preservation of F&V quality leading to an extended shelf life and this agrees with findings of Zakari *et al*. (2016) using EC under dry and arid conditions. Higher ambient temperatures and lower RH encourage increased tomato physiological activity resulting loss of fruit firmness due to the breakdown of cellulose, pectin and lignin by pectinesterases (PE), polygalacturonase (PG) and β-galacturose (β-gal) in the cell wall (Tigist *et al.,* 2013). It is based on this background that the use of IAC+EC performs as effectively as EC in dry and arid conditions for storing fresh tomatoes is significant and cannot be over emphasized.

Comparison of the firmness between the two harvesting maturity stages showed that the overall average firmness for the green-harvested tomatoes was 20.2% higher, with 8.74 N, than that of pink-harvested, which had an overall average of 7.27 N. The reduced firmness in pink harvested tomatoes is attributable to a physiological breakdown of the fruit cell wall as the fruit ripened from green to pink (Viskelis *et al.*, 2008). The average firmness of tomatoes decreased significantly with storage period from 11.16 N-day0, 9.76 N-day7, 7.81 N-day14, 7.03 N-day21 and 4.28 N-day28. The decline over the 28-day period is 61.6%. The longer the storage period, the longer enzymatic activity continues causing more tissue softening and affecting firmness (Pinheiro *et al.,* 2013). Tolesa and Workneh (2017) obtained a similar pattern in their study where they observed a decline in tomato firmness over storage period. The decrease in firmness is attributable to physiological deterioration in tomato as the fruit continues to transpire, respire and further ripen (Ngcobo *et al.,* 2012; Salveit, 2018**).** By day 21, the firmness of green-harvested tomatoes stored under IAC+EC was 8.86 N. The maturity stage at harvesting affects the firmness of the tomato fruit (Vinha *et al.,* 2013).

There were significant effects due to the interaction of storage conditions × harvesting maturity stage ($P<0.05$), storage conditions × storage period ($P<0.001$) and maturity stage x storage period ($P<0.005$) on the firmness of tomatoes as shown in Figure 5.4 and Figure 5.5. From Figure 5.4 tomatoes stored under IAC+EC maintained firmness for long periods than sampled tomatoes stored under ambient conditions. By day14, sampled tomatoes under ambient conditions had a firmness 6.32 N a value lower than 8.46 N, which is the recommended firmness for tomatoes suitable for supermarket shelves (Batu, 2004). By day21 tomatoes, stored IAC+EC had a firmness of 8.45 N a value almost equal the firmness for tomatoes suitable for supermarket shelves.

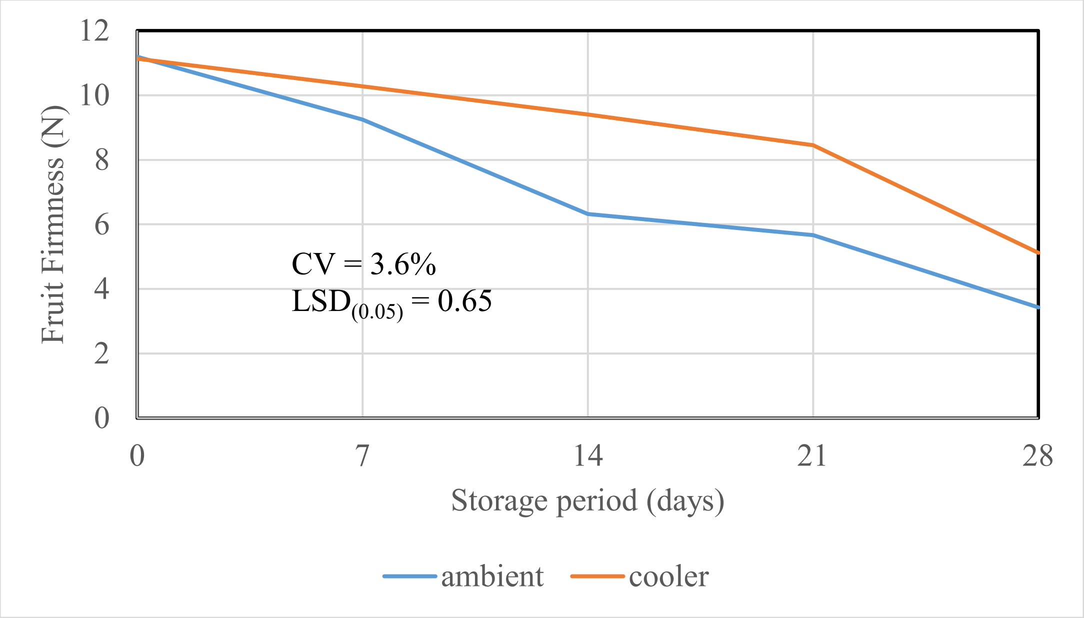

Figure 5.4. Storage condition x storage period

From Figure 5.5 the green harvested tomatoes were firmer than the pink harvested tomatoes over the storage period. By day 21 green harvested tomatoes had a firmness of 8.86 N which was higher than 7.38 N for pink harvested tomatoes at day14.

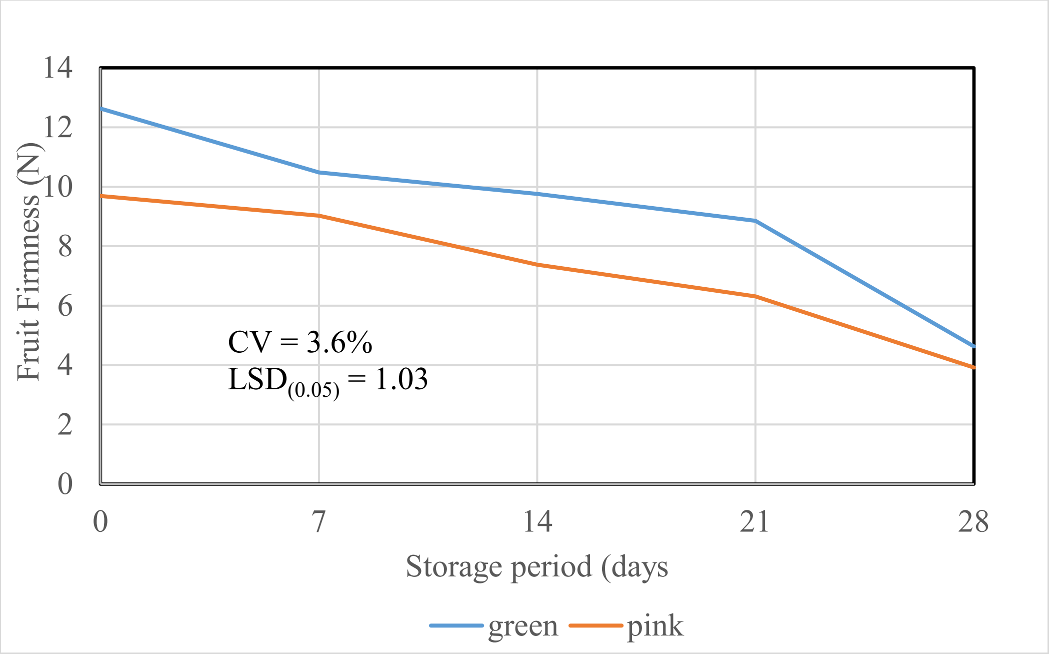

Figure 5.5. Maturity stage x storage period

The green stage harvested tomatoes when subjected to IAC+EC conditions gave the highest average firmness of 9.82 N followed by the pink harvested tomatoes with a breaking force of 7.86 N while the green and pink harvested fruits under ambient conditions had 7.66 N and 6.68 N breaking force respectively. The indication from the results is that storage of less mature tomatoes under IAC+EC provides firmer tomatoes over the storage period compared to all other combinations. A lower firmness of tomatoes regardless of stage of maturity at harvesting is indicating a weaker flesh skin often associated with ripe and soft fruit resultant of physiological deteriorations because of more rapid metabolism as confirmed by Sirisomboon *et al*. (2012).

The combinations of storage condition x storage period and maturity stage x storage period show green breaker stage tomatoes stored under IAC+EC conditions retained firmness (above 8.76 N) for an extended period of 21 days while the pink harvested retained firmness up to 14 days. According to Batu (2004), a firmness of 8.76 N is the minimum firmness requirement for very marketable fruit in supermarkets. Tomatoes in cold storage maintained higher firmness over the storage period than ambient air stored tomatoes.

5.3.2 Colour

Table 5.2 shows that both the h° and L* value was significantly ($P \leq 0.05$) influenced by storage condition, maturity stage at harvesting and the storage period. The tomatoes stored in the IAC+EC storage chamber had an overall 1% higher L* value and 3% higher h° value for the 28 days of storage, compared to those stored under ambient conditions. The h° and L* values decreased progressively over the period of storage from 76.61% at day0 to 49.45% at day28 and 53.47% at day0 to 35.36% at day28 respectively and the minimum values were reached on the last day of observation. A decrease in both h° and L* values with storage period indicates progression of colour change from green or pink to red as the fruit ripens. Cherono *et al*. (2018) had similar observation of colour changes with storage time. There are three colour changes of tomatoes during various stages of development, namely a green colour (chlorophyll), an orange colour (β-carotene) and a red colour (lycopene) according to Pinheiro *et al*. (2013). As a tomato ripens, there is colour change from green to white through chlorophyll degradation, then white to red by carotenoid biosynthesis (Hahn, 2002).

Table 5.2. Changes in L values and hue angle of tomatoes subjected to treatments of storage conditions, maturity stages and storage period.

			L values		
Treatment	**Day0**	**Day7**	**Day14**	**Day21**	**Day28**
Green, ambient	57.49^{k}	46.16^{h}	41.52^{fg}	39.16^{cdef}	34.12^{a}
Pink, ambient	49.95^{j}	45.16^{h}	41.38^{dfg}	37.95^{bc}	35.12^{a}
Green, cooler	57.08^{k}	46.71^{h}	47.13^{hi}	38.96^{cde}	36.12^{ab}
Pink, cooler	49.35^{ij}	46.77^{h}	42.47^{g}	38.95^{cd}	36.07^{ab}
Significance level					
Storage (A)			<0.05		
Maturity (B)			<0.001		
Day (C)			<0.001		
A x B			NS		
A x C			<0.05		
B x C			<0.001		
A x B x C			<0.05		

LSD$_{0.05}$ = 1.168, CV (%) = 4.2, SE = 0.812

			H values		
Treatment	**Day0**	**Day7**	**Day14**	**Day21**	**Day28**
Green, ambient	84.68^{d}	56.31^{abc}	51.55^{a}	52.91^{a}	48.31^{a}
Pink, ambient	69.33^{c}	53.83^{a}	53.74^{a}	52.14^{a}	49.43^{a}
Green, cooler	84.78^{d}	58.10^{abc}	68.53^{bc}	55.73^{ab}	50.43^{a}
Pink, cooler	67.64^{bc}	59.35^{abc}	53.13^{a}	54.38^{a}	49.64^{a}
Significance level					
Storage (A)			<0.05		
Maturity (B)			<0.001		
Day (C)			<0.001		
A x B			NS		
A x C			NS		

B x C	<0.001
A x B x C	<0.05
$LSD_{0.05}$ = 6.803, CV (%) = 9.2, SE = 3.416	

The lowest values coincide with time when the tomatoes have attained a deep red colour. Saltveit (2003) and Zakari *et al*. (2016) on their work on EC made similar observations. The average L values over the 28 days of observation for green tomatoes was 44.44% and 42.36% for pink tomatoes while the average h° values were 61.13% and 56.26% respectively.

The interactions of maturity stage × period of storage had significant ($P<0.05$) effects on the h° and the L* values of the tomatoes over the 28-day storage period. Further, the two-way interaction of storage conditions × period of storage significantly ($P<0.05$) influenced the changes in the L values of sampled tomatoes. The 3-way interaction of storage conditions x maturity stage x period of storage had a significant ($P<0.05$) effect on the values of h° and the L* of the sampled tomatoes under IAC+EC (Table 5.2). The green harvested tomatoes had the highest values of h° and the L* when storage in the IAC+EC storage chamber when observed over the period of storage. Therefore, the combination of green harvested tomatoes and IAC+EC environment is ideal for maintaining quality of tomatoes under sub-humid conditions an observation also made by Tolesa and Workneh (2017). Therefore, storage temperature, variety, storage period and maturity stage at harvesting factors influence the skin colour of fresh produce as alluded to by Baltazar *et al*. (2008).

5.3.3 Total Soluble Solids Content

Table 5.3 presents the TSS of green and pink harvested tomatoes subjected to either ambient conditions or IAC+EC storage conditions over 28 days. The storage conditions, the stage of maturity at harvesting and the storage period significantly ($P\leq0.001$) had an influence the TSS. A general increasing trend in the TSS was observed but was most evident at ambient conditions, compared to the IAC+EC storage conditions. The tomatoes stored in the IAC+EC storage chamber had on average TSS values of 4.10 compared to 4.58 for ambient conditions while on average green harvested and pink harvested tomatoes had TSS values of 4.19 and 4.49 over the storage period.

Lower TSS values imply a lower concentration of sugar. Similar findings were observed by Tefera *et al*. (2007) and Maftoonazad and Ramaswamy (2008) on the storage of mangoes.

Table 5.3. Changes in TSS (%) of tomatoes subjected to treatments of storage conditions, two maturity stages and storage period.

	Total Soluble Solids (%)				
Treatment	**Day0**	**Day7**	**Day14**	**Day21**	**Day28**
Green, ambient	3.848^{ab}	4.446^{bcdef}	4.472^{cdef}	$4.538d^{ef}$	4.980^{fg}
Pink, ambient	4.194^{abcd}	4.604^{def}	4.610^{def}	4.816^{efg}	5.294^{g}
Green, cooler	3.832^{a}	4.068^{abcd}	4.140^{abcd}	4.162^{abcd}	4.402^{cde}
Pink, cooler	4.174^{abcd}	4.336^{abcde}	$4.368a^{bcde}$	4.421^{cdef}	4.564^{def}
Significance level					
Storage (A)			<0.001		
Maturity (B)			<0.001		
Day (C)			<0.001		
A x B			NS		
A x C			<0.05		
B x C			NS		
A x B x C			NS		

$LSD_{0.05}$ = 0.0.163, CV (%) = 1.9, SE = 0.135

- The means separation was carried out by the Duncan's multiple range test ($p<0.05$) and the column means with similar superscripted letter(s) are not significantly different.
- A-storage environments; B-maturity stages; C-days of storage.

°Brix tends to increase as the ripening proceeds (Sammi and Masud, 2007). At low temperature and high RH storage conditions, the rate of increase was slower, compared to storage at ambient conditions. The increased temperature and reduced RH at ambient conditions 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.

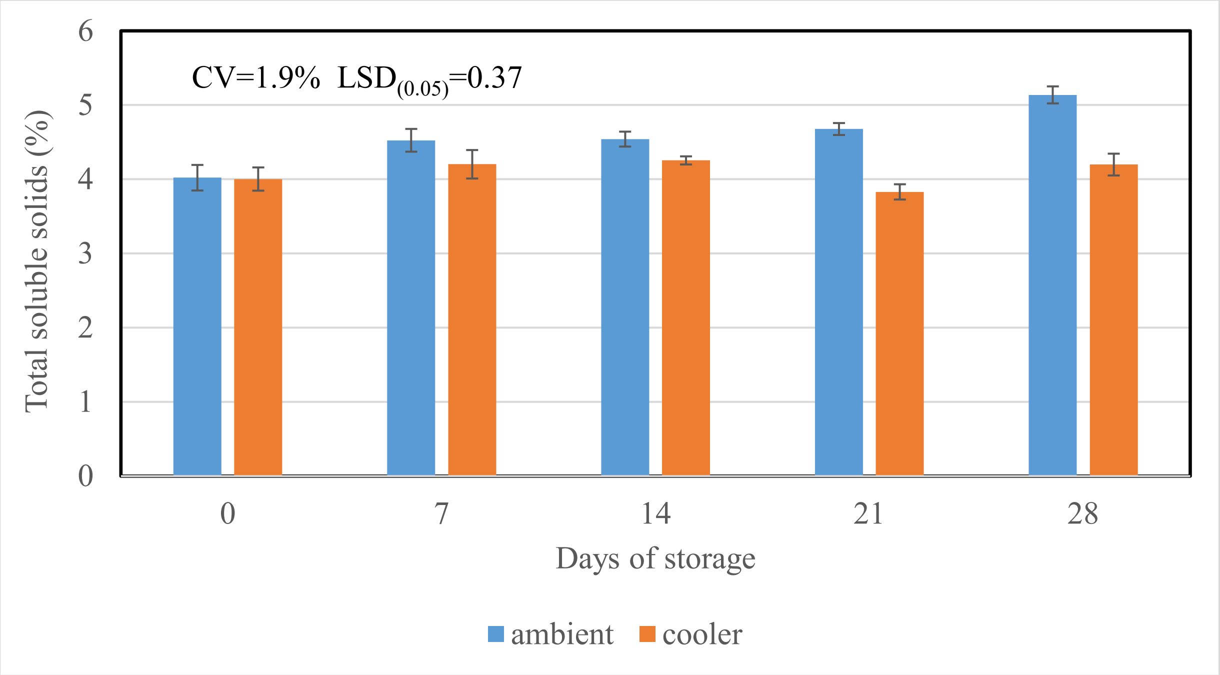

Figure 5.6. Percentage total soluble solids of green and pink harvested tomatoes.

The two-way interactions between storage conditions and storage period significantly ($P \leq 0.05$) influenced the TSS accumulation (Figure 5.6). The tomatoes that were stored in the IAC+EC storage chamber regardless of maturity stage at harvest had lower TSS than those stored under ambient conditions. This agrees with Young *et al*. (1993) that concluded changes that occur in sugar content during the development of tomato fruit increases progressively throughout the storage period as the fruit matures and ripens associated with the first appearance of yellow pigment in the walls of the fruit at the breaker stage through to red.

Soluble solids determine the sweetness of tomatoes, but there are other compounds responsible for flavour characteristics, such as acids and volatiles (Bumgarner and Kleinhenz, 2012). When tomatoes mature, the sugar levels increase, due to the metabolism of stored carbohydrates, lipids and proteins (Garcia and Barrett, 2006). At a later stage, these sugars are utilised for maintenance during growth, thus resulting in senescence (Beckles, 2012). TSS are a good index for the quality control of tomatoes. It is therefore very critical that for adoption postharvest cooling technologies, such as IAC+EC to slow down respiration and ethylene production and to thus retard ripening and senescence.

5.3.4 Physiological Weight Loss

The large proportion of water tomatoes contain, which constitutes up to 90% of the fresh weight largely influences the fruit size (Babitha and Kiranmayi, 2010; Zakari *et al.,* 2016). The perishable nature of tomatoes is a function of this large amount of water (Shahnawaz *et al.,* 2012). The physiological moisture loss varies and is dependent on the magnitude of the surrounding air-temperature and RH (Workneh and Osthoff, 2010). High temperature and low RH induce high respiration rate, which is the main cause of PWL (loss in saleable weight) and wilting (Mhina and Lyimo, 2013; Arah *et al.,* 2015; Jedermann *et al.,* 2017). The PWL of tomatoes harvested at the green-breaker stage and pink maturity stages, subjected to storage conditions of either IAC+EC or ambient conditions, and stored over 28 days are here presented. During the period of observation, the storage conditions, the maturity stage and the storage period were found to be highly significant ($P \leq 0.001$) with regard to the tomato PWL (Figure 5.7). The highest PWL was found in tomatoes stored under ambient conditions (9.5%) due to the considerably higher temperatures (± 26°C) and lower RH (< 60%), compared to the IAC+EC storage conditions (3.2%) over the 28 days storage period. Pink harvested tomatoes exhibited a higher PWL (7.9%) compared to green harvested tomatoes (4.8%) over the 28-day storage period. Sampled tomatoes stored under ambient conditions had PWL of 9.4% by day7 and 14.5% by day28 compared to 2.2% and 6.4% for IAC+EC for the same period. These conditions induced a larger vapour pressure deficit between the fruit and the surrounding external environment, as a result creating a driving force for moisture loss from the fruit (Getinet *et al.,* 2008; Thompson *et al*., 2018). The rate at which the moisture was lost by the tomatoes under ambient conditions occurred at a faster rate than under IAC+EC consequently contributing to a higher increase in the PWL. These findings are consistent with reported observations by Islam and Morimoto (2016).

PWL increased progressively over the period of storage and the highest values were reached on the last day of observation. There was continuous loss of moisture over time due to transpiration from the tomatoes and respiration under ambient conditions. This is the reason was PWL increased with storage period as the tomato fruit continues to ripen. The PWL was more pronounced under ambient conditions implying that senescence may occur earlier and, therefore, result in a shorter shelf life. Cherono *et al*. (2018) in their research study had similar observations. Therefore, the use of IAC+EC system for preserving and improving the shelf life of tomatoes cannot be avoided.

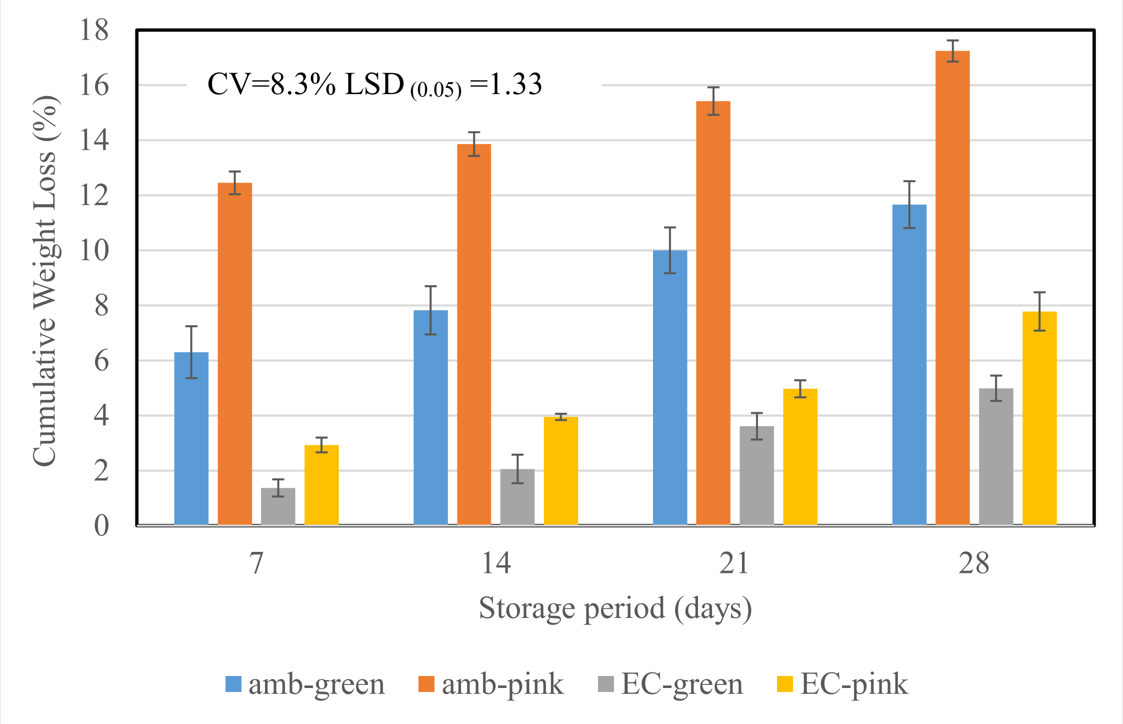

Figure 5.7. Physiological weight loss during storage period

FAO (1989) and Zakari *et al*. (2016) reported that water constitutes a large portion of most F&V and when lost from fresh produce translates to reduction in weight results in wilting and less marketability; hence, it is important to maintain the weight of fresh tomatoes to maximize profit.

The two-way interactions between (a) storage condition x maturity stage (b) storage condition x storage period and (c) maturity stage x storage period was found to be significant at $P \leq 0.001$. Green harvested tomatoes stored under IAC+EC conditions resulted in the lower PWL of 2.59% compared to pink under ambient at 11.79%. The variations are attributable to lower physiological activity in green tomatoes and the vital role of lower temperature under IAC+EC conditions that reduce rate of moisture loss and the amount of PWL in the tomatoes. The delay in harvesting of tomatoes may increase their susceptibility of decay and PWL as alluded to by Adewoyin (2017). The PWL increased progressively with storage period for tomatoes stored under ambient conditions and IAC+EC conditions and at the same increased progressively for tomatoes harvested either at the green-breaker stage or at pink stage.

The three-way interaction between storage conditions x stage of maturity x storage period were found to have a significant ($P \leq 0.05$) effect on the tomato PWL. Pink tomatoes stored under ambient had a PWL of 12.45% over a 7 day-storage period while the green-breaker stage harvested tomatoes had a PWL of 13.86% by day14 of storage. The green-breaker stage and pink harvested tomatoes subjected to the IAC+EC conditions had a PWL of 3.61% and 4.97% respectively by day21 of storage. This implies that by day21 the tomatoes under IAC+EC had not lost freshness and had no wilting appearance as such characteristics only exhibit after 5% PWL according to Sondi and Salopek-Sondi (2004). The PWL of green harvested tomatoes and stored in the IAC+EC storage chamber was 4.99% by day-28, exhibiting the lowest decrease. The green harvested and pink harvested tomatoes stored under IAC+EC stored over 28 days had a PWL below 8%, which in within the region that sustain good quality of tomatoes. According to Getinet *et al*. (2008), a 10% PWL corresponds to the threshold level for the termination of shelf life of fresh produce.

The results obtained mean that the rate at which the moisture was lost by the tomatoes occurred at a faster rate, when the fruit was subjected to ambient storage conditions and thus translating to an increase in the PWL. The implications are that senescence may occur earlier resulting in a shorter shelf life for both stages of tomato maturity. The physiological moisture loss from tomatoes varies and is dependent on the magnitude of the surrounding air-temperature and RH. High temperature and low RH induce high respiration rate, which is the main cause of PWL (loss in saleable weight) and wilting. The physiological nature of tomato that includes high moisture content, high respiration rate, and soft texture make it more vulnerable to post harvest qualitative changes and losses and therefore requires storage facility systems like IAC+EC. The IAC+EC conditions provide a low temperature-high RH environment that inactivated the enzymes responsible for the ripening process.

5.3.5 Marketability

Visual signs in fresh fruit are the first quality attributes that consumers consider when making decisions to buy and these largely influence marketability (USDA, 2011; Siddiqui *et al.,* 2015).

The storage conditions, maturity stage at harvesting and the storage period significantly ($P \leq 0.001$) influenced the marketability (Figure 5.8).

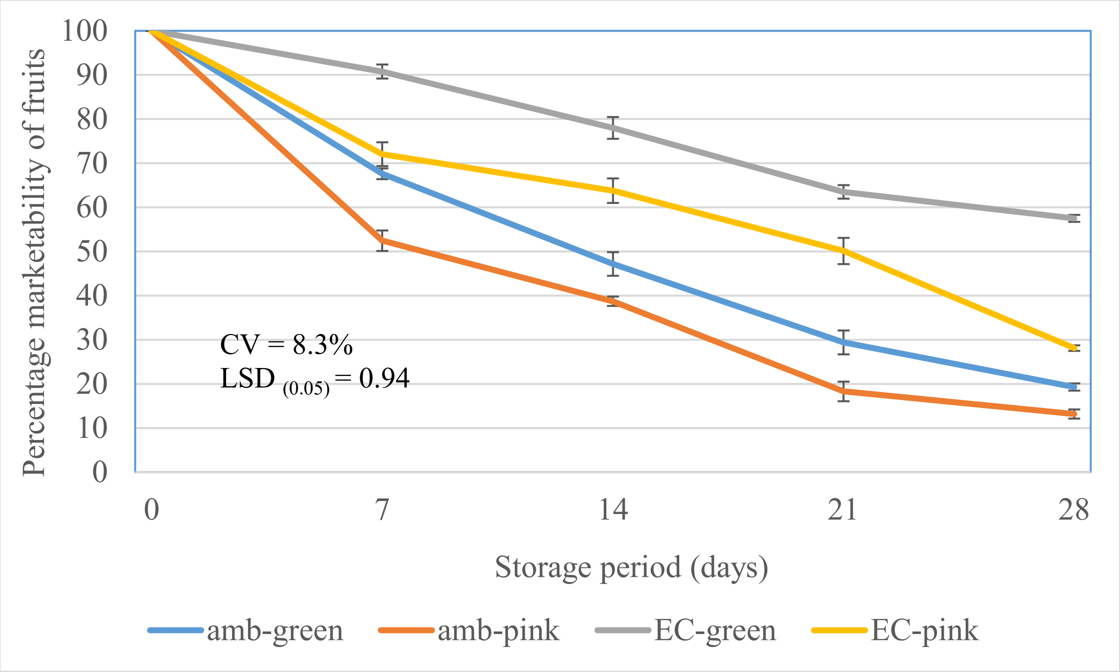

Figure 5.8. Percentage marketability of tomatoes during storage period

The percentage of marketability of tomatoes was at 100% on Day 0 and decreased with storage period for all treatments. Tomatoes stored in the IAC+EC storage chamber had on average a higher percentage marketability (70.38%) than those under ambient conditions (48.61%). Furthermore, green stage of maturity harvested tomatoes had a higher marketability of 38.4% by day28 compared pink harvested tomatoes of 20.6%. The higher percentage of marketability of tomatoes under IAC+EC is attributable to the low temperature storage conditions of the storage chamber, which resulted in lower moisture losses. The results are in conformity with the work done by Getinet *et al*. (2008) and Awole *et al*. (2011) and Rahman *et al*. (2016) for results obtained on strawberries. Higher ambient temperatures translate to higher moisture loss in fresh produce causing loss of marketable weight and inadvertently affecting appearance (wilting and shriveling) resulting in less marketability. As moisture is lost, the textural quality of tomatoes reduces thereby enhancing softening, loss of crispness and juiciness, and reduction in nutritional quality.

Marketability drastically decreased at ambient conditions from 100% to 42.9% by day14 and could have decreased further if there were more days with high temperatures during the period of observation. The sharp decline in marketability is because of excessive softening and shriveling caused by moisture loss, which is one of the factors leading to the PWL. Several tomatoes subjected to ambient conditions by day21 experienced decay, shriveling and extreme softness and were discarded while those still in good condition were retained to be observed again in day28. Under IAC+EC, the green harvested tomatoes were at 63.5% and 57.5% marketability at day21 and day28 while for pink harvested tomatoes there was a sharp decline from 50.1% marketability at day21 to 28.1% at day28. Therefore, IAC+EC preserved the organoleptic properties of the tomatoes.

5.4 Conclusion

This study was undertaken to determine the effects of postharvest storage environment, as well as tomato maturity stage at harvest and storage period on the postharvest quality of stored tomatoes. The deductions from the study is that the physical, chemical and subjective sensory quality parameters of tomatoes are largely dependent on maturity stage at harvest and storage environment as well as storage period. The storage conditions, stage of tomato fruit harvesting and the storage period consistently significantly ($P>0.001$) affected all of the analyzed tomato-fruit quality parameters. The IAC and EC systems ran at the same time to bring cumulative effect on air temperature and RH inside the storage chamber compared to ambient conditions. The IAC+EC system had a positive effect on the quality parameters and this extended the shelf life of tomatoes compared to samples that were stored under ambient conditions. The unbridled ambient conditions accelerated the tomato fruit ripening process, which was most evident in the conversion of the skin colour from green/pink to pink/red and the rapid reduction in firmness. This was more evident for pink harvested tomatoes, which on average were 20.2% softer, had 6.6% higher concentration of sugars, 3.1% higher PWL, 4.9% increase in hue angle and were 11.6% less marketable. The rapid ripening process under ambient conditions resulted in 18.9% reduced firmness, 10.5% increased TSS, 6.31% increased PWL, 3% reduction in hue angle and 24.8% reduced marketability. Compared to ambient storage, IAC+EC storage limited the PWL to 8% over 28 days, while ambient storage took 14 days to get to the same. The IAC+EC system increased shelf life of green-harvested tomatoes to 28 days with an improved marketability of 57.5% with PWL of 5%. The IAC+EC system inhibited ethylene production through reduction of enzymatic activities of tomatoes and thus prolonged shelf life and increasing the quality of fresh produce.

The objective of the current study was different from the previous research studies, which focused on prototype sized EC, since it considered low-cost IAC+EC technology tested on SSF sized, as well as the maturity stage of the tomato fruit on the quality during the storage period. The findings of this study showed that all green and pink tomatoes suffered a decrease in firmness and marketability, increase in PWL, TSS and hue angle, over 28 days. The tomatoes stored in IAC+EC storage chamber showed a higher firmness and marketability, a decrease in PWL, TSS and hue angle, when compared to the ambient conditions over the storage period. The green stage harvested tomatoes stored in the IAC+EC storage conclusively improved the shelf life and marketability of tomatoes. Therefore, a farmer in hot and humid areas can use a combination of tomatoes harvested at the green stage and IAC+EC to maintain a better quality of tomatoes and to extend their shelf life.

The work presented in this chapter is important because there is a scarcity of both quantitative and qualitative characterization of the performance of low-cost IAC+EC technology for cooling the microenvironment in the storage in order to maintain the quality of the tomato fruit, which can be used by small-scale and emerging farmers' cooperatives. This work has also contributed to improving the understanding of the effect of low-cost IAC+EC technology on the quality characteristics of fresh tomato fruit preserved under hot and sub-humid to humid conditions in Southern Africa. This study characterised the performance of IAC+EC and clearly demonstrated that the cooling system could maintain the physical, chemical and sensory characteristics of fresh tomatoes and most tropical and sub-tropical F&V. This study on IAC+EC has shown the considerable potential towards enhancing the performance and cooling capacity of the system for preservation of F&V. IAC+EC is therefore, recommended for storage of tropical and sub-tropical F&V as it can increase their shelf life.

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6 GENERAL DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

6.1 General discussions

The overall aim of this study was to design, construct and evaluate an integrated solar powered-postharvest cooling technology for storage of fruit and vegetables (F&V) in Southern Africa and specifically under hot and sub-humid to humid conditions. The study addressed the challenge of huge postharvest losses (PHL) experienced in F&V especially during the glut period for small-scale farmers (SSF) in sub-Saharan Africa (SSA). The delay between one harvest and the next as SSF await transport to the market, requires cooling for fresh produce to maintain quality and extend shelf life. Many SSF lose a significant portion of their fresh produce harvest because of lack of access to postharvest handling facilities. Cooling facilities remove field heat, which consequentially reduces physiological deterioration. A number of modern cooling facilities like mechanical refrigeration, hydro-cooling and vacuum cooling exists and are mainly exploited by large scale growers who can finance the high initial investment costs, maintenance costs, throughput and energy requirements.

Several research studies focusing on SSF in remote and isolated areas with no access to grid electricity, recommend low-cost cooling technologies, such as the evaporative cooling (EC) which work best in arid and semi-arid climatic regions for short-term storage of fresh produce. EC systems preserve fresh produce by the removal of sensible heat. EC systems encountered in literature reviews were very small direct evaporative coolers and for experimental purposes only, tested under hot and dry conditions mostly in North, East and West Africa. Literature also revealed that it is possible for EC systems for both greenhouse application and fresh produce preservation to work under one climatic condition and fail in another. Hence, the importance of developing and testing EC systems for specific climates and regions is necessary. Work on EC in SSA has been limited to other regions and there is dearth of information on the performance of EC systems in the Southern African sub-region.

EC has limitations in hot and sub-humid to humid areas because of inherent high humidity of the local air, which leads to low dry bulb temperature drops. Literature review proposes exploration of a combination of indirect air cooling and evaporative cooing (IAC+EC) for hot and humid areas like coastal regions in Sub-Saharan Africa. Despite the forecasted favourable results, the indirect air-cooling assisted EC is still an undeveloped technology and more focused research and investigation needs carrying out, a focus of this study. The novelty of such research is the introduction of indirect heat exchanger for sensible cooling of air before reaching the cooling pads for small-scale farmer sized storage structures. This study proposed investigation of an IAC+EC of fresh produce under hot and sub-humid to humidity conditions in Southern Africa. Literature reveals that to date EC has been done either direct or a combination of direct and indirect cooling for both greenhouse application and for cooling the microenvironment in fresh produce storage. There is little literature showing some attention to miniature IAC+EC experiments for comfort cooling, production process in metallurgical shops, cooling automobile engines and tractor cabins. Otherwise this area of research remains untaaped there is currently dearth of information on the performance of such a system for preservation of F&V. This has provided an opportunity to develop and characterise an IAC+EC for hot and sub-humid to humid conditions prevalent in coastal areas of SSA, which is innovation in terms of developing cooling facilities.

Because of coupling IAC unit on the EC system, additional electrical appliances of heat exchanger, fans for ventilation and water pump for reticulation are required and these need energy provision. As the study addresses SSF in remote areas with no access to electricity, use of solar energy was is the immediate option as it is abundant in most parts of SSA. Solar photovoltaic (SPV) systems can run IAC+EC and provide other advantages of low initial capital investment, and can be installed as an autonomous system to serve farmers that cannot be connected to the national grid. The amount of energy required to power an IAC+EC system is related to the size of the air ventilation system, water reticulations system, and desiccating media, which is the focus of this study. There exists a dearth of information regarding the actual performance and energy requirements of solar powered IAC+EC system under hot and sub-humid to humid conditions in Southern Africa.This study sought to provide data on the actual energy requirements for the cooling load and the performance of solar photovoltaics (SPV) in powering a small-scale farme sized storage chamber for tomatoes. As a result, an IAC+EC system with a 3.8-ton storage chamber was constructed.

A nine solar module SPV systems (3-strings- 3 –series) was designed and coupled with a battery bank facility to store energy for overnight use to power IAC+EC during the day and into the night until temperatures drop below 20ºC. From this system the practical power output was 2 639.1 W translating to 4 726.7 W.h^{-1} actual energy produced by the solar modules and to be stored by batteries in order to cool the 3.8 tons of tomatoes from 17h00 to 22h00. To cool one ton of tomatoes, using IAC+EC requires 1 200 W.h^{-1}. The value of 1 200 W.h^{-1} compares to the value of 700 W.h^{-1} for forced air EC of tropical F&V using a 0.1 HP. The difference in power requirements can be attributable to the additional indirect heat exchanger that was incorporated in this experiment. The overall system efficiency was 87% which is comparable to the values obtained in a comparative study of three types of grid connected photovoltaic systems based on actual performance. The SPV powered IAC+EC where 150 kg of tomatoes were stored while a similar quantity was stored under ambient conditions.

There is scarcity of information on the quantitative performance characterization of low-cost IAC+EC technology for cooling the microenvironment in order to maintain the quality and marketability of the tomato fruit. 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. Suscequently, to provide information on the performance of the IAC+EC system, variation in temperature, relative humidity (RH) and efficiency of cooling the cold air inside the IAC+EC cold storage chambers and under ambient conditions were studied.

There was a significant variation ($P<0.001$) in temperature between ambient, psychometrics unit, and storage chamber. The ambient temperature was on average 10.5℃ and 9.5℃ higher than the last cooling pad temperature and the average storage temperature respectively. A significant temperature gradient between the storage temperature and ambient temperature provides an effective heat transfer of the stored produce, cooling pad and a cold room. There was a significant variation ($P<0.001$) in ambient, exit point of the psychrometric unit and the storage chamber RH at various positions at entrance, centre and exhaust. The highest average RH was obtained at the outlet of the psychometric unit into the storage chamber (95.6%) the lowest average RH was at the ambient (65.4%). The cooler efficiency ranged between 86.8% and 97%. Between 05h00 and 09h00 of each day, the efficiency was about 92-95% and the values increased from 05h00 to 14h00, then declining thereafter to 86.8% by 18h00. The cooling curve efficiency shows that higher cooling efficiency obtain with higher temperature and lower RH of ambient air in the afternoon when the solar irradiation is highest. This is a desirable state as the cooling load is highest at the time that the SPV is providing the highest power.

There is scarcity of information on the qualitative performance of stored fresh produce under IAC+EC technology. In response, an analysis of low-cost cooling technologies (IAC+EC) under hot and sub-humid areas, tomatoes harvested at different maturity stage and storage periods on the quality and marketability was carried out. The study determined the best storage conditions for maintaining the quality and marketability of tomatoes during the storage period. There were significant effects due to the interaction of storage conditions × harvesting maturity stage ($P<0.05$), storage conditions × storage period ($P<0.001$) and maturity stage x storage period ($P<0.005$) on the firmness of tomatoes. Tomatoes stored under IAC+EC maintained firmness for long periods than sampled tomatoes stored under ambient conditions. By day14, sampled tomatoes under ambient conditions had a firmness 6.32 N a value lower than 8.46 N, which is the recommended firmness for tomatoes suitable for supermarket shelves. By day21 tomatoes, stored IAC+EC had a firmness of 8.45 N a value almost equal the firmness for tomatoes suitable for supermarket shelves. The 3-way interaction of storage conditions x maturity stage x period of storage had a significant ($P<0.05$) effect on the values of h° and the L* of the sampled tomatoes under IAC+EC. The green harvested tomatoes had the highest values of h° and the L* when storage in the IAC+EC storage chamber when observed over the period of storage. The two-way interactions between storage conditions and storage period significantly ($P\leq0.05$) influenced the TSS accumulation. The tomatoes that were stored in the IAC+EC storage chamber regardless of maturity stage at harvest had lower TSS than those stored under ambient conditions as changes occur in sugar content during the development of tomato fruit increases progressively throughout the storage period as the fruit matures and ripens associated with the first appearance of yellow pigment in the walls of the fruit at the breaker stage through to red. The highest PWL was found in tomatoes stored under ambient conditions (9.5%) due to the considerably higher temperatures (± 26℃) and lower RH (< 60%), compared to the IAC+EC storage conditions (3.2%) over the 28 days storage period. Pink harvested tomatoes exhibited a higher PWL (7.9%) compared to green harvested tomatoes (4.8%) over the 28-day storage period. Sampled tomatoes stored under ambient conditions had PWL of 9.4% by day7 and 14.5% by day28 compared to 2.2% and 6.4% for IAC+EC for the same period. Marketability drastically decreased at ambient conditions from 100% to 42.9% by day14 and could have decreased further if there were more days with high temperatures during the period of observation. Under IAC+EC, the green harvested tomatoes were at 63.5% and 57.5% marketability at day21 and day28 while for pink harvested tomatoes there was a sharp decline from 50.1% marketability at day21 to 28.1% at day28. Therefore, IAC+EC preserved the organoleptic properties of the tomatoes.

6.2 Conclusions

Modern cooling facilities like mechanical refrigeration, hydro-cooling and vacuum cooling were found to be unaffordable by SSF because of high initial investment costs, maintenance costs, throughput and energy requirements. From literature reviewed it is concluded that low-cost (material and energy) cooling technologies are vital for reduction of PHL in fresh produce under SSF in SSA. Selection of appropriate EC system depends mainly on local environmental conditions and performance varies from one to the other. Literature also concluded that more scope of research remains to be carried out to extent EC to hot and humid areas and this study proposes an additional unit of IAC for EC to be extended to such places. Recent literature concludes that IAC+EC should be of particular research interest because of potential high thermal performance. The inclusion of a heat exchanger for IAC is a concept that is not previously documented for cooling the microenvironment in storage of fresh produce and energy provision is required to power it. This provides an opportunity for the use of solar energy to power a heat exchanger for sensible cooling of air; water pump for water reticulation; fan to ventilate the storage chamber. From literature there is dearth of information on the performance of EC systems in the Southern African sub-region. From the literature evaluated this study proposes a different approach from the tradition of use of prototypes and laboratory scale set ups by constructing a 3.8-ton (53 m^3) storage chamber that mimics the amount of tomatoes a SSF needed to provide a cool environment for fresh produce between periods of one truckload and the next.

The energy supply from the solar panels was able to meet energy needs of powering the IAC+EC system during daytime and charging the battery bank for overnight operation of the cooling system until the temperatures were low enough. To cool one tonne of tomatoes, using IAC+EC requires 1 200 W.h^{-1} and the batteries had to store 4 726.7 W.h^{-1} to provide energy for the 3.8-ton storage chamber to cool tomatoes from 17h00 to 22h00 when the IAC+EC system was switched off. Therefore, the SPV systems used in the study supplied the energy during the critical period of the day when temperatures are high from 08h00 to 22h00 of each day. The study clearly showed that combinations of the solar array system can be used to power the cooling system at daytime during summer season and the excess power can be stored in a battery bank for use during the night hours. The energy of 2 639 W which can be supplied by 9 x 330 W solar panels, is enough to power a 3.8-ton storage chamber for tomatoes. The cost to establish this size of cooling system were R 190 190 with a payback period of 1.9 years to recoup the initial capital investment. Therefore, where grid electricity or other commercial energy sources are unavailable and solar energy is available, IAC+EC is a viable alternative to these more complex and costlier modern-day cooling systems. This shows that stand alone SPV systems have an expression in rural, dispersed and remote areas where grid electricity supply may not be readily accessible. Based on the results it is recommended that solar energy be integrated with IAC+EC for more effective reduction of decay and maintaining the F&V quality in areas that cannot be connected to the national grid.

The IAC+EC maintained a 13-41% higher RH and achieved 7-16℃ temperature gradient with ambient temperature and the microenvironment created was within the optimum range for the short-term storage of tomatoes. The cooler efficiency was 86.8-96.7% indicating that the combination of IAC and direct EC system was efficient in reducing the ambient temperature towards the wet bulb temperature. The IAC+EC system obtained similar results attained for EC system in hot and dry regions as temperature was reduced to 14-16℃ and RH raised to over 96% in the storage chamber. This work has contributed to improving the understanding of the effect of low-cost IAC+EC technology in provision of a microenvironment for storage of F&V under hot and sub-humid to humid conditions in Southern Africa. This study clearly demonstrated that the IAC+EC system could maintain the inside environmental conditions of air temperature and RH approximately constant and at recommended levels for tomatoes and most tropical and sub-tropical F&V. This work has therefore, contributed to improving the understanding of the effect of low-cost IAC+EC technology on temperature reduction and RH increase under hot and sub-humid to humid conditions in Southern Africa. IAC+EC is therefore, recommended for storage tropical and sub-tropical F&V as it can increase their shelf life.

On the qualitative performance of stored fresh produce under IAC+EC technology the findings of this study showed that all green and pink tomatoes experienced a decrease in firmness and hue angle over 28 days' experimental period. The tomatoes stored in the IAC+EC storage showed an 18.9% higher firmness, 10.5% lower concentration of sugars, 3% reduction in physiological weight loss, 3% higher hue angle and 24.8% increase in marketability, when compared to the ambient conditions of the stored tomatoes. IAC+EC storage reduced the PWL by 5% over 28 days, while by day21 the tomatoes stored under ambient conditions experienced decay, shriveling and extreme softness and were discarded. From the experiment, deductions are that the IAC+EC system increased shelf life of green-harvested tomatoes to 28 days with a 57.5% marketability. The combinations of green maturity stage at harvesting and IAC+EC storage greatly extended the shelf life and improved the marketability of tomatoes. Therefore, a farmer can use a combination of tomatoes harvested at the green stage and IAC+EC to maintain a better quality of tomatoes and to extend their shelf life. Based on the results the IAC+EC system can be recommended for use by SSF. Therefore, the characterisation of the performance of IAC+EC has clearly demonstrated that the cooling system could maintain the physical, chemical and sensory characteristics of fresh tomatoes and most tropical and sub-tropical F&V. This work has contributed to improving the understanding of the effect of low-cost IAC+EC technology on the quality characteristics of fresh tomato fruit preserved under hot and sub-humid to humid conditions in Southern Africa.

Finally, the work presented in this thesis is important because there is a scarcity of both quantitative and qualitative information on the performance of solar powered low-cost IAC+EC systems on the quality of the tomato fruit stored for extended storage periods under hot and humid conditions. The thesis has provided critical data for decision making by SSF and potential emerging farmers under the land re-distribution program in South Africa. This work has contributed to improved understanding of the effect of low-cost IAC+EC systems on the quality characteristics of fresh the tomato fruit subjected to this technology.

6.3 Recommendations for Future Research

It is expected that ongoing research will be conducted on the unit in terms of testing it on other F&V such as bananas, spinach, carrots or even on other horticultural commodities under full load (53 m^3 of fresh produce). The unit is immobile which limits its use between farms and market.

Some of the modifications and recommendations relating to the IAC+EC systems are as follows:

1. To automate the power provision system so that once the temperature in the storage chamber falls below 20℃, power supply is disconnected.
2. The storage chamber to be mobile for cold storage transportation of F&V 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.

6.4 Practical Relevance of the Research Study

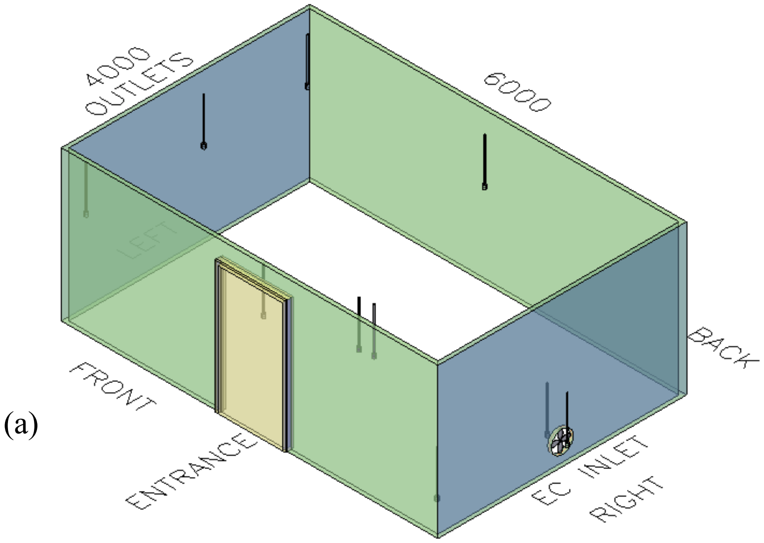
This research study addresses the following practical issues relating to F&V:

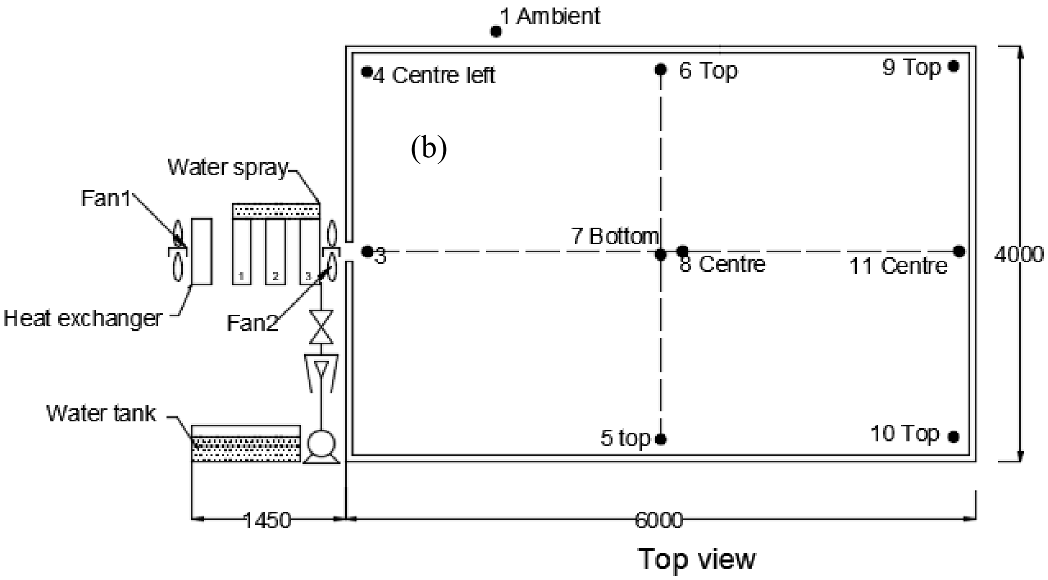
1. The implementation of low cost and environmentally friendly cooling system in addressing the challenge of PHL in F&V.
2. The storage chamber and psychrometric unit constructed from locally sourced materials.
3. Solar energy used a power source to drive the electrical appliances of the water reticulation and ventilation systems of the IAC+EC system.
4. The psychrometric unit of the IAC+EC system reduced temperature to 14-16℃ and increased RH of the storage chamber to 90-93%, which are optimum storage conditions for most tropical and sub-tropical F&V.
5. The IAC+EC increased the shelf life of green-harvested tomatoes to 28 days with a 57.5% marketability.
6. There is now a greater understanding of the performance of IAC+EC for preservation of F&V in Southern Africa under humid conditions.
7. This IAC+EC principle can be extended to other F&V.
8. The implementation of the SSF sized EC system means farmers could reduce their lack of storage facilities by direct adoption.
9. Small-scale farmers in remote, isolated, dispersed populations with no access to grid electricity can now access, a low-cost appropriate EC system for most tropical and sub-tropical F&V.

It is anticipated that the findings of this study will be applied to suit the postharvest handling of F&V in South Africa for both local and export markets.

7 APPENDICEES

7.1 APPENDIX 7.1: Drawings and images of the IAC+EC system





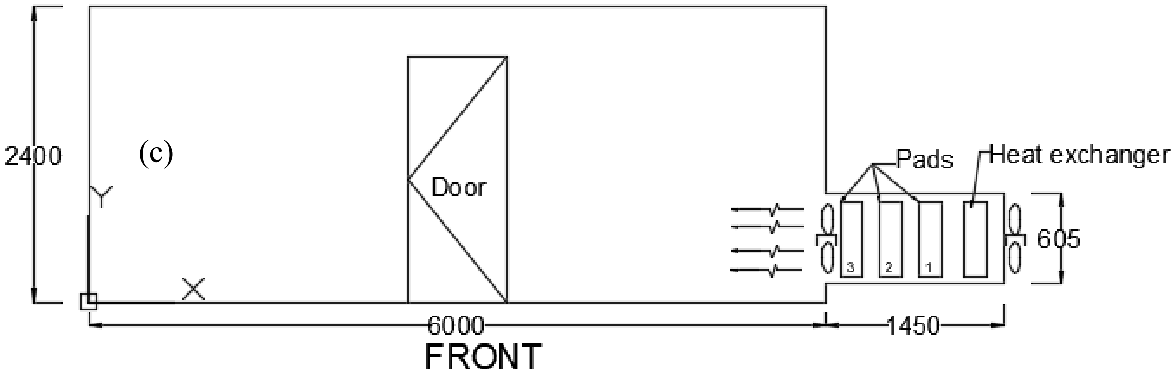


Figure 7.1. Drawings for IAC+EC system (a) Temp-RH sensor positions (b) Top View (Front View)

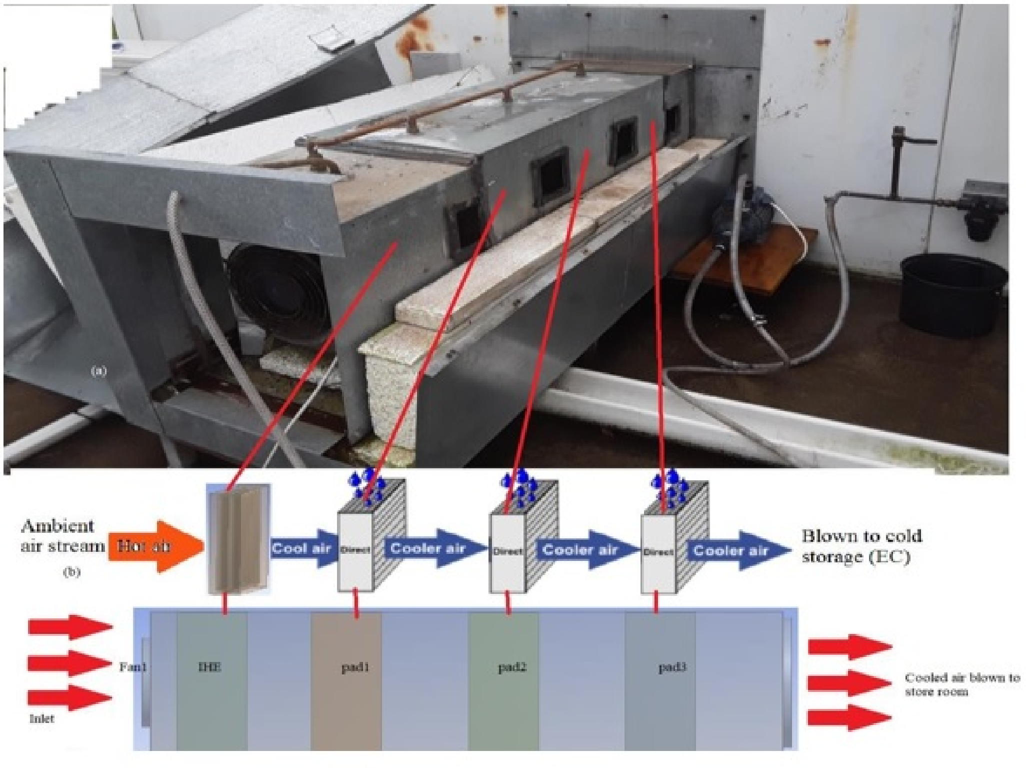


Figure 7.2. The skeleton of the psychometrics unit tunnel constructed from one heat exchanger and three direct cooling pads (Pad 1, 2 and 3) (a) structural schematic.

Figure 7.3. Pictorial image of the storage chamber in Ukulinga Research Station in Pietermaritzburg

7.2 APPENDIX 7.2: Day of the year and angles of elevation and declination

The other factors of consideration are power dissipation, stagnation, conduction losses, efficiency factors of the inverter and controller and differences in solar cell technologies of the modules. The aggregate sun-oriented radiation received at a given area on earth varies depending on t©he length of the insolation on a specific day and the power of sunlight-based vitality. Variations also arise because of latitude and the day or time of the year. Equation 7.1 calculates the day of the year.

$$d = i + D \tag{7.1}$$

Where, d= day of the year (days); D = day of the month (days), and

i = total number of days of the previous months of the same year (days).

The number of days is obtained from equation 7.1 $d = i + D$

For 22 June 2017, $d = 151 + 22 = 173\ days$

For 22 September 2017, $d = 243 + 22 = 265\ days$

The incident power on a PV module varies with power contained in the sunlight and the angle between the module and the sun. This implies that the power density is maximum when the PV module is perpendicular to the sun. However, as the angle between the sun and a fixed surface changes continuously, the incident sunlight is more than the power density on a fixed PV module. Figure 7.2 shows solar radiation received by any surface at different angles. In this study, the solar radiation values recorded over 50 years' and captured in the South African Atlas 18 of Agro-hydrology and climatology will be used.

From Figure 7.4 several useful angles are derived:

1. The tilt angle of the solar panel determines the optimum energy yield and is defined as the angle at which the solar panel is oriented against the horizontal plane.
2. δ is the declination angle and varies with the day of the year. It is the angle made between the plane of the equator and the line joining the two centres of the earth and the sun and the value lies between $-23.45 \leq \delta \leq 23.45$.
3. The elevation angle (α) is the angle between the horizontal plane and the incident solar radiation.

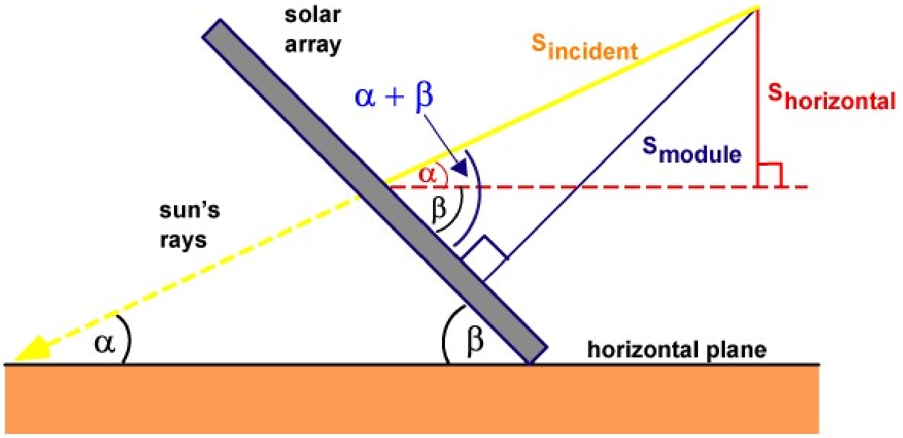


Figure 7.4. Tilting the module to the incoming light (Adopted from Honsberg and Bowden, S. 2016)

The equator of the earth is tilted at 23.45 degrees with respect to the plane of the earth's orbit around the sun and the declination varies from 23.45 degrees north to 23.45 degrees south at various times of the year as the earth orbits the sun. The declination angle δ shown in Figure 7.1 is determined through equation 7.2

$$\delta = -23.45 \sin\left(\frac{360}{365}(284 + d)\right) \tag{7.2}$$

Where δ = declination angle (^{0}) and d = day of the year (days).

The declination angle for this study is calculated from equation 7.2 and on 22 June 2017 the declination

$\delta = -23.45 \sin\left(\frac{360}{365}(284 + 173)\right) = -\ 23.45^\circ$and on the 22nd of September 2017 which is at equinoxes, declination is:

$$\delta = -23.45 \sin\left(\frac{360}{365}(284 + 265)\right) = 0^\circ$$

The elevation angle (α) (see Figure 7.1) is the angle between the horizontal plane and the incident solar radiation and is calculated by the equation:

$$\alpha = 90 + \delta - \varphi \tag{7.3}$$

Where α = elevation angle (^{0}); δ = declination angle (^{0}), where φ = 29.6006° in PMB.

Therefore, on 22 June declination δ is (-23.45^0) and 22 September 0^0 and PMB latitude (φ) of -29.6006 °, the elevation angle (α) are 96.15060 and 119.6006^0 respectively.

7.3 APPENDIX 7.3: Solar radiation at various tilt angles

Table 7.1 Solar radiation at horizontal tilt angle

	Horizontal	**Solar hours**	**Horizontal**	**Tilt angle**	**Latitude**	**Declination angle**	**Elevation angle**	**Day**	**Incident**	**Module**
	$MJ.m^{-2}$	hours	$W.m^{-2}$	β	φ	δ	α	days	$W.m^{-2}$	$W.m^{-2}$
January	22.3	6.00	1 032.41	0.00	-29.60	19.93	139.53	22.00	1 590.61	1 032.41
February	19.8	6.30	873.02	0.00	-29.60	10.87	130.47	53.00	1 147.59	873.02
March	18.9	6.50	807.69	0.00	-29.60	0.00	119.60	81.00	928.93	807.69
April	17.2	6.90	692.43	0.00	-29.60	-11.93	107.67	112.00	726.73	692.43
May	14.8	7.60	540.94	0.00	-29.60	-20.34	99.26	142.00	548.08	540.94
June	13.8	7.90	485.23	0.00	-29.60	-23.45	96.15	173.00	488.04	485.23
July	15.6	8.10	534.98	0.00	-29.60	-20.24	99.36	203.00	542.20	534.98
August	17.3	8.00	600.69	0.00	-29.60	-11.40	108.20	234.00	632.32	600.69
September	18.2	6.70	754.56	0.00	-29.60	0.61	120.21	265.00	873.11	754.56
October	19.5	6.20	873.66	0.00	-29.60	12.10	131.70	295.00	1 170.16	873.66
November	23.6	5.60	1 170.63	0.00	-29.60	20.64	140.24	326.00	1 830.22	1 170.63
December	27.3	6.00	1 263.89	0.00	-29.60	23.44	143.05	356.00	2 102.33	1 263.89

Table 7.2 Solar radiation at tilt angle = latitude + 15^0

	Horizontal	**Solar hours**	**Horizontal**	**Tilt angle**	**Latitude**	**Declination angle**	**Elevation angle**	**Day**	**Incident**	**Module**
	$MJ.m^{-2}$	hours	$W.m^{-2}$	β	φ	δ	α	days	$W.m^{-2}$	$W.m^{-2}$
January	22.30	6.00	1 032.41	-14.60	-29.60	21.27	140.87	15.00	1 635.93	1 318.96
February	19.80	6.30	873.02	-14.60	-29.60	10.87	130.47	53.00	1 147.59	1 032.59
March	18.90	6.50	807.69	-14.60	-29.60	0.00	119.60	81.00	928.93	897.27
April	17.20	6.90	692.43	-14.60	-29.60	-11.93	107.67	112.00	726.73	725.68
May	14.80	7.60	540.94	-14.60	-29.60	-20.34	99.26	142.00	548.08	545.70
June	11.50	7.90	404.36	-14.60	-29.60	-23.45	96.15	173.00	406.70	402.29
July	15.60	8.10	534.98	-14.60	-29.60	-20.24	99.36	203.00	542.20	539.93
August	17.30	8.00	600.69	-14.60	-29.60	-11.40	108.20	234.00	632.32	631.07
September	18.20	6.70	754.56	-14.60	-29.60	0.61	120.21	265.00	873.11	840.92
October	19.50	6.20	873.66	-14.60	-29.60	12.10	131.70	295.00	1 170.16	1 041.68
November	23.60	5.60	1 170.63	-14.60	-29.60	20.64	140.24	326.00	1 830.22	1 487.48
December	27.30	6.00	1 263.89	-14.60	-29.60	23.44	143.05	356.00	2 102.33	1 646.56

Table 7.3 Solar radiation at tilt angle = latitude

	Horizontal	**Solar hours**	**Horizontal**	**Tilt angle**	**Latitude**	**Declination angle**	**Elevation angle**	**Day**	**Incident**	**Module**
	MJ.m^{-2}	hours	W.m^{-2}	β	φ	δ	α	days	W.m^{-2}	W.m^{-2}
January	22.30	6.00	1 032.41	-29.60	-29.60	21.27	140.87	15.00	1 635.93	1 524.50
February	19.80	6.30	873.02	-29.60	-29.60	10.87	130.47	53.00	1 147.59	1 127.00
March	18.90	6.50	807.69	-29.60	-29.60	0.00	119.60	81.00	928.93	928.93
April	17.20	6.90	692.43	-29.60	-29.60	-11.93	107.67	112.00	726.73	711.03
May	14.80	7.60	540.94	-29.60	-29.60	-20.34	99.26	142.00	548.08	513.90
June	11.50	7.90	404.36	-29.60	-29.60	-23.45	96.15	173.00	406.70	373.12
July	15.60	8.10	534.98	-29.60	-29.60	-20.24	99.36	203.00	542.20	508.72
August	17.30	8.00	600.69	-29.60	-29.60	-11.40	108.20	234.00	632.32	619.84
September	18.20	6.70	754.56	-29.60	-29.60	0.61	120.21	265.00	873.11	873.06
October	19.50	6.20	873.66	-29.60	-29.60	12.10	131.70	295.00	1 170.16	1 144.16
November	23.60	5.60	1 170.63	-29.60	-29.60	20.64	140.24	326.00	1 830.22	1 712.79
December	27.30	6.00	1 263.89	-29.60	-29.60	23.44	143.05	356.00	2 102.33	1 928.77

Table 7.4 Solar radiation at tilt angle = latitude – 15^0

	Horizontal	**Solar hours**	**Horizontal**	**Tilt angle**	**Latitude**	**Declination angle**	**Elevation angle**	**Day**	**Incident**	**Module**
	MJ.m^{-2}	hours	W.m^{-2}	β	φ	δ	α	days	W.m^{-2}	W.m^{-2}
January	22.30	6.00	1 032.41	-44.60	-29.60	21.27	140.87	15.00	1 635.93	1 626.15
February	19.80	6.30	873.02	-44.60	-29.60	10.87	130.47	53.00	1 147.59	1 144.61
March	18.90	6.50	807.69	-44.60	-29.60	0.00	119.60	81.00	928.93	897.27
April	17.20	6.90	692.43	-44.60	-29.60	-11.93	107.67	112.00	726.73	647.93
May	14.80	221.00	540.94	-44.60	-29.60	-20.34	99.26	142.00	548.08	447.07
June	11.50	7.90	404.36	-44.60	-29.60	-23.45	96.15	173.00	406.70	318.52
July	15.60	8.10	534.98	-44.60	-29.60	-20.24	99.36	203.00	542.20	442.83
August	17.30	8.00	600.69	-44.60	-29.60	-11.40	108.20	234.00	632.32	566.36
September	18.20	6.70	754.56	-44.60	-29.60	0.61	120.21	265.00	873.11	845.70
October	19.50	6.20	873.66	-44.60	-29.60	12.10	131.70	295.00	1 170.16	1 168.66
November	23.60	5.60	1 170.63	-44.60	-29.60	20.64	140.24	326.00	1 830.22	1 821.37
December	27.30	6.00	1 263.89	-44.60	-29.60	23.44	143.05	356.00	2 102.33	2 079.54

7.4 APPENDIX 7.4 Packing of tomatoes in the chamber

500 mm long x 300 mm wide x 230 mm high plastic packing crates were selected as ideally for storage of tomatoes, which also farmers in KZN are using. The packing crates had at least 5% venting spacing of 100 mm allowed between packed crates for adequate airflow between tomatoes. The number of crates that the cooler could contain was determined by considering the dimensions for the storage chamber as follows.

In determining, the number of crates that could be stacked horizontally the following was accommodated:

(i) packing space of 100 mm was accommodated according to the procedure.
(ii) 0.9 m walkways were left in between the crates for ease of packing and unpacking.
(iii) 500 mm long x 300 mm wide x 230 mm high crates are used

The following image shows the storage chamber looks like.

Horizontal stacking

$$Number\ of\ crates\ along\ the\ length\ of\ the\ storage\ chamber = \frac{5.88\ m}{0.30\ m} = 19\ \ crates$$

$$Number\ of\ crates\ in\ the\ middle\ and\ along\ the\ storage\ chamber\ wall\ next\ to\ the\ door$$

$$= 2 \times \frac{5.88\ m - 0.90\ m}{0.30\ m} = 32\ \ crates$$

$$Total\ number\ of\ crates\ that\ can\ be\ stored\ on\ the\ floor\ of storage\ chamber = 19 + 32$$
$$= 51\ crates$$

Vertical stacking of crates

In considering, the vertical stacking of the crates in the chamber a spacing between crates of 25 mm was left between the crates. Therefore,

$$Height\ of\ stacking = height\ of\ crate + 0.025\ m\ = 0.255\ m$$

The bottom crates were stacked on a 200 mm stand and a minimum distance of 500 mm was left between the roof and the stacked crates. Therefore,

$$Total\ number\ of\ crates\ staked\ vertically = \frac{2.340\ m - (0.2\ m + 0.5\ m)}{0.255\ m} = 6\ crates$$

Therefore, a maximum of six crates can be stacked vertically.

Total capacity of the storage chamber

$$Total\ number\ of\ crates\ stored\ in\ the\ storage\ chamber = 6 \times 51 = 306\ crates$$

The mass of tomatoes that can be stored in crate is used to calculate the total mass that can be stored in the chamber. In packing tomatoes in a crate, there is a space of 0.12 m left in between the tomato layers.

$$Volume\ occupied\ by\ tomatoes\ in\ one\ crate = 0.51\ m\ \times 0.28\ m\ \times (0.38 - 0.12)$$
$$= 0.018\ m^3$$

Assuming that the bulk density of tomatoes is 694 kg.m^{-3}, mass of tomatoes per crate was calculated as:

$$Mass\ per\ crate = 694\ kg.m^{-3}\ \times 0.018\ m^3 = 12.5\ kg\ per\ crate$$

$$Total\ mass\ of\ tomatoes\ that\ can\ be\ stored\ in\ storage\ chamber = 12.5\ kg\ \times 306\ crates$$

$$\approx 3825\ kg$$

Three hundred and six (306) crates could be packed in the storage chamber. Each crate can hold 12.5 kg of tomatoes and based on this computation, the storage capacity of the chamber was found to be approximately 3 825 kg as shown in the following section.

7.5 APPENDIX 7.5: Cooling loads

The cooling loads to be removed from the storage chamber for cooling purposes are respiration heat, field heat, heat gain through the wall, air change heat load every time the storage chamber door is opened and miscellaneous heat gains from lights, fan and labourers during stacking and removal of tomatoes from the storage chamber.

DESIGN COOLING LOADS

The amount of heat removed for cooling purposes from any cold storage room is proportional to the mass that is loaded at a time. A cold storage room packed to its maximum capacity takes a long time to reduce the temperature of the stored products than when loaded to half or one-third capacity. For a cold storage area filled in batches, the target temperature of the product is reached in a shorter time. While small-scale farmers will not fill a 3.8 tonnes in one day for the purposes of calculating the cooling load a worst-case scenario where the storage chamber is filled to capacity is considered.

Heat of respiration

Respiration load is the heat load that results due to metabolic activity of the produce. Fruit respires at a higher rate at higher temperatures producing more heat and hence more heat load has to be removed from warm products that have just been introduced into the cold store. Heat of respiration, therefore, is the amount of respiration heat, which has to be removed in the storage chamber. The mass of tomatoes to be cooled is 3 825 kg. The heat transfer coefficient of mature green tomatoes is 543 J. kg^{-1}.

$$Q = m \times h \tag{7.1}$$

Whereby: m = mass of product to be cooled [kg], and

h = heat transfer coefficient of product [J. kg^{-1} = 543 J. kg^{-1}],

On the first day the heat of respiration is:

$$Q = 3825\ kg \times 543 \frac{\text{J}}{\text{kg}} \times \frac{1hr}{3600s} = 577\ \ W$$

$$= 0.577\ kW \quad is\ the\ heat\ of\ respiration$$

On the second day the heat of respiration is:

$$Q = 3825\ kg \times 300 \frac{\text{J}}{\text{kg}} \times \frac{1hr}{3600s} = 319\ \ W$$

$$= 0.319\ kW \quad is\ the\ heat\ of\ respiration$$

Sensible heat of containers

Crates, which are inside the storage chamber increase the amount of heat circulating inside the storage room causing deviations in the storage room temperature. The containers used for storage of the tomatoes are 500 mm long × 300 mm wide × 230 mm high and each weigh approximately 1.8 kg with specific heat of 1.67 kJ. kg^{-1}. The containers in this study are packed with fresh tomatoes at the farm at ambient temperature of 32°C and brought to the storage chamber for cooling 12-14 °C . Three hundred and six crates can fit inside the storage chamber.

$$Q = \frac{m \times c_p(T_2 - T_1)}{3600 \times n} \tag{7.2}$$

Where: m = mass of product to be cooled [kg],

c_p = Specific heat of crates[KJ. kg^{-1}],

n = operation time [hrs],

T_2 = Storage temperature of products in crates [°C], and

T_1 = Initial crates temperature [°C],

On the first day, the temperature will decrease from 32°C to 15°C and therefore the sensible heat of containers will be:

$$Q = \frac{306 \times 1.8 \times 1.67(32 - 15)}{3600 \times 16}$$

$$= 0.271 \text{ kW is the sensible heat of containers}$$

On the second day, the temperature will decline to 14°C from 15°C and therefore the sensible heat of containers will be:

$$Q = \frac{306 \times 1.8 \times 1.67(15 - 14)}{3600 \times 16} = 0.016 \text{ kW}$$

Field heat

Field heat is the heat removed from the freshly harvested tomatoes by introducing into the cold store by reducing the field temperature of the tomatoes to the desired storage temperature. Field heat in the case of this study, therefore, is the amount of heat removed from the tomatoes as they cool from initial harvest temperature to final storage temperature. The mass of the tomatoes is 3 825 kg and the operating time is assumed at 16 hours. The specific heat of tomatoes is 4.02 kJ. kg^{-1}) and the field heat is calculated as from the equation:

$$Q = \frac{m \times c_p(T_2 - T_1)}{3600 \times n}$$

Where:

m = mass of product to be cooled, kg

c_p = Specific heat of tomatoe , k J. kg^{-1}

n = operation time, hrs

T_2 = Storage temperature of products in crates, ℃

T_1 = Initial product in crates temperature, ℃

On the first day, the temperature will decline from 32℃ to 15℃ and therefore the field heat of containers will be:

$$Q = \frac{3825 \times 4.02(32 - 15)}{3600 \times 16} = 4.504 \text{ kW}$$

On the second day, the temperature will decline to 14℃ from 15℃ and therefore the field heat of containers will be:

$$Q = \frac{3825 \times 3.99(15 - 14)}{3600 \times 16} = 0.265 \text{ kW}$$

Heat loss through walls and roofs

In a storage chamber, there is heat transfer because of leakages between the outside air and inside air through the walls and the roof as a result of the temperature gradient between the outside and inside temperature and is computed from the equation:

$$Q = \frac{k \times A(T_2 - T_1)}{x} \tag{7.3}$$

Where: k = Thermal conductivity [W.m^{-1}.K^{-1}], A = Surface area [m^2],

x = Thickness of insulation material [m],

$T_2 =$ Storage temperature of products in crates[°C], and

T_1 = Initial product in crates temperature [°C],

The walls are 2.0 m high and × 1.98m wide and 1.825m high x 1.98m long the roof is 1.98 m wide × 2.0 m length. The insulation material is polyurethane with thermal conductivity of 0.026 W.m^{-1}. K^{-1} and the thickness of the insulation is 60 mm.

$$Area\ of\ roof + walls = (6m \times 4m) + (6m \times 2.4\ m\ \times 2) + (4m \times 2.4m\ \times 2\ ) = 72\ m^2$$

$$\mathrm{Q} = \frac{0.026 \times 72(32 - 15)}{0.05} = 0.637\ \mathrm{kW}$$

Heat loss through floor area

The heat loss through the floor is given by the formula according to Albright (1990).

$$Q_f = FP(T_o - \ T_i) \qquad (7.4)$$

Where F = perimeter heat loss factor [W.m^{-1}. K^{-1}], and

P = storage chamber perimeter [m], (Albright, 1990).

The perimeter heat loss factor of 1.6 W.m^{-1}. K^{-1} is used. The perimeter, P of the floor is obtained by the summation of the dimensions of the rectangular storage chamber as:

$$P = (Length(m) \times Width(m)) \times 2 = (6\ m\ \times 2\ \ sides) + \ (4\ m\ \times 2\ sides) = 20\ m$$

With values F = 1.6 W.m^{-1}. K^{-1} and P = 20m

$$Q_f = 1.6\ W.m^{-1}.K^{-1}\ \times 20\ m\ \times (32 - 15) = 0.544\ kW$$

Air infiltration

Air-change heat load rises from warm air entering the storage chamber every time the door is opened. The temperature of such air has to be reduced to the storage temperature and any water that condenses has to be compensated. The infiltration (air-change load) is the heat gain through doorways from air exchange. In this study, the width of the door is 0.55 m and the height are 1.8 m. PVC will cover the door entrance.

Air change load:

$$P_a = m_a(h_a - h) + m_w C_{pw}(T_a - T) \tag{7.5}$$

Where P_a = air change load [W],

m_a = mass of air entering the chamber every hour [kg. s^{-1}],

h_a = enthalpy of ambient air [kJ.kg^{-1}],

m_w = mass of water condensing in the chamber every hour [kg],

h = enthalpy of air in the storage chamber [kJ.kg^{-1}],

C_{pw} = specific heat capacity of water [kJ.kg^{-1}. $^{o}C^{-1}$],

T_a = ambient air temperature [°C], and

T = air temperature inside the chamber [°C]

Assuming that h_a = 50 kJ.kg^{-1},

$$Mass\ of\ Air\ (m_a) = \frac{volume\ of\ the\ storage\ chamber}{Specific\ volume\ of\ dry\ Air \times 3600s} \tag{7.6}$$

$$= \frac{53.4\ m^3}{0.874\ m^3.kg^{-1} \times 3600s} = \frac{61.098\ kg}{3600s}$$

$$(m_w) = Humidity\ ratio \times Mass\ of\ water \tag{7.7}$$

Maximum condensation occurs when temperature drops to wet bulb temperature of outside ambient air at 17.7°C.

$$m_w = \frac{(12.7 - 7)g.kg^{-1}}{3600\ s} \times 61.098\ kg = 0.0967\ g.s^{-1} = 9.67 \times 10^{-5}\ kg.s^{-1}$$

$$m_a(h_a - h) = 0.01697\ kg.s^{-1}(50 - 20.5)kJ.kg^{-1} = 0.5006\ kW$$

$$m_w c_{pw}(T_a - T) = 9.67 \times 10^{-5}\ kg.s^{-1} \times 4.18\ kJ.kg^{-1}°C^{-1}(32 - 12)°C = 0.0081\ kW$$

$$P_a = 0.5087kW \approx 0.51\ kW$$

Heat from operators and lights

The operators or people who pack and unpack tomatoes in the storage chamber release heat and the lights, which are switched on during packing and unpacking of product. Miscellaneous heat loads are the heat loads generated by labour, equipment such as fans, electric motor and lights. Heat evolved by operators and lights is obtained by assuming that two operators will enter the cooling chamber at a time as it is relatively small and the chamber will only have one light of 60 W. Each operator will spend four hours loading and unloading crates and one person produces about 1000 kJ.hr^{-1}.

$$Q_{O\&L} = \frac{Q}{3600 \times n} \qquad (7.8)$$

Q = Total amount of heat that lights and operators release in the chamber [kW], and

n = number of hours per day [hours],

Heat evolved by operators and lights is determined as:

$$Heat\ generated\ by\ operators\ \ during\ packing\ and\ unpacking = 2 \times 1000 \times 4$$
$$= 8000\ kJ$$

$$Then\ the\ rate\ of\ heat\ removal\ = \frac{8000kJ}{16 \times 3600} = 0.14\ kW$$

In addition, the heat due to lighting

$$Heat\ of\ the\ 60W\ bulb = 60\ W = 0.006\ kW$$

Total heat due to lights and operators is:

$$\text{Total heat due to lights and operators} = 0.14 + 0.006 = 0.20\ kW$$

Table 7.5 Maximum design cooling load

Heat source	Day 1	Day 2	Total
Sensible heat (containers)	0.27 kW	0.016 kW	0.287 kW
Field heat (tomatoes)	4.504 kW	0.265 kW	4.769 kW
Heat of respiration	0.577 kW	0.319 kW	0.896 kW
Wall and roof heat gain	0. 637 kW		0. 637 kW
Floor heat gain	0. 544 kW		0. 544 kW
Air-change load	0.509 kW		0.509 kW
Lights	0.06 kW		0.06 kW
Labour	0.14 kW		0.14 kW
Fan	0.38 kW		0.38 kW
Total			8.22 kW

The same procedure was used to calculate the heat load when the storage chamber is filled to one third of its capacity on the first day. Table 7.6 shows the cooling loads for one-third capacity.

Table 7.6 Cooling load at one-third capacity

Heat source	Day 1	Day 2	Total
Sensible heat (containers)	0.090 kW	0.005 kW	0.095 Kw
Field heat (tomatoes)	1.501 kW	0.088 kW	1.589 kW
Heat of respiration	0.192 kW	0.106 kW	0.298 kW
Wall and roof heat gain	0. 637 kW		0. 637 kW

Floor heat gain	0. 544 kW	0. 544 kW
Air-change load	0.509 kW	0.509 kW
Lights	0.06 Kw	0.06 kW
Labour	0.14 Kw	0.14 kW
Fan	0.38 Kw	0.38 kW
Total		4.252 kW

Design load = 1.1 × Actual load (Thompson, 2004), therefore design load is calculated as:

$$Design\ load\ = 1.1\ \times 4.252\ kW\ = 4.677\ kW$$

7.6 APPENDIX 7.6: Determination of ventilation rate and fan selection

Mechanical ventilation systems using fans and air inlets and outlets are required for temperature regulation in the storage chamber. In the psychrometric unit, the fan attached to the indirect heat exchanger evaporates water from the cooling pads by blowing air across the pads thus creating an evaporative cooling effect. The second ventilation fan at the inlet of the storage chamber blows out warm and wet air whilst introducing cool and dry fresh air. The ventilation rate V is calculated from equation 7.9.

$$V = \frac{q_s}{1006\rho_{air}(T_o - T_i)} \tag{7.9}$$

Where V = ventilation rate required [$m^3. s^{-1}$],

ρ_{air} = density of air [$kg.m^{-3}$],

T_o = outside air temperature [°C], and

T_i = inside air temperature [°C],

$$V = \frac{4677\ W}{1006 \times 1.105 \times (32 - 14)} = 0.234\ m^3.s^{-1}$$

Fan selection for storage chamber

Using a ventilation rate of 0.234 m^3. s^{-1} a 308,7/6-6/P3HL/25/PA @1.440min-1 @ 100% Immersion fan was selected that provides an air-flow rate of 0.278 m^{-3}s^{-1} at static pressure of 68.27 Pa with a power rating of 0.290 kW and air velocity of 3.6 m. s^{-1}. Its performance curve is shown in Figure 7.5 below.

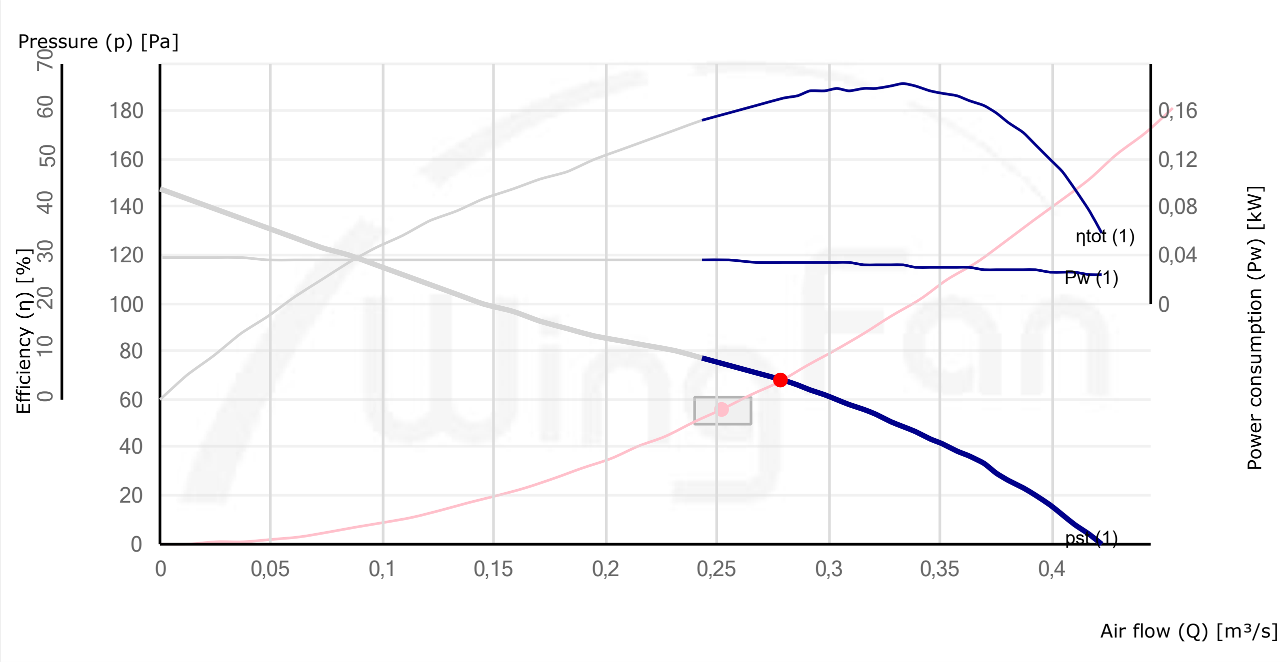


Figure 7.5 Performance curve for evaporative cooling fan

7.7 APPENDIX 7.7: Evaporative cooling pads design

The amount of cooling required, the required airflow rate and the air velocity have already been determined in Appendix 7.4 and Appendix 7.5 and face velocity was obtained from literature. To size the cooling pads equation 7.10 determines the area of cooling pads:

$$A_p = \frac{Q}{v} \tag{7.10}$$

Where A_p = cooling pad area [m^2],

Q = volumetric flow rate [m^3. s^{-1}], and

v = recommended face velocity [m.s^{-1}].

Assuming a face velocity of 1.5 m. s^{-1} and a cooling pad thickness is 0.15 m. In Appendix 7.5, Q was determined as 0.234 m^3. s^{-1}.

$$A = \frac{0.234\, m^3.s^{-1}}{1.5\, m.s^{-1}} = 0.156\ m^2$$

The available cooling pads are size standardized with options of choosing from: Height: (500 mm, 600 mm, 900 mm,1000 mm) +(30 mm height Water distribution pad), Width: (300 mm, 600 mm) and Thickness: (50 mm, 75 mm, 100 mm, 150 mm). From the available cooling pad sizes the smallest option will provide 0.5 m x 0.3 m = 0.15 m^2 which is very close to what is required.

Alternatively using coal that was readily available

$$If\ it\ is\ assumed\ that\ \ A\ =\ L \times W \qquad 7.11$$

Where L = length of cooling pad [m], and

W = width of cooling pad [m].

In choosing square shaped cooling pads implies that the length and width are the same

$$Then\ L = W = \sqrt{0.156\ m^2} = 0.395\, m\ {\sim}0.40\, m$$

The pad volume and amount of charcoal required, assuming a bulk density of charcoal of 200 kg.m^{-3} are derived from equations 7.12 and 7.13:

$$V\ =\ A \times t \qquad (7.12)$$

Where V = volume of each cooling pads [m^3],

A = air flow area [m^2], and

t = thickness of the cooling pads [m].

$$V\ = 0.156\, m^2\ \times\ 0.15\, m\ =\ 0.0234\, m^3$$

Mass of charcoal per cooling pad is given by equation 7.13:

$$m =\ V\ \times\ \rho \qquad (7.13)$$

Where m = mass of charcoal per cooling pad [kg]

V = volume per cooling pad [m^3]

ρ = bulk density of charcoal [kg.m^{-3}]

$$m\ \ = 0.0234\, m^3 \times 200\ kg.m^{-3} = 4.68 \text{ kg}$$

7.8 APPENDIX 7.8: Determination of head losses and pump selection

Centrifugal pumps deliver water to the cooling pads. Centrifugal pumps handle small discharges and small heads such as the discharge found for this evaporative cooling unit. The required discharge was 0.115 $m^3.hr^{-1}$ and the total head against which the pump must discharge was 3.33 m and a net positive suction head of 8.31 m. The power requirement for the pump was determined as 0.072 kW. From these specifications, the smallest pump in the local market satisifying the requirements were Pedrollo PVm 55 centrifugal pump supplied complete with a 0.26 kW motor.

The total head against which the pump must discharge

$$H_T = H_S + H_{FS} + H_D + h_{FD} + H_{EX} \tag{7.14}$$

Where H_T = total head against which the pump must discharge [m],

H_S = static suction lift [m],

h_{FS} = head loss due to friction in the suction pipe [m],

H_D = static delivery lift to the discharge point into the water distribution bath at the top of the cooling pads [m],

h_{FD} = friction losses in the delivery pipe [m], and

H_{EX} = Pressure loss in the heat exchanger [m]

Discharge = 0.117 $m^3.hr^{-1}$,

H_S = 0.72 m,

H_D = 1.1 m (maximum),

h_{FD} = 50 Pa. m^{-1} for a 15 mm pipe delivering 0.117 $m^3.hr^{-1}$ (Figure 7.3) and delivery pipe length is 3.3 m.

$$h_{FD} = 50\ Pa.m^{-1} \times 3.3\ m \times \frac{10\ m}{100\ 000} = 0.0165\ m$$

h_{FS} = 50 Pa. m^{-1} (from Figure 7.3) and suction pipe length is 0.7 m

$$h_{FS} = 50\ Pa.m^{-1} \times 0.7\ m \times \frac{10\ m}{100\ 000} = 0.0035\ m$$

H_{EX} = 0.7 m (From Table 7.3) Specifications for Lytron Heat Exchangers)

The pump head losses are summarized in Table 7.7.

Table 7.7 Pump head losses

Component	Head loss (m)
Heat exchanger	0.7
Delivery pipe friction	0.0165
Static delivery lift	1
Suction pipe friction	0.035
Suction pipe lift	0.7
Total head loss	2.5 m

Net positive suction head for the pump (NPSH) available:

$$NPSH_{available} = h_d - h_f - h_{vp} - h_s \tag{7.15}$$

Where h_d = atmospheric pressure [m],

h_f = suction line losses [m],

h_{vp} = vapour pressure of water [m], and

h_s = static suction head [m]

At Pietermaritzburg elevation of 750 m, $h_d = 9.4$ m and $h_{vp} = 0.32$ m for water at 25 °C.

$$NPSH_{available} = 9.4\ m - 0.075\ m - 0.32\ m - 0.7\ m = 8.31\ m$$

Pump Power Requirements

$$P = \frac{\rho \times g \times H \times Q}{36\,000 \times \eta} \tag{7.16}$$

Where P = pump power requirement

ρ = density of water (kg.m^{-3})

g = acceleration due to gravity (kg.m. s^{-2})

H = head required (m)

Q = flow discharge (m^{3}.hr^{-1})

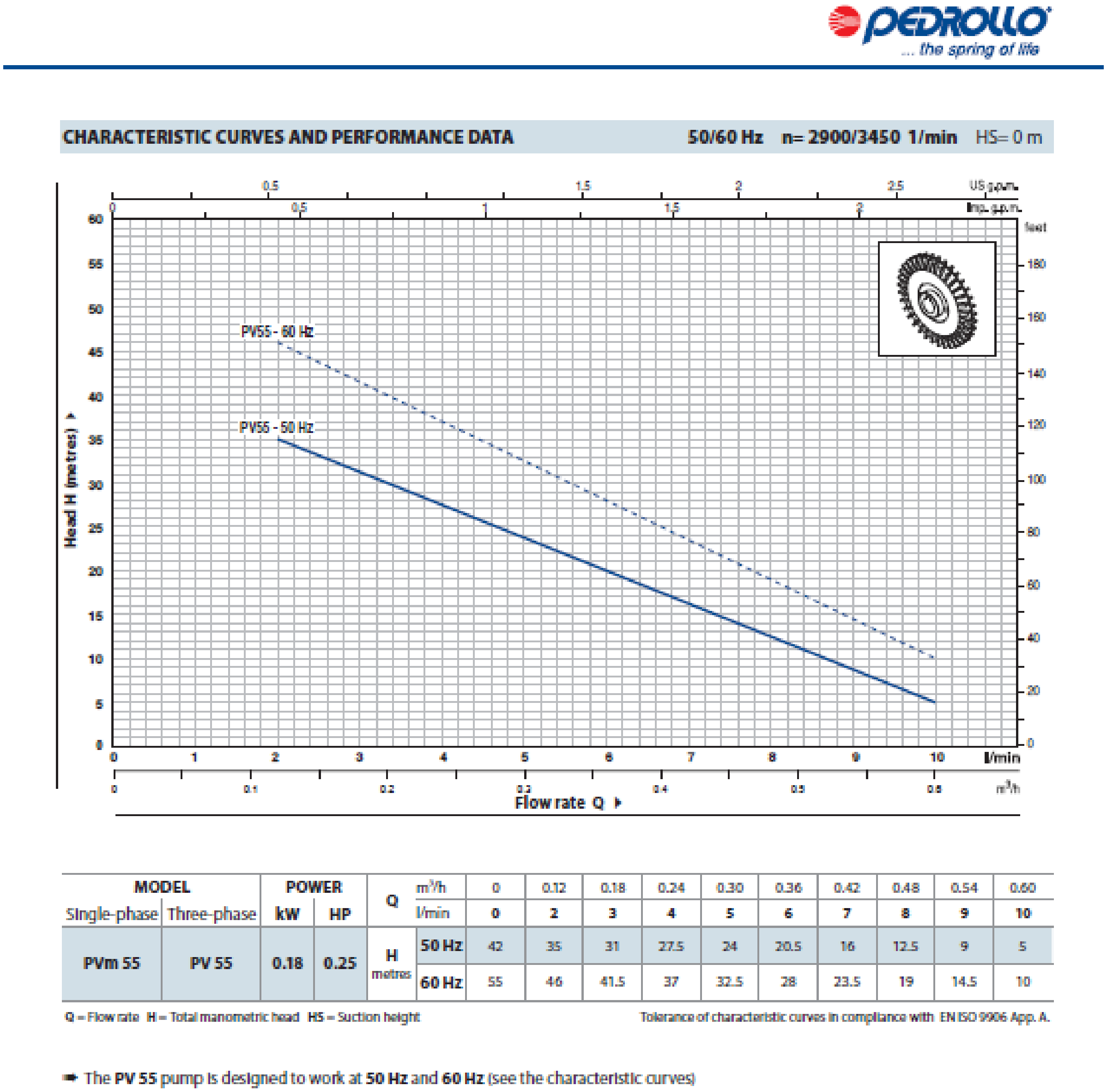
η = pump efficiency,

$\eta = 0.84$

$$P = \frac{1000 \times 9.81 \times 2.3 \times 0.115}{36\,000 \times 0.84} = 0.086\ kW$$

The pump selected was a Pedrollo PVm 55.

Figure 7.6 Pump characteristic curves and performance data



PEDROLLO ... the spring of life

CHARACTERISTIC CURVES AND PERFORMANCE DATA **50/60 Hz** **n= 2900/3450 1/min** HS= 0 m

MODEL		POWER		Q	m³/h	0	0.12	0.18	0.24	0.30	0.36	0.42	0.48	0.54	0.60
Single-phase	Three-phase	kW	HP		l/min	**0**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
PVm 55	**PV 55**	**0.18**	**0.25**	H metres	**50 Hz**	42	35	31	27.5	24	20.5	16	12.5	9	5
					60 Hz	55	46	41.5	37	32.5	28	23.5	19	14.5	10

Q = Flow rate H = Total manometric head HS = Suction height

Tolerance of characteristic curves in compliance with EN ISO 9906 App. A.

➠ The **PV 55** pump is designed to work at **50 Hz** and **60 Hz** (see the characteristic curves)

7.9 APPENDIX 7.9: Primary fan specifications

A fan with the specifications shown in Table 7.8 was mounted on the storage chamber with the centre at 492.5 mm above the floor and 2.252 m from the far-left end corner.

Table 7.8 Primary Fan Specifications

Economy Code	Power Rating (kW)	Flow Rate (m^3. s$^{-1)}$	Size (mm) H × W × Ø	Grill Code
OW354	0.12	0.25	340 × 340 × 260	OW595

Unlike the rest of the psychrometric unit components, the fan was directly mounted on the storage chamber after which the psychrometric unit was aligned and attached to the side of the storage chamber. The primary fan was working on the South African standard frequency and voltage (50 Hz, 220 volts) while a transformer was necessary for the secondary fan to drop the voltage from 240 V to 220 V.

7.10 APPENDIX 7.9: Heat exchanger design calculations

The following image shows the enclosure for the heat exchanger and the cooling pads.

The psychometrics unit tunnel constructed from M14-20 indirect heat exchanger and three direct cooling pads (Pad 1, 2 and 3) (a) structural schematic, (b) arrangements

$$Q = UA\Delta T = \dot{m}C_p(T_{ai} - T_{ao}) \tag{7.17}$$

$$\dot{m} = \frac{V}{\rho} \tag{7.18}$$

Where V = required ventilation rate [m^3. s^{-1}],

ρ = density of air [kg.m^{-3}],

C_p = specific heat capacity of air at inlet [kJ.kg^{-1}. °C^{-1}],

T_{ai} = temperature of air at the inlet section of the heat exchanger [°C],

T_{ao} = desired temperature of exiting air [°C], and

$\dot{m}$ = mass flow rate of air [kg. s^{-1}]

$\rho = 1.020$ kg.m^{-3}

C_p= 1.006 kJ.kg^{-1}. $°C^{-1}$

V = 0.234 m^3. s^{-1}

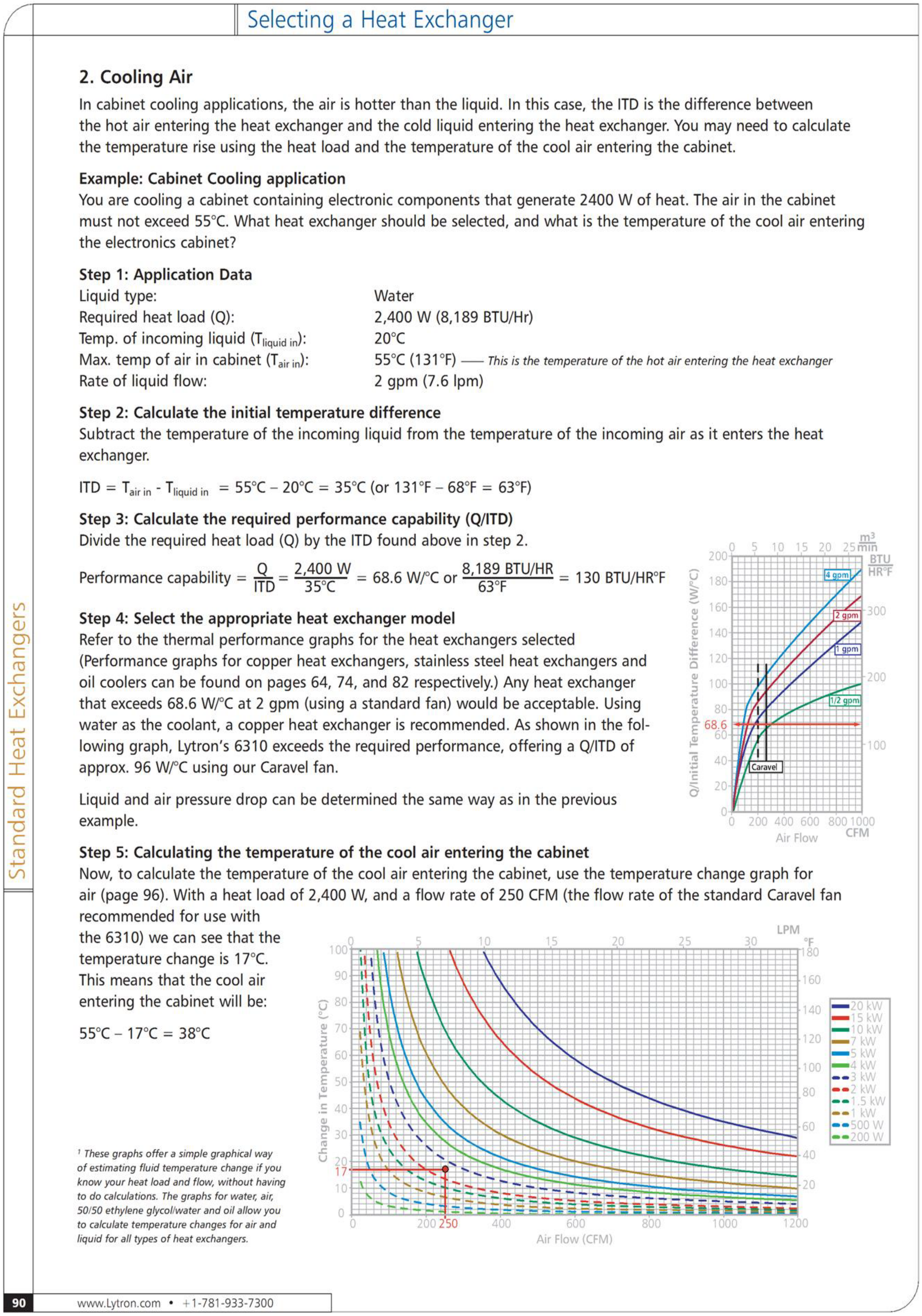
T_{ai}-T_{ao} = 32°C - 25°C = 7°C

$$Q = 0.234\ \mathrm{m^3 s^{-1}} \times 1.020\ \mathrm{kg.m^{-3}} \times 1006\ \mathrm{J.kg^{-1}.°C^{-1}} \times 7\ \mathrm{°C}$$
$$= 1681\ \mathrm{W}$$

The heat exchanger was selected according to the heat exchanger selection procedure for Lytron heat exchangers (Figure 7.6).

$$\frac{Q}{ITD} = \frac{1342\ W}{(32-25)\mathrm{°C}} = 192\ W.\mathrm{°C}^{-1}$$

Where ITD = initial temperature difference (inlet air temperature – inlet water temperature). From Lytron heat exchanger catalogue specifications in Figure 7.6, model number M14–120 was selected. From the performance graphs for M14 - 120 in Figure 7.6, the pressure drop of water flowing in the heat exchanger was found to be 0.7 m.



Selecting a Heat Exchanger

Standard Heat Exchangers

2. Cooling Air

In cabinet cooling applications, the air is hotter than the liquid. In this case, the ITD is the difference between the hot air entering the heat exchanger and the cold liquid entering the heat exchanger. You may need to calculate the temperature rise using the heat load and the temperature of the cool air entering the cabinet.

Example: Cabinet Cooling application

You are cooling a cabinet containing electronic components that generate 2400 W of heat. The air in the cabinet must not exceed 55°C. What heat exchanger should be selected, and what is the temperature of the cool air entering the electronics cabinet?

Step 1: Application Data

Liquid type:	Water
Required heat load (Q):	2,400 W (8,189 BTU/Hr)
Temp. of incoming liquid ($T_{\text{liquid in}}$):	20°C
Max. temp of air in cabinet ($T_{\text{air in}}$):	55°C (131°F) —— *This is the temperature of the hot air entering the heat exchanger*
Rate of liquid flow:	2 gpm (7.6 lpm)

Step 2: Calculate the initial temperature difference

Subtract the temperature of the incoming liquid from the temperature of the incoming air as it enters the heat exchanger.

$$\text{ITD} = T_{\text{air in}} - T_{\text{liquid in}} = 55°\text{C} - 20°\text{C} = 35°\text{C (or } 131°\text{F} - 68°\text{F} = 63°\text{F)}$$

Step 3: Calculate the required performance capability (Q/ITD)

Divide the required heat load (Q) by the ITD found above in step 2.

$$\text{Performance capability} = \frac{Q}{\text{ITD}} = \frac{2{,}400\ \text{W}}{35°\text{C}} = 68.6\ \text{W/°C or } \frac{8{,}189\ \text{BTU/HR}}{63°\text{F}} = 130\ \text{BTU/HR°F}$$

Step 4: Select the appropriate heat exchanger model

Refer to the thermal performance graphs for the heat exchangers selected (Performance graphs for copper heat exchangers, stainless steel heat exchangers and oil coolers can be found on pages 64, 74, and 82 respectively.) Any heat exchanger that exceeds 68.6 W/°C at 2 gpm (using a standard fan) would be acceptable. Using water as the coolant, a copper heat exchanger is recommended. As shown in the following graph, Lytron's 6310 exceeds the required performance, offering a Q/ITD of approx. 96 W/°C using our Caravel fan.

Liquid and air pressure drop can be determined the same way as in the previous example.

Step 5: Calculating the temperature of the cool air entering the cabinet

Now, to calculate the temperature of the cool air entering the cabinet, use the temperature change graph for air (page 96). With a heat load of 2,400 W, and a flow rate of 250 CFM (the flow rate of the standard Caravel fan recommended for use with the 6310) we can see that the temperature change is 17°C. This means that the cool air entering the cabinet will be:

55°C – 17°C = 38°C

[1] *These graphs offer a simple graphical way of estimating fluid temperature change if you know your heat load and flow, without having to do calculations. The graphs for water, air, 50/50 ethylene glycol/water and oil allow you to calculate temperature changes for air and liquid for all types of heat exchangers.*

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Figure 7.7 Selection procedure for Lytron heat exchanger