PERFORMANCE CHARACTERIZATION OF A THIN-FILM PHOTOVOLTAIC SYSTEM POWERED EVAPORATIVE CHARCOAL COOLER FOR PRESERVATION OF AVOCADO (*PERSEA AMERICANA* MILL.)

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Performance Characterization of a Thin-Film Photovoltaic System Powered Evaporative Charcoal Cooler for Preservation of Avocado (*Persea americana* Mill.)

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university.

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DEDICATION

I dedicated this thesis to my parents for their support and prayers throughout the journey of my studies.

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NOTATIONS

$\boldsymbol{A}$	Annual equivalent payment (Ksh)
$\boldsymbol{B_{pv}}$	Present value benefits (Ksh)
$\boldsymbol{c}$	Standardized value (-)
CoI	Cost of investment (Ksh)
$\mathbf{C_{pa}}$	Specific heat of moist air (kJ/kg/K)
$\boldsymbol{C_{pv}}$	Present value costs (Ksh)
EER	Efficiency ratio (-)
FVI	Final value of investment (Ksh)
$\boldsymbol{i}$	Interest rate (%)
IVI	Initial value of investment (Ksh)
$\boldsymbol{l}$	Aliquot (ml)
$\boldsymbol{M}$	Air mass flow rate (kg/s)
$\boldsymbol{n}$	Number of periods (years)
P	Electrical power (kW)
$\boldsymbol{P}$	Present worth (Ksh)
$\boldsymbol{RH_a}$	Ambient relative humidity (%)
$\boldsymbol{RH}_\mathbf{c}$	Cooler relative humidity (%)
s	Sample weight (g)

T_a	Dry bulb temperature of ambient air in (^oC)
T_c	Dry bulb cooler temperature (^oC)
T_i	Dry bulb temperature of cooled air (^oC)
T_{wb}	Wet-bulb air temperature of outside air (^oC).
t_1	Initial ambient temperature (^oC)
t_2	Initial ambient temperature (^oC)
v	Volume of metaphosphoric acid-acetic solution (ml)
w_1	Initial moisture content of air (g/kg)
w_2	Initial moisture content of air (g/kg)
W_1	Initial weight (g)
W_2	Final weight (g)
Δh	Difference between the enthalpies (kJ/kg)
$\eta_{cooling}$	Cooling efficiency (%)

ABBREVIATIONS AND ACRONYMS

ABED	Agricultural and Biosystems Engineering Department
AfDB	African Development Bank
AFRICA-*ai*-JAPAN	**Africa**n Union-***a****frican* ***i****nnovation*-**J**KUAT **A**ND **PA**USTI **N**etwork Project
ANOVA	Analysis of Variance
AOAC	Association of Official Analytical Chemists
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BCR	Benefits Cost Ratio
DC	Direct Current
DEC	Direct Evaporative Cooling
DHT	Digital Humidity and Temperature
EER	Energy Efficiency Ratio
EPIA	European Photovoltaic Industry Association
EPSRC	Engineering and Physical Sciences Research Council
FAO	Food and Agriculture Organization
IDE	Integrated Development Environment
IEC	Indirect Evaporative Cooling
IRR	Internal Rate of Return

JICA	Japan International Cooperation Agency
JKUAT	Jomo Kenyatta University of Agriculture and Technology
KIPPRA	Kenya Institute for Public Policy Research and Analysis
LED	Light Emitting Diode
OECD	Organisation for Economic Cooperation and Development
NPV	Net Present Value
PHEVs	Plug-in Hybrid-Electric Vehicles
PPR	Polypropylene Random Pipe
PV	Photovoltaic
RH	Relative Humidity
ROI	Return on Investment
SD	Secure Digital
SDG	Sustainable Development Goals
SSC	Soluble Solids Concentration
UNEP	United Nations Environment Programme
USD	United States Dollar
ZECC	Zero Energy Cool Chamber

ABSTRACT

Avocados are high moisture content agricultural produce with high vitamin C levels. However, they are highly perishable, and suffer from high postharvest losses ifappropriate and adequate storage facilities are not provided. The losses noted with the use of conventional storage techniques, such as under shade, result from physical, chemical and physiological changes that result from loss in moisture content. This study aimed on characterizing the performance of a thin-film photovoltaic (PV) system powered evaporative charcoal cooler for preservation of avocado. Specifically, the study focused on characterizing the performance of the PV technology under varying ambient conditions as an off-grid backup energy system, evaluating the performance of an improved evaporative charcoal cooler utilizing the PV technology for preservation of avocado, and assessing the cost-benefit of using the improved evaporative charcoal cooler utilizing the PV technology for preservation of avocado. The evaporative cooler consisted of a double wire mesh that held charcoal in place and was fitted with a drip for wetting the charcoal-laden walls, axial fans and data logger with digital humidity-temperature sensors. The study was conducted in Kimicha (Kirinyaga County, Kenya) with an evaporative charcoal cooler to investigate the optimal tilt angle for thin-film PV, and also at Juja (Kiambu County, Kenya) for comparison purposes. The results revealed that the optimum tilt angle is 5^o (347.9±231.9 W) in Kimicha and 15^o (517.7±131.3 W) in Juja for average maximum solar radiation of 973.5±219.9 and 1086.4±211.41 W/m^2 in Kimicha and Juja, respectively. No load tests using the cooler showed that a 0.5 m/s air velocity had the greatest drop in temperature, which was 6.4°C, and the highest cooling efficiency of 84.7%. The average temperature of the cooler decreased significantly ($P < 0.05$) for both Hass and indigenous avocado, while the relative humidity increased significantly ($P < 0.05$). These conditions gave mean cooling efficiencies of 83.0% for the Hass variety and 87.2% for the indigenous variety, and an energy efficiency ratio of 14.21 for the cooler. The study found that the Hass avocados experienced a 3.9 and 7.5% weight reduction in the cooler and outdoors, respectively, while indigenous avocados had a 5.03 and 12.90% weight reduction in the cooler and outdoors, respectively. No significant change in vitamin C content, total soluble solids and firmness of Hass and indigenous avocados was noticed. The benefit-cost ratio and return on investment for the cooler were 2.88 and 188%, respectively. These results suggest that investing in an evaporative charcoal cooler is a viable option for small-scale farmers.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The world population is incessantly rising and consequently, the demand for food in many countries is also rising. The world population is projected to hit the 8 billion mark by 2025 (Cohen, 2003). Agricultural engineers are facing an uphill task of coming up with proper technology that will ensure that farmers meet the food demand of the rising global population, whilebetter keeping the price affordable. Due to lack of adequate storage facilities, major postharvest losses are experienced in the global south (popularly known as third-world countries),according to Rhoads et al. (2019). These postharvest losses are greatly linked to humidity and temperature(Yahaya and Mardiyya, 2019).

In Southeast Asia, for example, postharvest losses are in the range of 10 to 50% depending on the country in question (Von Braun and Bos, 2005). Food losses in developed nations are comparable to those in third world countries, although more than 40% of the losses in the third world countries occur at the post-harvest and processing stages, whereas more than 40% of food waste in developed countries are at the retail and consumer stage. Food losses at the consumer level in developed countries (222 million tons) is nearly equal to total net food production in Sub-Saharan Africa (SSA) of 230 million ton (Blakeney, 2019).

The market for solar photovoltaic systems has been growing rapidly in Sub-Saharan Africa and with a huge potential further development (Nygaard et al., 2016). In regards to adoption and spread, Kenya is among the leading countries in SSA especially when it comes to small-scale, decentralized energy production and consumption (UNEP, 2019). The expansion of the solar PV market offers Kenya's economy prospects that go beyond providing access to clean energy and electricity in rural areas and instead spur important socio-economic developments such as industrial development, private sector growth, and creation of employment (Bhamidipati et al., 2021). Kenya has an estimated potential of 15000 MW of PV power but currently generates slightly more than 100 MW capacity, with the Garissa solar power project which is the largest installation producing 55 MW capacity. Others are the 55 MW Kesses 1, 40 MW Cedate, and 40 MW Selenkei, and 52 MW Malindi solar plant (KIPPRA, 2022).

Avocado fruits also called alligator pear varies in shape from round, oblong or pear-shaped. The skin varies in texture from rough to smooth and the colour ranges from green-yellow, reddish-purple, purple, or black. Botanically, the fruit is berry, and it has a single, enormously rounded seed with two cotyledons. Avocado fruits contain green or yellowish flesh that is buttery in texture and flavour. They are frequently consumed in salads but also as desert in different nations as dessert (Encyclopedia Britannica, 2023).

Kenya produces avocados for both commercial and subsistence purposes(Mwaura, 2021) and with a planted area of approximately 26 000 hectares and an output of 417 000 metric tonnes in 2021 which is a double of that of 2016, it is currently the sixth largest avocado producer in the world (EastFruit, 2023). According to OECD-FAO Agricultural Outlook 2021-2030 report, avocado production is anticipated to triple from the 2010 level to 12 million tonnes in 2023 and is expected to increase in export by an estimated 22% to approximately 100,000 tonnes in 2021 (FAO, 2021).

The utilization of evaporative cooling methods and procedures in the reduction of temperatures is ancient, but this technique got to be embraced at the turn of the 20th century. The ever-increasing cost of power being consumed by storage appliances has caused a shift in the types of equipment and facilities that save on power. The greatest beneficiary of this migration was the evaporative cooler which was able to minimize the installation and the operation cost by about 50% (Bhatia, 2012). Studies show that evaporative coolers can preserve fruits and vegetables, without causing chill injuries and changes in colour and this is something that compression refrigerators could hardly achieve (Ronoh et al., 2018).

Fruits are generally categorized as perishable crops. If they are not quickly and properly preserved after being harvested, fruits tend to wither, shrivel, or even rot away very fast, especially under hot conditions (Chinenye, 2011). A bigger fraction of these perishable crops is water. The loss of water from the crop commonly marks the loss of quality of fruits or vegetables. The loss of water in many scenarios means that the produce visuals change, and shrivelling or even wilting can take place. Environmental relative humidity where the fruits are supposed to be kept is another aspect that ought to be considered. Pathological activities are slowed down by low temperatures and high relative humidity, and thus for a storage environment for perishable crops to be considered safe, it must replicate these conditions. Low temperatures and high humidity in the storage environment suppress respiratory activities and enzymatic degradation. It also reduces the rate of water loss, inhibits microorganism growth while slowing the rate of ethylene production (Katsoulas and Kittas, 2011).

1.2 Problem Statement

Farmers in rural areas are faced with challenge of power outageand cannot afford to invest in the current refrigeration technologies because of high capital requirement. This makes them to incur huge postharvest losses and subsequently low returns. These postharvest losses that many farmers experience negatively impact their livelihood in terms of food and nutrition insecurity. Fruits, such as avocados, are highly perishable and hence they require efficient preservation systems before they get delivered to their end consumers. In Kenya these fruits are grown by smallholder farmers in rural areas, mostly without modern infrastructure. Despite the fact that avocados are harvested daily, 50% of losses is incurred due to inadequate infrastructure and poor storage (Kirui, 2023). Thus, development of affordable systems suitable for this environment is important. Collette and Nauen (1983) advocated for the design of a system that is sustainable in terms of water usage, energy-efficient, and affordable to the farmers. The advancement made in the field of science allows humans to make charcoal cooler even more effective and efficient when it comes to the utilization of solar energy, which is abundant in the tropics. To make the charcoal cooler more efficient, this study sort to integrate a thin-film PV system into an existing evaporative charcoal cooler (Kanali et al., 2017) and characterize the performance of the improved cooler for the preservation of avocados.

1.3 Objectives

1.3.1 Main objective

The main objective of this study was to characterize the performance of an improved evaporative charcoal cooler powered by a thin-film photovoltaic system for the preservation of avocado.

1.3.2 Specific objectives

i. To characterize the performance of a thin-film photovoltaic technology under varying ambient conditions as an off-grid backup energy system.
ii. To evaluate the performance of an improved evaporative charcoal cooler utilizing thin-film photovoltaic technology for preservation of avocado.
iii. To assess the cost-benefitof using the improved evaporative charcoal cooler utilizing thin-film photovoltaic technology for preservation of avocado.

1.4 Research Questions

i. How does a thin-film photovoltaic technology perform under varying ambient conditions as an off-grid backup energy system?
ii. How does an improved evaporative charcoal cooler utilizing thin-film photovoltaic technology perform for preservation of avocado?
iii. What is the cost benefit of using the improved evaporative charcoal cooler utilizing thin-film photovoltaic technology for preservation of avocado?

1.5 Justification of the Study

The study is in line with Kenya's Big Four Agenda(2018-2022) number two on food security and nutrition.To steer the nation towards the realization of the Kenya Vision 2030, there is an urgent need to develop affordable technologies that would help in mitigating postharvest losses normally associated with the storage of fresh produce (such as fruits). The evaporative charcoal cooler benefits small-scale farmers to curb postharvest losses and increase the shelf life of their fruits and vegetables. Once these losses have been curbed, Sustainable Development Goals (SDGs) one and two on ending hunger and zero poverty, respectively can be achieved.

1.6 Scope of the Study

The focus of the study was in terms of improvement on an evaporative charcoal cooler through the incorporation of a thin-film PV system and characterizing the performance of the improved cooler (in terms of system performance, quality evaluation, and cost-benefit assessment) for the preservation of avocado. The system performance parameters were cooling efficiency, air temperature, relative humidity, and energy efficiency ratio. The quality parameters that were evaluated during storage included vitamin C content, firmness, total soluble solids, and weight loss. The study was conducted for 12 days because at this point the firmness level of the samples in the cooler had fallen below acceptable levels of 10 N and moreover those in the ambient environment had begun spoiling. Vitamin C content, firmness and total soluble solids tests were carried out after every 4 days because of the distance from the study site to the lab in JKUAT. In terms of cost-benefit analysis, the study focused majorly on the benefit-cost ratio of using the improved thin-film PV powered evaporative charcoal cooler. The study was conducted in Kirinyaga County using an existing evaporative charcoal cooler,which was improved, but also partly in Juja for the first objective during the comparison of PV tilt angle tests (Kanali et al., 2017).

CHAPTER TWO

LITERATURE REVIEW

2.1 Theoretical Review

2.1.1 Avocado production

Global avocado output has grown quickly over the past ten years, with a compound annual growth rate of 7%, reaching 8.4 million metric tons in 2022. Mexico, which produces 30% of the world's avocados has seen a 6% increase in the past ten years. Three other Latin American nations, Chile, Colombia, and Peru, round up the top 10 global producers in addition to Mexico. Colombian and Peruvian production, which now accounts for 12 and 9% of world production, respectively, has climbed by 15and 12%, respectively (Ramirez, 2023).In terms of export, Mexico exceeded 1 metric tons in 2022 with Chile, Colombia, Kenya, Peru, and Spain leading the way with a 22% compound annual growth rate. However, avocado exports in Kenya, the only African country, increased by 15% between 2012 and 2022, and are now exporting at a rate of around 2 million metric tons yearly (Ramirez, 2023).

The county government of Kirinyaga, where the study was conducted, has urged farmers to embrace avocado production as it reaches maturity after five years of planting with an average of 500 to 2000 fruits per acre and it commands 75% of the market share in the international market (Farmbiz Africa, 2019). In the year 2019, the county government of Kirinyaga distributed 50,000 seedlings of avocado to farmers to promote and encourage the farmers to embrace avocado production and planned to distribute a total of 100,000 seedlings in the year 2020. It also planned on providing extension services to the farmers to make sure that the farmers are planting quality seeds. The demand for Kenyan avocados is very high in Europe, especially in France, Netherlands, and Middle East countries (Kenyan News Agency, 2020).

Farmers in Kirinyaga County formed a cooperative society for marketing their produce. A delegation from China visited the farmer’s organization to discuss the ways of marketing the produce directly overseas (Muchira, 2019).In Kenya, the major avocado varieties are Hass, Fuerte, and Puebla and African avocados are the most preferred in the world because of the quality varieties (Kanali et al., 2017).

2.1.2 Avocado varieties grown in Kenya

a) Hass avocado

Hass avocado is a cultivar of avocado with dark green-coloured, bumpy skin (Figure 2.1). This cultivar was first grown and sold by Rudolph Hass, an amateur horticulturist, and it was named after him (Tan et al., 2017). The avocado is a large-sized fruit that weighs between 200 to 300 g. When ripe, its skin changes to a dark purplish colour, and it yields under slight pressure. When the inside changes to white-green, then the fruit is ready to serve.

Figure 2.1: Photo of unripe Hass avocado

Due to its taste, size, shelf-life, and high growing yield, the Hass cultivar is recognized as the most commercially successful avocado globally and the fruit account for more than 80% of the fruit (Tan et al., 2017). The fruit is also popular in Kenya as it is considered the new goldmine by the contemporary farmers. In Kenya, most county governments are encouraging their constituents to engage in Hass-avocado farming. This is attributed to the fact that these avocados do not demand a lot of labour and maintenance time (Oxfarm-Eshop, 2018).

Counties in central Kenya, lower Nyanza, Central Rift Valley, and all the counties in Western Kenya have the best climate for the cultivation of Hass-avocados. In the former Eastern province, Hass-avocados do well in individual pockets such as Kathiani and Kang'undo (Oxfarm-Eshop, 2018). The more towering Meru and Embu counties have suitable climates too for the growth of the avocado. Before the avocado market regulation, farmers used to part with their fruits at Kshs 1 per fruit. After the government intervention, the farmers make a net of Kshs 8 per fruit. The Hass-avocado exporters sell the fruit for as high as Kshs 30 in Kenya.

b) Fuerte avocado

Fuerte seedling is believed to have been found in Mexico in 1911. It is believed to be a hybrid of Mexican and Guatemalan varieties. It is very desirable both in local and overseas markets as it is known to be the best commercial cultivar until the present day. It has a long period of bloom which makes it possible to have more sets of fruits simultaneously on the trees. Fuerte is among the cold-tolerant varieties with a long picking season and a good shelf life (Griesbach, 2015).This avocado cultivar has smooth green skin (Figure 2.2). It has creamy and pale green flesh and weighs an average of 140-395 g per fruit. Fuerte avocado tree is highly susceptible to both Anthracnose and Scab**.** The fruit is pear-shaped and with a medium seed and it remains green when matured (JICA, 2020). Fuerte variety is termed "green skin" because it does not change the green colour when ripe. In 2012, Kakuzi purchased 1,245 tonnes locally from the smallholder farmers (Kakuzi, 2012).

Figure 2.2: Photo of unripe Fuerte avocado

c) **Puebla avocado**

The origin of the Puebla variety seedling is in Atlixco, Mexico in 1911 and is considered a pure Mexican even though some suggest that it is a crossbreed of Mexican and Guatemalan that belongs to flower type A. It is a medium-sized cultivar and ovate-shaped. During maturity, the skin is smooth, glossy, and purplish-red (Figure 2.3). The flesh is light green and fleshy with 20% oil content (Griesbach, 2015). Puebla is spreading and is used as rootstock with a maturity of 5 to 7 months after blossoming (Infonet, 2020). Puebla is a compact fruit that resembles the Hass variety but it has velvety flesh with a good aroma and a taste of rich butter (JICA, 2020). The Puebla tree is rapidly growing with erect and drooping branches and its fruit has few fibres, easy to harvest because of its spreading tree, and easy peeling of flesh from the skin (Griesbach, 2015).

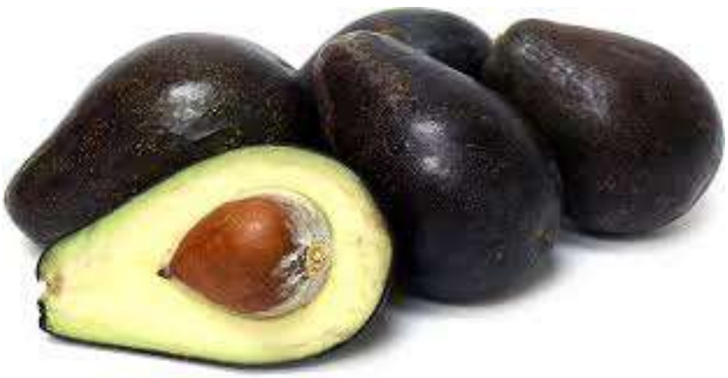

Figure 2.3: Photo of ripe Puebla avocado

d) **Indigenous variety (Jumbo)**

This is a native avocado type from East Africa is called Jumbo or ‘kienyeji’ which means indigenous (Figure 2.4). This naturally occurring cultivar weighs more than its counterparts Hass, Fuerte and Puebla. It has a rough, shiny exterior and is free of salt, cholesterol, and trans fats. It also contains a lot of monounsaturated fat and vitamin E.

Figure 2.4: Photo of ripe jumbo avocado

2.1.3 Avocado nutritional value and health benefits

The pulp of avocado is abundant in protein, fibre, and vitamins A, B, C and E. It is a superior source of potassium and phosphorus and includes mono-unsaturated fatty acids that significantly lower blood levels of low density lipoproteins, preventing cardiovascular disease(Nair and Chandran, 2018). It is also rich in concentration of phenolic compounds such as flavonoids, tocopherols, anthocyanidins and gallic acids, all of which have considerable antioxidant, neuroprotective, and cardiovascular protective properties (Santana et al., 2019).

Avocado-seed extracts also possess a wide range of bioactive qualities that are beneficial to health, including those that are anti-hyperglycemic, anti-cancer, anti-hypercholesterolemic, antioxidant, anti-inflammatory, and anti-neurogenerative. These qualities show that it can be used to fortify food (Bangar et al., 2022).Avocado peels are a prominent by-product of avocado processing and greatly increase the amount of waste produced annually. However, it can be utilized to produce phenolic compound-rich extracts with a variety of biological qualities that can be incorporated into various matrixes for diverse sectors, food, cosmetics, and pharmaceutical (Ferreira et al., 2022).

2.1.4 Photovoltaic cells and thin-film photovoltaic system

a) Photovoltaic cells

A PV cell is a device that is tasked with the conversion of light energy directly into electricity. This is both a physical and chemical phenomenon. PV cells are also known as solar cells. Individual PV cells can be brought together to create modules that are popularly known as solar panels. In layman's terms, a single-junction silicon solar cell is capable of producing a maximum open-circuit voltage of about 0.6 V (Como et al., 2016).

Solar technology is considered the safest, and the most reliable clean energy and PV power generation is the most outstanding way of harnessing solar energy. The current global energy crisis has given PV power generation an edge over its competitors because of its resource sustainability. The PV industry has been developed based on combining semiconductors technology with new energy requirements.

b) Thin-film PV system

The interest of this study lied in studying the impact a thin-film PV system incorporated on a charcoal cooler would have on the preservation of avocados. Thin-film PV cells are the new generation of solar cells. Thin-film solar cells contain numerous thin-film layers made of PV materials (Yoshimura, 2016). Thin-film PV cells present the best way of producing electricity from sunlight. These panels can be implemented in traffic and street lights, solar fields, and forest areas. These solar panels are known to be cheaper.

Semiconductors are the fundamental substance of a PV cell. The semiconductors that are doped with phosphorus are synonymous with developing a surplus of free electrons, while the semiconductor doped with either boron, indium, or gallium develops a hole. The semiconductor doped with phosphorus is called the N-type material, while the semiconductor doped with either boron, indium, or gallium is known as the P-type material. Both the N and the P-type materials join forces to create a PV cell. In the absence of light, a minute number of atoms are excited and they end up moving across the junction, hence leading to a decrease in voltage across the junction but in the presence of light, more and more atoms are excited and they flow across the junction and thus leading to a large current. The current can be harnessed and stored in a battery or utilized in other applications depending on the requirement (Como et al., 2016).

2.1.5 Evaporative cooling systems

Evaporative cooling is defined as the process of adiabatic saturation of air and it occurs when sprayed water is made to evaporate into it with zero conveyance of heat to or from the environment. An evaporative charcoal cooler is a storage chamber which uses the principle of evaporative charcoal cooling to maintain the interior temperatures cool for preservation of commodities(Ahmed, 2021). By moving air over water, this causes its surface to evaporate and therefore lower the surrounding air's temperature, a process known as evaporative cooling. Direct evaporative cooling (DEC) is a thermal method using adiabatic immersion in which water vapour evaporates into the air to cool and humidify it. While using direct evaporative cooling, the wet bulb temperature is maintained while the dry bulb temperature drops. Indirect evaporative cooling (IEC) is the point where the air that is meant to be cooled is isolated from the evaporation procedure, and hence it is not humidified while being cooled. This process employs a heat exchanger where the secondary air stream is cooled by water which in turn is used to cool the primary air. The secondary air escapes as exhaust while the primary air is utilized as cooled air (Bhatia, 2012). The fundamental property of this particular process lies in the fact that its efficiency is incremented tremendously when the temperatures rise (Duan et al., 2012).

Evaporative cooling is also attractive because of its low energy consumption, and easy maintenance. Because of the utilization of a total airflow renewal, evaporative cooling eliminates the re-circulation flow and multiplication of microorganisms, an incessant problem in customary cooling frameworks. Figure 2.5 illustrates the process of evaporative cooling where t_1 and t_2 are the initial and final ambient temperatures and w_1 and w_2 initial and final moisture contents of the air. The process occurs along the constant wet bulb temperature line (Xichun et al., 2008).

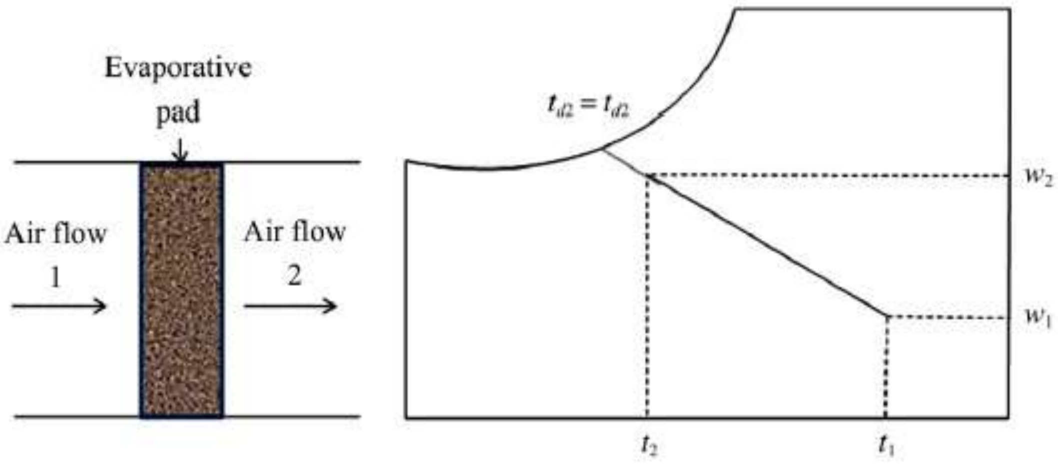

Figure 2.5: Illustration of evaporative cooling

Source: (Akton, 2009)

2.2 Empirical Review

2.2.1 Thin-film photovoltaic technology and off-grid backup energy systems

According to the European Photovoltaic Industry Association's solar generation 6 of 2011, thin-film PV technology is a PV technology made through the deposition of thin layers of photosensitive material on a low-cost material like glass, or plastic. A laser is then used to cut the attached photosensitive material on the backing. The commercially available thin-film modules are; Amorphous silicon (a-Si) (1 µm thick semiconductor material, low flow of electrons resulting in the efficiency of 4-8%), Multi-junction thin silicon film (a-Si/µc-Si) (the µc-Si layer utilize red and infrared light raising efficiency to 10%), Cadmium telluride (CdTe) (has a module efficiency of 11%), Copper, indium, gallium, (di)selenide/ (di)sulphide and copper, indium, (di)selenide/(di)sulphide (CIS) (has module efficiency in the rage of 7-12%).

The production process of thin-film PV technology is low but they are less efficient with efficiencies ranging between 5-13% and a lifespan range of 15-20 years. The inefficiency of this type of technology indicates that bigger modules of a similar type are required to produce the same amount of power as mono and polycrystallinemodules (Bahta, 2013). The off-grid system is divided into two; off-grid domestic and off-grid non-domestic. Off-grid domestic are those used to provide electricity to homesteads and villages with no utility electricity network.On the other hand, off-grid non-domestic are those used to provide electricity to telecommunication networks and water pumping among other applications (Miller and Lumby, 2012).

Sustainable solar energy is the natural choice for many, and this is due to the rise in demand for energy in the agricultural sector and the negative impacts that are linked to fossil fuels. PV agriculture has some application modes when it comes to agriculture. The main goal of a PV agricultural greenhouse is obtaining great agricultural returns by enabling one to create a suitable environment for the sake of plant growth. The anti-season planting can also be achieved because the temperatures inside a greenhouse can be raised in winter. With the utilization of transparent and semi-transparent PV panels, one can raise the amount of sunlight getting into the greenhouse, and through the utilization of selective plastic films, corresponding wavelengths of light absorption for growth can be availed for different plants (Xue, 2017). Also, there is a possibility of integrating natural radiation with artificial lighting that has been powered by the PV energy, or during the night, LED lights that are powered using PV generation can be installed to provide the light that promotes growth. To ensure that the breeds are improved, PV power plants can be constructed directly above fish ponds or on the rooftop of a building utilized in breeding to provide green and sustainable energy (Xue, 2017). This mode increments the efficiency on the use of land, and also raises land productivity in a given unit area, through the establishment of PV panels above water and breeding fish underneath.

The current environmental pollution has become a serious menace in both urban and rural areas, and sewage is the biggest problem. However, a solar wastewater system that uses power generated by PVs can be embraced in the treatment of wastewater (Xue, 2017). The aforementioned process has no energy transfer or pollution. PV water pumping is noted as an economical solution when it comes to the provision of water for irrigation. The system is advantageous in that it has zero emissions of CO_2 when compared to the traditional pumping machines that are based on fossil fuels and electricity. PV water pimping also saves on operating costs (Xue, 2017).

2.2.2 Evaporative coolers

Past studies have shown that evaporative cooling may be used to attain lower temperatures than those in the surrounding environment and higher relative humidity than that found in the surrounding air. According to studies done in India, zero energy cool chambers (ZECCs) have a higher relative humidity (RH; 85–90%) than the field (RH; 21–94%), according to Ambuko et al. (2017). Also, in the same zero-energy cool chamber, relatively low temperatures were achieved with minimal variation between the minimum and the maximum compared to the conditions in the field. The fruits stored in ZECC had an improved shelf life, unlike those that were in the shed or still in the field. Also, very minimal physiological mass loss was recorded compared to the ambient temperatures (Ambuko et al., 2017). A study conducted in India showed that a temperature difference of between 10 and 15˚C could exist between the interior of a cooler and the exterior. The interior of the same cooler had a 30 to 40% RH more than the cooler's surroundings (Dadhich et al., 2008). These conditions drastically curtailed the progression of loss of freshness and wilting. Hence, the fruits inside the cooler stayed fresh for an extra 3 to 4 days more than the outside.

The key advantage to this type of cooling is the fact that they do not need both electrical and mechanical energy to run them, and hence appropriate for small-scale farmers who are found on the global south of the planet. Plus, the evaporative cooler can be made using cheap and locally available materials, utilizing unskilled labour thus making the whole construction cheap. Research shows that a 200 kg storage facility can be as cheap as USD 200 and larger units can cost about USD 1000 (Kitinoja and AlHassan, 2012). Despite the numerous advantages that the evaporative cooler possesses, its adoption by small-scale farmers is quite wanting.

2.2.3 Cost-benefit analysis

Cost-benefit analysis is a tool used to evaluate the project by comparing the benefits, capital cost estimation and operating cost. It is used at the initial stages of the project to help decide whether the project should go ahead or not, or to choose between two different project options. It can as well be applied to two or even more projects with potential benefits to see which provides the best benefit (Shively, 2013).Numerous cost-benefit assessments have been performed to determine whether the anticipated economic and sustainability benefits of buildings that have received a green building certificate have actually been realized and while some research have shown mostly favorable findings, others have revealed unfavorable ones (Chen et al., 2018). Ried et al. (2013) applied cost benefit analysis to compare of the costs (vehicle purchase costs and energy costs) and benefits (reduced petroleum consumption) of Plug-in hybrid-electric vehicles (PHEVs) relative to hybrid-electric and conventional vehicles.Makul, (2020) conducted a study on the application of cost-benefit analysis approach to the manufacture of ready-mixed, high-performance concrete in Thailand using recycled concrete material.

2.3 Summary of the Literature Review and Research Gap

Evaporative cooling is defined as the process of adiabatic saturation of air and it occurs when sprayed water is made to evaporate into it with zero conveyance of heat to or from the environment. This process is utilized in the design and construction of an evaporative cooler. Evaporative coolers are useful structures when it comes to the preservation of fresh produce (such as fruits), which are synonymous with perishability. To make the coolers even more efficient, then PV cells can be added. PV cells are tasked with the conversion of light energy directly into electricity. This is both a physical and chemical phenomenon. Individual PV cells can be brought together to create modules that are popularly known as solar panels. The PV cells have been used previously in agriculture in some innovations and this is because sustainable solar energy is the natural choice for many, due to the rise in demand for energy in the agricultural sector and the negative impacts that are linked to fossil fuels (Tariq et al., 2021).

In evaporative cooling systems, solar energy is used to run the fans and water pumps. Thus, it is important to create a solar-powered evaporative cooling system that is more efficient for use by small-scale farmers in Sub-Saharan Africa. A solar-powered evaporative cooling system might be a game-changer for those living in the tropics or other places with high humidity and high temperatures (Sipho and Tilahun, 2020).

2.4 Conceptual Framework

The conceptual framework that was adopted in the study is presented in Figure 2.6. It relates the independent and dependent variables. The independent variables were characterized in terms of the PV system, performance evaluation, and techno-economic factors. PV system characterization variables included: radiation, tilt angle, and location; performance evaluation variables included: temperature, humidity, vitamin C, total soluble solids, weight loss and firmness; and the techno-economic variables included: energy consumption, product storage duration, direct and indirect costs. The dependent variables included energy efficiency ratio, cooling efficiency, energy cost-saving and shelf life. The performance of the system when the charcoal was wet with water but with no produce (no load) and when the system with fans running, charcoal wet and produce inside the cooler (loaded) was conducted and both cooler and ambient conditions as well as product quality parameters recorded.

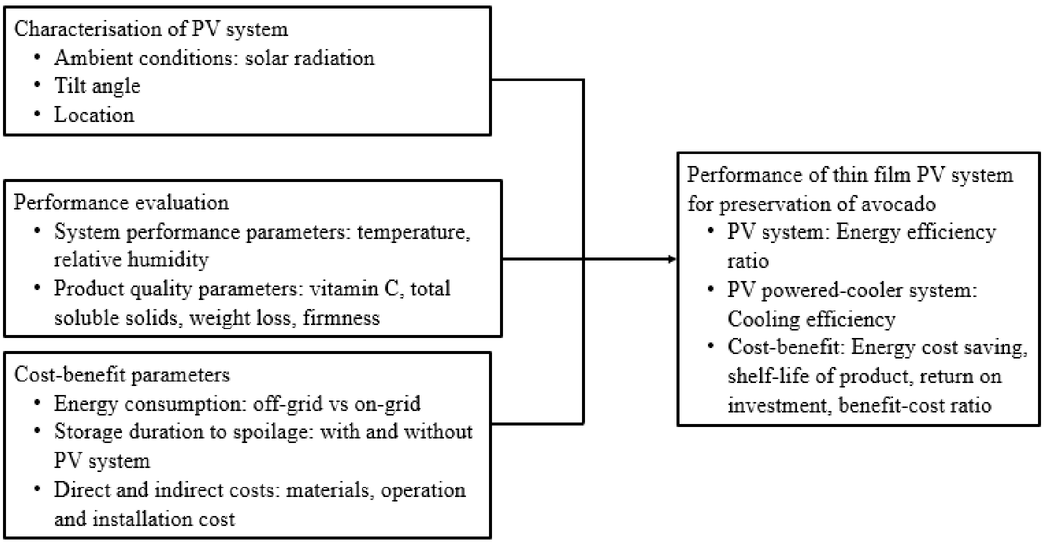

Figure 2.6: Conceptual framework for the study

CHAPTER THREE

MATERIALS AND METHODS

3.1 Experimental Site

The evaporative cooler is located in Kimicha (Kirinyaga County, Kenya). The coordinates of the actual location were 37.294^{o} E longitude and 0.594^{o} S latitude. The study site was located at an altitude of 1258 m above sea level (Ronoh et al., 2018).The experiments were also partly conducted in Juja (Kiambu County, Kenya) located at 37.014˚E longitude, 1.093˚S latitude and an altitude of 1550 m above sea level.

3.2 Acquisition of Avocado Fruits for the Experiment

The avocado fruits for the experiment were obtained locally from the farmers one day before the experiment commenced. They were harvested in the evening and transported to the site using a sack by a motorbike in the morning of the experiment.

3.3 Description of the Evaporative Charcoal Cooler

The evaporative charcoal cooler used in the study (Figure 3.1) has dimensions of 4 m in length, 4 m in width, and 2.5 m in height, resulting in a total storage capacity of 40 m^3. The cooler's wall, which was 150 mm thick, was crammed with charcoal which was held in position by weld and chicken meshes. Charcoal was used because of its porous nature, which enabled it to absorb and store water, and its heat conductivity of 0.084 W/mK.

Figure 3.1: Evaporative charcoal cooler system with a preparation area.

Several African nations choose charcoal over more expensive alternatives due to its low price. A plastic vented crate measuring 0.578 m in length, 0.385 m in width, and 0.21 m in height was used to store the fruit because it allowed for better air circulation, which prolonged its freshness. To moisten the charcoal, a perforated water drop pipe (20 mm in diameter) was installed above the charcoal walls. The charcoal was drenched with water after every two hours a day by the drip lines connected to a 1000-litre water cistern placed 2.5 m above the ground, and located at a corner next to the cooler. The interval of water application on the charcoal was determined from a preliminary test using a cartridge model of 30 cm × 30 cm and a thickness of 15cm filled with charcoal as shown in Figure 3.2. The weight and subsequently the volume of water applied on the cartridge until saturation was determined by subtracting the weight of the charcoal and cartridge before wetting and after wetting. The water in the charcoal was allowed to naturally evaporate by hanging it in an open space until the weight was almost close to before wetting and this informed the next time of wetting. This time was established to be 1 hour and 43 minutes and upon implementing this on the existing charcoal cooler, the wetting time was extended to 2 hours because of the nature of the weather (showers of rain) when data was being collected.

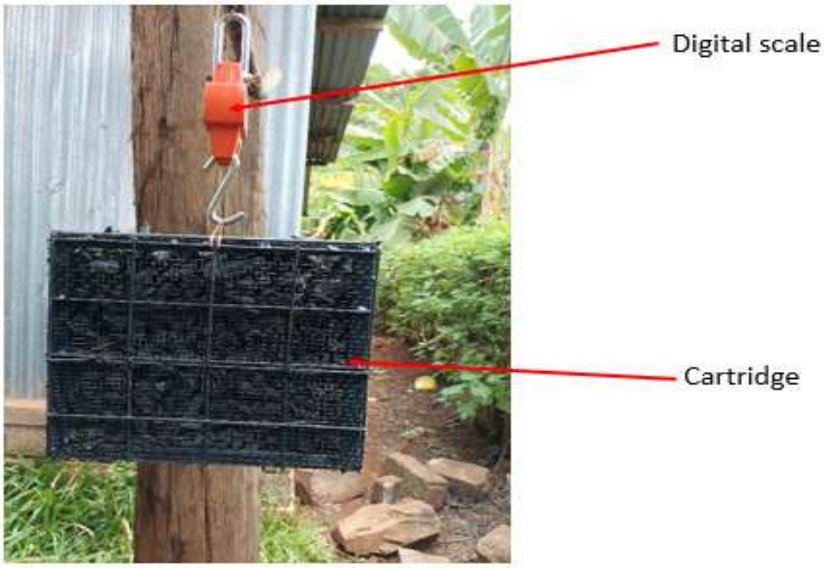

Figure 3.2: Cartridge model of the charcoal wall.

To ensure proper usage and management of the cooling facility, a 20 m^2 preparation area and a 12 m^2 office next to the cooler were included in the design. The preparation area had a concrete bench for sorting and grading of the produce before the desirable produce could be stored, and the undesirable produce discarded. The office on the other hand was meant for the records (relevant for the running of the cooling facility) safe-keeping (Kanali et al., 2017).

3.4 Description of Improvements in the Cooler

A number of modifications was done on the existing charcoal cooler with an aim of improving its performance for storage of avocados. A water pump (0.5 hp Pedrollo PKM 60, Italy) and 180 CFM axial fans (REC 21725 A2 W, India) were installed in the cooler to facilitate water circulation and hence reduced time of wetting charcoal and removal of warm air from the cooler, respectively. This equipmentwere powered by the thin photovoltaic system which also powered the data acquisition system and computer in the records office. In addition, charcoal was added to the cooler to fill the existing spaces. Finally,a half inch generic plastic water meter was used to monitor and record the water usage in the cooler.

3.4.1 Data acquisition system in the cooler

The charcoal cooler employed a developed instrumentation system. The system was powered by a thin-film PV system and made use of temperature-humidity sensors (DHT 22) sensors which were installed both inside and outside of the cooler. The system recorded both humidity and temperature values at 30-minute intervals and the readings were displayed on an LCD screen (20×4) while being stored in the SD card. The algorithm (Appendix 1) that ran the system was developed using a C++ program by the use of Arduino integrated development environment (IDE) version 1.8.9

3.4.2 Thin-film PV system and SPN1 sunshine pyranometer

The energy hub is powered by a foldable solar PV array that has a power output range of 0.9 kW–1.6 kW (Figure 3.3). The energy hub can be powered by two mats at once, however, this varies by design (Renovagen, UK). The energy hub is fitted with an LCD screen that displays the PV power generated by the two fast-fold mats. The solar radiation wasmeasured using a sunshine pyranometer (SPN1, USA) and data recorded using a GP1 data logger (Figure 3.4).

Figure 3.3: Portable off-grid energy hub (left) and foldable thin-film solar mat (right)

Figure 3.4: SPN1 sunshine pyranometer (left) and GP1 data logger (right).

3.4.3 Working principle of the cooler

The air through the charcoal (padding material) was cooled and humidified, and it was very vital in removing the total heat load of the charcoal cooler. The most important parameters needed in the determination of the cooling process design are the heat load and the time of processing. The sources of heat to be eliminated from the cooler include the heat of conduction, the heat that gets into the cooler via the walls and the floor, field heat of the produce (this is the total amount of heat picked by the produce from the farm), the heat of respiration (heat created by the product as a respiration product) and infiltrations (this is the heat from the surrounding environment that makes its way through cracks and opened doors).

3.5 Characterizing the Performance of the Thin-film Photovoltaic Technology

The performance of a thin-film PV technology wascharacterized by taking the readings of the power being generated by the fast-fold mat under different tilt angles ranging from 0^o(PV horizontal to the ground) to 30^o. The thin-film PV system was first set at 0^o to the horizontal, then repeated at 5^o intervals until it reached a maximum of 30^o as shown in Figure 3.5. The various angles were achieved by attaching the frame with anchorage bars (Appendix 2) with holes drilled at various distances to replicate the various angles as determined using trigonometry. For the study, two locations were selected: Kimicha, Kirinyaga County, where the charcoal cooler was situated, and Juja (Kiambu County). The first test was carried out at Jomo Kenyatta University of Agriculture and Technology (JKUAT) in the Agricultural and Biosystems

Engineering Department.The studies were carried out from 11 am because of the logistical challenges (transport of system from Juja to Kirinyaga and back) and the time required to set up the system (time to taken to fit the frames with bolts and nuts).The parameters of interest during the tests included PV power and solar radiation. Data were collected (November 2021) for Kimicha and (January 2022) for Juja. The maximum angle chosen was based on the minimum slope of more than 10^{o} from the horizontal pitched roofs (Kenya Gazette, 2022).

Figure 3.5: Thin-film PV system tilt angle set-up.

3.6 Evaluating the Performance of the Improved Evaporative Charcoal Cooler

3.6.1 Performance testing at different air speeds at no load

Before the fans were installed in the field, a lab-scale model of an existing cooler was used to run the fans at different air speeds. The cooling chamber was made of a rectangular conduit composed of stainless-steel sheets. The active section of the cooler had a 300 mm by 300 mm cartridge that held 150 mm thick of charcoal, and the end had a 135 W exhaust fan (Deco Appliances, India). The air inlet section was made of a screen that permits air to pass through the charcoal. The top of the cartridge was fitted with a perforated pipe that fed water to the pad while at the bottom a collection tank was positioned to collect water draining from the pad. Different air speeds were achieved by running the air speed sensor (YGC-FS-24V, China) with an accuracy of ±1 m/s for 30 minutes from an initial speed of 0.5 m/s. Thereafter, the air speed was successively increased to 1, 1.5, 2, 2.5, and 3 m/s. This was necessary to obtain a suitable air speed that would be adopted for other research works in the field. Before the air speed sensor was used, calibration was done using the data sheet that accompanied it. Using these different speeds, temperature and relative humidity were recorded using a fabricated data logger and DHT sensors and analysed both for ambient and inside the cooler.

3.6.2 Developing an improved charcoal cooler with a thin-film PV system

To develop an improved evaporative cooler that was efficient, several factors were considered. The following were the necessary design considerations: The charcoal cooler was observed to have a uniform surface area and the water uniformly wetted the charcoal. The polypropylene random pipe (PPR) were marked and drilled at an equal spacing of15 cm and thereafter joined using a PPR welding machine (PPR welding machine, China). They were then fastened on the wall using binding wire with the holes drilled facing the charcoal wall. The improvement done on the cooler were the use of a 0.5 hp pump (Pedrollo PKM 60, Italy) to circulate the water in the pipes and hence shorten the charcoal wetting duration, incorporation of thin-film PV system that provided power to the charcoal cooler's electrical demand such as the pump and axial fans with each 180 CFM (REC 21725 A2 W, India) that assisted in extracting the warm air from the cooler. Figure 3.6 represents an external view of the improved evaporative charcoal cooler with a fan and a water meter.

Figure 3.6: External view of the improved evaporative charcoal cooler

3.6.3 Data acquisition

Temperature and relative humidity of the improved evaporative charcoal cooler were monitored using digital humidity-temperature (DHT 22, China) sensors with a humidity range of 0 to 100% and 2-5% accuracy and -40 to 80°C temperature with an accuracy of ±0.5°C. Three sensors were hanged inside on the ceiling of the cooler and one for outside conditions (Figure 3.7). The data were recorded using a data logger at 30 minutes intervals throughout the study period. The study involved monitoring the microclimate within the evaporative charcoal cooler and the control environment (outdoors) under both unloaded and loaded conditions.

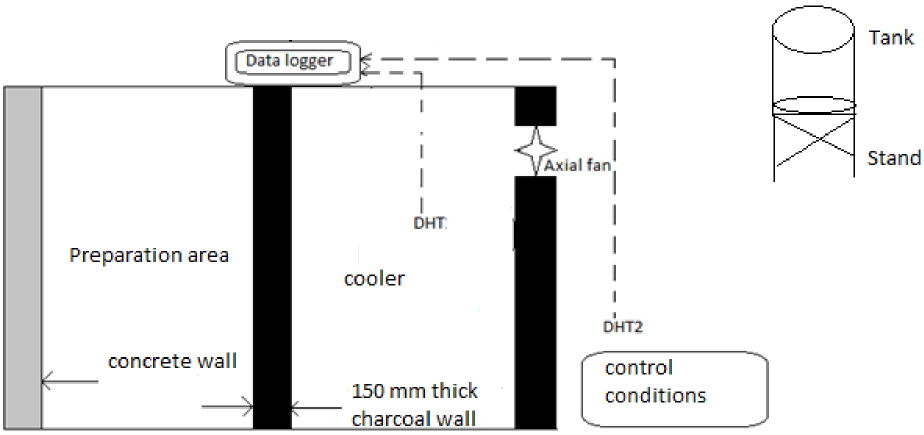

Figure 3.7 Schematic of the arrangement of a control system in an evaporative charcoal cooler.

3.6.4 Cooling efficiency

The cooling efficiency was another critical parameter that was used to assess the performance of the improved evaporative charcoal cooler. This can be simplified as expressed in equation (3.1), according to von Zabeltitz (2011), where $\eta_{cooling}$ was the cooling efficiency (%). In the equation, T_a is the dry bulb temperature of the ambient conditions (°C), T_i is the cooled air dry bulb temperature (°C) and T_{wb} is the ambient air wet bulb temperature (°C), which was determined by use of a psychrometric chart by American Society of Heating, Refrigeration and Air conditioning (ASHRAE) and confirmed by ASHRAE calculator (Herrmann et al., 2009) by applying the known inputs (ambient relative humidity, RH_a and T_a).

$$\eta_{cooling} = \frac{T_a - T_i}{T_a - T_{wb}} \times 100 \qquad =(3.1)$$

3.6.5 Energy efficiency ratio

The energy efficiency ratio (EER) is a parameter that is used to assess the industrial rate of the air conditioning unit (El-Dessouky et al., 2010).EER is defined as the amount of thermal energy extracted from air intended for cooling per watt of energy used, given by equation (3.2) as per El-Dessouky (2010). In the equation, EER is the efficiency ratio, Δh is the difference between the enthalpies of inlet and outlet air streams, and P is the electrical power of the axial air inlet fan, control system, and entire electrical devices in the cooler measure using power consumption meter (Myriann, China).

$$\mathrm{EER} = \frac{\Delta \mathrm{h}}{\mathrm{P}}$$

(3.2)

The change in enthalpy (Δh) in kJ/kg was calculated using equation (3.3), where M is the air mass flow rate in kg/s, C_{pa} is the specific heat of moist air in kJ/kg/K, T_a is the dry bulb temperature of ambient air in °C and $T_i$is the cooled air dry bulb temperature in ^{o}C (Tilahun, 2010).

$$\Delta h = MC_{pa}(T_a - T_i) \qquad (3.3)$$

3.6.6 Monitoring the stored avocado fruits physiological changes

The following factors were used to monitor physiological changes in the fruits over the study period; vitamin C, total soluble solids, weight loss and firmness.

a) Vitamin C

Three samples of avocado obtained after one day of harvesting were randomly selected from the crates and taken to the lab in JKUAT using an insulated cooler box for vitamin C content analysis after every four days. The amount of vitamin C content (mg/100g) was determined using vitamin C testing procedure (AOAC, 2010),where titration was performed and the titre result converted into vitamin C level in mg/100 g, given by equation (3.4). In the equation, *c* was the standardization value, *v* was the volume prepared, *l* was the aliquot made and *s* was the sample weight.

$$Vitamin\ C = \frac{titre-(blank\times c\times v)}{l\times s}\times 100 \quad (3.4)$$

b) Total soluble solids

The data for total soluble solids determination was collected in °Brix. Brix is a unit of measurement for the total soluble solids in a liquid and is commonly used to determine the sweetness of fruits and vegetables. In general, 1°Brix equals 1 g of sugar per 100 g of liquid, such as water (Lizcano et al., 2020). Total soluble solids concentration (TSSC%, ^{o}Brix) were determined using a handheld refractometer (Atago 2360 N-8, Japan). Here representative wedge slices of the stem end of the avocado were cut from 3 avocado samples using a generic slicer. They were crushed using a mortar and pestle and squeezed through a cheesecloth to obtain the juice. The glass prism of the refractometer was rinsed with clean water and dried with a clean soft cloth to wick the remaining water off. Drops of sample juice were then put on the glass measuring surface and readings were taken through the eyepiece while holding the refractometer up to natural light.(Misco, 2014). The procedure was repeated three times and the average value obtained.

c) Weight loss

Physiological weight loss was determined by weighing three avocado samples (from the cooler and the ambient conditions) labelled S_1, S_2 and S_3 three times a day (morning, noon and evening)using a digital weighing scale (A&D Gulf, India), with a precision of ±0.01 g in the preparation area section of the cooler. Weight loss was expressed as the percentage of the initial weight using equation (3.5) (Jahun et al., 2016). In the equation, w1 is the initial weight at the first day of experiment and w2 is the final weight after twelve days.

Weight loss (%) $= \frac{W1-W2}{W1} \times 100$ (3.5)

d) Firmness

Firmness also called puncture test was determined using Sun Rheometer Compac 100 (Sun Scientific Co. Ltd, Japan) fitted with an8 mm hemispherical probe. This was carried out in food science laboratory in JKUAT using three randomly selected avocado samples from the cooler and ambient environment obtained after every four days. The maximum force at a penetration rate of 20 mm/min at which the probepierced the outer layer was measured in three spots along the fruit's equatorial region(Hershkovitz et al., 2005) and the procedure was repeated three times for every sample.

3.7 Assessing the Cost-Benefit of Using the Improved Evaporative Charcoal Cooler

3.7.1 Present worth analysis

Present worth (*P*) was calculated using the equal-payment series capital recovery amount method to determine the benefit-cost ratio (BCR) and return on investment (ROI) for the improved charcoal cooler thin-film PV system. In the equal- payment series capital recovery method [(equation (3.6)], the parameters *P*, *A*, *i* and *n* are present worth, annual equivalent payment and interest rate, respectively (Pearson, 2021).

$$A = P\,\frac{i(1+i)^n}{(1+i)^n-1} \qquad (3.6)$$

3.7.2 Benefit-cost ratio

An analysis was conducted to evaluate the benefit-cost ratio (BCR) of the cooler. The BCR measures the relationship between current benefits and current costs as in equation (3.7). The BCR was achieved by dividing the present value benefits with present value costs (Kennedy, 1981), where $B_{pv}$and C_{pv} were present value benefits and present value costs, respectively. Energy saved in using the PV system was determined and present value benefits computed considering the unit cost of energy and the revenue generated through selling the avocados. The costs associated with the system were construction, installation of the piping system and PV system. It was then compared with the cost savings on electricity that would have been used for the same purpose and the projected avocado sales

$$BCR = \frac{B_{pv}}{C_{pv}} \tag{3.7}$$

3.7.3 Return on investment

Return on investment (ROI) is a measure used to assess to what extent the invested capital will produce a gain or a loss. It is calculated as the ratio of the profit from capital invested divided by the amount invested. The result of ROI is expressed in terms of percentage as in equation (3.8), according to Beattie (2022), where FVI is the final value after investment, IVI the initial value of the investment and CoI the cost of investment.

$$\mathrm{ROI} = \frac{\mathrm{FVI} - \mathrm{IVI}}{\mathrm{CoI}} \times 100\% \tag{3.8}$$

The amount invested is based on the cost construction of the cooler, installation of the dripping system; the cost of the pump, piping system, labour, and control system. The revenues are obtained by cost savings on energy and through sale of avocados assuming that the cooler was full of avocados.

3.8 Data Analysis

All measurements were conducted with three replications for each parameter considered in the study. For data analysis, the collected data were averaged to take care of the inconsistency within the performance evaluation period. The data were presented graphically. Analysis of variance (ANOVA) was also performed to ascertain whether or not the use of the improved charcoal cooler had any significant effect on the microclimate conditions and the chosen quality parameters. Differences among treatments were evaluated using an ANOVA procedure in R statistical software (R-4.0.0). The student's *t*-test was also used in conjunction with the ANOVA to determine the differences between means. Another key aspect used in interpreting the test statistics was the *p*-value.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Performance of the Thin-film Photovoltaic Technology Under Varying Ambient Conditions

4.1.1 PV power at different tilt angles

The PV power generated (read from display screen of energy hub) was used as a measure to evaluate the effectiveness of the thin-film photovoltaic technology.Figures 4.1 and 4.2 show the power generated at different angles for Kimicha and Juja study sites, respectively. The maximum power generated during the study day for Kimicha were 612, 798, 619, 617, 536, 562 and 532 W at 0^o, 5^o, 10^o, 15^o, 20^o, 25^o and 30^o, respectively, which were realized between 1 and 2 pm when the solar energy was incident to the PV film. The minimum PV power generated were 68, 71, 52, 57, 41, 33 and 33 W at 0^o, 5^o, 10^o, 15^o, 20^o, 25^o and 30^o, respectively, recorded at 5 pm and this can be attributed to the sun's position (lowest point) when the solar intensity was low (Tijjani et al., 2020). These results were based on the instantaneous solar radiations at individual tilt angles of the thin film PV. The pattern of high and low exhibited in Figure 4.1 is attributed to the atmospheric conditions and more specifically the cloud cover during the month when the research was conducted.

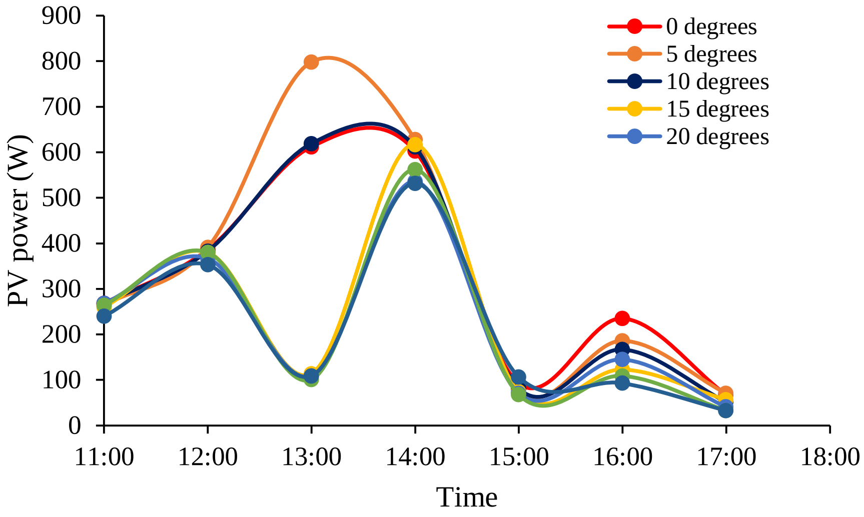

Figure 4.1: PV power at different angles for Kimicha

The PV power generated for different angles between 0° and 30° at a succession of 5° for Juja is presented in Figure 4.2. From the results, the power generated by the thin film PV technology increased for the majority of the tilt angles up to between 1 and 2 pm and thereafter reduced for the other period. This can be attributed to the fact that the amount of solar radiation changes depending on the sun's position, which is constrained by the air mass, with the peak amount of solar radiation occurring in the afternoon (Jazayeri et al., 2013). The maximum PV power during the study period were 596, 612, 652, 637, 607 589 and 482 W for 0°, 5°, 10°, 15°, 20°, 25° and 30°, respectively. The minimum PV power obtained were 192, 233, 307, 314, 236, 189 and 171 W at the tilts angles of 0°, 5°, 10°, 15°, 20°, 25° and 30°, respectively. The maximum value obtained at 11 am for the 30° angle can be attributed to the fact that the readings were recorded instantaneously. The difference between the results obtained for Kimicha and Juja can be attributed to the different geographical locations and the fact that it was somehow cloudy when data collection was done for Kimicha.Clouds significantly reduce the amount of direct solar energy that reaches the surface of the module, resulting in low output power. As a result, the module produces

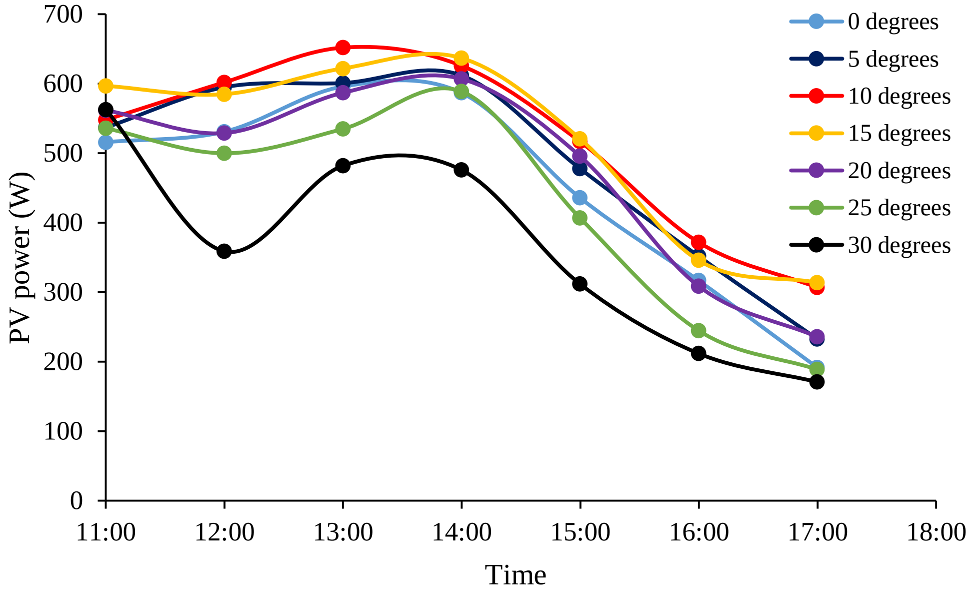

Figure 4.2: PV power different angles in Juja.

4.1.2 Average PV power

Figures 4.3 and 4.4 show the variations of PV power with tilt angle for Kimicha and Juja, respectively. The maximum average PV power for Kimicha was 347.9±231.9 W corresponding to a tilt angle of 5° and the minimum average power was 248.1±175.3 W at 30°. The maximum average PV power for Juja was 517.7±131.3 W and the average minimum was 367.9±146.7 W corresponding to 15° and 30°, respectively. These results agree with (Wardhana et al., 2021) who discovered that the higher the solar intensity the higher the output voltage of the solar panel. He also discovered that voltage was maximum at an angle of 30° when compared to 0° and 60°. Also, research done by Jacobson and Jadhav (2018) for optimal tilt angles for all the countries showed that the optimal angle in Nairobi near the meteorological station was 4 ±10° for other regions in Kenya.

The acquired results can be ascribed to the fact that incident light was perpendicular to the PV system for both Kimicha and Juja. This angle of 5° for Kimicha and 15° for Juja ensured that the most solar energy was received (Vidyanandan, 2017). Nevertheless, as the sun moves from east to west, the angle of incidence changes substantially, which reduces the amount of solar energy that the PV panel can collect since more light is reflected off the glass than it is absorbed (Asowata et al., 2014). The average PV power showed a decline as the tilt angle increased for the two sites.

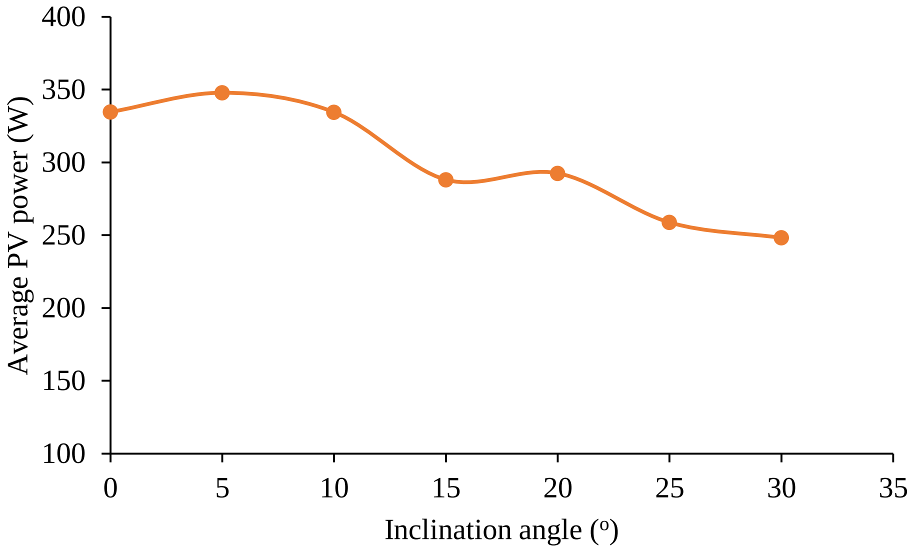

Figure 4.3: Average PV power for Kimicha.

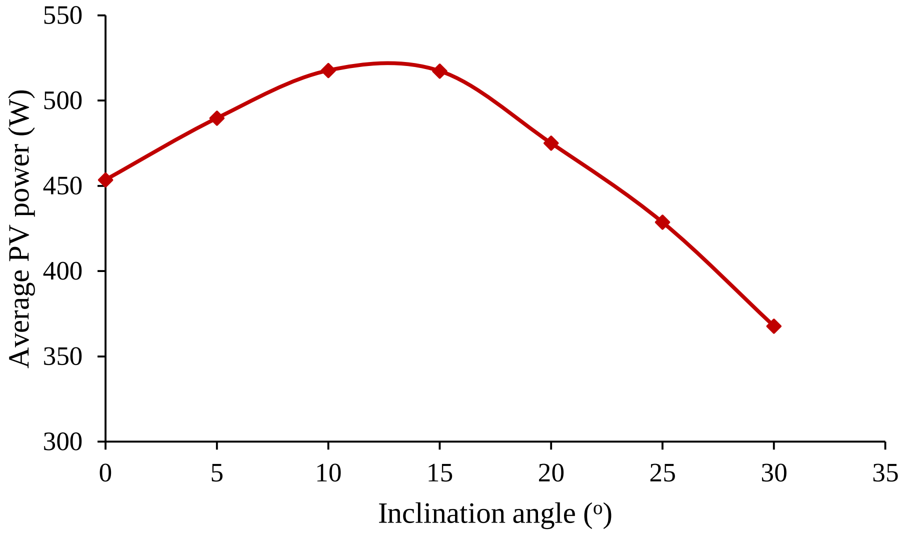

Figure 4.4: Average PV power for Juja.

4.1.3 Solar radiation

The solar radiation results (measured using SPN1 pyranometer) for Juja and Kimicha are presented in Figures 4.5 and 4.6, respectively. It is noted from the results that solar radiation increased to a maximum around 2 pm before it started decreasing to a minimum at 5 pm. This can be attributed to the fact that regions close to the equator at noon are almost perpendicular to the direction of incoming light since the earth is spherical. Everywhere else, the light strike at an angle (Lindsey, 2009). From the results, the maximum solar radiation in Juja were 1145.5, 1110.3 and 1003.4 W/m^2 and minimum of 531.6, 620.9 and 435.7 W/m^2 for the 1st, 2nd and 3rd, respectively, and the maximum of 1080.5, 829.7 and 1010.33 W/m^2 with the minimum of 485.9, 240.6 and 359.8 W/m^2 for the 1st, 2nd, and 3rd day, respectively in Kimicha.In addition to the strength of the sunlight itself, the solar radiation intensity impacting a PV module is also influenced by the angle at which the module is facing the sun. Aldobhani's (2014) study found that the tilt angle has a strong effect on the amount of solar radiation that hits a surface.

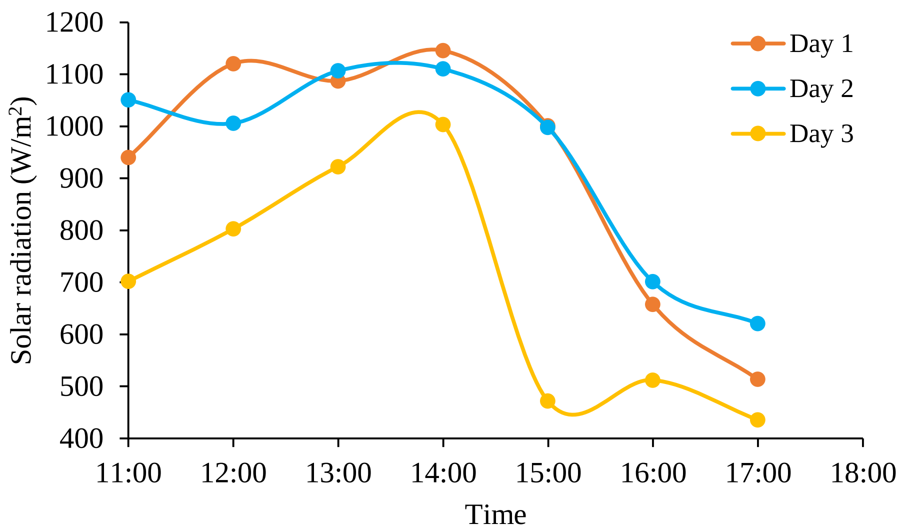

Figure 4.5: Solar radiation for 3-day period for Juja.

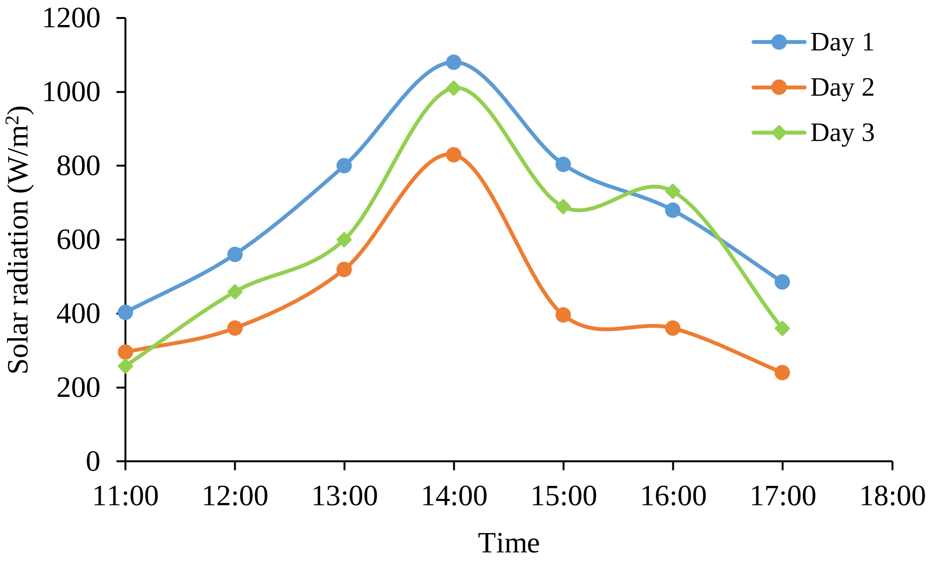

Figure 4.6: Solar radiation for 3-day period for Kimicha.

The daily individual solar radiations shown above were used to compute the average solar radiations for Kimicha and Juja and are presented in Figures 4.7 and 4.8, respectively. The maximum and minimum average solar radiations for Kimicha were 973.5±219.9 and 319.0±219.9 W/m^2 at 2 pm and 11 am, respectively.The maximum and minimum average solar radiation for Juja were 1086.4±211.4 and 523.4±211.4 W/m^2 at time 2 and 5 pm, respectively. The results agree with that byDaut et al. (2012) who conducted research between 7 am and 7 pm and achieved maximum solar radiation between 2 and 3 pm and minimum solar radiation at 7 pm. His research concluded that the sun's radiation is most intense when the sun is at its peak in the sky at noon, but it hits the earth at a lesser angle at other times.

The intensity of the energy is reduced as a result of it being scattered over a larger surface area (Vidyanandan, 2017). The PV surface absorbs the most solar energy when the incident sunlight and the absorbing surface of the PV system are perpendicular to one another. On the other hand, incident solar energy fluctuates with the position of the sun because the angle created by the sun and a horizontal surface changes continuously throughout the day (Markam and Sudhakar, 2016).

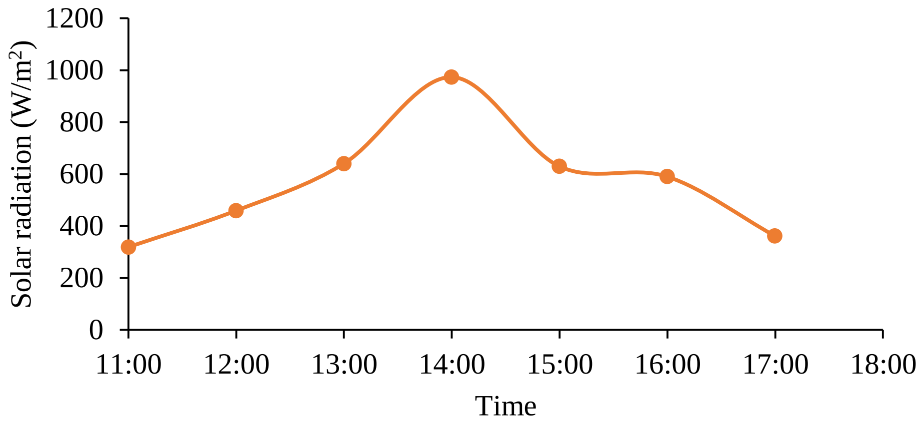

Figure 4.7: Average solar radiations for Kimicha.

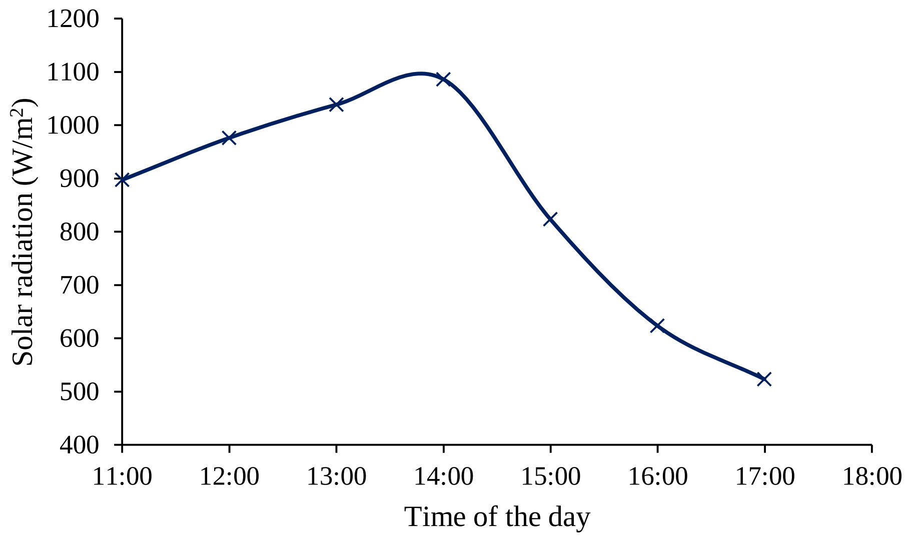

Figure 4.8: Average solar radiations for Juja.

4.1.4 Relationship between solar radiation and PV power

The relationship between solar radiation and PV power for Juja is shown in Figure 4.9. The average maximum solar radiation recorded was 1086.4 W/m^{2}at 2 pm which produced a peak power of 517.7 W and the minimum solar radiation was 523.4 W/m^{2}at 5 pm which generated the minimum PV power of 367.9 W.It can be seen that the conversion has a time-variation aspect in addition to being non-linear. Specifically, compared to the morning and evening, the conversion rate is generally greater in the afternoon.The amount of solar energy falling on each square meter perpendicular to the direction of the sun is measured as insolation. On particularly clear days, the insolation can reach well over 1,000 W/m^2 around noon, which will cause solar panels` to produce more power (Gaughan, 2019).Maximum solar strength is reached when the sun's beams are perpendicular to the PV module. Solar energy is reflected whenever the rays are not parallel. Normal daytime sun generation peaks between 11 am and 4 pm (Regen Power, 2022).

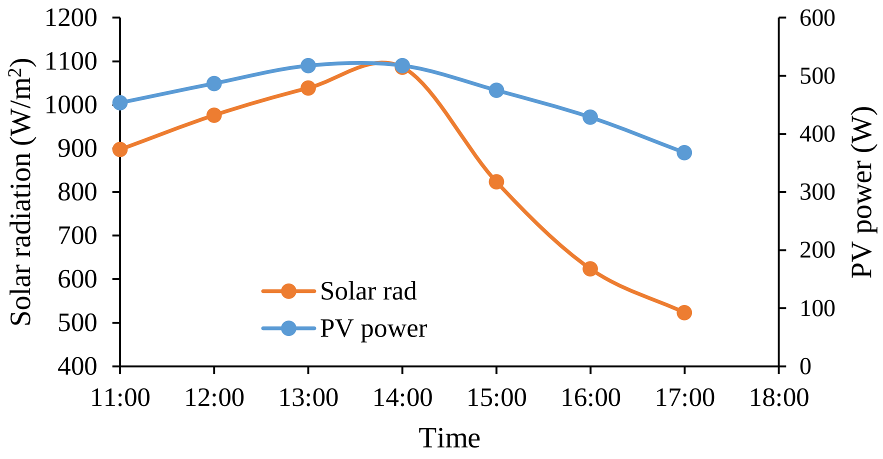

Figure 4.9: Relationship between solar radiation and PV power.

4.2 Performance of the Improved Evaporative Charcoal Cooler Utilizing Thin-Film Photovoltaic System for Preservation of Avocado

4.2.1 Performance of the improved evaporative charcoal cooler at no load

a) Performance of charcoal cooler at different air speeds

To evaluate the performance of the improved charcoal cooler, ambient and cooler temperature and relative humidity data were collected and the results analysed as shown in Table 4.1. The results in the table show that the highest temperature drop was 6.4^{o}C which occurred at an air speed of 0.5 m/s. At a higher air speed of 3 m/s, the drop in temperature was 3.8^{o}C. These results indicate that higher temperature drop leads to better cooling efficiencies while higher air velocities lead to greater cooling capacities as such high velocities lead to increased mass flow rates and evaporation heat absorption (Hassan et al., 2022).

Table 4.1: Average ambient and charcoal cooler conditions at different air speeds

Air speed (m/s)	Ambient		Charcoal cooler		
	***T_a* (ºC)**	***RH_a* (%)**	***T_c* (ºC)**	***RH_c* (%)**	***T_a*-*T_c* (ºC)**
0.5	33.0	56.9	26.7	85.0	6.4
1	32.6	56.9	26.8	85.7	5.8
1.5	33.0	57.1	27.5	85.4	5.5
2	32.8	56.6	27.8	88.1	5.0
2.5	32.1	56.8	28.2	94.0	3.9
3	32.8	57.0	29.0	95.0	3.8

In the table: T_a, ambient temperature; RH_a, ambient relative humidity; T_c, charcoal cooler temperature; RH_c, charcoal cooler relative humidity

The data in Table 4.3 was used to compute and plot the relationship between cooling efficiency with different air speeds as shown in Figure 4.10. It was noted that the maximum cooling efficiency obtained was 84.7% at an air speed of 0.5 m/s. On the other hand, the minimum cooling efficiency was 51.3% at 2.5 m/s. It was noted that higher cooling efficiency occurred at low air velocity. This is due to the longer time needed for heat and mass to transfer when the air and water in the medium are moving at low air speeds (Yan et al., 2021). Low air velocity encourages better air retention on the cooling pad surface, allows for more evaporation to occur, and lowers temperature (Hassan et al., 2022).

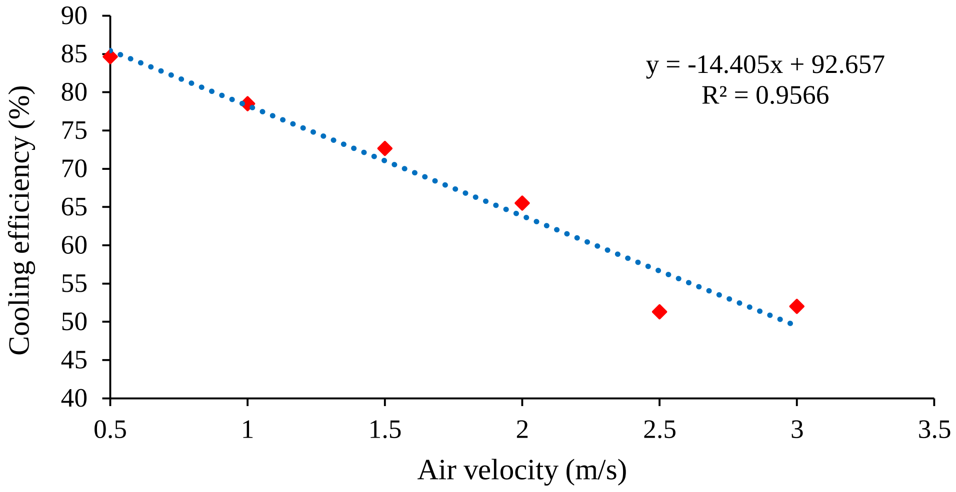

Figure 4.10: Average cooler efficiency variation at different air velocities.

b) Daily and average cooler and ambient conditions

i) Daily temperature

Figure 4.11 shows the hourly characteristics of the charcoal cooler and ambient air over three days. The effectiveness of the evaporative cooler was assessed from 7 am to 6 pm at a 1-hour interval each day for temperature fluctuations at no load where CT1, CT2 and CT3 are the cooler temperatures for days 1, 2 and 3, respectively, and AT1, AT2 and AT3 are ambient temperatures for days 1, 2 and 3, respectively. The outdoor temperatures for the three days increased with time and later on decreased in the evening while the temperatures inside the cooler were relatively low. The cooler temperature ranged from 22.0 to 26.6, 21.4 to 26.6 and 21.1 to 26.0^{o}C for days 1, 2 and 3, respectively while the ambient temperature ranged from 21.8 to 36.6, 20.2 to 37.1 and 21.5 to 36.3^{o}C, respectively. As can be seen from the results, the cooler temperatures were consistently lower than the ambient temperatures, especially, in the hottest periods when cooling is much needed and the same was observed by (Tejero & Franco, 2021). The temperatures in the cooler are rarely ideal for storage during the hottest parts of the day. However, the significant decreases in outdoor temperature that are achieved during these hot spells can significantly reduce commodity loss during storage (Thirupathi et al., 2006).

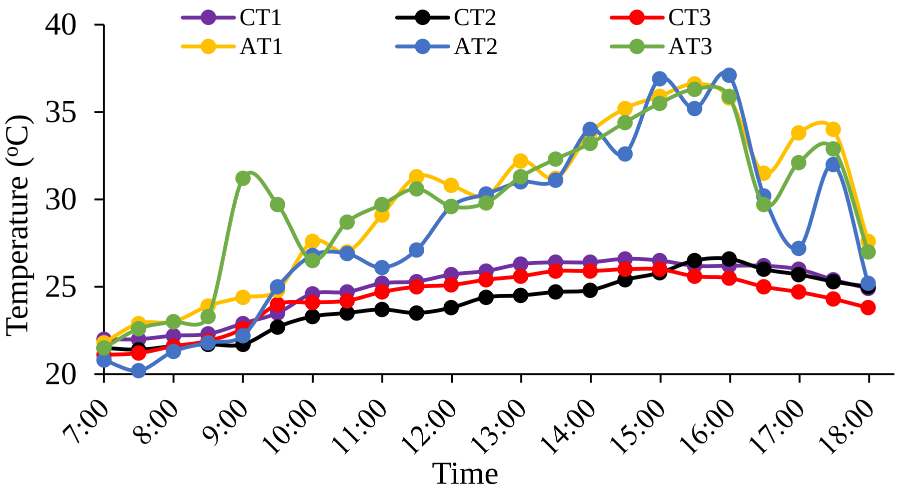

Figure 4.11: Temperature variation with time for 3 days.

ii) Average temperature

The average ambient and charcoal cooler temperatures recorded for the 3-day test between 7 am and 6 pm are shown in Figure 4.12. The average ambient temperature was 29.0±4.67ºC with a minimum of 21.5±4.67ºC at 7 am and a maximum of 36.2±4.67ºC at 4 pm. There was, however, a decrease in ambient temperature afterwards from 5 pm. The charcoal cooler displayed a maximum temperature of 26.1±1.69ºC at 7 am, a minimum of 21.5±1.69ºC at 4 pm and an average of 24.3±1.69ºC.Also, the ambient temperature varied from 21.5 to 36.2°C while the average temperature of the charcoal cooler ranged from 21.5 to 26.1°C. The maximum temperature drops in the cooler happened during the daytime when ambient temperatures were generally high in all of the daily test scenarios. As a result, evaporative cooling has a chance to be used during this time of day, making the system practical for preserving fresh produce (Thirupathi et al., 2006). There was a significant reduction in the charcoal cooler temperatures ($P<0.05$) as represented in Table 4.2.

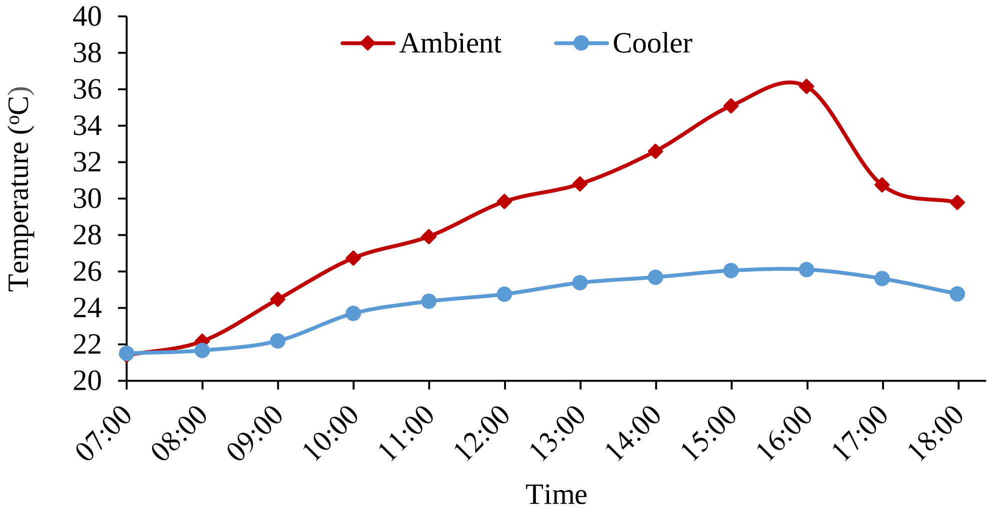

Figure 4.12: Average temperature at no load.

Table 4.2: ANOVA results for ambient and charcoal cooler temperatures at no-load

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	130.2004	1	130.2004	10.55501	0.003682	4.30095
Within Groups	271.3792	22	12.33542			
Total	401.5796	23				

In the table: SS = sum of squares, df = degrees of freedom, MS = mean sum of squares, F crit = F-statistic, F = Fcomputed

iii) Daily relative humidity

Figure 4.13 shows that the relative humidity values inside the charcoal cooler remained consistently high, in contrast to the highly fluctuating ambient relative humidity values. The cooler relative humidity values for days 1, 2, and 3 were denoted as CRH1, CRH2, and CRH3, respectively, while the ambient relative humidity values for the same days were denoted as ARH1, ARH2, and ARH3. The maximum relative humidity values for the cooler were 82.1, 82.9 and 82.2% while the minimum values were 75.7, 77.2 and 75.7% for days 1, 2 and 3, respectively. On the other hand, the maximum ambient relative humidity values were 80.7, 88.6 and 77.0% with minimum of 37.6, 37.8 and 32.0% for days 1, 2 and 3, respectively. The higher relative humidity values for the ambient were recorded at 7 am when the air was still moist. The cooling chamber's air humidity was higher than the ambient and therefore its capability of reducing excessive moisture loss of the produce (Umar et al., 2016).These findings show that the evaporative cooler may be helpful in the preservation of agricultural produce for a short duration, more so during the hottest period of the day when cooling would most be required.

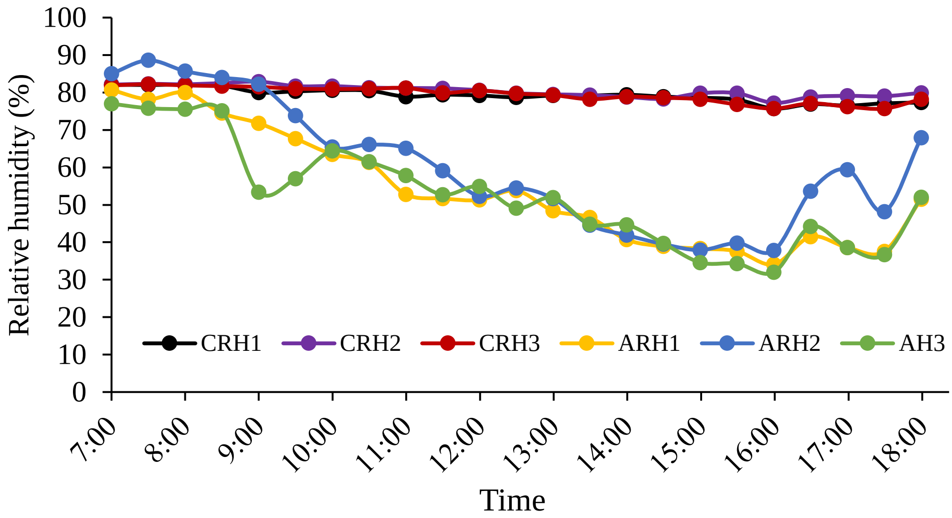

Figure 4.13: Relative humidity variation with time for 3 days.

iv) Average relative humidity

The average ambient relative humidity fluctuated greatly during the day (7 am to 6 pm) when compared to that for the evaporative charcoal cooler which was relatively constant (Figure 4.14). It was observed that the highest cooler relative humidity recorded ranged from 77.4 to 81.7% and ambient relative conditions ranged from 80.9 to 35.4%. The average ambient and cooler relative humidity values were 56.7±15.6% and 79.9±1.7%, respectively. This difference can be attributed to the weather conditions (rain drizzles) during one of the days in the test period. Kenghe et al. (2015)had previously stated that the relative humidity of between 80 to 90% could significantly increase the shelf life of most fruits therefore the recorded relative humidity of 77.4 to 81.7% observed in this study could preserve the postharvest quality and reduce weight loss of avocados. Mohapatra et al. (2013) suggested that avocados should be stored at temperatures between 3-13°C and at a relative humidity of 85-95%, which will allow them to remain fresh for 14-56 days but these conditions can only be realized through the use of a refrigerator. The high RH maintained by the cooler indicated that it was capable of preserving avocados for a longer duration compared to the outdoor environment. There was a significant increase in the cooler RH (P<0.05) when compared to outdoor RH (Table 4.3).

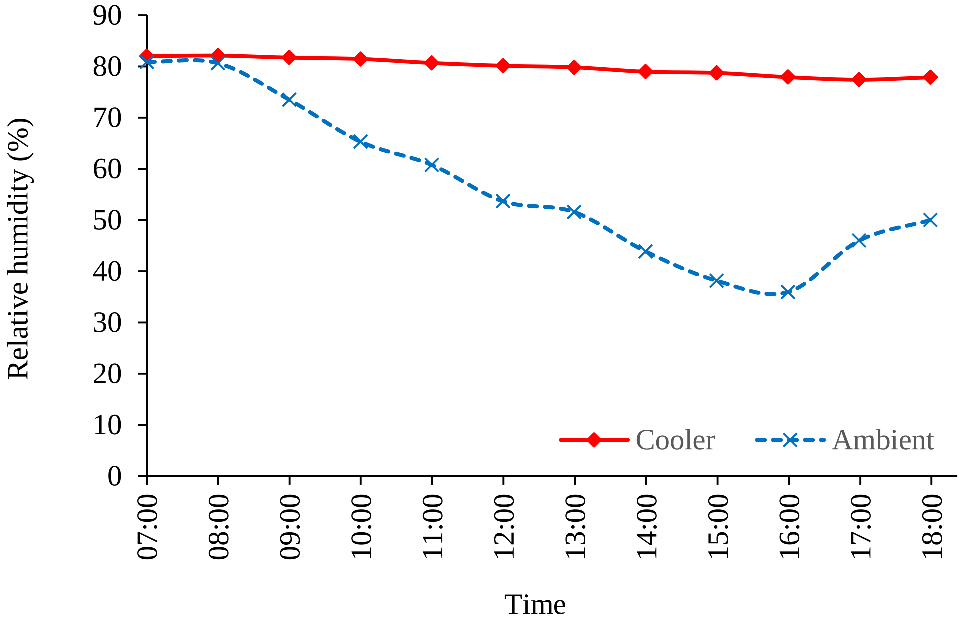

Figure 4.14: Average Relative humidity at no load.

Table 4.3: ANOVA results for ambient RH and charcoal cooler RH at no-load

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3229.44	1	3229.44	26.36062	3.81E-05	4.30095
Within Groups	2695.22	22	122.51			
Total	**5924.66**	**23**				

4.2.2 Performance of charcoal cooler under loaded conditions

a) Temperature

The daily average ambient and cooler temperatures during the storage of Hass and indigenous avocados is shown in Figure 4.15. The evaporative cooler temperatures recorded during Hass and indigenous avocados storage for the 12 days reduced significantly ($P<0.05$) (Tables 4.4 and 4.5, respectively), thus extending the storage duration of avocados in comparison to those stored in the open air. The average temperature of the cooler was 25.0±0.37 and 24.4±0.31ºC for Hass and indigenous varieties, respectively. The average ambient temperatures were 32.1±0.99 and 30.2±0.48ºC for Hass and indigenous avocados, respectively. The highest and lowest average temperatures in the cooler were 25.7 and 24.5ºC, respectively against 33.5 and 30.2ºC ambient conditions for Hass avocado. The corresponding highest and lowest average temperatures were 24.9 and 24.1ºC (cooler) against 31.0 and 24.9ºC (ambient conditions) for indigenous avocados.It can be noted that the charcoal cooler temperatures were consistently lower than those outdoors. Such circumstances are suitable for storing fruits (avocados) as well as lowering fruit weight reduction and postharvest moisture loss, both of which reduce postharvest losses (Tilahun,2010). Low temperatures are required to keep the agricultural produce fresh for a much longer amount of time (Mogaji & Fapetu, 2011). These findings show that the evaporative cooling method can be effective for the short-term preservation of produce. The results of the improved evaporative charcoal cooling system obtained from this study were in agreement with those of Mogaji and Fapetu (2011), who ascertained that an evaporative cooling system can maintain a temperature of 16 to 26°C during the hottest part of the day when cooling is highly needed. These findings are likewise similar to those reported by Azene et al. (2014), who found that the evaporative cooling system maintained a temperature of 17 to 26°C.

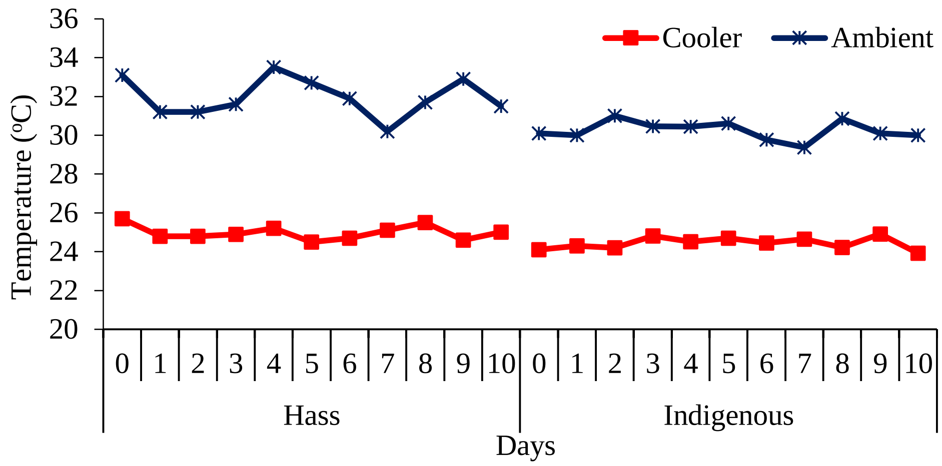

Figure 4.15: Daily average ambient and cooler temperatures during storage of Hass and indigenous avocados

Table 4.4: ANOVA results for ambient and charcoal cooler temperatures during Hass avocado storage

Source of Variation	SS	df	MS	F	P-value	F crit
Temperature	277.255	1	277.255	330.1727	6.68E-14	4.351244
Within Groups	16.79455	20	0.839727			
Total	**294.0495**	**21**				

Table 4.5: ANOVA results for ambient and charcoal cooler temperatures during indigenous avocado storage

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	185.7719	1	185.7719	1127.197	4.61E-19	4.351244
Within Groups	3.296174	20	0.164809			
Total	**189.0681**	**21**				

b) Relative humidity

The cooler was able to keep a steady relative humidity, which was evidenced by the limited variation of relative humidity inside the cooler compared to outside as illustrated in Figure 4.16 for Hass and indigenous avocado. The evaporative cooling system's RH increased significantly for Hass and indigenous avocados ($P<0.05$)

(Tables 4.6 and 4.7, respectively), extending the shelf-life of avocados as compared to the ambient. The average relative humidity inside the cooler was 76.8±1.6% while that of ambient conditions was 43.3±2.8% for Hass avocado. For the indigenous avocado, the relative humidity was 81.2±0.69% inside the cooler and 54.1±4.48% under ambient conditions. The maximum and minimum differences in relative humidity between the charcoal cooler and ambient condition were 37.7 and 31.2%, respectively, for Hass and 32.0% maximum and 25.3% minimum for indigenous varieties. The maximum relative humidity values attained in the cooler were 78.5 and 82.1% for Hass and indigenous avocados, respectively. The relative humidity values obtained in this study were found to be sufficient for retaining the quality and reducing the weight loss of avocados. These results are in agreement with Xuan et al., (2012) who asserted that 100% relative humidity cannot be achieved in the evaporative charcoal cooler because of the loosely packed nature of the pads and the minimal contact time between air and water resulting in insufficient heat and mass transfer. Produce retains its marketable weight, appearance, nutritional content, and flavour under high relative humidity, although shrinking, softening, as well as juiciness is lowered. At low relative humidity air can only retain a section of the entire amount of vapour that is capable of holding, and the air can also absorb extra moisture. Low relative humidity raises the rate of transpiration (Odesola and Onyebuchi 2009). Because humidity and warmth or high temperature in conjunction favour the growth of fungus and bacteria, high humidity must be used with cold storage (Basediya et al., 2013).

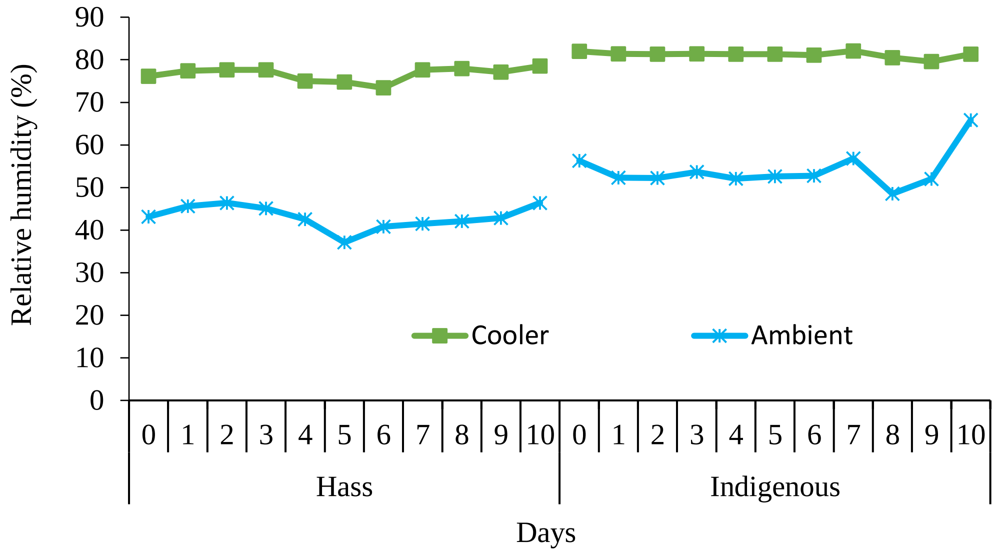

Figure 4.16: Average daily relative humidity variation of the cooler and ambient environment for the study.

Table 4.6: ANOVA results for ambient and charcoal cooler relative humidity during storage of Hass avocados

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	6209.28	1	6209.28	1208.608	2.32E-19	4.351244
Within Groups	102.7509	20	5.137545			
Total	**6312.031**	**21**				

Table 4.7: ANOVA results for ambient and charcoal cooler relative humidity during storage of indigenous avocados

Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	4044.677	1	4044.677	395.6483	1.2E-14	4.351244
Within Groups	204.4582	20	10.22291			
Total	**4249.135**	**21**				

c) Cooling efficiency

The cooling efficiency [computed using equation (3.1)] of the evaporative charcoal cooler was 83.0% at 8.3^{o}C and 87.2% at 6.8^{o}C for Hass and indigenous varieties, respectively.The maximum and minimum cooling efficiency values were realized at the maximum and minimum temperature difference between the cooler and ambient environment, respectively. This relationship was also reported by Basediya et al. (2013). These findings back up those of Helmy et al. (2013) who found that the best cooling efficiency is attained at 2 pm when ambient temperatures are typically at their highest. The sharp drop in cooling efficiency to 50.5 and 65.1% for Hass and indigenous avocado, respectively as shown in Figure 4.17, could be attributed to a decrease in the ambient temperature as the intensity of the sun decreases (Seweh et al., 2016).Typically, the effect of evaporative cooling increases with temperature gradient between dry and wet bulb(Mehere et al. 2014).

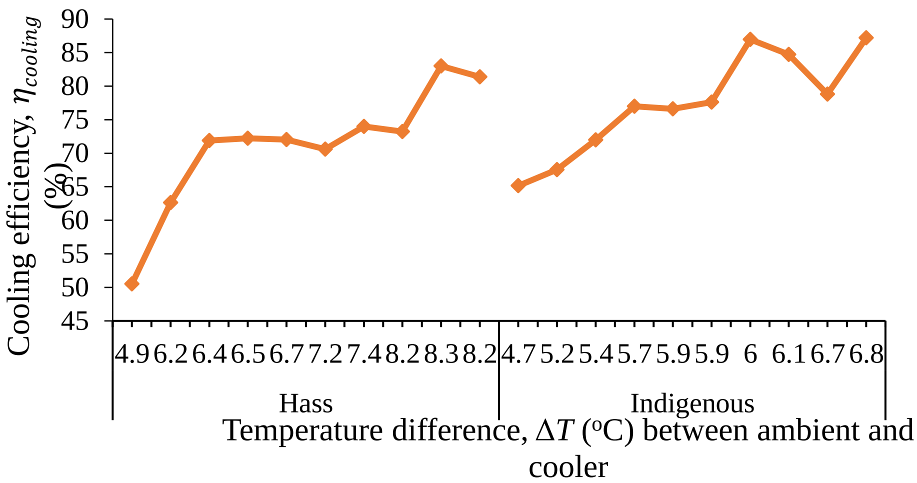

Figure 4.17: Effect of temperature changes on the cooling efficiency of the cooler.

d) Energy efficiency ratio

For a fixed mass flow rate of 0.3905 kg/s, the average power consumption of a water pump and three axial fans was 1.56 kWh resulting to 0.195 kW in average of 8 hours. The difference in enthalpy of inlet and outlet air streams was 2.77 kJ/kg as calculated from equation (3.3). At 0.3905 kg/s air mass flow rate, the energy efficiency ratio

(EER) was 14.21 calculated from equation (3.2). This shows that for every 1 kW of energy consumed by the pump and axial fans, the cooler provided 14.21 kJ of cooling effect (i.e., energy removed from the air for cooling). The results obtained from this study agree with (Tilahun, 2010) who realized EER of 26.3.

e) Effect of Cooling on Avocado Quality

i) Weight loss

The evaporative cooler system had higher relative humidity and lower air temperature than the ambient storage conditions, thus preventing the fruits from losing too much moisture. The physiological weight loss of the avocado samples with storage duration is plotted in Figure 4.18.Hass avocados placed in the cooler lost 3.9%while those in the ambient environment lost 7.5%. In the same way, indigenous avocados stored in the evaporative cooler lost 5.03 % of weight, but avocados stored in the open air lost 12.90%.The mean effect of the number of days on the weight loss for avocados in the charcoal cooler and the ambient conditions was not significantly different for Hass and indigenous avocados ($P>0.05$) (Tables 4.8 and 4.9, respectively). Produce (such as avocado) retains its saleable weight, appearance, nutritional quality, and flavour when relative humidity is high while softening is decreased at high relative humidity (Basediya et al., 2013).Water loss during storage, which is dependent on temperature and relative humidity, affects the quality of most fruits and vegetables (Perez et al., 2003). According to Hardenburg et al. (1986), storing fruits at a low temperature is the most efficient way for maintaining quality since it reduces respiration rate.When relative humidity is increased, the vapour pressure deficit is lowered, resulting in less water loss (Blakey, 2011). The low percentage of weight loss observed in samples stored in the cooler for both avocado varieties was attributed to high humidity which reduced the excessive moisture loss (Jahun et al., 2016).One of the most commonly employed criteria for the export of avocados is weight, which is regarded as the most important quality element given by trade organizations around the world (Ramírez-Gil et al., 2019).High temperature, according to Ryall and Pentzer (1982) and Salunkhe et al. (1991), raises the vapour differential pressure between the fruit and the surrounding atmosphere, which enhances the possibility for rapid moisture movement from the fruit to the ambient air.

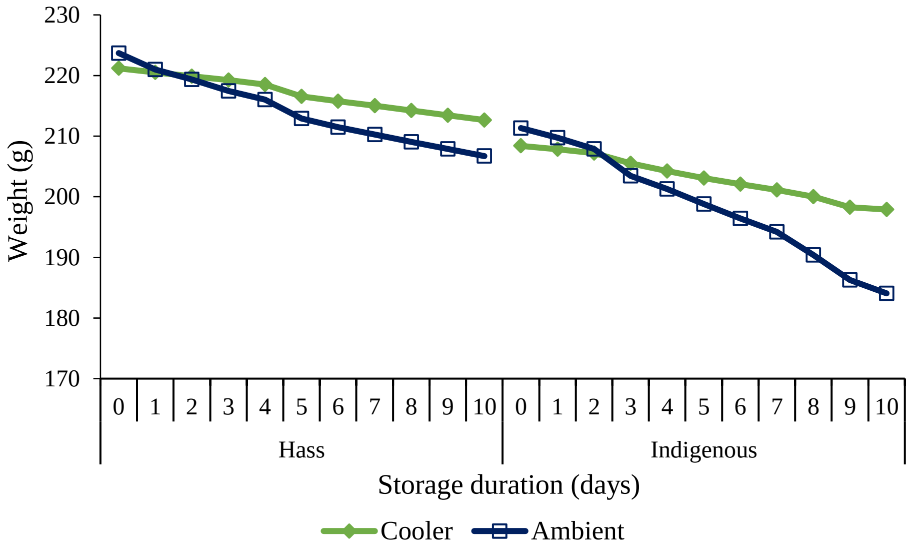

Figure 4.18: Physiological weight loss for two avocado varieties in the cooler and ambient environment

Table 4.8: ANOVA results for the physiological weight of Hass avocados stored under ambient and cooler conditions

Source of Variation	SS	df	MS	F	P-value	F crit
Storage treatment	44.11107	1	44.11107	2.129352	0.16003	4.351244
Within Groups	414.3145	20	20.71572			
Total	**458.4255**	**21**				

Table 4.9: ANOVA results for the physiological weight of indigenous avocados stored under ambient and cooler conditions

Source of Variation	SS	df	MS	F	P-value	F crit
Storage treatment	121.9471	1	121.9471	2.45155	0.133095	4.351244
Within Groups	994.8577	20	49.74288			
Total	**1116.805**	**21**				

ii) Vitamin C

Vitamin C content in Hass and indigenous avocados decreased gradually during storage as shown in Figure 4.19. The initial vitamin C content was 30.25 mg/100g and 11.52 mg/100g for Hass and indigenous varieties, respectively. At the end of day 12, the vitamin C content for Hass in the cooler was 18.75 mg/100 g and 17.26 mg/100 g for outdoors which translated to 39.0 and 49.6% reduction of the initial, respectively. Similarly, the vitamin C content in the indigenous variety at the end of 12 days was 9.43 mg/100 g for those stored in the cooler and 5.34 mg/100 g for those in an ambient environment representing 18.2 and 53.7% reduction of the initial, respectively. The combination of high temperatures and low relative humidity is largely to blame for the reduction in vitamin C levels in these circumstances (Moneruzzaman et al., 2009). Vitamin C is a water-soluble substance therefore is easily lost through moisture loss at high temperatures.

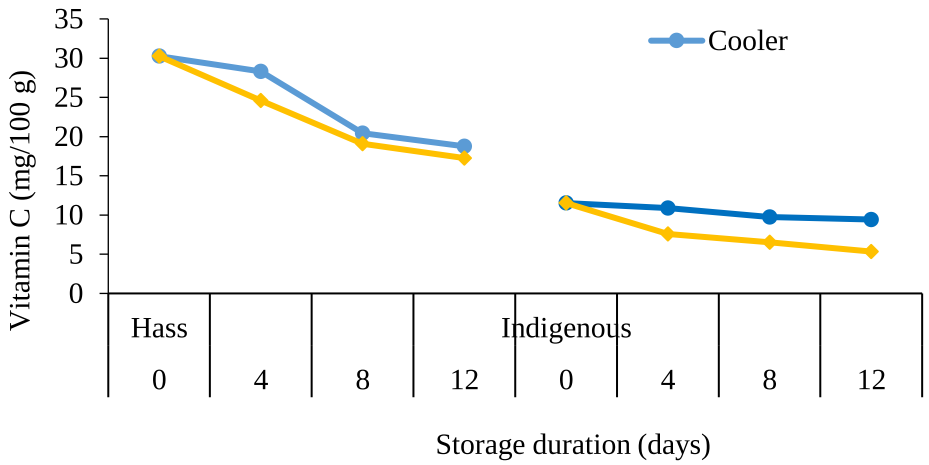

Figure 4.19: Vitamin C change in charcoal cooler and ambient conditions for Hass and indigenous avocado.

Table 4.10: ANOVA results for vitamin C for Hass avocados stored under ambient and charcoal cooler conditions

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	5.325978	1	5.325978	0.159598	0.703359	5.987378
Within Groups	200.2274	6	33.37124			
Total	**205.5534**	**7**				

Table 4.11: ANOVA results for Indigenous vitamin C in the cooler and in ambient environment

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	14.14056	1	14.14056	3.470392	0.111774	5.987378
Within Groups	24.44778	6	4.074629			
Total	**38.58834**	**7**				

iii) Total soluble solids

Throughout the storage time, the avocados exposed to the various treatments showed a general increase in total soluble solids (TSS) as presented in Figure 4.20. Compared to evaporative cooler storage conditions, an increase in TSS occurred at a higher rate in ambient conditions for both avocado varieties. The TSS level in the cooler in Hass increased from 0.5 to 1.6 Brix compared to 0.5 to 2.6 Brix in the ambient conditions representing 220 and 420% increase from the initial, respectively. The TSS level in indigenous avocados rose from 0.5 to 1.7 Brix and 0.5 to 2.2 Brix in the cooler and outdoors, respectively. The percentage increase from the initial for indigenous was 240% for the samples in the cooler and 340% for that outdoors. There was no significant difference ($P>0.05$) in both avocado varieties (Tables 4.12 and 4.13). This shows that increase in TSS is influenced by storage conditions but not by avocado variety. The high temperature and low RH under ambient conditions might have caused increased hydrolysis of carbohydrates into soluble sugars within the avocado fruit (Kassim and Workneh, 2020). Increased TSS during storage could be linked to the conversion of pectic compounds, starch, hemicelluloses, and other polysaccharides into soluble sugar, as well as fruit dehydration(Singh et al., 2003).These results also were consistent with Stover and Simmonds (1987), who found that one of the most significant changes in ripening fruits was the transformation of starch to sugars. Temperature influences a variety of fruit ripening processes, including colour, ethylene generation, respiration, softening of the fruit and metabolic activities of the cell wall and volatile formation.

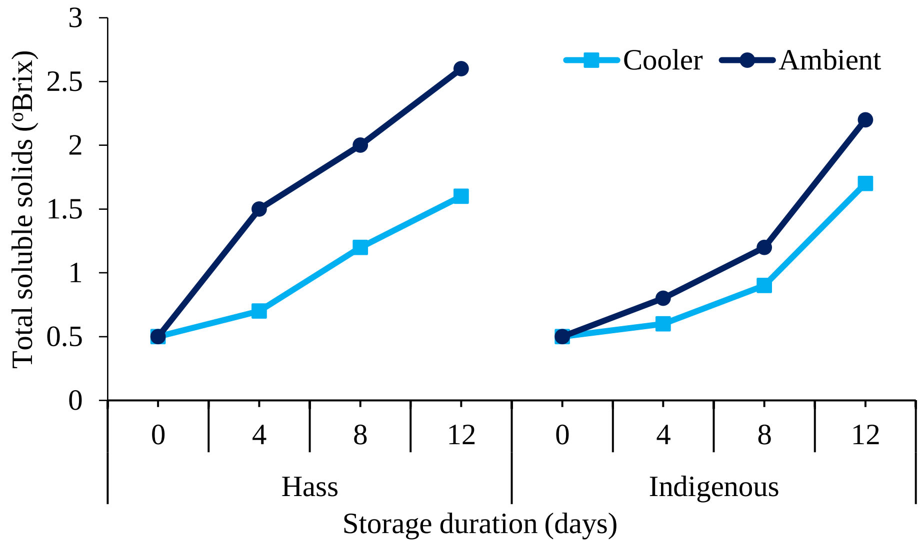

Figure 4.20: Total soluble solids change for avocados in the cooler and ambient environment.

Table 4.12: ANOVA results for vitamin C for Hass avocados stored under ambient and charcoal cooler conditions

Source of Variation	SS	df	MS	F	P-value	F crit
Storage conditions	5.325978	1	5.325978	0.159598	0.703359	5.987378
Within Groups	200.2274	6	33.37124			
Total	**205.5534**	**7**				

Table 4.13: ANOVA results for vitamin C for indigenous avocados stored under ambient and charcoal cooler conditions

Source of Variation	SS	df	MS	F	P-value	F crit
Storage conditions	14.14056	1	14.14056	3.470392	0.111774	5.987378
Within Groups	24.44778	6	4.074629			
Total	**38.58834**	**7**				

iv) Firmness

The fruit hardness decreased continuously, for both the samples inside the cooler and those in the ambient environment as shown in Figure 4.21. The lowest penetration value was realized on the first day at an average of 65 N for Hass and 62 N for indigenous. The firmness of Hass avocados decreased to 10.7 N in the cooler and 8.0 N for ambient while it fell to 11.0 N in the cooler and 6.5 N for ambient for the indigenous. The charcoal cooler increased the shelf life of the avocados by 4 days as the acceptable firmness was still realized on the 12th day in the cooler but was lost on the 8th day in the ambient environment. There was no significant difference ($P>0.05$) in both varieties (Tables 4.14 and 4.15). This implies that firmness is affected by storage conditions regardless of the avocado variety.

The findings of this research agreed with those of Brashlyanova et al. (2014), who discovered a correlation between hardness and both temperature and variety during storage. The results of this research corroborate those of Cantwell et al. (2009), who discovered that grape tomato firmness was influenced by temperature. Avocado fruit softening and loss of firmness during ripening could be caused by two or three processes. The first is when starch is broken down into soluble sugar. The second is the solubility of pectin compounds, which results in the collapse of cell walls or a loss in the cohesion of the middle lamella. The third is osmosis, which is the transport of water from the peel to the pulp during ripening (Dadzie & Orchard, 1997). This could be due to the conversion of pectin material to soluble forms through a series of physiochemical changes produced by pectin enzymes including esterase and polygalacturonase (Weichmann, 1987).

As the temperature rises, the process of structural compound degradation accelerates, resulting in a loss in fruit firmness (Defilippi et al., 2018; Ochoa-Ascencio et al., 2009). Avocado fruits softened as storage time progressed, which could be owing to textural changes caused by the hydrolysis of polysaccharides such as pectin, cellulose, and hemicelluloses that occur during ripening (Irtwange, 2012).It is generally known that changes in fruit texture are caused by component polysaccharide alterations, which lead to a breakdown of the primary cell wall and the structure of the middle lamella owing to the enzymatic activity on the carbohydrate polymers (Manrique and Lajolo, 2004).

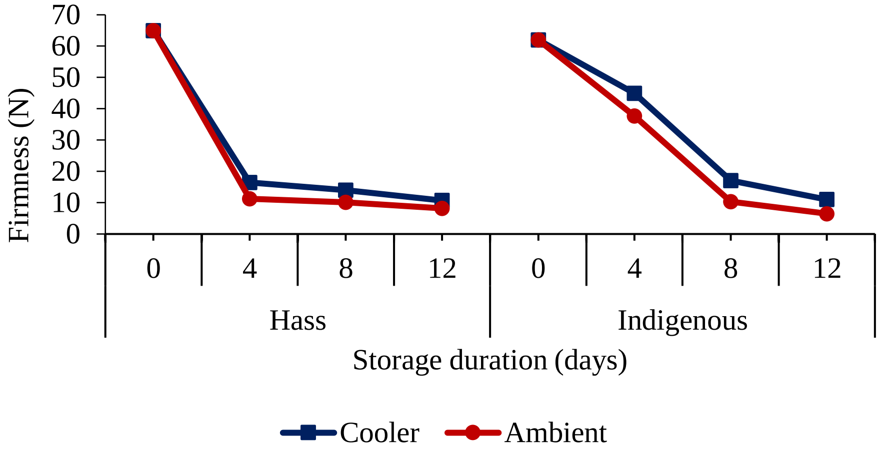

Figure 4.21: Firmness change with time of avocados in the cooler and ambient conditions.

Table 4.14: ANOVA results for vitamin C for Hass avocados stored under ambient and charcoal cooler conditions

Source of Variation	SS	df	MS	F	P-value	F crit
Storage conditions	16.82	1	16.82	0.023619	0.882896	5.987378
Within Groups	4272.78	6	712.13			
Total	4289.6	7				

Table 4.15: ANOVA results for vitamin C for indigenous avocados stored under ambient and charcoal cooler conditions

Source of Variation	SS	df	MS	F	P-value	F crit
Storage conditions	42.78125	1	42.78125	0.068675	0.802041	5.987378
Within Groups	3737.738	6	622.9563			
Total	**3780.519**	**7**				

4.3 Cost-Benefit Assessment of Using Improved Evaporative Charcoal Cooler

The evaporative charcoal cooler measured 4 m by 4 m floor dimensions. Three (3) trays were installed inside with a gangway width of 1 m for free movement (loading and unloading) as shown in Figure 4.22.

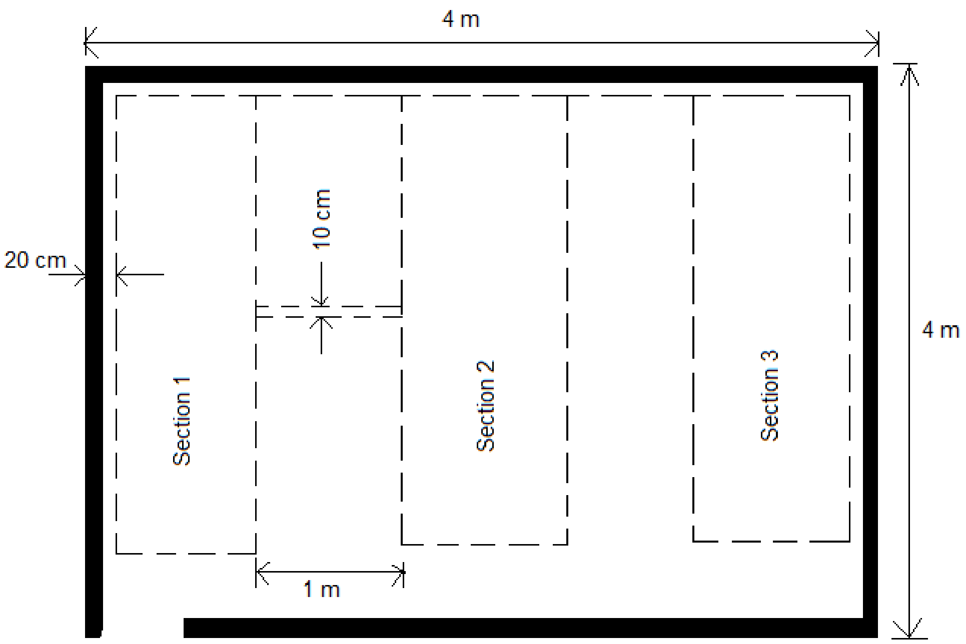

Figure 4.22: Charcoal cooler floor layout

Eleven crates (11) per layer can be stacked in the charcoal cooler to avoid instability and collapsing of the produce (Index Fresh, 2023). The spacing between the walls and the crates is 20 cm while the gap between the crates and the ceiling is 50 cm to aid in ventilation (Paltrinieri, 2017). The crates were placed on top of the pallets to direct contact with the floor. In addition, a 10 cm allowance between adjacent crates was left to allow for ventilation. A 570 mm × 387 mm × 178 mm with 16.8 kg capacity reusable plastic vented crates (Index Fresh, 2023) were used. A total of 165 vented crates can be stacked in the cooler at 55 crates per section and 11 crates per layer at 2.0 m height (considering the height of the crates and the space between the ceiling and the crate).

Table 4.16: Avocado and energy benefits for seven months

Item	Measurement	Value	Total
Quantity of avocado (kg)	Monthly	1,441	10,087
Total income (Kshs)	Cost per kg	100	1,008,700
Total power units consumed (kWh)	Units per month	77.71	543.97
Total energy savings (Kshs)	Kshs per unit	26.39	14,355.37

Table 4.17: Water usage cost in the cooler during storage duration of seven months

Item	Measurement	Value	Total
Total water usage (m^3)	Unitsper month	39	273
Total cost of water (Kshs)	Kshs per unit	125	34,125

The evaporative charcoal cooler increases shelf-life by four days which is equivalent to 33% of the produce saved and taking losses of 7% due to mechanical injury and rough handling of produce (Oliy, 2020), the produce savings is 26% which represents 10,087 kg of avocados. From Table 4.16, the total income for seven (7) months (avocado availability period) is Kshs 1,008,700 when the cost per kg is taken to be Kshs 100 per keg and the total energy savings is Kshs 14,355.37 when the cost per unit is taken to be Kshs 26.39 (Shah, 2023). This demonstrated the potential backup energy from the thin-film PV system (Ndirangu et al., 2022) for cooling. The total cost for water usage is Kshs 34,125 when the unit cost per metre cubic is taken to be Kshs 125 (current cost in Kirinyaga) as shown in Figure 4.17. A summary of the total costs for developing the thin-film PV powered evaporative charcoal cooler system is presented in Table 4.18.

Table 4.18: Total costs for the development of a thin-film PV powered evaporative charcoal cooler

Item	Costs (Kshs)
Pipes and pipe fittings	16,500
Electrical and electronic components	30,000
Metals and cooler structural costs	572,295
Double drain sink and accessories	15,000
Water pump	7,500
Water tank	7,200
Labour and transport	100,000
Charcoal	20,000
PVC ceiling board	9,600
Thin-film PV system	1,000,000
Total	**1,770,895**

As shown in Table 4.19, salvage values of 10% (Ishaque et al., 2022) and 20% (Vigneswaran et al., 2008) were taken for charcoal cooler and thin-film PV system, respectively. The discount rate of 12% (Ghanbariamin, 2015) was adopted for both charcoal cooler and PV system with lifespans of 10 years for PV system (American Solar Energy Society, 2021) and charcoal cooler (Ishaque et al., 2022). The maintenance cost of the thin film PV system was taken to be 2% of the PV cost annually (Mysun, 2016) and an average of Kshs 10,000 was assumed for the charcoal cooler. Assuming two (2) casual workers would be needed to help in produce preparation, recording, loading and unloading of the crates. The daily rate of Kshs 411 per person per day for general labour (Kenya Gazette, 2022) was used for an average of 24 days a month (monthly storage duration). This would translate to Kshs 19,728 a month and Kshs 138,096 annually. The loan interest rate was taken as 12.38% (CEIC data, 2022) at average repayment period of 5 years for a loan of Kshs 2,000,000.

Table 4.19: Financial summary of PV system and charcoal cooler

Item	PV system	Charcoal cooler
Capital cost (Kshs)	1,000,000	770,895
Discount rate (%)	12	12
Maintenance cost annually (%)	2	*
Salvage value (%)	20	10
Labour cost annually (Kshs)	-	210,000
Lifespan (years)	10	10
Interest rate per annum (%)	12.38	12.38

In the table, (-) shows that there is no maintenance required in PV and (*) not in percentage but monetary value based on the previous maintenance.

The annual amount compounded at equal-payment present-worth of costs and benefits of the thin film and evaporative charcoal cooler as calculated using equation (3.6) is shown in Table 4.20. The total annualised fixed and variable costs of the thin film evaporative cooler are Kshs 6,379,251while the total annual benefits are Kshs 18, 352,039.90 (Appendix 3). The BCR of the system is 2.88 [equation (3.7)] which means that for every shilling in the cost of the cooler, the expected benefit is Kshs 2.88. For a BCR of more than 1, the project has a positive net present value (NPV) and a positive internal rate of return (IRR) (Hayes, 2021).

Based on the capital cost of the thin film evaporative cooler and the total revenue from avocado sales and energy savings the ROI is 188% [equation (3.8)]. This means that for every shilling spent on the cooler, the net profit is Kshs 1.88. ROI essentially shows how much money is made or lost on a project or investment after the cost is deducted (Fernando, 2022). The BCR and ROI values achieved indicate the viability of the investment in thin film PV evaporative charcoal cooler and therefore it should be adopted as an alternative preservation method for small-scale farmers, cooperative societies and exporters of perishable commodities.

Table 4.20: Present worth of costs and benefits of thin film evaporative charcoal cooler

	Cost (Kshs)					Benefits (Kshs)		
Year	**PV and cooler capital**	**PV maintenance**	**Cooler maintenance**	**Casual labour**	**Water usage**	**Energy savings**	**Salvage value**	**Avocado sales**
1	560,052	35,396.83	17,698.42	244,408.05	60,395.84	25,406.73	200,000	1,785,239.26
2	560,052	35,396.83	17,698.42	244,408.05	60,395.84	25,406.73	45,580	1,785,239.26
3	560,052	35,396.83	17,698.42	244,408.05	60,395.84	25,406.73		1,785,239.26
4	560,052	35,396.83	17,698.42	244,408.05	60,395.84	25,406.73		1,785,239.26
5	560,052	35,396.83	17,698.42	244,408.05	60,395.84	25,406.73		1,785,239.26
6		35,396.83	17,698.42	244,408.05	60,395.84	25,406.73		1,785,239.26
7		35,396.83	17,698.42	244,408.05	60,395.84	25,406.73		1,785,239.26
8		35,396.83	17,698.42	244,408.05	60,395.84	25,406.73		1,785,239.26
9		35,396.83	17,698.42	244,408.05	60,395.84	25,406.73		1,785,239.26
10		35,396.83	17,698.42	244,408.05	60,395.84	25,406.73		1,785,239.26
Total	**2,800,260**	**353,968.30**	**176,984.20**	**2,444,080.50**	**603,958.40**	**254,067.30.10**	**245,580**	**17,852,392.60**

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

i. As for the characterization of the performance of the thin-film photovoltaic technology under varying ambient conditions as an off-grid backup energy system, the findings show that the maximum average PV power for one of the sites (i.e., Kimicha) was 347.9±231.9 W corresponding to 5^o tilt angle while, the maximum average PV power for another site (i.e., Juja) was 517.7±131.3 W corresponding to 15^o. There was no significant difference ($P>0.05$) between the solar radiation for both sites.

ii. The results of the evaluation of the performance of the improved evaporative charcoal cooler utilizing thin-film photovoltaic technology for the preservation of avocado show that the temperatures of the cooler were significantly cooler ($p<0.05$) than the ambient temperature for both the no load and loaded conditions for both the Hass and indigenous avocados. The average temperature of the cooler for the no load conditions was 24.3±1.69^{o}C, while when loaded, it was 25.0±0.37^{o}C for Hass avocados and 24.4±0.31^{o}C for the indigenous variety. Additionally, the relative humidity in the cooler was significantly higher ($p<0.05$) than ambient, reaching 76.8±1.6% for Hass and 81.2±0.69% for the indigenous avocados. These cooler conditions resulted in a cooling efficiency of 83.0% for Hass and 87.2% for the indigenous variety, with an energy efficiency ratio of 14.21. The product quality parameters such as weight loss, vitamin C content and firmness were greater for ambient conditions than in the cooler, while the average total soluble solid was significantly higher in the cooler.

iii. In terms of cost-benefit of the cooler benefit-cost ratio of 2.88 and the return on investment of 188% obtained imply that the cooler has a positive net-present-worth and a positive internal rate of return and therefore should be adopted as an alternative preservation method.

5.2 Recommendations

5.2.1 Recommendations from this study

i. The results of this study extended the shelf-life of the avocados by 4 days as opposite to ambient conditions. Therefore, it is recommended that the improved evaporative charcoal cooler powered by the thin film photovoltaic technology be employed in the storage of such produce for smallholder farmers.
ii. The evaporative charcoal cooler used an average of 1.56 kWh per day to run the pump, three axial fans, a data logger and the appliances in the records office indicating that thin-film PV system is a viable option to provide such backup power.

5.2.2 Recommendations for further research

The following significant areas were identified for further research:

i. Further research should be undertaken using materials such as pumice as a cooling pad to evaluate its performance and efficiency in avocado preservation of avocado.
ii. Testing the effects of changes in factors, such as air velocity, air temperature, air humidity and charcoal packing density on the performance of the cooler.
iii. There is need to research the effect of varying degree of wetness of charcoal on the efficiency of the charcoal cooler.

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APPENDICES

Appendix I: Charcoal cooler data logger code

```
#include "Wire.h" // For I2C
#include "LiquidCrystal_I2C.h"
#include <SD.h>
#include "DHT.h"
#include <DS3231.h>
#include <SPI.h>
LiquidCrystal_I2C LCD(0x27, 20, 4);
File myFile;
int cs = 10;
DS3231  rtc(SDA, SCL); // tell arduino where to establish I2C communication with the real time rtc
Time t;
float h1, t1, h2, t2, h3, t3, h4, t4;
#define  Dht1Pin 6// specify where we are connecting the digital pins to DHT sensors
#define  Dht2Pin 7
#define  Dht3Pin 8
#define  Dht4Pin 9

DHT Dht1(Dht1Pin, DHT22); //tell arduino where we are connecting our DHT sensors
DHT Dht2(Dht2Pin, DHT22);
DHT Dht3(Dht3Pin, DHT21);
DHT Dht4(Dht4Pin, DHT21);
void setup() {
pinMode(cs, OUTPUT);
  LCD.init();
  LCD.backlight();
  LCD.setCursor(0, 0);
  LCD.print("initializing        ");
rtc.begin();// initialize the real time clock
```

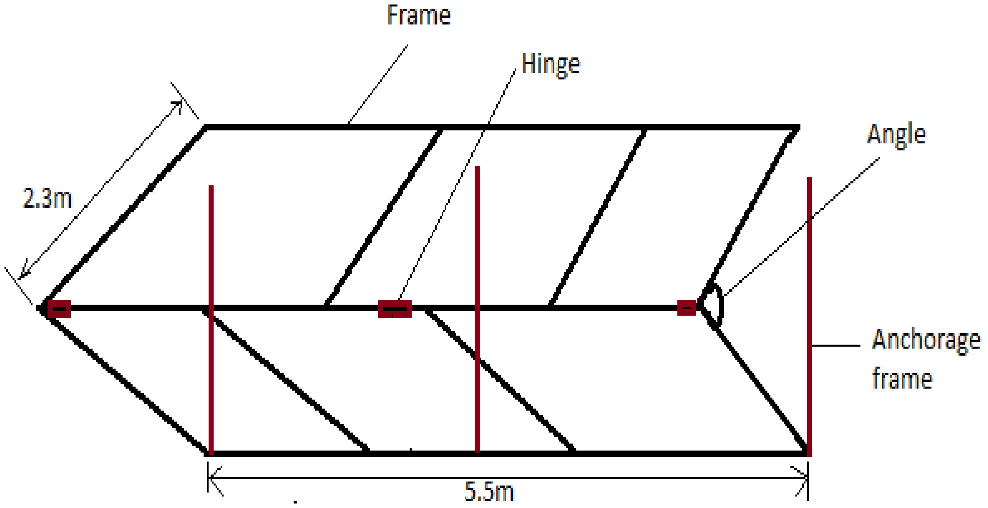
```
delay(1000);
  if (!SD.begin(cs)) {
    LCD.setCursor(0, 0);
    LCD.print("SD fail             ");
delay(1000);
    return;
  }

  LCD.setCursor(0, 0);
  LCD.print("SD success          ");
delay(3000);
  Dht1.begin();  // initialize the sensors so that we can read values from them
  Dht2.begin();  //initialize the DHT senors
  Dht3.begin();
  Dht4.begin();
 }
void loop() {
printTime();
  t = rtc.getTime();
printTime();
    LCD.setCursor(0, 3);
    LCD.print("timer out          ");
    //reading the sensors
    LCD.setCursor(0, 1);
    LCD.print("reading sensors     ");
    LCD.setCursor(0, 2);
    LCD.print("                    ");
      h1 = Dht1.readHumidity();
      t1 = Dht1.readTemperature();
      h2 = Dht2.readHumidity();
      t2 = Dht2.readTemperature();
      h3 = Dht3.readHumidity();
```

```
      t3 = Dht3.readTemperature();
       h4 = Dht4.readHumidity();
      t4 = Dht4.readTemperature();
printTime();
    t = rtc.getTime();
    if (t.min % 30 == 0 && t.sec==0) {
printTime();
      LCD.setCursor(0, 3);
      LCD.print("Waiting   ");
      LCD.setCursor(12, 3);
//      LCD.print(9 - k);
      LCD.setCursor(11, 3);
      LCD.print("min ");
      LCD.setCursor(15, 3);
      LCD.print("  ");
      LCD.setCursor(1, 3);
      LCD.print(60 - (t.sec));
      LCD.setCursor(17, 3);
      LCD.print("sec");
      myFile = SD.open("data.csv", FILE_WRITE);
    if (myFile) {
      LCD.setCursor(0, 2);
      LCD.print("Saving values       ");
      myFile.print(rtc.getDOWStr());
      myFile.print(" , ");
      myFile.print(rtc.getDateStr());
      myFile.print(" , ");
      myFile.print(t.hour);
      myFile.print(" , ");
      myFile.print(t.min);
      myFile.print(" , ");
      myFile.print(h1);
```

```
      myFile.print(" , ");
      myFile.print(t1);
      myFile.print(" , ");
      myFile.print(h2);
      myFile.print(" , ");
      myFile.print(t2);
      myFile.print(" , ");
      myFile.print(h3);
      myFile.print(" , ");
      myFile.print(t3);
      myFile.print(" , ");
      myFile.print(h4);
      myFile.print(" , ");
      myFile.print(t4);
      myFile.println(" , ");
delay(1000);
      myFile.close();// close the file:
printTime();
delay(1000);
      LCD.setCursor(0, 2);
      LCD.print("Values saved        ");
delay(1000);  }
    else {
      LCD.setCursor(0, 2);
      LCD.print("Not saved           ");
delay(1000);
      return;
    }
    }
printTime();
  LCD.setCursor(0, 3);
  //LCD.print("Waiting   ");
```

```
  LCD.setCursor(10, 3);
//  LCD.print(9 - k);
  LCD.setCursor(11, 3);
  LCD.print("min ");
  LCD.setCursor(15, 3);
  LCD.print("  ");
  LCD.setCursor(15, 3);
  LCD.print(60 - (t.sec));
  LCD.setCursor(17, 3);
  LCD.print("sec");
delay(1000);
}
void printTime() {
  t = rtc.getTime();
  LCD.setCursor(12, 0);
  LCD.print("        ");
  LCD.setCursor(12, 0);
  LCD.print(rtc.getTimeStr());
}
```

Appendix II: PV tilt angle frame



Appendix III: Present worth analysis

The equal-payment series recovery amount was calculated to determine the annual equivalent *(A*) that must be recouped at every interest period (*i*) for (*n*) periods compounded at each interest period. The term (*A/P*, *i*, *n*) is called equal-payment series capital recovery factor.

<u>Costs</u>

The investment cost of the PV system and charcoal cooler is Kshs 1,500,000 at an interest rate of 12.38% over 5 years

$$A = P\frac{i(1+i)^n}{(1+i)^n - 1}$$

$$A = 2{,}000{,}000 \times \frac{0.1238(1+0.1238)^5}{(1+0.1238)^5 - 1}$$

$$= Ksh\ 560{,}052$$

The maintenance cost of the PV system and evaporative cooler are:

i. PV system (maintenance cost of 2% of total cost per annum, discount rate of 10% over 10 years)

$$= 0.02 \times 1{,}000{,}000 \times 10$$
$$= 200{,}000$$

$$A = 200{,}000 \times \frac{0.12(1+0.12)^{10}}{(1+0.12)^{10} - 1}$$

$$= Kshs\ 35{,}396.83$$

ii. Charcoal cooler (Ksh 10,000 for 10 years)

$$= 10{,}000 \times 10$$
$$= 100{,}000$$

$$A = 100{,}000 \times \frac{0.12(1+0.12)^{10}}{(1+0.12)^{10} - 1}$$

$$= Kshs\ 17{,}698.42$$

iii. Water (273 m^3 annually for 10 years)

$$= 273 \times 125 \times 10$$

$$= Kshs\ 341{,}250$$

$$A = 341{,}250 \times \frac{0.12(1+0.12)^{10}}{(1+0.12)^{10}-1}$$

$$= Kshs\ 60{,}395.84$$

The labour cost involved in evaporative charcoal cooler (2 workers, Kshs 500 per day each, average of 30 days a month for 10 years)

$$= 411 \times 24 \times 7 \times 10 \times 2$$

$$= Kshs\ 1{,}380{,}960$$

$$A = 1{,}380{,}960 \times \frac{0.12(1+0.12)^{10}}{(1+0.12)^{10}-1}$$

$$= Kshs\ 244{,}408.05$$

Benefits

i. Salvage value

a. PV system

$$0.2 \times 1000000$$

$$= Kshs\ 200{,}000$$

b. Evaporative cooler

$$0.1 \times 455800$$

$$= Kshs\ 45{,}580$$

ii. Avocado sales

$$10 \times 1{,}008{,}700$$

$$Kshs\ 10{,}087{,}000$$

$$A = 10{,}087{,}000 \times \frac{0.12(1+0.12)^{10}}{(1+0.12)^{10}-1}$$

$$Kshs\ 1{,}785{,}239.26$$

iii. Energy savings

$$14{,}355.37 \times 10$$

$$= Kshs\ 143{,}553.70$$

$$A = 143{,}553.70 \times \frac{0.12(1+0.12)^{10}}{(1+0.12)^{10}-1}$$

$$= Kshs\ 25{,}406.73$$

$$\text{Total cost} = 2{,}800{,}260 + 353{,}968.30 + 176{,}984.20 + 2{,}444{,}080.50 + 603{,}958.40$$

$$= Kshs\ 6{,}379{,}251$$

$$\text{Total benefits} = 245{,}580 + 17{,}852{,}392.60 + 254{,}067.30$$

$$= Kshs\ 18{,}352{,}039.90$$

$$\text{Benefit cost ratio} = 18{,}352{,}039.90/6{,}379{,}251 = 2.88$$