

*Review*

# Potential causes of postharvest losses, low-cost cooling technology for fresh produce farmers in Sub-Saharan Africa

Sipho Sibanda<sup>1\*</sup> and Tilahun Seyoum Workneh<sup>2</sup>

<sup>1</sup>Agricultural Research Council, Institute for Agricultural Engineering, Pretoria, South Africa.

<sup>2</sup>School of Engineering, University of KwaZulu Natal, Pietermaritzburg, South Africa.

Received 10 January, 2020; Accepted 17 February, 2020

The aim of this review was to identify the causes of postharvest losses (PHL) in fruit and vegetables 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 and lack access to postharvest facilities. When these factors are contained, sufficient supplies of fresh produce reach the consumer and improve nutrition, income and food security at household level. This article described the PHL experienced by farmers along the cold chain and explored the advantages and disadvantages of the use of various cooling technologies. There are already existing modern cooling technologies but these are capital intensive and require electricity, which is not always available to small-scale farmers (SSF). This review proposes evaporative cooling as appropriate for SSF in SSA as it has proven to be effective under hot and dry areas and is a simpler and cheaper technology. The review recommends that with the incorporation of a desiccating unit, evaporative cooling could be extended to hot and humid areas. Solar and wind energy can be used to power the desiccating unit in remote and isolated areas with no access to grid electricity. Therefore, research needs to be carried out on developing or adapting a solar or wind powered evaporative cooling system under both hot-dry and hot-humid conditions.

**Key words:** Fruit and vegetables, low-cost cooling, postharvest technology, renewable energy, small-scale farming.

## INTRODUCTION

Sub-Saharan Africa (SSA) has potential for fruit and vegetables (FV) production as there has been annual increases in price and quantities produced in the last five to ten years (Sibanda, 2019). 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

\*Corresponding author. E-mail: [sibandas@arc.agric.za](mailto:sibandas@arc.agric.za).

**Table 1.** Vegetable production per (1000t) and their average prices at major fresh produce market for 2010 and 2015 (DAFF, 2016).

Parameter	Vegetables production (1000t)		Average price at major fresh produce market (R/t)	
	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
Cauliflower	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

et al., 2012). Small-scale farmers (SSF) on the other hand on average own small land holdings of less than 1.5 ha and are characterized by low output and very little investment in infrastructure for production (Tscharrntke et al., 2015). Despite these setbacks, SSF contribute approximately 80% of all FV farming activities in SSA (OECD/FAO, 2016).

The increasing population and shifts in consumer demand have resulted in an exponential demand and price hikes for fresh FV in SSA (Ntombela, 2012). For example, the demand has seen annual price increases in horticulture of 7% in South Africa (SAYB, 2015) and generally increased fresh produce quantities from 2010 to 2015 as shown in Table 1. This scenario should improve farmers' living conditions including health and income while at the same time ensuring food security at household level. An increasing demand for fresh produce at the right prices is likely to move SSF from subsistence to commercial scale farming. The greatest challenge constraining rural households from attaining commercial farming status is the quality deterioration experienced in the production cycle of fresh produce (Nkolisa et al., 2018). 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. However, in SSA appropriate post-harvest technologies for SSF have not been developed or adapted for the proper handling of perishable commodities (Cherono et al., 2018). With no appropriate postharvest facilities, which may include packaging, cooling technologies during storage and transportation, food security is threatened. The traditional peddling of fresh produce at farm gate at low prices to avoid losses is not an enduring solution as it ultimately undermines sustenance (Saran et al., 2012; Cherono and Workneh,

2019).

Furthermore, the fact that most SSF are located in remote areas with no access to grid electricity and have poor road infrastructure connecting them to major towns, hinders growth and productivity in small-scale farming (Kim and Ferreira, 2008; Korir et al., 2017). Small-scale farmers are in many instances forced to sale their produce to intermediaries (middle-men) that offer them low prices rendering their enterprises unprofitable (Cherono and Workneh, 2019; Sibanda, 2019).

Although there are a number of modern cooling technologies developed and imported into the region, SSF have not been able to adapt and utilise such facilities as they are both capital and energy intensive (Ejeta, 2009; Nkolisa et al., 2019). Despite the numerous researches on both production and postharvest handling of commodities in the region, there is less adaption or application of the research results to solve the post-harvest handling problems under SSA conditions particularly for small-scale farming (Stathers, 2017). Therefore, in order to discuss appropriate low cost cooling technologies this review has found it necessary to explore causes mainly related to postharvest physiology of crops since cooling mainly applies to slowing down respiration and ethylene production and the extent of postharvest losses (PHL). The review further considers different types of cooling technologies and explores alternative renewable energy options available for possible integration with low-cost technologies to preserve FV accessible by SSF.

### Post-harvest losses

Postharvest losses are the quantifiable depression in a given produce during harvest or along the value chain of

**Table 2.** PHL in selected countries in SSA.

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	Masarirambi et al. (2010)

a post-harvest system (Sawicka, 2019). Fruit and vegetables are perishable commodities and highly susceptible to physiological deterioration in the supply chain, which is the primary reason of high PHL experienced in their production (Pathare et al., 2012; Singh and Sharma, 2018). Azene et al. (2011) claim that PHL have the potential to discourage farmers from venturing into production and marketing of fresh produce and thus affecting the availability and consumption of FV in mostly urban areas. Therefore, efforts that reduce PHL, particularly if they are economically feasible are of great significance to farmers and consumers alike (Miller et al., 2017). Reducing PHL, as an important component of food security, has potential to lower food prices to vulnerable communities in the region. In this food-scarce part of the world, FV not reaching the intended market are a significant waste of resources. In a survey carried out by Mashau et al. (2012) in the Tshakuma fruit market, in Limpopo province of South Africa showed that fresh fruits like bananas, oranges, avocados, paw-paws and tomatoes, experience deterioration in both quality and quantity of 43.3% mainly due to over-ripening.

Postharvest losses 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 the losses (Adeoye et al., 2009; Sibomana et al., 2016; Singh and Sharma, 2018). Postharvest losses in FV in the region estimate to over 50% though they vary from crop to crop and country to country (FAO, 2008; Kader, 2010; Mashau et al., 2012). Table 2 provides examples of estimated percentage PHL of perishable commodities for selected countries in East Africa, Central Africa, West Africa and Southern Africa. These high losses as shown in the Table 2 are a precursor to food insecurity for SSA communities. Small scale farming exporters of FV in the region have complained about these huge losses experienced during short periods of storage (awaiting transportation) and during transportation to markets and alleviation of these should be a research priority (Tigist et al., 2011).

### Causes of PHL

Maintenance of fresh produce quality requires precise application of optimum cold chain conditions from harvest, grading, packaging, storage and transportation to the consumer and this review discusses these conditions.

Postharvest losses occur due to many factors that include, environmental (Rayaguru et al., 2010), biological and chemical, physiological (Joas and Lechaudel, 2008), as well as technical factors (Kader, 2010). The main environmental factors that result in significant PHL in FV are temperature and relative humidity (Prusky, 2011; Bradford et al., 2018). The biological and chemical factors arise because FV are prone to microbial contamination during growth, harvest and postharvest operations (Ambaw et al., 2013a). Physiological deterioration of fresh produce happens since FV are living tissues (Sitorus et al., 2018). So, as lively tissues the produce continues to transpire, respire and further ripen even after they have been detached from the mother plant during harvesting (Ngcobo et al., 2012; Gupta and Dubey, 2018). As the anaerobic process continues, it in turn increases respiration further with even more heat generation either inside or outside the fruit. This sustained respiration in fresh produce means decreased food value, associated with loss of flavour, loss of saleable weight (through loss of moisture), and more rapid deterioration (Ait-Oubahou, 2013). The technical factors that affect fresh produce quality are mainly associated with mechanical damage or injury to FV (Paull and Duarte, 2011), lack of skilled labour in handling of fresh commodities (Beckles, 2012) and prolonged storage time (Wilson et al., 1999).

Controlling these factors provides improved efficiency of broader value chains and systems in fresh produce (Sawicka, 2019). On the other hand, social factors are associated with trends such as urbanization, where many people from rural areas move to large cities causing a high demand for FV at urban centres, thus increasing the need for more efficient supply-chains (Parfitt et al., 2010). 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.

### Losses during harvesting and packaging

Harvest-labour should be skilled to know when to harvest the produce, as it is an essential requirement of industrial postharvest handling (Beckles, 2012). According to Bachmann and Earles (2014), harvesting of fresh

produce should take place during the coolest part of the day, either early in the morning or in late afternoon. Harvesters also should be trained on how to handle the crop carefully to avoid injury; harvesting dry whenever possible and at proper maturity; handling each produce no more than is necessary, while at the same time avoiding careless handling e.g. dropping fresh produce (Prusky, 2011). Therefore, farmers have to exercise good harvesting practices that will not result in mechanical injury to fresh produce.

Van Zeebroeck et al. (2007) described mechanical damage as posing a challenge to the quality of fresh produce and having a potential to reduce the value of FV. According to Basediya et al. (2011), mechanical injury due to impact when produce is dropped/tossed during harvesting can result in 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, which may lead to a shorter shelf life (Tijskens, 2007). Mechanical damage to FV may result from inappropriate packaging or containers and over or under packaging of containers (Vigneault et al., 2009; Mashau et al., 2012). Packaging should ensure that produce is loaded into convenient units for handling during distribution, storage and marketing (Wills et al., 2007). However, many SSF in production of tomatoes utilise traditional baskets as packaging material (Ugonna et al., 2015). Whenever fresh produce is loaded in baskets/plastic crates, it applies a static load on itself (Adeoye et al., 2009). The static load results 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 (Ugonna et al., 2015). This scenario occurs when baskets are used or when there is over-packaging. In under-packaging, the movement of fresh produce in the container is high, resulting in collision that damages the fruit (Prusky, 2011). In some instances, these plastic crates have rough internal surfaces, which can injure FV by contact (Sibomana et al., 2016).

Another cause of losses during harvesting and packaging is due to physiological deterioration of fresh produce as they continue respiration and ripening. The respiration rate of a product strongly determines its transit and postharvest life (Yahia, 2011). The higher the temperature at harvest, the higher the respiration rate will be, resulting in reduced shelf life (Sandhya, 2010).

### **Causes of losses during on-farm storage and transportation**

Fruit and vegetables in some instances are stored at the farm gate for extended periods until either transport to the market becomes available or local buyers/market purchase the produce for consumption or resale (Hardenburg

et al., 1986). Often the transport and local markets are without temperature-controlled environmental conditions resulting in further deterioration of fresh produce (Kitinoja and Thompson, 2010). In circumstances where on-farm storage and transportation facilities are not kept at below optimum environmental conditions, the ripening of FV continues resulting in physiological deterioration as fruit rot organisms spread most rapidly at warm storage temperatures and low relative humidity (Maliwichi et al., 2014; Sibomana et al., 2017). Physiological, chemical and enzymatic changes are speeded up when fresh produce is subjected to high ambient temperature and low relative humidity during temporary storage and transportation at the back of trucks (Fadeyibi and Osunde, 2011; Chijioke, 2017).

In some instances, the ambient temperatures in SSA especially in tropical and sub-tropical climates can be 7-20°C higher than the recommended 15°C for tomatoes (Kitinoja and AlHassan, 2012; Tolesa and Workneh, 2017). These two environmental factors can result in a significant loss of nutritional value, decreased returns due to poor produce quality (wilting, shrivelling), loss of saleable weight and in many cases the whole fruit or vegetable is lost (Odesola and Onyebuchi, 2009). Respiration rate, metabolic processes and ethylene biosynthesis of some fruits increase with air/room temperature within a given range (Workneh, 2010). Respiration rates can double, triple or even quadruple with every increase in temperature (Zagory and Kader, 1988). Therefore, the storage of FV at low temperature immediately after harvesting will reduce the rate of decomposition and microbial spoilage (Workneh and Osthoff, 2010). Fresh produce shelf life can double by reducing temperature from 10 to 5°C (Sun and Zheng, 2006). Typically, the storage temperature of FV is 0 to 12°C and most tropical and subtropical fruits require high temperatures of 5 to 13°C according to (Paull and Duarte, 2011) and as shown in Table 3.

Relative humidity is another important aspect considered during storage and transportation of FV. Occurrence of high humidity during temporary storage and transportation of fresh produce reduces water loss, helping FV maintain weight, appearance, nutritional quality and flavour, while wilting, softening and juiciness are reduced (Laguerre et al., 2013). According to Cantwell et al. (2009), the recommended storage relative humidity for most horticultural crops is 70 to 95%. Table 3 provides a summary of recommended storage relative humidity for selected FV. Most fresh produce under small scale production are stored at relative humidity levels lower than recommended resulting in excessive moisture loss (Singh et al., 2014). Subsequently, the FV suffer wilting, shrivelling and dryness resulting from small moisture losses of 3-6% (Nunes et al., 2009; Okanlawon and Olorumisola, 2017). These changes affect marketability of produce or economic value especially if FV are sold by weight (Yahia, 2011). Usually weight loss

**Table 3.** Optimum storage temperature and relative humidity of selected vegetables (Adopted from Krishnakumar, 2002).

Product	Optimum Temperature (°C)	Optimum relative humidity (%)
Broccoli	0	90-95
Cabbage	0	98-100
Lettuce	0	90-100
Carrots	0	98-100
Tomatoes	13-15	≥ 85
Guava	5-10	90
Mango	13	85-95
Potatoes	5-16	90-95
Onions	1-2	65-70
Garlic	0	65-70
Banana (green)	13-14	90-95
Cucumber	10-13	95

from perishable commodities is high if surrounding air temperature, flesh moisture content and temperature is high. Thus, under poor postharvest management conditions of storage or in transit, perishable commodities lose excessively large weight (Workneh, 2010).

Among other key contributors to high PHL in fresh produce are demographic and socio-economic characteristics of small-scale FV producers. Small-scale farmers have to travel to cities to sale their fresh produce and due to lack of transport; they tend to keep FV over long periods at the farm gate awaiting transportation to markets (Kader, 2003). When the waiting period at the farm gate is prolonged, there is further mechanical damage to produce due to over handling (Knee and Miller, 2002). The damaged FV allow easy penetration of microbial population into the tissue increasing chances of decay and growth of microorganisms (Fadeyibi and Osunde, 2011). As packaged produce applies static load on itself the degree of deformation on FV will depend on the period the static load is applied (Sirisomboon et al., 2011). 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 (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 (Kereth et al., 2013). For SSF in SSA, trucks that pick up produce are 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 FV to the market (Sibanda, 2019). To eliminate this challenge, it is required that the duration between harvest and arrival at the markets be minimized (Sibomana et al., 2017)

### Research in cold chain technologies and their 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 down the product but to do so as quickly as possible after harvest (Paull, 1999). A cold chain is a temperature-controlled supply chain consisting of uninterrupted range of systems that monitor or maintain produce at a given temperature and keeps history (Aung and Chang, 2013). 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. It is clear, however, that in SSA the challenges to be addressed go beyond whether or the fact that no cooling technologies exist. For SSF producing FV other factors come into play like volume cooled per day, harvest temperature versus recommended storage temperature, capital and operating costs (Azene et al., 2011). 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). Availability of electricity is one of the critical factors to consider as an energy input to power cooling technologies (Kitinoja et al., 2011).

Possible areas of consideration should allow low energy cool storage facilities so that fresh produce reaches markets at recommended storage conditions (Chaudhari et al., 2015). 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 FV immediately after harvest. These cooling methods include among others, mechanical refrigeration (James et al., 2009; James and James, 2011), hydro-cooling (ASHRAE, 2011; Ambaw et al., 2013b), evaporative cooling (Ambaw et al., 2013b) and vacuum cooling (Wang and Sun, 2001; Zheng and Sun, 2006).

## Performance of various types of cooling technologies

Mechanical refrigeration, forced air cooling, vacuum cooling, hydro-cooling and evaporative cooling of fresh produce have previously been described in detail by reviews that include Brosnan and Sun (2001) and Thompson et al. (1998) who placed emphasis to the different performance parameters of various cooling methods. Mechanical refrigeration refers to the process where heat absorption takes place at one point and heat dispersion at the other (Moureh et al., 2009). 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). The compressor can be powered through an electric motor. The refrigeration system is energy intensive as electricity power is consumed throughout the cold chain (Hera et al., 2007b). 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). However, where there is a ready and cheaper supply of electricity, mechanical refrigeration is the most reliable cooling technology (Kitinoja and Thompson, 2010).

Hydro-cooling is a fast, uniform cooling process of removing field heat from freshly harvested FV by bathing in chilled water or running cold water over it (Gomez-Lopez, 2012). Since the produce will be at higher temperature immediately after harvest, the heat movement takes place from the produce to the water leading to cooling (Rennie et al., 2003). 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 serves as a means of cleaning at the same time. Hydro-cooling reduces, water loss as the product is bathed in water, the rates of microbiological and biochemical changes in order to prevent spoilage and maintain quality and increase shelf life (Gustavsson et al., 2011). However, hydro-cooling has limitations in that 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 (Bachmann and Earles, 2014).

Vacuum cooling is a rapid evaporative cooling method for porous and moist foods to meet the special cooling requirements (Zhang and Sun, 2006). In this case cooling obtains by evaporation of moisture from the surface and within the produce (Sun and Zheng, 2006). Evaporation is encouraged and made more efficient by reducing the pressure to the point where boiling of water takes place at low temperature. 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). 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). The speed and efficiency of vacuum cooling relate to the ratio between the 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 cannot be damaged by the removal of such water.

Evaporative cooling or humidification of surrounding air in FV storage involves the use of principles of moist air properties or psychometrics (Workneh, 2007; Shahzad et al., 2018). In this system, 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). Evaporative cooling provides cool 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. Evaporative cooling is regarded as a low-cost cooling system requiring no electricity input in a passive system or just an electric fan in a forced air system (Tigist et al., 2011; Chijioke, 2017; Sibanda and Workneh, 2019). Evaporative cooling has been reported for achieving a favourable environment in storage structures for FV 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 (Chaudhari et al., 2015). In the work done by Anyanwu (2004) evaporative cooling increased, the shelf life of tomatoes by a factor of three above open-air storage values.

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. Regrettably, 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 discussed in the next section.

## Selection of a suitable cooling technology for different fruits and vegetables

Where there is, uninterrupted electricity supply, investment capital is not limited to cover purchase and

**Table 4.** Summary of advantages, disadvantage and characteristics of different cooling technologies

Cooling technology	Advantages	Disadvantages	Performance characteristics	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°C below ambient; Can achieve relative humidity of 90%; Can increase shelf life from 3 days to 15 days. Typical cooling time is 40-100 h in passive cooling and 20-100 hours in fan-ventilated systems.	Mordi and Olorunda (2003) Anyanwu (2004) Basediya et al. (2011) Chaudhari et al. (2015) Tigist et al. (2011)
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; not suitable for products that do not tolerate wetting; not suitable for products that can be damaged by falling water; water left on surface can lead to fungus growth or discoloration; capital cost is relatively high; the equipment is not portable	Cooling can be achieved in 20-30 min; 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°C depression;	Wills et al. (2007) Brosnan and Sun (2001) Rennie et al. (2003) Prusky (2011)
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 decay contamination; equipment is portable.	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 temperature there is 1% weight loss;	Turk and Celik (1993) Kim et al. (1995) Ito et al. (1998) Brosnan and Sun (2001) Rennie et al., (2003)

cost of installation, availability of technical skills to maintain and run the facility, mechanical refrigeration would be the ideal cooling system (Basediya et al., 2011). However, mechanical refrigeration is not suitable for several FV; for example, banana, plantain, tomato etc. cannot be stored in the domestic refrigerator for a long period as such produce is susceptible to chilling injury (Chinenye, 2011). A small scale commercial mechanical refrigeration system with a capacity of one tonne complete and ready for use in the USA will cost about US\$7000 for 3.5 kW (Kitinoja and Thompson, 2010). This cost is way above what most SSF in the region can afford for a cooling capacity of one tonne. Table 4 describes the advantages; disadvantages and the performance characteristics of evaporative cooling, vacuum cooling

and hydro-cooling. The selection of suitability of each cooling technology for a certain crop will depend on such performance characteristics and parameters.

Hydro-cooling, is only suitable for leafy produce and has other limitations of low energy efficiency, requirement of expensive water resistant containers to avoid cross decay contamination (Thompson et al., 1998; Vigneault et al., 2000). The application of hydro-cooling by SSF will be 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). Vacuum cooling 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). Any cooling method unsuitable for tomatoes would

be unattractive as this fruit is a major commodity grown for SSF in a number of countries in the region (Mashau et al., 2012).

Both vacuum cooling and hydro-cooling are regarded as energy intensive and expensive methods for example it would require for hydro-cooling, 110 to 150 kWh (15-22 kWh for vacuum cooling) of energy at a cost US\$22-US\$30 to cool one metric tonne of fresh produce (Kitinoja and Thompson, 2010; Rayaguru et al., 2010; Basediya et al., 2011). Vacuum cooling and hydro-cooling therefore, need to be operated for relatively longer periods in a year to justify an investment (Boyette et al., 1994). Brosnan and Sun (2001) concluded that since the vacuum chamber system for vacuum cooling was expensive then this cooling technology was only feasible for large growers who 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 like cherries for hydro-cooling and lettuce, cabbage, mushroom or produce with high surface to volume ratio for vacuum cooling (Kim et al., 1995; Thompson et al., 1998; Brosnan and Sun, 2001; Kitinoja and Thompson, 2010).

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). Sometimes farmers would often 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 is a good marketing system (Boyette et al., 1994). In developing countries where intermediaries set prices at farm gate, SSF may find themselves selling their produce below the production costs (Cherono and Workneh, 2018).

Evaporative cooling could provide a solution, as the cooling technology has low initial investment, low installation and maintenance costs and in a passive system can be set up without electricity (Nkolisa et al., 2019). It is possible to construct an evaporative cooling system of 1-2 MT at US\$1,300 at an energy use per MT of 0.7 kWh (Kitinoja and Thompson, 2010). The energy costs to cool one MT of tropical FV using evaporative cooling is \$0.14 (Kitinoja and Thompson, 2010). Evaporative cooling presents itself as an appropriate cooling technology for small-scale farming of fresh produce in SSA as it is suitable for sub-tropical and tropical FV, the volumes for cooling per farmer per unit time are not huge, the storage temperature is around 15°C. Chaudhari et al. (2015) reviewed the work done on evaporative cooling from 1987 to 2010 and concluded

that this system is not harmful to the environment, has low initial costs, can be constructed from local available material (storage chamber, cooling chamber, water tank, cooling pad media). Components that require maintenance like the motor, extraction fan and heat exchanger are repairable at low cost (Deoraj et al., 2015) and therefore, what is only left is finding relevant and cheap energy sources for its up scaling.

### **Relevance of evaporative cooling to small-scale farmers in SSA**

A number of studies have shown the attractiveness in the use of evaporative coolers by SSF in Africa as evidenced by the work of a number of authors; Anyanwu (2004) in Nigeria, Ahmed et al. (2011) in Sudan, Samira et al. (2011) in Ethiopia. The results of use of evaporative cooling have demonstrated that coolers can maintain cooling spaces at temperatures below ambient with a depression reaching 12°C (Anyanwu, 2004). In evaporative 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). Should a forced air systems be required through use of a fan, the energy requirements are low and the cooling technology is energy efficient and a possibility exists to integrate it with use of alternative energy like wind or solar energy (Sibanda and Workneh, 2020). Fossil fuels could power the cooling methods but these contribute to greenhouse gas emissions (Best et al., 2012).

### **RENEWABLE ENERGY USE IN POSTHARVEST HANDLING**

Renewable energy technologies have a high adaptation rate in many industries due to benefits related 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 (Mentis et al., 2015). The consideration of 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 (Chaudhari et al., 2015). This is especially true for remote, dispersed populations with low and scattered energy demands. 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).

The consumption of fossil fuel is the major contributor



to the greenhouse gases emitted to the atmosphere thus causing global warming (Hassan and Mohamad, 2012). Biomass is combusted for heating and cooking and is convertible into electricity (David et al., 2002). Direct combustion of biomass produces steam, which turns turbines that drive generators, producing electricity (Ayhan, 2006). 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 (Godish, 1991). Grid electrification is expensive and yet other sources of energy can meet all the energy requirements (Deveci et al., 2015). Senol (2012) recognizes 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). The 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  $5 \text{ ms}^{-1}$ , and is  $490 \text{ MJ.m}^{-2}$  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 seasonal 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). 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  $2000 \text{ kWh m}^{-2}$  (Davis and MacKay, 2013). In this region, the average solar radiation ranges between  $4.5$  to  $6.5 \text{ kWh.m}^{-2}$  for an average of  $6-7 \text{ h}$  (Fluri, 2009). This, according to Saxena et al. (2013), is enough solar radiation that is convertible to electricity. There has been application of solar energy in generating solar thermal or directly conversion to electricity through photovoltaic cells (Hassan and Mohamad, 2012). There is a lot of research work currently for absorption based refrigeration and air conditioning systems that use solar energy (Said et al., 2012). Solar energy has also been integrated with evaporative cooling by many researchers (Tiwari and Jain, 2001; Maerefat and Haghghi, 2010; Naticchia et al., 2010) for cooling of buildings. Naticchia et al. (2010) exploited both air ventilation and heat exchange by use of porous insulating material as an absorption matrix. Maerefat and Haghghi (2010) integrated a solar system employing a solar chimney with evaporative cooling 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  $200 \text{ W.m}^{-2}$  and high ambient temperature of  $40^\circ\text{C}$ . Finocchiaro et al. (2012) employed

a solar energy assisted desiccant and evaporative cooling 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.

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. 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).

### **Relevance of solar energy in evaporative cooling of fresh produce**

Best et al. (2012) estimate that energy demand for cooling processes and greenhouse gas emissions will increase by 60% by 2030 compared to 2000 levels. Kim and Ferreira (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 renewable energy because much of the continent has limited access to grid electricity (Szabo et al., 2011).

Therefore, the high-energy demands on existing power sources and global warming threats provide 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. The use of solar energy for evaporative cooling 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. The use of solar energy to power a water pump and fan is very limited and literature was not found providing evidence that wind energy has been used for evaporative cooling for fresh produce.

Evaporative cooling 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 photovoltaic solar energy to operate low-cost cooling technologies for FV has a high potential. However, engineering design especially to convert solar energy into electrical energy and the storage of this energy in a battery to run the technologies

during night remains one of the important research and development areas that need the attention of engineers. Similarly, wind energy is also suitable to provide sufficient energy to operate simple low-cost cooling technology that is appropriate for temporary storage of FV by SSF. Hence, an integrated approach of evaporative cooling and renewable energy as a source of power could be highly suitable for SSF that are engaged in production of FV 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.

## DISCUSSION

All categories of farmers' experience high PHL in SSA. The deterioration in quality of FV 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. 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. It is evident from literature that biological processes play a key role in aggravating PHL if not properly controlled. The control of temperature and relative humidity is through the introduction of appropriate cold chain storage facilities in the produce supply chain. This review identified a number of modern cooling technologies available in the market such as vacuum cooling, hydro-cooling and mechanical refrigeration. The different modern cooling technologies have inherent challenges in their application by SSF in SSA as they are energy intensive, expensive, require sustained higher volumes throughout the year and their use is specific to certain types of FV. However, this review showed that in developing countries like in SSA there is lack of access to proper cold chain storage facilities because of these aforementioned challenges.

Hence, there is a need to identify, develop or adapt appropriate low cost cold chain facilities for access by SSF. This is the only way SSF can rise from subsistence farming to commercial fresh produce production. Further, this review also recognizes that evaporative cooling is a simple and cheap method compared to conventional cooling technologies. Evaporative cooling also premises on removal of sensible heat, which makes it relatively efficient under hot and dry environmental conditions obtained in SSA. Evaporative cooling does not necessarily need an external power source as it relies on velocity of natural wind through wetted pads. Evaporative cooling is ideal, for both pre-cooling and cooling and observations are that it increases shelf life of fresh

produce. Evaporative cooling has had a big impact in cooling of buildings in Asia and is practiced by some SSF in SSA. At the same time, many SSF are practicing natural ventilated evaporative cooling as they do not have access to grid electricity to power forced air evaporative cooling.

Grid electricity is not available in remote and isolated areas in SSA, while fossil fuels as energy source have a limitation in that they emit greenhouse gases. The immediate alternative then is the use of renewable energy sources like solar and wind, which are abundant in SSA. As a result, there exists a research scope in the utilisation of wind and solar energy to support evaporative cooling of fresh produce. This integrated system could be very useful to SSF in SSA producing FV in ensuring that they rise from high PHL incurring farmers to profitable farmers who are able obtain returns enough to sustain their families. Therefore a scope exists develop an integrated system that involves renewable energy sources like solar or wind combined with a cooling technology. There is no evidence of research work on the use of wind energy as a power source for cooling technologies. However, there is potential in the use of solar energy to power non-passive evaporative cooling for buildings. These success stories in this regard provide an opportunity for the use of solar energy to power a water pump and fan to drive non-passive evaporative cooling. From the conclusions made above, the proposition is carrying out a study to develop or adapt a wind and solar powered evaporative cooling system for temporary storage and transportation of FV.

## RECOMMENDATIONS

Literature has shown that evaporative cooling is effective in hot and dry areas but 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. It is recommended that researchers incorporate a desiccating unit for sensible cooling of air before reaching the cooling pads for evaporative cooling to find expression in hot and humid areas. Therefore, from the review, researchers can consider to develop and evaluate a solar or wind energy powered evaporative cooling system combined with an indirect air-cooling unit for use in hot and humid areas for storage of fresh produce.

## ACKNOWLEDGMENT

The authors are grateful to the University of KwaZulu Natal, School of Engineering in Pietermaritzburg for allowing the research team to review the work done on evaporative cooling at the university research farm. This work was supported by the Institute of Agricultural Engineering of the Agricultural Research council through

the Economic Competitive Support Package of the National Treasury of South Africa.

## CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

## REFERENCES

- Adeoye B, Odeleye O, Babalolaand O, Afolayan O (2009). Economic analysis of tomato losses in Ibadan Metropolis, Oyo estate, Nigeria. *African Journal of Basic and Applied Science* 1(5-6):87-92.
- Ahmed M, Abaas O, Ahmed M, Ismail R (2011). Performance evaluation of three types of local evaporative cooling pads in greenhouses in Sudan. *Sudanese Journal of Biological Science* 18:45-51.
- Ait-Oubahou A (2013). Postharvest technologies in sub-Saharan Africa: status, problems and recommendations for improvements. In *Acta Horti*; International Society of Horticultural Science (ISHS): Leuven, Belgium, pp. 1273-1282.
- Ambaw A, Delele A, Defraeye T, Ho T, Opara U, Nicolai M, Verboven P (2013a). The use of CFD to characterize and design post-harvest storage facilities: Past, present and future. *Computers and Electronics in Agriculture* 93:184-194.
- Ambaw A, Verboven P, Defraeye T, Tijskens E, Schenk A, Opara UL, Nicolai BM (2013b). Effect of box materials on the distribution of 1-MCP gas during cold storage: A CFD study. *Journal of Food Engineering* 119:150-158.
- Anyanwu EE (2004). Design and measured performance of a porous evaporative cooler for preservation of fruit and vegetables. *Energy Conversion and Management* 45:2187-2195.
- Archer CL, Jacobson MZ (2005). Evaluation of global wind power. *Journal of Geophysical Research* 120(12):1-20.
- ASHRAE (2011). Standard for the design of high-performance green buildings. American Society of Heating, Refrigerating and Air Conditioning Engineers Inc., Atlanta, GA. ASHRAE/USGBC/IES standard 189:1-2011.
- Aung MM, Chang Y (2013). Temperature management for the quality assurance of a perishable food supply chain. *Food Control* 40(1). Available at: <https://doi.org/10.1016/j.foodcont.2013.11.016>.
- Ayhan D (2006). Global Renewable energy resources, Energy Sources, Part A: Recovery, Utilization, and environmental effects 28(8):779-792. Available at: <https://doi.org/10.1080/00908310600718742>.
- Azene W, Workneh TS, Woldestadik K (2011). Effect of packaging materials and storage environment on postharvest quality of papaya fruit. *Journal of Food Science and Technology*. Available at: <https://doi.org/10.1007/s13197-011-0607-6>.
- Bachmann J, Earles R (2014). Postharvest of fruit and vegetables. (Internet). National Center for Appropriate Technology (NCAT). Available at: <https://attra.ncat.org/attra-pub/viewhtml.php?id=378>. [Accessed 08 January 2020].
- Basediya ALD, Samuel VK, Beera V (2011). Evaporative cooling system for storage of fruit and vegetables – a review. *Food Science Technology*. Available at: <https://doi.org/10.1007/s13197-011-0311-6>.
- Beckles DM (2012). Factors affecting the postharvest soluble solids and sugar content of tomato (*Solanum lycopersicum* L.) fruit. *Postharvest Biology and Technology* 63:129-140.
- Best B, Aceves JJ, Islas HJM, Manzini SFB, Pilatowsky PIF, Scoccia R, Motta M (2012). Solar cooling in the food industry in Mexico: A case study. *Applied Thermal Engineering*. Available at: <https://doi.org/10.1016/j.applthermaleng.2011.12.036>.
- Boyette MD, Wilson LG, Estes EA (1994). Hydro-cooling. North Carolina Cooperative Extension Services, Raleigh /North Carolina Agricultural and Technical State University, Greensboro AG-414-4.
- Bradford KJ, Dahal P, Asbrouck JV, Kunusoth K, Bello P, Thompson J, Wu F (2018). The dry chain: Reducing postharvest losses and improving food safety in humid climates. *Trends in Food Science and Technology* 71:84-93. Available at: <https://doi.org/10.1016/j.tifs.2017.11.002>
- Brosnan T, Sun D (2001). Precooling techniques and applications for horticultural products—a review. *International Journal of Refrigeration* 24(2):154-170.
- Cantwell MI, Nie X, Hong G (2009). Impact of storage conditions on grape tomato quality. Sixth ISHS Postharvest Symposium, International Society of Horticultural Science, Antalya, Turkey.
- Chaudhari, BC, Sonawane, TR, Patil SM, Dube A (2015). A review on evaporative cooling technology. *International Journal of Research in Advent Technology* 3(2):88-96.
- Cherono K, Workneh TS (2018). A review of the role of transportation on the quality changes of fresh tomatoes and their management in South Africa and other emerging markets. *International Food Research Journal* 25(6):2211-2228.
- Cherono K, Sibomana M, Workneh TS (2018). Effect of infield handling conditions and time to pre-cooling on the shelf-life and quality of tomatoes. *Brazilian Journal of Food Technology* <https://doi.org/10.1590/1981-6723.01617>.
- Chinenye NM (2011). Development of clay evaporative cooler for fruit and vegetables preservation. *Agricultural Engineering International, CIGR Journal* 13(1).
- Chijioko OV (2017). Review of evaporative cooling systems. *Greener Journal of Science, Engineering and Technological Research* 7(1):1-20.
- DAFF (2016). Abstracts of agricultural statistics. Department of Agriculture, Forestry and Fisheries. Republic of South Africa.
- David P, Megan H, Michele G, Mathew Z, Richard A, Katrina B, Jeff E, Benita H, Ryan S, Anat, G, Thomas S (2002). Renewable Energy: Current and Potential Issues. *Biological Science* 52(12):1111-1120. Available at: [https://doi.org/10.1641/0006-3568\(2002\)052](https://doi.org/10.1641/0006-3568(2002)052).
- Davis J, MacKay F (2013). *Solar Energy in the Context of Energy Use, Energy Transportation, and Energy Storage* [Internet]. University of Cambridge. Cambridge, UK. Available from: <http://www.inference.eng.cam.ac.uk/sustainable/book/tex/RSsolar.pdf> [Accessed 17 April 2016].
- Deoraj S, Ekwue EI, Birch R (2015). An evaporative cooler for storage of fresh fruits and vegetables. *West Indian Journal of Engineering* 38(1):86-95.
- Deveci O, Onkol M, Unver HO, Ozturk Z (2015). Design and development of a low-cost solar powered drip irrigation system using systems modelling language. *Journal of Cleaner Production* 102:529-544.
- Ejeta G (2009). Revitalising agricultural research for global food security. *Food Security* 1:391-401.
- Fadeyibi A, Osunde ZD (2011). Measures against damage of some perishable products on transit. *Advances in Agriculture, Sciences and Engineering Research* 1(1):1-8
- FAO (2005). Harvest handling and losses. Food and Agriculture Organisations of the United Nations, Rome.
- FAO (2008). The world vegetable center. Newsletter. Food and Agriculture Organisations of the United Nations, Rome.
- Finocchiaro P, Beccal, M, Nocke B (2012). Advanced solar assisted desiccant and evaporative cooling system with wet heat exchangers. *Solar Energy* 86:608-618.
- Fluri TP (2009). The potential of concentrating solar power in South Africa. *Energy Policy* 37(12):5075-5080.
- Godish T (1991). *Air Quality*. Chelsea (MI): Lewis Publishers.
- Gomez-Lopez VM (2012). *Decontamination of Fresh and Minimally Processed Produce*. Oxford, United Kingdom: John Wiley and Sons. Inc., 9600 Garsington Road.
- Gupta J, Dubey RK (2018). Factors affecting post-harvest life of flower crops: A review. *International Journal of Current Microbiology and Applied Sciences* 7(1):548-557. Available at: <https://doi.org/10.20546/ijcm.2018.701.065>.
- Gustavsson J, Cederberg C, Sonesson U, Van Otterdijk R, Meybeck A (2011). Global food losses and food waste: extent, causes and prevention, FAO Rome.
- Hardenburg RE, Watada AE, Wang CY (1986). *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks*, USDA Handbook No. 66 (revised), 136. USDA, Washington, USA.
- Hassan HZ, Mohamad AA (2012). A review on solar cold production

- through absorption technology. *Renewable Energy and Sustainable Energy Reviews* 16:5331-5348.
- Hera D, Drughean L, Girip A (2007a). Improvement of the energy efficiency in the refrigeration plants. 22nd International Congress of Refrigeration 1:859-865. ISBN: 978-1-62276-045-9.
- Hera D, Ilie A, Dumitrescu R (2007b). Aspects regarding the energy efficiency's increase in the case of refrigeration systems and heating pumps in Bucharest-Romania. 22nd International Congress of Refrigeration 5: 4136-4143. ISBN: 978-1-62276-045-9.
- Ito H, Takase N, Sato E (1988). Effect of low temperature on keeping quality of butterbur during distribution. *Research Bulletin of the Aichi ken Agricultural Research Center* 20:269-277, ISSN 0388-7995.
- James SJ, Swain MJ, Brown T, Evans JA, Tassou SA, Ge YT, Eames I, Missenden J, Maidment G, Baglee D (2009). Improving the energy efficiency of food refrigeration operations. *Proceedings of the Institute of Refrigeration, Session 2008-09*. 5-1-5-8.
- James SJ, James C (2011). Improving energy efficiency within the food cold chain. 11th International Congress on Engineering and Food (ICEF) 22-26 May 2011. Athens, Greece.
- Jha SN, Kudas Aleskha SK (2006). Determination of physical properties of pads for maximising cooling in evaporative cooled store. *Agricultural Engineering* 43(4):92-97.
- Joas J, Lechaudel M (2008). A comprehensive integrated approach for more effective control of tropical fruit quality. *Stewart Postharvest Review* 4:1-14.
- Kader AA (2003). A perspective on postharvest horticulture (1978-2003). *HortScience* 38:1004-1008.
- Kader AA (2010). Handling horticultural perishables in developing countries versus developed countries. *Acta Horticulturae* 877:121-126.
- Kereth GA, Lymo M, Mbwana HA, Mongi RJ, Ruhembe C (2013). Assessment of postharvest handling practices: knowledge and losses of fruits in Bagamoyo district of Tanzania. *Food Science and Quality Management* 11:8-15.
- Kim BS, Kim DC, Lee SE, Nahmgoong, Choi MJ, Joong MC (1995). Freshness prolongation of crisp head lettuce by vacuum cooling. *Agricultural Chemistry and Biotechnology* 38(3):239-247.
- Kim DS, Ferreira CAI (2008). Solar refrigeration options – a state of the art review. *International Journal of Refrigeration* 31:3-15.
- Kitinoja L, AlHassan HA, Saran S, Roy SK (2010). Identification of appropriate postharvest technologies for improving market access and incomes for small horticultural farmers in sub-Saharan Africa and South Asia. IHC Postharvest Symposium August 23, 2010. Lisbon, Portugal.
- Kitinoja L, Thompson JF (2010). Pre-cooling systems for small-scale producers. *Stewart Postharvest Review*. Available at: <https://doi.org/10.2212/spr.2010.2.2>.
- Kitinoja L, Saran S, Roy SK, Kader AA (2011). Postharvest technology for developing countries: challenges and opportunities in research, outreach and advocacy. *Journal of Science Food Agriculture* 91:597-603.
- Kitinoja L, AlHassan HY (2012). Identification of appropriate postharvest technologies for small-scale horticultural farmers and marketers in sub-Saharan Africa and South Asia – Part 1. PHL and quality assessments. *Acta Horticulturae* 31-40.
- Knee M, Miller AR (2002). Mechanical Injury. In: (ed) Knee, M. *Fruit quality and its biological basis*. Sheffield academic press, Sheffield, pp. 157-179.
- Korir MK, Mutwiwa UN, Kituu GM, Sila DN (2017). Effect of near infrared reflection and evaporative cooling on quality of mangoes. *Agricultural Engineering International: CIGR Journal* 19(1):162-168.
- Krishnakumar T (2002). Design of cold storage for fruits and vegetables. Technical report. Available at: <https://doi.org/10.131340/RG.2.2.14335.82082>.
- Laguerre O, Hoang HM, Flick D (2013). Experimental investigation and modelling in the food cold chain: Thermal and quality evolution. *Trends in Food Science and Technology* 29:87-97.
- Maerefat M, Haghighi AP (2010). Natural cooling of stand-alone houses using solar chimney and evaporative cooling cavity. *Renewable energy* 35:2040-2052.
- Maliwichi LL, Pfumayaramba TK, Katlego T (2014). An analysis of constraints that affect smallholder farmers in the production of tomatoes in Ga-Mphahlele, LepelleNkumbi municipality, Limpopo Province, South Africa. *Journal of Human Ecology* 47(3):269-274.
- Masarirambi MT, Mavuso V, Songwe VD, Nkambule TP, Mhazo N (2010). Indigenous postharvest handling and processing of traditional vegetables in Swaziland: A review. *African Journal of Agricultural Research* 5(24):3333-3341.
- Mashau ME, Moyane JN, Jideani IA (2012). Assessment of post-harvest losses of fruits at Tshakhuma fruit market in Limpopo province, South Africa. *African Journal of Agricultural Research* 7(29):4145-4150.
- McDonald K, Sun DW (2000). Vacuum cooling technology for the food processing industry. *Food Engineering* 45:55-65.
- Mentis D (2013). Wind Energy Assessment in Africa A GIS-based Approach. Unpublished Master of Science Thesis, KTH School of Industrial Engineering and Management, vetenskap och konst KTH, Stockholm, Sweden.
- Mentis D, Hermann S, Howells M, Welsch M, Siyal SH (2015). Assessing the technical wind energy potential in Africa a GIS-based approach. *Renewable Energy* 83:110-125.
- Miller V, Mente A, Dehghan M, Rangarajan S, Zhang X, Swaminathan S, Dagenais G, Gupta R, Mohan V, Lear S, Bangdiwala SI, Schutte AE, Wentzel-Viljoen E, Avezum A, Altuntas Y, Yusoff K, Ismail N, Peer N, Mapanga R (2017). Fruit, vegetable and legume intake, and cardiovascular disease and deaths in 18 countries (PURE): a prospective cohort study. *The Lancet* 390(10107):2037-2049. Available at: [https://doi.org/10.1016/S0140-6736\(17\)32253-5](https://doi.org/10.1016/S0140-6736(17)32253-5).
- Mordi JI, Olorunda AO (2003). Effect of evaporative cooler environment on the visual qualities and storage life of fresh tomatoes. *Food Science Technology* 40(6):587-591.
- Moureh J, Tapsoba S, Derens E, Flick D (2009). Air velocity characteristics within vented pallets loaded in a refrigerated vehicle with and without air ducts. *International Journal of Refrigeration* 32(2):220-234.
- Naticchia B, D'Orazio M, Persico I (2010). Energy performance evaluation of a novel evaporative cooling technique. *Energy and buildings* 42:1926-1938.
- Ngcobo MEK, Delele MA, Opara UL, Zietsman CJ, Meyer CJ (2012). Resistance to airflow and cooling patterns through multi-scale packaging of table grapes. *International Refrigeration* 35(2):445-452.
- Nkolisa N, Magwaza LS, Workneh TS, Chimphango A (2018). Postharvest quality and bioactive properties of tomatoes (*Solanum lycopersicum* L.) stored low-cost and energy-free evaporative cooling system. *Science of Horticulture* 241:131-143. Available at: <https://doi.org/10.1016/j.scienta.2018.06.079>.
- Nkolisa N, Magwaza LS, Workneh TS, Chimphango A, Sithole NJ (2019). Evaluating evaporative cooling system as an energy-free and cost-effective method for postharvest storage of tomatoes (*Solanum lycopersicum* L.) for smallholder farmers. *Heliyon Journal*. Available at: <https://doi.org/10.1016/j.heliyon.2019.e02266>
- Ntombela S (2012). South African fruit trade flow. Promoting market access for South African agriculture. Issue No. 6, June 2012. National Agricultural Marketing Council, Pretoria, South Africa.
- Nunes MCN, Emond JP, Rauth M, Dea S, Chauk V (2009). Environmental conditions encountered during typical consumer retail display affect fruit and vegetable quality and waste. *Postharvest Biology and Technology* 51(2):232-241.
- Odesola IF, Onyebuchi O (2009). A review of porous evaporative cooling for the preservation of fruit and vegetables. *Pacific Journal Science Technology* 27(1):19-21.
- OECD/FAO (2016). *Agriculture in sub-Saharan Africa: Prospects and challenges for the next decade in OECD-FAO Agricultural Outlook 2016-2025*, Paris.
- OECD/IEA and IRENA (2017). Chapter [1 to 4] of *Perspectives for the energy transition – investment needs for a low-carbon energy system* ©OECD/IEA and IRENA 2017.
- Okanlawon SA, Olorumisola AO (2017). Development of passive evaporative cooling systems for tomatoes Part 1: construction material characterization. *Agricultural Engineering International: CIGR Journal* 19(1):178-186.
- Parfitt J, Barthe M, Macnaughton S (2010). Food waste within food supply chains: quantification and potential for change to 2050. *Philosophical Transactions of the Royal Society B-Biological Sciences* 365:3065-3081.

- Pathare PB, Opara UL, Vigneault C, Delele MA, Al-Said FA (2012). Design of packaging vents for cooling fresh horticultural produce: Review paper. *Food Bioprocess Technology* 5:2031-2045.
- Paull RE (1999). Effect of temperature and relative humidity on fresh commodity quality. *Postharvest Biology and Technology* 15:263-277.
- Paull RE, Duarte O (2011). *Tropical fruits*, CAB International.
- Prusky D (2011). Reduction of the incidence of postharvest quality losses, and future prospects. *Food Security* 3(4):463-474.
- Rayaguru K, Khan MK, Sahoo NR (2010). Water use optimisation in zero energy cool chambers for short-term storage of FV in coastal area. *Food Science Technology* 47(4):437-441.
- Rennie T, Vigneault C, DeEll JR, Raghavan GSV (2003). *Cooling and Storage. Handbook of Postharvest Technology: Cereals, fruits, vegetables, tea and spices*. Ed. Chakraverty MA, Raghavan GSV, Ramaswamy HS. New York (NY), USA: Marcel Dekker Inc. pp. 505-538.
- Said SAM, El-Shaarawi MAI, Siddiqui MU (2012). Alternative designs for a 24-h operating solar-powered absorption refrigeration technology. *International Journal on Refrigeration*. Available at: <https://doi.org/10.1016/j.ijrefrig.2012.06.008>.
- Samira A, Woldetsadik K, Workneh TS (2011). Postharvest quality and shelf life of some hot pepper varieties. *Journal of Food Science Technology*. Available at: <https://doi.org/10.1007/s13197-011-0405-1>.
- Sandhya (2010). Modified atmosphere packaging of fresh produce: Current status and future needs. *LWT-Food Science and Technology* 43:381-392.
- Saran S, Roy SK, Kitinjoja L (2012). Appropriate postharvest technologies for small-scale horticultural farmers and marketers in sub-Saharan Africa and South Asia – Part 2. Field trial results and identification of research needs for selected crops. *Proc. XXVIIIth IHC-IS on Postharvest Technology in the Global Market* Eds.: M.I. Cantwell and D.P.F. Almeida. *Acta Horticulture* 934:41-52.
- Sawicka B (2019). Postharvest losses of agricultural produce. Sustainable development. Available at: [https://doi.org/10.1007/978-3-319-69626-3\\_40-1](https://doi.org/10.1007/978-3-319-69626-3_40-1)
- SAYB (2015). *South African Year Book 2014/15, Agriculture*. Department of Communication and Information System. Republic of South Africa.
- Saxena A, Agarwal N, Srivastava G (2013). Design and Performance of solar air heater with long term heat storage. *International Journal of Heat and Mass Transfer* 60:8-16.
- Schalkwyk HD, Groenewald JA, Fraser GC, Obi A, Tilburg A (2012). Unlocking markets to smallholders: Lessons from South Africa Mansholt publication series - I, 10. Available at: <https://doi.org/10.3920/978-90-8686-168-2>.
- Senol R (2012). An analysis of solar energy and irrigation systems in Turkey. *Energy Policy* 47:478-486.
- Shahzad MK, Chaudhary GQ, Ali M, Sheikh NA, Khalil MS, UrRashid T (2018). Experimental evaluation of a solid desiccant system integrated with cross flow Maisotsenko cycle evaporative cooler. *Applied Thermal Engineering* 128: 1476-1487. Available at: <https://doi.org/10.1016/j.applthermaleng.2017.09.105>.
- Sibanda S (2019). Development of a solar powered indirect air-cooling combined with direct evaporative cooling system for storage of horticultural crops in hot and humid areas. PhD Thesis; University of KwaZulu Natal, Pietermaritzburg, South Africa.
- Sibanda S, Workneh TS (2019). Effects of Indirect air-cooling combined with direct evaporative cooling on the quality of stored tomato fruit. *CyTA Journal of Food* 17(1):603-612. Available at: <https://doi.org/10.1080/19476337.2019.1622595>.
- Sibanda S, Workneh, TS (2020). Performance of Indirect Air Cooling Combined with Direct Evaporative Cooling for Fresh Produce. *Heliyon Journal*. Available at: <https://doi.org/10.1016/j.heliyon.2020.e03286>
- Sibomana MS, Workneh TS, Audain K (2016). A review of postharvest handling and losses in the fresh tomato supply chain: a focus on sub-Saharan Africa. *Journal of Food Security* 8:389-404. Available at: <https://doi.org/10.1007/s12571-016-0562-1>.
- Sibomana MS, Ziema LW, Schmidt S (2017). Influence of transportation conditions and postharvest disinfection treatments on microbiological quality of fresh market tomatoes (cv. Nemo-netta) in a South African supply chain. *Journal of Food Protection* 80(2):345-354.
- Singh V, Hedayetullah M, Zaman P, Meher J (2014). Postharvest technology of fruit and vegetables: An Overview. *Journal of Post-Harvest Technology* 2:124-135.
- Singh D, Sharma RR (2018). Postharvest diseases of fruits and vegetables. In: Siddiqui (Ed) *Postharvest disinfection of fruit and vegetables*. Academic Press 1:1-52.
- Sirisomboon P, Tanaka M, Kojima T (2011). Evaluation of tomato textural mechanical properties. *Journal of Food Engineering* 111(4):618-624.
- Sitorus T, Ambarita H, Ariani F, Sitepu T (2018). Performance of the natural cooler to keep the freshness of vegetables and fruits in Medan City. *IOP Conference Series: Materials Science and Engineering*, 309, 012089. Available at: <https://doi.org/10.1088/1757-899X/309/1/012089>.
- Sontake VC, Kalamkar VR (2016). Solar photovoltaic water pumping system - A comprehensive review. *Renewable and Sustainable Energy Reviews* 59:1038-1067.
- Stathers T (2017). Quantifying postharvest losses in Sub-Saharan Africa with focus on cereals and pulses. [Internet]. Presentation at the Bellagio workshop on Postharvest management 12-14 September 2017. Available at: [http://www.fao.org/fileadmin/user\\_upload/food-loss-reduction/Bellagio/T.Stathers\\_QuantifyingPHLinSSA.PDF](http://www.fao.org/fileadmin/user_upload/food-loss-reduction/Bellagio/T.Stathers_QuantifyingPHLinSSA.PDF). [Accessed 03 February 2020].
- Sun W, Wang L (2004). Experimental investigation of performance of vacuum cooling for commercial large cooked meat joints. *Journal of Food Engineering* 61(4) 527-532.
- Sun W, Zheng L (2006). Vacuum cooling technology for the agri-food industry: Past, present and future. *Food engineering* 77:203-214.
- Swain MJ, Evans JE, James SJ (2009). Energy consumption in the UK food chill chain—primary chilling. *Food Manufacturing Efficiency* 2(2):25-33.
- Szabo S, Bódis K, Huld T, Moner-Girona M (2011). Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension. *Environmental Research Letters* 6(3):1-9.
- Thompson JF, Mitchell FG, Rumsey TR, Kasmire RF, Crisoto CC (1998). *Commercial cooling of fruits, vegetables and flowers*. USA: DANR publication, UC Davis. Publication No. 21567:61-68.
- Tigist M, Workneh TS, Woldetsadik K (2011). Effects of variety on quality of tomato stored under ambient temperature conditions. *Food Science Technology*. Available at: <https://doi.org/10.1007/s13197-011-0378-0>.
- Tijksens E (2007). Impact damage of apples during transport and handling. *Post-harvest Biology Technology* 45(2):157-167.
- Tiwari GN, Jain D (2001). Modelling and optimal design of evaporative cooling system in controlled environment greenhouse. *Energy Conversion and Management* 43:2235-2250.
- Tolesa GN, Workneh TS (2017). Influence of storage environment, maturity stage and pre-storage disinfection treatments on tomato fruit quality during winter in KwaZulu-Natal, South Africa. *Journal of Food Science and Technology* 54(10):3230-3242. Available at: <https://doi.org/10.1007/s13197-017-2766-6>.
- Tscharntke, T, Milder JC, Schroth G, Clough Y, DeClerck F, Waldron A, Rice R, Ghazoul J (2015). Conserving biodiversity through certification of tropical agroforestry crops at local and landscape scales. *Journal of the Society for Conservation Biology* 8(1):14-23. Available at: <https://doi.org/10.1111/conl.12110>.
- Turk R, Celik E (1993). The effects of vacuum precooling on the half cooling period and quality characteristics of iceberg lettuce. *Acta Horticulture* 343: 321-324.
- Tyagi VW, Panwar NL, Rahim NA, Kothari R (2012). Review on solar air heating system with and without thermal energy storage. *Renewable and Sustainable Energy Reviews* 16:2289-2303.
- Ugonna CU, Jolaoso MA, Onwuolu AP (2015). Tomato value chain in Nigeria: issues, challenges and strategies. *Journal of Scientific and Reports* 7(7): 501-515.
- Van Zeebroeck M, Van linden V, Ramon H, De Baerdemaeker J, Nicolai BM, Tijksens E (2007). Impact damage of apples during transport and handling. *Post-harvest Biology Technology* 45(2):157-167.
- Vigneault C, Sargent SS, Bartz JA (2000). Postharvest decay risk associated with hydro-cooling tomatoes. *Plant Disease* 84(12):1314-1318.
- Vigneault C, Thompson J, Wu S (2009). Designing container for

- handling fresh horticultural produce. *Postharvest Technologies for Horticultural Crops* 2:25-47.
- Wang LJ, Sun DW (2001). Rapid cooling of porous and moisture foods by using vacuum cooling technology. *Trends in Food Science and Technology* 12:174-184.
- Wills R, Glasson M, Graham D, Joyce D (2007). *Postharvest: An Introduction to the physiology and handling of fruit, vegetables and ornamentals*, (4th edition). New York, USA: University of New South Wales Press
- Wilson LG, Boyette MD, Estes EA (1999). *Postharvest handling and cooling of fresh fruits, vegetables and flowers for small farms. Horticulture information leaflets*. USA: North Carolina Cooperative Extension Service 17:800-804.
- Workneh TS (2007). Present status and future prospects of postharvest preservation technology of fresh fruit and vegetables in Ethiopia. *Journal of the Ethiopian Society of Chemical Engineers* 10(1):1-11.
- Workneh TS (2010). Feasibility and economic evaluation of low-cost evaporative cooling system in fruit and vegetables storage. *African Journal of Food Agriculture, Nutrition and Development* 10(8):2984-2997.
- Workneh TS, Osthoff G (2010). A review on integrated agro-technology of vegetables. *African Journal of Biotechnology* 9(54):9307-9327.
- Yahia EM (2011). *Modified and controlled atmospheres for the storage, transportation, and packaging of horticultural commodities*. Boca Raton, Florida: CRC press.
- Zagory D, Kader AA (1988). Modified atmosphere packaging of fresh produce. *Food Technology* 70-77.
- Zhang Z, Sun DW (2006). Effect of cooling methods on the cooling efficiencies and qualities of cooked broccoli and carrot slices. *Journal of Food Engineering* 77:320-326.
- Zheng LY, Sun DW (2006). Innovative Applications of power ultrasound during food freezing processes - A Review. *Trends in Food Science and Technology* 17(1):16-23.
- Zou Q, Opara LU, McKibbin R (2006). A CFD modeling system for airflow and heat transfer in ventilated packaging for fresh foods: II. Computational solution, software development, and model testing. *Journal of Food Engineering* 77(4):1048-1058.