EVALUATION OF THE QUALITY CHANGES OF KALES AND TOMATOES STORED IN AN IMPROVED ZERO ENERGY COOLER

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Evaluation of the Quality Changes of Kales and Tomatoes Stored in an Improved Zero Energy Cooler

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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

This thesis is dedicated to my beloved wife Abigael Wanjiru Waweru. Due to her steadfast belief in my potential, unwavering moral support, and her encouragement which formed a strong cornerstone, from which this scholarly pursuit was built. From data collection, data analysis and thesis presentation, she maintained consistency in inspiration and emotional resilience. Her ability to provide logistical support enabled me to maintain the needed focus on the high-level research in this study. It is with gratitude that I appreciate and recognize her role, not only as a supportive partner, but also as a major component of this academic research.

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ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
CBA	Cost Benefit Analysis
FAO	Food and Agriculture Organisation
GDP	Gross Domestic Product
GHC	Green House Gases
H.E	His Excellency
HCD	Horticultural Crop Directorate
IBM	International Business Machines
JKUAT	Jomo Kenyatta University of Agriculture and Technology
MANOVA	Multivariate Analysis of Variance
NPV	Net Present Value
PHL	Postharvest Losses
RUJWASCO	Ruiru-Juja Water and Sewerage Company
SD	Standard deviation
SEM	Standard Error of the Means
SPSS	Statistical Package for Social scientists
TSS	Total Soluble Solids
USDA	United States Department of Agriculture
WASREB	Water Services Regulatory Board
WHO	World Health Organisation
ZEC	Zero Energy Cooler
ZES	Zero Energy Storage

ABSTRACT

The world is faced with myriad challenges like climate change and ever-increasing population making the achievement of global food security a challenge. Although highly perishable, tomatoes and kales are popular food commodities, farmers must sell the commodities soon after harvest for fear of deterioration. For longer storage, the two crops require an environment with low temperature and high relative humidity. Cooling systems such as refrigeration are not accessible to most small-scale farmers because they require connection to the grid. In this study, a zero-energy cooler was developed and evaluated for the storage of ripe tomatoes and mature kales. The system adopted the principle of evaporative cooling and comprised of walls filled with pumice coupled with a pond filled with water on the roof and below the storage space. A full factorial experimental design was employed. This design allowed water to drip from an elevated tank through the pumice walls and drain into the reservoir below the storage space before recirculation using a solar powered pump. The tomatoes (cultivar Ann F1) were harvested at the turning stage and kales (cultivar thousand headed) were harvest at mature stage. At different times, the two crops were stored in the cooler (treatment) and in the ambient condition (control). The relative humidity in the cooler was significantly higher than in the ambient environment while the temperature in the cooler was generally lower than the temperature at the ambient environment. Data was analysed using ANOVA at $p \leq 0.05$. For tomatoes, quality attributes namely firmness, colour, pH, total soluble solids (TSS) and shelf life were evaluated on a seven-day interval for 28 days. For kales the same quality attributes were evaluated on daily basis for ten days. For tomatoes, results showed a significant ($p \leq 0.05$) difference for pH, TSS, and firmness between tomatoes stored in the treatment and control. However, there was no significant ($p > 0.05$) difference in the colour (hue angle) for the fruits under the treatment and control. Compared to the control, the developed solar powered storage system increased the shelf life of tomatoes from 14 days to 28 days. On the other hand, kales results showed a significant ($p \leq 0.05$) difference for a* colour parameter, and in b* colour parameter. However, comparing the quality parameters between kales stored in the cooler and in the ambient environment, there was no significant ($p > 0.05$) difference between quality parameters; ΔE, TSS and pH. The cooler improved the shelf life of kales from 5 days (control) to 9 days (cooler). The results from this study indicate that pumice padded zero energy evaporative cooler preserves the quality of perishable tomatoes. However, the notable effect of the cooler on kales was maintenance of green colour (a*) and prevention of yellowing (b*). The Cost Benefit Analysis of the cooler under tomatoes was 10.6 and 4.21 for storage of tomatoes and kales respectively. The pay back periods for the cooler under kales and tomatoes were 7.2 Months and 1.9 months respectively. The findings of this study shows that the developed pumice-padded/roof pond zero-energy cooler provides an accessible solution for off grid and resources constrained small-scale farmers. By extending the shelf life of kales and tomatoes without reliance on electricity, the cooler directly addresses the major cause of post-harvest losses in fruits and vegetables. The resultant reduction in spoilage will not only minimize economic losses but will also allow farmers greater flexibility in marketing their produce and further enabling them to avoid distress sales and hence access better prices. From a food security angle, the ability to preserve vegetables for a longer period contributes to enhanced availability and stability of nutritious foods in the local markets. The system under study supports eco-friendly agriculture by utilizing zero-energy evaporative, thereby reducing traditional dependence on fossil fuel-based refrigeration and hence lowering negative environmental impact. The low-cost design of the cooler based on use of locally available materials such as pumice, proves its adaptability and scalability across different regions facing post-harvest challenges. Overall, the technology demonstrates a sustainable and economically viable innovation with a high potentiality of wide utilization among smallholder farmers, rural communities and cooperatives. This innovation will contribute to enhancement of agricultural systems, reduced post-harvest losses and improved livelihoods. The zero-energy cooler is recommended for use with other crops besides kales and tomatoes.

Key words: Zero energy cooler, Combined cooling mode, Post harvest losses, Kales, Tomatoes, solar powered cooling system

CHAPTER ONE

INTRODUCTION

1.1. Background of the Study

To feed the increasing population globally, there is a need to improve the sustainability of food production. Increased food production contributes to the realization of the United Nation (UN) Sustainable Development Goal number 2, whose objective is to achieve zero hunger by 2030. However, a large proportion of perishable vegetables and fruits is lost after harvesting due to inappropriate storage practices (Ronoh et al., 2018).

(Twum-Dei et al., 2026) found that postharvest losses of fruits and vegetables in developing countries average 50.2% while other studies indicate that postharvest losses of fruits and vegetables in developing countries average 40% (Affognon et al., 2015). In addition findings by Fabien et al. (2026) reported post-harvest losses of up to 34.7% for perishable crops globally. In Kenya, postharvest losses of horticultural produce remain high. Research indicated that losses in fruits and vegetables average 45% (Ambuko et al., 2017), where tomato postharvest losses on average is 40%, and for kales and other leafy vegetables is above 50% (Gomes et al., 2021).

Environmental factors such as relative humidity, temperature, gaseous composition and airflow have been identified as main determinants of vegetable quality and shelf life (Opara & Pathare, 2014). In addition, the post-harvest losses are attributed to factors such as inefficient transportation, inadequate cooling, poor storage facilities and improper handling practices (Sethi et al., 2020). Therefore, maintaining optimal storage conditions is important in reducing microbial spoilage and physiological deterioration of fresh produce. Although refrigeration provides a favourable low-temperature conditions for storage, they are expensive and depend on access to electricity. Consequently, such technologies are inaccessible to many smallholder farmers. There is therefore a need to develop low-cost, energy efficient and environmentally friendly storage technologies to reduce post-harvest losses and consequently enhance food security (Ambuko et al., 2017; Kitinoja et al., 2011).

Zero Energy Storage (ZES) systems under which evaporative coolers fall, have emerged as sustainable alternatives for postharvest management. These systems rely on passive cooling, particularly evaporative cooling, without using external energy (Nzabarinda et al., 2021). Additionally, studies have demonstrated that ZESs can effectively maintain low temperatures and high relative humidity, thereby preserving the high quality of vegetables and fruits for longer periods (Sharma et al., 2009). Evaporative cooling technology has in the recent past gained increasing attention as a low-cost alternative for postharvest storage. Studies show that evaporative cooling can highly reduce ambient temperatures by 10–20°C depending on ambient climatic conditions and hence extend the shelf life of perishable produce (Basediya et al., 2019). This makes the technology assessable to smallholder farmers in regions with limited accessibility to electricity.

However, a study by Kamaldeen et al. (2026) which directly compared evaporative cooling system and solar refrigeration found out that solar refrigeration maintained lower temperatures and better nutrient retention compared to evaporative cooling. Although solar-powered refrigeration systems achieve lower storage temperatures and better nutrient retention than evaporative coolers, evaporative coolers are more affordable and suitable for smallholder farmers in off-grid areas (Kamaldeen et al., 2026; Sibanda & Workneh, 2020). In addition, evaporative coolers have been reported to significantly reduce postharvest losses at lower operational costs without dependence on refrigeration compressors or batteries (Nkolisa et al., 2018).

From the reviewed literature, it is evident that improving storage systems is essential in reducing Post harvest losses (PHL). It is in response to the reported PHL both in developed and developing countries that the current study was conducted. The study developed a cooler while employing a combination of roof pond cooling, convective cooling and evaporative cooling with pumice (as padding material). While under no load, the developed cooler was evaluated on the bases of its chamber temperature and relative humidity. In the second phase, the quality attributes of kales and tomatoes stored in the developed cooler were evaluated and compared with similar vegetables stored under ambient conditions. Finally, the cooler's cost–benefit analysis (CBA) was conducted to determine its economic feasibility relative to conventional storage methods.

1.2. Problem Statement

Postharvest losses remains a major a constraint to vegetable and fruit productivity, most particularly in developing countries. Numerous studies have reported that post harvest losses of vegetables and fruits in developing countries exceed 40% due to inadequate storage facilities and limited access to preservation technologies (Affognon et al., 2015; Ambuko et al., 2017; Gomes et al., 2021; Twum-Dei et al., 2026). PHL reduces food availability, constrains farmers' incomes, and negatively affects food security. It is also reported that the core bottleneck in production of horticultural crops in Kenya is post-harvest losses particulars because the production is handled by small scale farmers who operate under weak post-harvest systems (Kilelu et al., 2024).

Although different types of cold storage technologies exist, their uptake by small scale farmers is very low because of their high energy and capital requirements Since small scale farmers in developing countries contribute approximately 80% of fruits and vegetables FAO, (2016), prevention of postharvest loss through provision of accessible storage solutions is a critical gap which requires urgent intervention.

In the journey towards alleviating postharvest, most of the cooling technologies already developed and in use are capital intensive and small-scale farmers cannot afford them. Therefore, there is need to have a solution for the current and forecasted postharvest losses. Evaporative cooling system technology integrated with gunny bags and roof pond seems to be the solution for the postharvest losses because it is widely recognized as affordable, environmentally friendly and highly effective in preserving horticultural crops Small scale farmers can benefit a lot by utilizing the evaporative cooling technology (Mugwaneza et al., 2024). Further report from developing countries, that evaporative cooling systems can markedly reduce postharvest losses, prolong shelf life, and maintain optimal storage conditions for horticultural crops without external energy input (Isah et al., 2026; Onwude et al., 2026). Moreover, use of evaporative cooler saves on cost of crop preservation by up to 55% compared with electrical cooling (El Loubani et al., 2021). Using an evaporative cooler with pumice as the evaporative pad, the study sought to evaluate the change in quality characteristics of kales and tomatoes stored in an evaporative cooler.

The cold storage structure in this study is adopted from Sow et al. (2020) which in particular had transpiration roof, where heat from the roof was dissipated through transpiration. The current study was built on the previous studies with incorporation of the current evaporative cooling technologies like roof pond system cold storage and floating gunny bags (Onwude et al., 2026). Earlier foundational studies by Runsheng et al. (2003) realised impressive cooling results with the use of floating gunny bags. As described by the study, the efficiency of the roof pond cooling is because of thermal insulation where the water at the bottom of the roof pond has the lowest temperature compared with the other top layers (Tang & Etzion, 2004). Thermal insulation results into high heat flux out of the structure through the roof.

The novelty of the present study was based on the integration of roof pond, gunny bags, evaporative cooling and convective cooling technology to enhance the cooling performance of the cooling chamber.

1.3. Objectives

1.3.1 General Objective

To evaluate the quality changes of kales and tomatoes stored in an improved zero energy cooler.

1.3.2 Specific Objectives

(i) To design, develop a pumice- roof-pond evaporative cooler and assess the performance of the cooler with no load.

(ii) To evaluate the performance of the developed cooler when preserving kales and tomatoes.

(iii) To determine the cost-benefit analysis of using the cooler for preservation of kales and tomatoes.

1.4. Research Questions

(i) How can an evaporative cooler that operate on different heat transfer principles be designed, constructed and assessed of its performance under no load?

(ii) What performance levels can be achieved by the developed cooler when preserving kales and tomatoes?

(iii) What are the costs and benefits associated with using developed cooler compared with storage of kales and tomatoes in the ambient conditions?

1.5. Rationale and Justification of the Study

The global population has continued to grow steadily over the past two decades, reflecting sustained demographic increase worldwide. In 2010, the world population was estimated at approximately 6.99 billion people, by 2015 it rose to about 7.43 billion and by 2023 the population was 8.05 billion (Organization, 2023). The overall upward trend places increasing pressure on global resources, especially housing, infrastructure and food systems. This continued population growth underscores the urgent need to adopt efficient and affordable storage technologies and enhance agricultural productivity through minimization of postharvest losses.

To keep to the pace of the population growth, postharvest losses must be reduced, by use of coolers to preserve fruits and vegetables. Farmers sell horticultural crops hastily to avoid the loss of crop through deterioration, but when farmers adopt evaporative cooling technologies, they are no longer under pressure to sell their produce immediately after harvest. Instead, they can store it for prolonged periods, allowing them to take the advantage of higher prices, thereby increasing their profits.

The vegetable production in Kenya is not only high but also contribute to the country's economy, for instance horticultural crops development authority HCDA (2014) stated that in 2014, Kenya received 70.9 billion (36% of GDP) from sale of vegetables. Tomatoes and kales are commonly consumed vegetables worldwide. It is recorded that in terms of popularity and consumption, tomatoes are rated second after potatoes globally, while kales is a highly consumed vegetable especially in urban areas of Kenya (Owino, 2019). Fruits and vegetables have a high post-harvest loss. It is therefore important to develop a cooler that bridges the postharvest need of the small-scale farmers.

Cost saving strategies of alleviating postharvest losses should be a priority (Bell et al., 2000). The cooling efficiency differs from technology to another. It has been researched and found out that evaporative cooling has the advantage of being simple, cost effective and environmentally friendly. Additionally, Runsheng et al. (2003) found out that roof pond with gunny bags is a more improved room cooling technology than evaporative colling. Therefore, the study combined the evaporative cooling technology with roof pond technology to come up with a superior cold storage. Sibanda and Workneh (2020) recommended use of evaporative cooling technologies in hot and dry regions because they are effective in areas with high dry bulb temperatures. Alternative to the evaporative coolers is the use of electricity powered technologies like refrigeration and vacuum cooling because there is a huge number of small-scale farmers who cannot access electricity, particularly in Kenya, more than half of the population have no access to electricity (Organization, 2021). It is also found that small-scale farmers being mainly in remote areas are hardly connected to the power grid (Lee et al., 2020). In addition, the installation and maintenance cost of refrigeration cooling is relatively high (Arah et al., 2016). However, despite the need to research on preservation of perishable crops, there is inadequate research in this area. More research towards alleviation of postharvest losses is needed (Affognon et al., 2015).

1.6. Scope and Limitations of the Study

This study focused on the evaluation of performance of a pumice-padded roof pond zero energy evaporative cooler for the storage of kales and tomatoes. The study was conducted under ambient conditions, where relative humidity and temperature were monitored, recorded and compared with those inside the cooler's chamber. The quality parameters of kales and tomatoes assessed were; firmness, pH, total soluble solids (Brix), colour and shelf life. The study examined the effectiveness of combined cooling mode (evaporative, convective, and roof pond cooling) in the extension of the storage life of kales and tomatoes. Economic viability was also evaluated using payback period, cost–benefit analysis, accounting rate of return and internal rate of return. The study was limited to small-scale who are off-grid and did not cover large scale commercial cold storage systems.

However, the study had some constraints, first, the steady performance of the developed cooler was influenced by fluctuations in ambient weather conditions, particularly relative humidities and temperatures, which could not be controlled. Second, the study was implemented over a limited period and hence it may not have fully capture long-term storage behaviour in diverse seasons. Third, the study dealt with only two types of crops (kales and tomatoes) which limits the generalization of the findings to other different crops. Additionally, constraints in materials and financial resources may have affected the scale of the experimental setup.

1.7. Definition of Terms

Accounting Rate of Return (ARR)- A financial metric that measures the expected income on investment based on accounting profits expected.

Ambient Conditions- The surrounding environmental conditions outside the cooling system.

Colour - A visual quality attribute which is used to assess ripeness, freshness and overall acceptability of produce by consumers (buyers).

Combined Cooling Mode - The integration of evaporative, convective, and roof pond cooling methods to optimise overall cooling efficiency.

Convective Cooling- Heat transfer that occurs through the movement of air, helping to remove heat from the cooler's chamber.

Cooler Operate with No load - Means the cooler is operating without any fruit or vegetable stored inside it

Cost–Benefit Analysis - An economic analysis comparing the costs of constructing and operating the cooler with the benefits gained from the use of the cooler.

Evaporative Cooling -A cooling process that takes place when water evaporates, absorbing heat from the surrounding air.

Firmness - A quality parameter that measures the resistance of crop to deformation indicating structural stability and freshness.

Internal Rate of Return (IRR) - The discount rate at which the net present value (NPV) of an investment becomes zero.

Payback Period -The time it takes to recover the initial investment cost of the cooling system.

pH - A measure of acidity or alkalinity of a produce, influencing microbial stability, taste and crop quality.

Pumice Padding -The use of porous volcanic rock (pumice) as a medium to retain water and enhance evaporative cooling due to its high water-holding capacity and high surface area.

Relative Humidity (RH) -The amount of moisture present in the air as expressed in percentage of the maximum amount the air can hold at a certain given temperature.

Roof Pond Cooling - A passive cooling technique where a water is placed on the roof surface to absorb heat and promote cooling through evaporation.

Shelf Life - The duration for which kales and tomatoes remain fresh and suitable for consumption under specific storage conditions.

Small-Scale Off-Grid Farmers - Farmers who operate on a small-scale production and do not have access to electricity.

Total Soluble Solids (TSS or Brix) - The concentration of dissolved sugars and other soluble components in a produce and is measured in degrees Brix.

Zero Energy Evaporative Cooler (ZEEC) - A cooling system that operates using the principle of evaporation and without use of electricity.

CHAPTER TWO

LITERATURE REVIEW

2.1 Design and Development of Pumice- Roof-Pond Evaporative Cooler

This section contains a description of the materials used in the construction of the evaporative cooler, a review of the previous studies, and the scientific principles underlying evaporative cooling technology. It further describes the characteristics of the cooler's internal environment under no-load condition and reviews the common padding materials used in construction of evaporative coolers design and construction. In addition, the section examines role of roof pond in improving cooling performance and outlines the optimum dimensions of the various cooler components for efficient operation of the system.

2.1.1 Technologies Used to Alleviate Postharvest Losses

Researchers have documented various technologies used to decimate post-harvest losses. The common crop cooling technologies include hydrocooling, vacuum cooling, forced air cooling, refrigeration and evaporative cooling (Hoffmann et al., 2025; Onwude et al., 2026; Wang & Zhang, 2020). The principle behind refrigeration is absorption of heat from the materials stored in them and dissipating heat out of the refrigerator chamber and by so doing cooling the product (Hoffmann et al., 2025). Hydro cooling starts with water being applied on a crop, where the heat from the crop is transferred to the water thereby cooling the crop (Elansari & Mostafa, 2020). Vacuum cooling is rapid cooling of crops by reducing storage pressure resulting into lowering of boiling point of water significantly (Zhang & Sun, 2006). Evaporative cooling entails evaporation of water, as water evaporates, it picks heat from the crop (latent heat of vaporization) resulting into cooling of the crop (Isah et al., 2026).

The cost of preservation of perishable agricultural products through cooling technologies should be minimized to enhance affordability and sustainability within small-scale farming. Studies indicate that global energy demand for crop cooling systems continues to rise drastically due to urbanization, increasing food preservation requirements and climate change, thereby increasing operational costs (Hoffmann et al., 2025). The dependence on fossil-fuel-based energy for refrigeration and cooling systems has increasingly intensifying greenhouse gas emissions hence prompting increased interest in the development of sustainable cooling technologies which are powered by renewable energy sources such as wind and solar energy (Haile et al., 2024; Rizzo, 2025).

Recent studies recommended the use of coolers as a solution to the PHL because coolers reduce temperature and increase relative humidity leading to prolonged shelf life resulting to increased farmers' net returns (Rizzo, 2025; Yeneneh & Walle, 2025). Solar energy is one of the most suitable renewable energies for agricultural cooling because of its wide availability, particularly in tropical and subtropical regions (Hoffmann et al., 2025). Recent researchers therefore recommend enhanced engineering research on integrating solar energy with evaporative cooling technologies with the aim of minimizing environmental impacts, improving energy efficiency and reduction of operational costs (Oyewole et al., 2025; Rizzo, 2025). Knowledge of the causes of postharvest losses should trigger urgency of alleviating the postharvest losses, among them using evaporative cooling technology. Determination of quality changes of stored crops as well as determination of the relative cost of each technology should be a priority in fighting postharvest losses.

2.1.2 Convective, Roof-pond and Evaporative Cooling Principles

Agricultural crop cold storage operates on various principles, among them are convective, evaporative and roof pond cooling. The convective cooling leverages on air movement to lower temperature in the cooler chamber. In other words, convective cooling is based on the principle of heat transfer through fluid in motion. Evaporative cooling operates on the principle of latent heat of vaporization. Roof-pond cooling uses the water stored on the building roof to regulate temperatures by radiation and heat absorption.

2.1.2.1 Convective Cooling

Convective cooling works on the principle of air movement blowing across the stored crop. Convective cooling entails circulation of air in the cooler, therefore, maintains the uniformity of temperature in the cooler (Dai et al., 2025; Hoffmann et al., 2025). Pressure created by airflow is described by equation 2.1 (Dai et al., 2025).

$$P = KV^{1.8} \quad (2.1)$$

In equation (2.1), P is pressure drop created by airflow, V is the velocity of the air in m/s and K is a constant. This equation shows that air velocity in the cooler creates pressure drop which attracts air through the cooling medium, hence accelerating the cooling.

The convective heat transfer coefficient (H_c) given in $Wm^{-2}K$ is described by the equation 2.2.

$$H_c = \frac{N_u X k_a}{l_c} \quad (2.2)$$

Where:

H_c is convective heat transfer coefficient

K_a is Thermal conductivity of air (W/mK)

N_u is Nusselt number (dimensionless)

l_c is characteristic dimension

2.1.2.2 Roof Pond Cooling

Roof-pond cooling operates on the principle of evaporation, where water at the roof absorbs heat and evaporates, leading to cooling effect that reduces indoor temperature through heat transfer processes. Earlier study indicate that roof-based evaporative cooling systems highly reduce heat gain through building roofs, which are a main source of thermal load in buildings located in hot climates (Citaristi, 2022). It has been reported that roofs can account for up to 60% of total heat gain in poorly insulated buildings, making them a critical target for passive cooling interventions (Campbell, 2021). Evaporative cooling from roof ponds leads to substantial heat loss due to latent heat transfer, thereby lowering room temperatures and reducing cooling loads. Experimental and simulation studies have shown that roof-pond systems can significantly reduce indoor temperatures and cooling energy demand, especially in hot and dry climates (Santamouris, 2017). In addition, a comparative study indicate that under certain climatic conditions, water-based roof pond cooling systems can provide greater cooling effects than alternative passive techniques such as green roofs (Santamouris, 2017). The cooling performance of roof ponds depends on design parameters such as roof pond water depth, climatic conditions and the thermal properties of roof pond construction materials. Recent findings suggest that shallow water depths (5 cm and 30 cm) are effective in enhancing evaporative cooling, with optimal performance achieved when the system balances daytime heat absorption and night-time heat dissipation (Renewable Energy, 2024). Materials with high thermal conductivity further enhance heat transfer efficiency, improving overall cooling efficiency. Overall, roof-pond cooling remains an effective passive cooling strategy that can significantly reduce indoor temperatures, lower cooling loads, and improve thermal comfort in buildings, particularly in regions with high solar radiation and low humidity.

To calculate the solar power absorbed by the water and roof surface (TSA) as follows in equation 2.3.

$$\mathrm{TSA} = TA + (ISOL + \mathrm{IRS} - \mathrm{IEVAP} - \mathrm{IRW}) * \mathrm{RCO} \tag{2.3}$$

Where:

TSA is solar power absorbed by the water and roof surface

TA is ambient temperature

ISOL is solar power absorbed by the water

IRS is downward sky infrared radiation absorbed by the water

IEVAP is the pond evaporative cooling power

IRW is water infrared radiation emitted towards the sky

RCO is convective heat resistance of roof pond

Study by (Varju & Poós, 2024; Homes et al., 2025) described the rate of water evaporation as being proportional to the difference between the saturation vapor pressure at the evaporating surface and the vapor pressure of the surrounding air, as expressed in equation 2.4

$$E = k \cdot (P_{sat} - P_{\infty}) \tag{2.4}$$

Where:

E= evaporation rate

$P_{sat} - P_{\infty}$= vapor pressure difference (driving force)

k= mass transfer coefficient

In the current study the roof pond had a fan to blow air above the roof pond surface. The flow of air aided in evaporation.

(Renewable Energy, 2024) described the evaporation cooling power (in Watt) with the following equation:

$$I_{evap} = h_m \cdot A \cdot (P_s - P) \tag{2.5}$$

Where:

I_{evap}= evaporative cooling power (W)
A= surface area (m²)
h_m= mass transfer coefficient (depends on air velocity and conditions)
$P_s - P$= vapor pressure difference between the surface and ambient air

2.1.2.3 Evaporative Cooling

Evaporative cooling works on the principle of latent heat of evaporation. Evaporation cooling requires an evaporation pad, which essentially is a porous material. Other factors of concern in the design of evaporative coolers are pad thickness, airflow rate and the pad material because they also determine the energy efficiency and effectiveness of cooling. In evaporative cooling, water evaporates and takes in heat (latent heat of vaporization). The latent heat of vaporisation for water is 2,260 kJ/kg. This means that evaporation of one (1) kg of water will ideally draw 2260 kJ of energy from the cooler chamber and from the cooler surrounding. The amount of heat withdrawn from the evaporation can be represented by equation (2.6).

$$Q = m * L \tag{2.6}$$

Equation (2.6) shows that the quantity of heat Q (J) is a multiple of mass of water m (kg) evaporated and the latent heat of evaporation of water (2,260,000 J/kg). The solar radiation emission from the sun is 1.367 kW/m^2 (Duffie & Beckman, 2013). Furthermore, based on 62.5% transmission through the atmosphere to the earth's surface, the earth receives 3.4×10^{24} W/year of solar radiation and only 1/32000 of this energy is utilized (Agbo et al., 2021). However, only 35 to 40% of the solar energy is used in cooling stored product, the remaining over 60% is lost in removing warm air getting into the system, heat from lights, fans, heat from operators (Kitinoja, 2013).

Equation 2.7 shows the heat energy dissipated by the cooler during evaporative cooling:

$$\Delta \mathrm{H} = c_p * \ m * \Delta \mathrm{T} \tag{2.7}$$

Where:

C_p is specific heat capacity of water (4,181$Jkg^{-1}K^{-1}$)

m is mass of water evaporated (kg)

ΔT is change in temperature (^{0}C)

Saravacos and Maroulis (2011) in a study where they carried out a solar drying experiment recorded that average solar radiation is 0.6 kw/m^2 for 7 hours in a day, which is 15 MJ/day at 40^{o}C; they further added that on average the evaporation of water is 0.72 kg/m^{2}h. The evaporation rate is related to the solar radiation figures and therefore they were useful in the consideration of solar radiation effect on the cooler in this study.

The vast amounts of untapped solar radiation can be utilized as a renewable source of energy that can potentially be used to supplement and improve the efficiency of evaporative coolers. To increase absorption of the solar radiation and hence increase evaporative cooler's efficiency, the cooler wall is painted black (Esfahani et al., 2011; Kabeel & Abdelgaied, 2018). Although evaporative cooling is an old method, Ndukvu and Manuwa (2015) pointed out that research about them started in the 1980s, in addition the study stated that there is shallow and at times no application of evaporative cooling in some parts of the world. The study by Ndukvu and Manuwa (2015) recommended the use of evaporative cooling because they not only increase food supply but they also lower food prices. Sibanda and Workneh (2020) suggested the use of evaporative cooling by small-scale farmer because the technology is not only affordable to small scale farmers, but also simple. In addition, Sibanda and Workneh (2020) recommended use of solar and wind to power evaporative cooling system.

2.1.3 Saturation Efficiency of an Evaporative Cooler

Saturation efficiency (also called cooling efficiency) is the quantity of water that the evaporative pad can be able to evaporate into the air. In this study saturation efficiency is the amount of moisture in the pumice pad that will evaporate into the air. According to Velasco-Gómez et al. (2020) the saturation efficiency of pumice padded cooler is determined using equation 2.8.

$$\eta = [1 - exp\left(-\frac{h_c A_w}{m_a c_{pu}}\right)] * 100 \tag{2.8}$$

Where:

η is saturation efficiency

C_{pu} is specific heat of water vapour of humid air (J/kgK)

A_w is total wetted area of the evaporation pad (m^2)

h_c is convective heat transfer efficiency (W/m^2K)

m_a is mass flow rate of air (kg/s)

Saturation efficiency (η) of a cooler can also be expressed by equation 2.9 (Giabaklou & Ballinger, 1996).

$$\varepsilon = \frac{T_{in} - T_{out}}{T_{in} - T_{wb}} \times 100 \tag{2.9}$$

Where:

ε= saturation efficiency (%)
T_{out}= outlet air temperature (°C)
T_{in}= inlet dry-bulb temperature (°C)
T_{wb}= wet-bulb temperature (°C)

Alternatively, saturation efficiency can also be expressed using humidity ratio as:

$$\varepsilon = \frac{\omega_{out} - \omega_{in}}{\omega_{sat} - \omega_{in}} \times 100 \tag{2.10}$$

Where:

ω_{in} = inlet humidity ratio

ω_{out}=outlet humidity ratio

ω_{sat}= saturation humidity ratio

$\omega_{in}$and $\omega_{out}$are the inlet and outlet humidity ratios, respectively, and $\omega_{sat}$is the saturation humidity ratio at the wet-bulb condition. This form highlights the mass transfer process governing evaporation and is commonly applied in advanced thermodynamic

Equation 2.10 highlights the mass transfer process of evaporation. In this study, the saturation efficiency represents the ability of the pumice particles to facilitate evaporation and enhance result into cooling by increasing the moisture content of the air in the cooler as well as reducing its temperature in the cooler.

2.1.4 The Cooling Capacity of an Evaporative Cooler

Water evaporation rate (W) expressed in mm/day is described by equation 2.11 as,

$$W = 0.097(\mathrm{PS} - P)V \tag{2.11}$$

Where:

PS is saturation pressure at water temperature.

P is ambient vapour pressure in mbar.

V is wind speed in ms^{-1}

Kulkarni and Rajput (2013) used the formula (2.12) in the determination of the cooling capacity of an evaporative cooler.

$$Q = \dot{\mathrm{m}}_a c_{pa}(\mathrm{t}_1 - t_a) * 3.6 \tag{2.12}$$

Where:

Q is cooling capacity (kJ/h)

C_{pa} is specific heat of air (J/kgK)

M_a is mass flow rate of air (kg/s)

t_1 actual dry bulb temperature inlet air (^oC)

t_2 actual dry bulb temperature of outlet air (^oC)

2.1.5 Evaporation Pads Used in Evaporative Cooling

To hold water for evaporation, various evaporation pads are used. The common evaporation pads are charcoal, wood, sand and jute sacks. Other evaporative pads used are; cloths, cellulose papers, charcoal and pumice (Bodile et al., 2025; Nada et al., 2019; Sow et al., 2020). The results of their finding showed that the cooler relative humidities and temperatures ranged from 80 to 90%, and 21 to 25^oC respectively, and conditions in the cooler had relative humidity and temperature ranging from 30 to 35% and 40 to 42^oC respectively. Roy and Khurdiya (1986) used sand and gunny cloth as the evaporative cooling media where the top of the cooler was covered with the gunny cloth while the side walls were stuffed with sand. In this structure no mechanical ventilation was done. The results showed that the cooler maintained an average temperature of less than 28^oC, with the maximum ambient temperature being 44^oC.

Aror and Narasimham (1988) used cloths as the evaporative media in a cooler of about 0.1 m^3, the walls were made of 2 mm, the top of the cooler had a water reservoir where clothes were immersed and hanged towards the iron sheet wall. The clothes drew water from the reservoir by capillary action. The result of this study was that shelf life of apples and of coorg mandarins were increased by 6 times and 4 times, respectively. Eltawil et al. (2006) did an experiment with two model coolers where the first one had wire mesh (2.5 cm by 2.5 cm) walls and the second one had metal sheet walls. The two models were cooled using gunny clothes, which were immersed in water at the top of the structure. The first model with wire mesh maintained a relative humidity of 95% while the second model with metal sheet wall maintained an average relative humidity of 85%. They attributed the high relative humidity in the wire mesh walled cooler to the free circulation of air. Sharma and Kachru (1990) used sand as the evaporative cooler in a potato storage and observed that wetting the sand walls daily resulted in a cooler micro-environment which enabled storage of potatoes for 90 days compared to jute bags that achieved a storage period of 60 days. This is an indication that sand evaporation pads perform better than jute bags. Eltawil et al. (2006) developed a simulation model of an evaporative cooler and demonstrated that evaporative coolers work optimally when the relative humidity is low. The simulation also showed that, relative humidity can remain close to 100% and that structural orientation has insignificant effect on the cooler microenvironment. However, Eltawil et al. (2006) showed that evaporative coolers work best when the longer sides face the North–South. Evaporative cooler with longer sides facing North–South means that the two sides receive sunshine throughout the day as compared to the east- west orientation where east side receives sunshine in the morning and the West side receives sunshine in the afternoon. Camargo et al. (2005) developed a mathematical relationship from a thermal comfort direct evaporative cooling laboratory experiment. The laboratory experiment gave a temperature difference of 7.4^{o}C between the cooler chamber and the ambient temperature. Using cellulose papers as the evaporative media, Nada et al. (2019) recorded a temperature drop of 18^{o}C. Doğramacı et al. (2019) used eucalyptus fibres as evaporative media and observed a temperature drop range between 6.6^{o}C and 11.3^{o}C, and the cooling efficiency between 49 and 71%. Doğramacı et al. (2019) also found out that the cooling capacity is dependent on airflow with the cooling capacities being 108 W and 409 W with 0.1 m/s and 0.6 m/s air flow, respectively. Charcoal is the commonly used evaporative medium, even though Manuwa and Odey (2012) ranks it poorly based on a study where four evaporative cooling media were tested. The padding materials for evaporative coolers are based on their thermophysical properties. Hamad et al. (2026) assessed different evaporative cooling pad materials while Xia et al. (2026) researched on the application of advanced evaporative cooling technologies using palm fibres, cellulose pads and other porous materials for effective cooling in cooling systems.

2.1.6 Porosity and Particle Size of Pumice Evaporative Pad

Pumice stones are derived from a readily available highly porous volcanic rock (Elankumaran et al., 2024). The micro-porous nature of pumice has a relatively big surface area. Besides the porosity of pumice, Kitis et al. (2005) records that closed air pores in pumice provides a high level of insulation. This insulation is important when it is used in making a cooler, as it shields the cooler from direct interference of the ambient weather conditions. Ersoy et al. (2010) reported the pore size of pumice to range between 0.05 µm to 2 mm. In addition it has been found out that as the particle size decreases, pore surface area increases significantly (Ersoy et al., 2010; Kitis et al., 2005).

Breaking the pumice to small particles increases the surface area volume ratio leading to increased saturation efficiencies. The porosity of pumice determines the cooling efficiency (Arenas et al., 2025; Elankumaran et al., 2024). Pumice has a porosity of about 85% (Kitis et al., 2005), while Usta (2003) reported that charcoal has porosity range of 65-75%. Therefore, based on porosity, pumice is a better evaporative medium than commonly used charcoal. The high porosity of pumice is important in evaporative cooling in that it is in those pores where the evaporating water is momentarily stored.

Further study by Rashwan et al. (2025) studied two wall thickness (10cm and 15 cm and reported that the thinner the wall the higher the cooling efficiency. Gunhan et al. (2007), in their study of three wall thicknesses (5 cm,10cm and 15cm), recorded 15cm thickness of the pumice wall as the optimum thickness in the design of a zero-energy cooler. Therefore, the wall thickness design of the study at hand was pegged on this wall thickness dimensions (15cm). Research has also revealed that, the cooling pad should not be compacted, because compaction reduces the cooling efficiency (Rashwan et al., 2025).

2.1.7 Mass and Heat Balance in the Evaporative Cooler

Figure 2.1 depicts how ambient air (hot air) enters the cooler through an evaporative pad. As the ambient air passes through the wet evaporative pad, the air, which is generally at a higher temperature is cooled as it loses heat to the evaporating water in the cooler wall. Through the principle of latent heat of evaporation, the evaporation process absorbs water from the incoming air resulting into cooling of the air entering the cooler chamber. As the air passes through the evaporative pad, dry bulb temperature (DBT) reduces to attain a temperature almost equivalent to that of wet bulb temperature (WBT). The attained temperature is the lowest temperature which can be attained through evaporative cooling alone. Similarly, the dew point temperature (DPT) rises to attain a temperature almost near to the WBT. The increase in DPT is because of the increase in humidity level gained from the wet evaporative pads. The figure also shows how excess water (which do not evaporate) is collected at the reservoir below the cooler. This pool of water evaporates and causes the cooler chamber cooling. Hence, the water in the reservoir reinforces additional cooling in the cooler chamber.

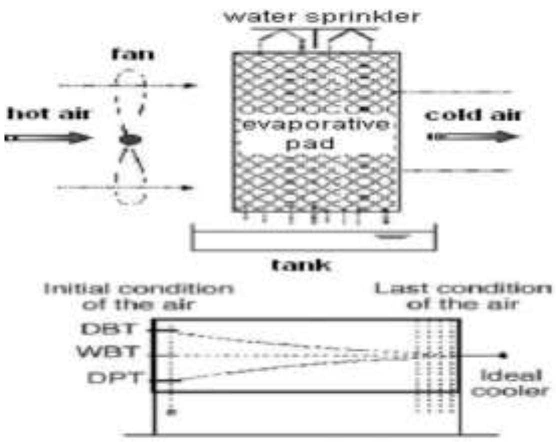

Figure 2.1: Evaporative Cooler Showing Variation In Dew Point, Wet Bulb And Dry Bulb Temperatures (Heidarinejad & Bozorgmehr, 2008)

By applying the principles of mass and energy conservation, the mass balance equation is as shown in equation 2.13.

$$\dot{m}_a(x - x_0) = \dot{m}_w(Y_o - Y) \qquad (2.13)$$

Where:

$\dot{m}_a$: is air flow rate in kg/kg of dry air/ second

x_o: is the moisture content of the air (kg/kg) before passing through the cooler wall x: the moisture content of the air after passing through the saturated wall of the cooler

$\dot{m}_w$: the mass flow rate of water (kg/kg dry bases)/second

Y_o : the initial moisture content of the cooler wall (kg/kg).

Y : the final moisture content of the cooler in (kg/kg) wall after water has evaporated in kg/kg.

The mass and heat balance in the evaporative cooler is expressed by figure 2.2.

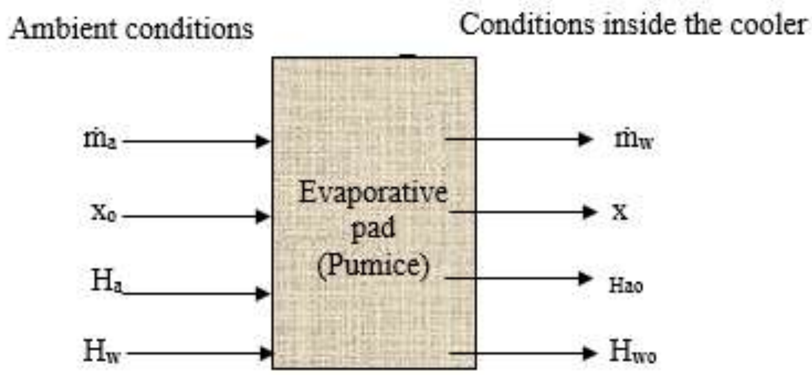

Figure 2.2: Mass and Heat balance in the Evaporative Cooler (Ashrae, 2009)

The thermal load (Q) is obtained by the energy balance equation 2.14.

$$Q = H_a - H_{ao} + H_w - H_{wo} \quad (2.14)$$

Where:

Q: the heat exchange (kJ)

H_{ao}: enthalpy of air after passing through the cooler wall (kJ/kg)

H_a: the enthalpy of air before entering the cooler wall (kJ/kg)

H_{wo}: the enthalpy of the water (water vapour) after vaporisation (kJ/kg)

H_w: the enthalpy of the water film in the cooler wall (kJ/kg)

There is heat and mass transfer between water and air, the mass transfer lowers the dry bulb temperature (DBT) of the air and hence raises its humidity (Heidarinejad & Bozorgmehr, 2008). Heidarinejad and Bozorgmehr (2008) adds that, the evaporative cooling process is adiabatic and hence the resulting enthalpy and wet bulb temperature (WBT) will not change. Therefore, the lowest temperature the air can reach in the evaporative cooler chamber is WBT.

2.1.8 Insulation of an Evaporative Cooler

Insulation of a cooler reduces the cooling load, it is vital because the condition inside the cooler is maintained only if they are not subjected to thermal interference by the ambient conditions or head entry, this implies that the efficiency of the cooler is low in non-insulated coolers (Haile et al., 2024). Eltawil et al. (2006) pointed out that all cracks and air entrance points must be sealed to enhance cooling efficiency. The research also points out that the transfer of heat from the ambient conditions to the cooler depend on the all the U-values of the wall, ceiling and floor. Heat transmission is expressed in equations (2.15) and (2.16) in which U refers to thermal transmittance, R refers thermal resistance while x and k refers to material thickness and material thermal conductivity, respectively (Alwetaishi, 2025).

$$U = \frac{1}{R} \tag{2.15}$$

$$R = \frac{x}{k} \tag{2.16}$$

Eltawil et al. (2006) pointed out that the factors determining the rate of heat flow through the wall are the; U-values, difference in temperature between the inside (T_i) and outside (T_o) as shown in equation (2.17) in which Q represents the quantity of heat (Joules) transferred through the cooler wall, A is the surface area of the cooler (m^2) and T_o ambient temperature in ^oC.

$$Q = UA(T_o - T_i) \tag{2.17}$$

2.1.9 Time lag and Cooling Loads in an Evaporative Cooler

The wall thickness of the cooler is a pointer that there is time lag between the solar radiation and when the radiation's maximum effect is felt inside the cooler (Xu et al., 2025). This shows that the reading in the cooler cannot be correlated with the ambient conditions at the same time, hence the need to determine the time lag for each cooler. This creates a need to determine the time lag for the cooler under study. The time lag can be determined by an evaporative cooler simulation and thermal performance analysis (Bin Nadeem et al., 2026).

The cooling load for an evaporative cooler included; heat gain through the walls, heat brought in by new air coming in, material respiration, heat generated by the fans and the actual cooling of the agricultural product itself (Duan et al., 2025; Jiang et al., 2025). The cooling load can be reduced by taking various precautions like increasing wall and roof insulation (He et al., 2025; Xu et al., 2025)

There is a relationship between temperature, crop deterioration and shelf life (Table 2.1).

Table 2.1: Effect of Temperature on Respiration Rate, Deterioration Rate and Crop Loss per Day in the Cold Chain (USDA, 2004)

Temperature, ^{o}C	Deterioration rate	Relative shelf life	% Loss (per day)
1	1.0	100	1
10	3.0	33	3
20	7.5	13	8
30	15.0	7	14
40	22.5	4	25

Table 2.1 show how temperature is instrumental in determination of the crop deterioration, shelf life and percentage loss. Crop deterioration and crop loss increase with temperature rise while shelf life decreases sharply with temperature rise. The description emphasizes the need for cold chain management to ensure that the temperature is as low as possible. By reducing postharvest losses, resources used in

crop production like farm inputs, water, fertilizers can be minimized (Kitinoja, 2013). However, gaps in cold chain like inadequacy of cold storage, poor transportation infrastructure lead to increased postharvest losses (Maheshwar & Chanakwa, 2006).

2.2 Nutritional, and Quality Parameters of Kales and Tomatoes

Kales and tomatoes are among the most highly consumed crops owing to their health-promoting properties and high nutritional value. This section will hence describe the nutritional value of kales and tomatoes, outline the key quality parameters (of kales and tomatoes) that require preservation during storage, and finally demonstrate how the role of kales and tomatoes as well as their production network. in Kenya and beyond. The section will also highlight how postharvest practices influence both nutritional values and marketability of kales and tomatoes.

2.2.1 Nutritional Value of Kales and Tomatoes

Kiburi et al. (2017) noted that, besides economic importance of kales and tomatoes, vegetables in general have high health and nutritional values. FAO (2004) painted the picture that many deaths related cardiovascular, diabetes and obesity are associated with, diet, alcohol, inactivity, and tobacco. If right actions are taken and people take optimum amount of fruits and vegetables 2,700,000 people can be saved from early deaths (Baumgartner & Grand, 2006).

Kales (*Brassica oleracea var. Acephala*) belong to Brassicaceae family with other vegetables like, cabbages. Brassica vegetables have been reported to be rich in bioactive compounds, vitamin C, carotenoids, polyphenols and glucosinolates (Podsędek, 2007). Among Brassica family vegetables, kale has the highest level of oxidants (Hwang & Kim, 2025; Łukaszyk et al., 2025). In addition, kales as nutritional powerhouse because they have high level of minerals, vitamins, carbohydrates and low protein levels (Thavarajah et al., 2019; Thavarajah et al., 2016). Their low-calorie level helps in preventing obesity. There are different varieties of kales which include green kale, dwarf, kales, marrow stem kales and curl kales. Kales can be consumed fresh as salads, cooked or canned and frozen. Murtaza et al. (2005) found out that the antioxidant activities and content of phenols and vitamin C differ with genotype where wild genotype has higher level of oxidants than the cultivated kales. Based on possibilities of reducing heart and non-communicable diseases, United states centre of disease control ranked kales at number 15 (Di Noia, 2014). A study by Kim (2012) found out that kales leaves have high antioxidant levels; the leaves have high level of polyphenol. Polyphenol is important in preventing development of cardiovascular disease, neural generative disease and diabetes, while antioxidants foods have enzymes and vitamins which prevent the damaging effects caused by oxidation, hence, they reduce damage to human cells, which cause cancer. Brassica vegetables where kales belongs, contribute fibre which is necessary for digestion (Mpofu et al., 2020). Besides kales having important minerals like manganese, iron, calcium and phosphorous, kales is also said to have vitamins B1, B2, B6, C and E (Mpofu et al., 2020). Generally, vitamins are important in protecting human body from diseases. Emebu and Anyika (2011) recorded that cucumber, celery, angelica keiskei, kales and carrot were found to have vitamin C contents shown in Table 2.2.

Table 2.2: Vitamin C Content in Selected Vegetables (Emebu & Anyika, 2011)

Vegetables	Composition of vitamin C (mg/100 g)
Kales	105.14
Carrots	52.05
Celery	7.50
Cucumber	9.30
Angelica keiskei	31.40

Table 2.2 shows that among the five selected vegetables, kales is the leading vegetable in vitamin C. Out of the five vegetables, kales provide more than 50% Vitamin C. (105.14 mg/100g). This is an indication that kales are highly nutritious and important for healthy diets and hence its importance in improving the nutrition and health of citizens in Kenya and globally. Vitamin C is not only an antioxidant but also prevents scurvy (Santos & Silva, 2008). Further study on comparison of vitamins content was conducted by Natesh et al. (2017) as indicated in Table 2.3.

Table 2.3: Vitamins Composition for Kales, Spinach and Duck Weed (Natesh et al., 2017)

Vitamin content	Kales	Spinach	Duck weed
Vitamin A, IU*	130,000	85,000	77,900
Vitamin B1, mg	0.9	0.9	1.1
Vitamin B2,mg	0.9	1.8	2.8
Vitamin B5, mg	0.9	0.9	2.1
Vitamin B6, mg	2.5	1.8	1
Vitamin C mg	1014	256	94
Vitamin E mg	9.3	18.2	45.7
Vitamin K1 mg	6900	4400	51

*IU: International Units

Table 2.3 shows that; of the three vegetables (Kales, spinach and Duck weed), kales dominate in vitamin A (130,000 IU) vitamin B6 (2.5 mg/100g), Vitamin C (1014 mg/100g) and vitamin K1 (6900 mg/100g). According to table 2.3, kales top the list of useful vitamins compared to spinach and duck weed. Vitamin C can be used in treatment and prevention of diseases, with Cheng (2020) suggesting the use of a high dose of vitamin C to treat corona virus disease (COVID-19), while Wang et al. (2020) recommended moderate vitamin C supplementation to prevent COVID-19.

Emebu and Anyika (2011) described the mineral content of kales as shown in Table 2.4.

Table 2.4: Nutritional Content of Kales (Emebu & Anyika, 2011)

Minerals and nutrients	Composition of kales (mg/100g)
Magnesium	6.69
Calcium	4.05
Potassium	7.03
Zinc	2.16
Sodium	4.69

Table 2.4 gives five nutritional compositions of kales. Besides vitamin C content, kales are rich in potassium and magnesium. Potassium is important in facilitating normal cell function while Magnesium's role in the body is to maintain normal functioning of nerves, muscles and heart beats. Emebu and Anyika (2011) also described kales as a source of protein at 11.6% compared to cocoyam leaf (3.4%), moringa oleifera (4.2%) and

amaranths (6.1%). Acho et al. (2014) concluded that leafy vegetables when consumed in adequate amount would contribute immensely to nutritional requirements.

Tomatoes (*Lycoperscicon esculentum*) is referred to as power house of nutrients as they are rich in minerals and vitamins (Ray et al. (2011). Tomatoes have a balanced content of vitamins; K, A, E, B1, and vitamin C (Kaur & Aggarwal, 2015). Tomatoes have been reported to have Chromium which controls blood pressure, Beta carotene in tomatoes helps in increasing human body immunity (Bhowmik et al., 2012). In addition, tomatoes contain lycopene, which reduces risk of diseases like cardiovascular diseases and cancer.

2.2.2 Quality Parameter of Kales and Tomatoes

Kales and tomatoes possess quality parameters that are largely influenced by both post-harvest storage conditions and pre-harvest environmental conditions. Generally, the quality of fruits and vegetables is determined by sensory attributes, including appearance, flavour and texture, which is a determinant of the customers' acceptance (Ashraf et al., 2025). Appearance comprises characteristics such as colour, shape, size and presence or absence of decay (Morton et al., 2025).

Key quality indicators of kales and tomatoes as well as other vegetables and fruits include pH, total soluble solids (°Brix), shelf life, firmness and colour. When these quality parameters are maintained the marketability of the crop is increased. The quality preservation of fruits and vegetables can be achieved through appropriate storage methods (Ashraf et al., 2025).

Firmness is an important quality parameter of fruits and vegetables and is evaluated using mechanical tests such as compression, deformation and puncture methods (Abbott, 1999). Firmness is closely associated with resistance to mechanical damage during handling and storage.

Colour is an indicator of ripeness, freshness, and overall quality, and it significantly influences consumer's purchasing decisions. Buyers often rely on visual attributes such as firmness and colour when selecting fresh produce (Pathare et al., 2013). Moisture content of fruits and vegetables is another important quality because it determines water activity. Water activity influences respiration, microbial growth and overall rate of deterioration of the agricultural produce. Fresh vegetables have moisture content of 80% to 90% making them susceptible to perish within a short time (Ashraf et al., 2025). High water activity builds a favourable condition for microbial growth and quick spoilage of agricultural produce if not managed properly.

Shelf life refers to the duration a product maintains quality which is acceptable by consumers. Increasing shelf life is important because it reduces post-harvest losses and improves profitability. Increasing relative humidity and lowering temperature such as through evaporative cooling can lead to extension of shelf life of vegetables and fruits (Statistics, 2024).

Tomato quality parameter is influenced by its colour, firmness, pH, and total soluble solids (TSS), all of which determine the shelf life and consumer acceptability. Firm tomatoes are preferred in the due to their long storage potential and resistance to mechanical damage. Loss of firmness is associated with softening of tomatoes and leads to increased susceptibility to spoilage (Teka, 2013) As it ripens tomato colour changes due to the accumulation of lycopene, which is responsible for the red colour, lycopene is also an important antioxidant (Morton et al., 2025). The colour parameters (such as a*/b*) increase as ripening progresses on, indicating improved visual quality. The pH of tomatoes is another important quality parameter, especially when processing tomatoes, when pH value is low, it is desirable for preservation because low pH (high acidity) prevents microbial growth. Tomato pH ranges between 3.5 and 4.5 and varies depending on stage of maturity, growing conditions and cultivar (Teka, 2013). Environmental factors such soil conditions, irrigation and production systems (open field versus greenhouse) also influence level of pH.

Total soluble solids (TSS) represent the sugar content, and it determines the flavour and taste. TSS includes organic acids, sugars and other soluble compounds. TSS values increase during ripening as sugars accumulate and later decrease as because they are utilized in metabolic processes (Beckles, 2012).

This finding encourages the use of evaporative coolers on vegetable preservation. Evaporative coolers can reduce air temperature, with reductions ranging from 5 °C to 15 °C under moderate weather conditions and can reach up to about 20 °C under hot and dry weather conditions, depending on ambient relative humidity and temperature (Statistics, 2024). Longer shelf life means a reduction in losses and hence an increase in profit from the stored agricultural product. Sow et al. (2020) showed that, raising of relative humidity and reduction of temperature in the cooler chamber increases shelf life. Ronoh et al. (2010) reported an increase in shelf life of amaranths from 2 to 7 days in a charcoal evaporative cooler. Zakari et al. (2016) also observed an increase in shelf life from 2 days to 6 days, when investigating the shelf life of tomatoes stored in an evaporative cooler.

2.2.3 Economic Role of Vegetables and their Level of Production in Kenya

Vegetables are a major part of Kenyan diet, in addition vegetables play a major role in the country's gross domestic product (GDP). As revealed by Kanali et al. (2017), vegetables in Kenya contributed 36% of Kenya's gross domestic product (GDP) in 2014, this high GDP contribution is an indication of the worth of vegetables in Kenya's economy. Their study also revealed that farmers prefer growing vegetables because they mature quickly and hence fetch income quickly. Besides increase in GDP, vegetable trade increase net returns of farmers and traders (Jha, 2008). In so doing vegetable farming provide employment to many citizens. Therefore, preservation of the vegetables not only improves GDP but also alleviate employment in a country.

Table 2.5. is a summary of the percentage consumption of various vegetables by households, in terms of monthly purchases and the mean monthly expenditure on various vegetables.

Table 2.5: Vegetable Consumption in Kenya (FAO 2024)

Vegetables	% of Households Purchasing	Mean Quantity (kg/month)	Avg. Monthly Expenditure (KES)
Cabbages	81	4.2	95
Onions	96	5.2	165
Sweet potatoes	35	8.5	70
Kales (Sukuma wiki)	88	13.5	120
Tomatoes	98	10.5	300
Irish potatoes	85	24.0	210
Carrots	72	5.8	100
Cooking bananas	42	14.5	85
French beans	28	4.5	55

Table 2.5 shows that household consumption of tomatoes (98%) which is the highest household purchase rate followed by onions (96) and third is kales (88), indicating they are an essential food staff in almost every meal. This suggests both kales and tomatoes are core components of diets. Kales consumed at 13.5 kg/month and tomatoes consumed at 10.5kg are third and fourth largest quantity consumed respectively after Irish potatoes (24.0 kg/month) and cooking bananas (14.5 kg/month). Similarly, tomatoes take the highest share of expenditure (KES 300/month) while kales take significantly low expenditure (KES 120/month). Meaning that kales are more affordable. In addition, Kales are a low-cost, bulky staple, while tomatoes are a high value, but widely consumed commodity. Although perishable, kales and tomatoes have high demand internationally hence technologies which can improve their quality and shelf life is of paramount importance. This literature strongly justifies the need for evaporative cooling systems, as preserving these two crops through reduction in losses, stabilising prices and improving farmers income.

In terms of percentage Kamau et al. (2010) pointed out that a budget of 21% of peoples' income in each house hold goes to purchase of fruits and vegetables. Kales and tomatoes have liberated women from poverty because it provides self-employment for many in rural and urban areas. As such, kales and tomatoes are very popular vegetables and hence worthy investigating.

Production of vegetables is wide spread in Kenya. Ayieko et al. (2005) recorded that fruits and vegetables (F&V) form an important food source in Kenya. A study by Muendo and Tschirley (2004) revealed that 90% of the small-scale farmers in Kenya produce fruits and vegetables a huge amount of this (90%) is locally consumed. Urbanisation has increased the demand for fresh fruits and vegetables as Parfitt et al. (2010) stated that, increased urbanization is the main factor that has brought increased demand for fruits and vegetables. In 2003 it was recorded that the total land which was under vegetable production in Kenya was 100,000 hectares (Van der Lans et al., 2012). The same study recorded that only 4% of that production was exported in the year. Therefore, majority of vegetable (96%) produced in Kenya is consumed internally. Van der Lans et al. (2012) added that vegetable production offers direct and indirect employment to more than 3 million people in Kenya. Production of vegetables is on a rising trend, the average rise in production taking a case of 2018 was 5.03%, in that year 2.55 million tonnes of vegetables was produced (Van der Lans et al., 2012). Table 2.5 shows the amount and trend of vegetable production in Kenya.

Table 2.6: Annual Production of Some Common Vegetables in Kenya in Million Tons (HCDA, 2010)

Crop	2006	2007	2008	2009	2010	Average yield
Tomatoes	503,730	567,780	402,070	526,923	590,137	518,128
Cabbages	518,376	609,292	461,129	627,603	588,432	560,966
Kales	426,885	423,750	378,791	356,861	502,058	417,669
Irish potatoes	2,692,950	2,789,160	2,176,012	2,550,128	3,148,213	2,671,293

Table 2.6 shows that tomatoes and kales are among the top five crops produced between 2006 and 2010 with an average of 518,128 million tons and 417,699 million tons, respectively. According to the study, Irish potatoes topped the list with 2,671,293 million tons produced per annum. From HCDA (2010) it is reported that the average hectares under each crop are; 114,700.4 (Irish potatoes), 27,026.4 (kales) 19,840 (cabbages) and 18,206.2 (tomatoes). Therefore, it is evident that kales and tomatoes

are among the top crops with the largest acreage. In terms of supplying Nairobi city with vegetables, Table 2.7 shows the top four regions and their percentage contribution in the supply. (Ngotho, 2010) noted that there is a contribution of vegetables from urban farmers in all towns in Kenya.

Table 2.7: Volume Share of Vegetable Trade at Nairobi City for 2004 and 2005 (Tschirley & Ayieko, 2008)

District	Volume share (Percentage)
Nyandarua	37
Meru	19
Narok	22
Nakuru	12
Others	10
Total	100

Table 2.7 shows that in 2004 and 2005 90% of vegetable supply came from four district (Nyandarua, Meru, Narok and Nakuru). It is also evident that more than a third of the supply came from Nyandarua district. Vegetable farming face many constraints, with Van der Lans et al. (2012) highlighting the major hindrance to farming as; lack of research, inadequate farm inputs (fertilizers and certified seeds) inappropriate farming policies and crop wastes.

2.3 Cost Benefit Analysis of a Cooler

Cost–Benefit Analysis (CBA) is an economic feasibility tool used to determine the viability and worth of a venture by comparing the envisaged benefits with the associated costs. Studies have described CBA as an important approach for evaluating the economic feasibility and long-term performance of engineering and agricultural investments (Rizzo, 2025). In postharvest systems, CBA is applied to assess the profitability of storage projects and renewable energy projects.

Although investment projects require a substantial cost (installation and operational costs), users get economic benefits from the services and products as generated by the project, making profitability evaluation necessary (Oyewole et al., 2025). Economic studies explain that CBA involves expressing all investments' costs and benefits in monetary terms to compare and make decision (Brealey et al., 2011). The outcomes of CBA are used in determining indicators such as Benefit–Cost Ratio (BCR), discounted payback period, Net Present Value (NPV), and Internal Rate of Return (IRR), and all together assist in evaluating the financial worthiness of a project (Boardman et al., 2020).

CBA normally employ discounted cash flow methodology to convert future costs and benefits into present monetary values, thereby putting into account the effect of inflation, investment risks and time value of money (Brealey et al., 2011). CBA as an important tool for decision-making because it supports the selection of a project that makes maximum use of invested resources and minimises cost (Rizzo, 2025).

However, CBA has been criticized by some researchers blaming its reliance willingness-to-pay approaches and undervalue social equity considerations (Liscow & Sunstein, 2024). Other scholars argue that using monetary values to factors like health, and human life and environmental sustainability may introduce ethical concerns (Liscow & Sunstein, 2024).

In the current study, the cost-benefits of storage in the conventional way (room storage without artificial cooling) was compared with the costs and benefits of using the pumice evaporative cooler with roof pond in crop preservation (Boardman et al., 2020).

Jain (2007) in the study on evaporative cooler reported that the cooler saves fruits by 27% compared to the ambient storage while Kinney (2004) documented that evaporative cooler with good maintenance can have a lifetime of more than 20 years. The payback period for an evaporative cooler was found to be less than 1 years and 3 months (Tilahun, 2010). According to Ndukwu and Manuwa (2015) the maintenance cost of an evaporative cooler is 5% of the initial cost of investment).

2.4 Summary of Literature Review and Research Gaps

The summary of the literature review based on the key findings of the key researchers is as shown in Table 2.8.

Table 2.8: Summary of Literature Review Showing the Key Findings and the Knowledge Gaps Identified

Reference(s)	Key Literature in the study	Knowledge gap
Alexandri and Jones (2006)	Roof ponds have led to lower temperature than green roofs	Need for quantitative data on the temperature difference.
Kanali et al. (2017)	Study area: Energy Efficiency in food processing Findings: postharvest losses of fruits and vegetables is 50% in developed and developing countries Statistics: 36% of GDP in Kenya come from vegetables.	There is need to determine fruits and vegetable wastage figures for Kenya
Kharrufa and Adil (2008)	Roof cooling reduces cooling load by 29%	The design material of roof pond not stated, hence the need to determine the cooling effect of aluminium roof pond
Ronoh et al. (2010)	Evaporative medium: Charcoal Finding: Humidity to attain a difference of 38.07%, vitamin C, colour and weight are reduced with cooling. Amaranths increase in shelf life from 2 to 7 days.	Need to compare the charcoal cooler with other evaporation media. The cost saving of a cooler ought be studied.
Sibanda and Workneh (2020)	Evaporative cooling is cheap and simple	Research recommended on solar and wind power aided evaporative coolers.
Sow et al. (2020)	Findings: Use of evaporative coolers increase relative humidity and reduce temperature Evaporative coolers increase shelf life of fruits and vegetables.	Besides shelf-life other quality parameters on vegetables like brix, firmness, microbial load, colour and vitamin C
Zakari et al. (2016)	Finding: Using evaporative cooler Tomatoes shelf- life increased from 2 to 5 days	The study was limited to tomatoes; hence the need determines shelf-life of kales

The knowledge gap as revealed by the literature review are that; evaporative coolers aided by solar energy is a field recommended by researchers, the study's objective number one was based on this knowledge gap.

Although studies have portrayed pumice as better than charcoal as an evaporation pad, the actual financial worthiness can be determined by evaluating the benefit cost ratio which, according to the previous study has not been done. Therefore, the study at hand has analysed the financial implication of using the pumice/roof pond evaporative cooler compared to the conventional method of storing vegetables under ambient conditions or using electricity. The review also found out that the cost implication is the main hindering factor towards the use of electricity-based technologies like freezing. Therefore, evaporative cooling appears to be the solution towards making the technology affordable and available. As Sibanda and Workneh (2020) pointed out, there is a research gap in the use of solar and wind energy to support evaporative cooling.

2.5 The Conceptual Framework

Figure 2.3 is a conceptual framework showing how the cooler modifies the relative humidity and temperature in relation to the ambient conditions. The figure also shows how the cooler modify the cooler's chamber condition. The data on temperature and relative humidity in the cooler and respective ambient condition was used to analyse the coolers effect on stored vegetables (tomatoes and kales).

The conceptual framework is shown in Figure 2.3.

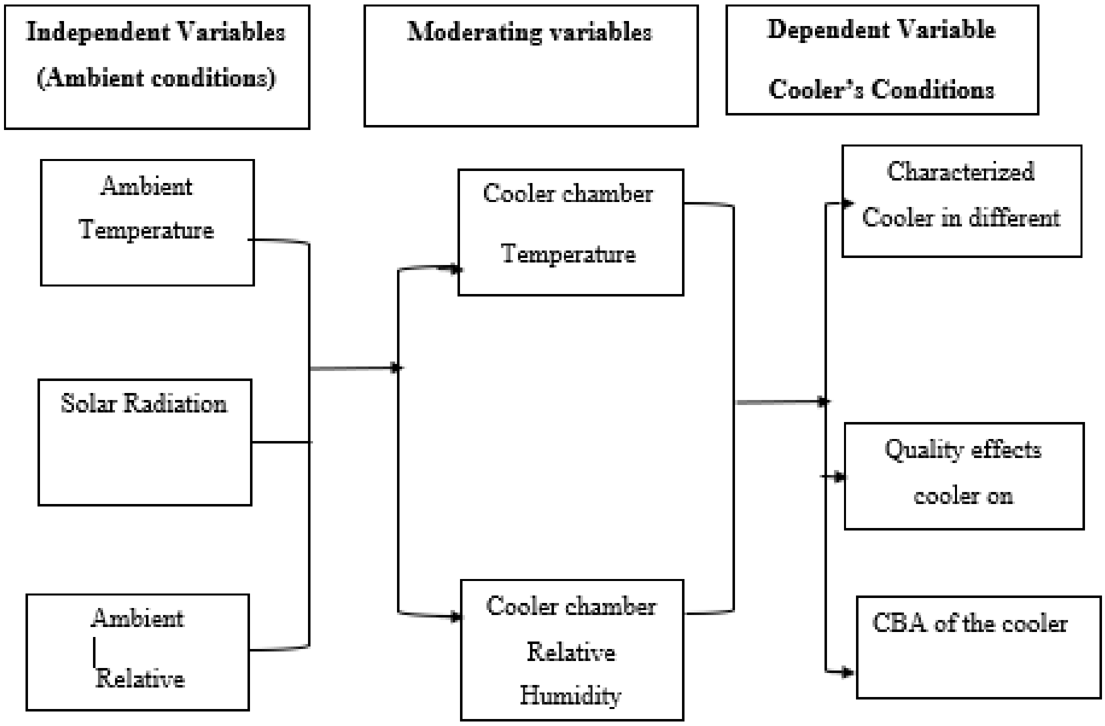

Figure 2.3: A Conceptual Framework Showing the Relationship Between Ambient and the Cooler Conditions

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Site

The study was carried out at Jomo Kenyatta University of Agriculture and Technology (JKUAT) in Agricultural and Bio-system Engineering Department. JKUAT is at an altitude of 1550 m, longitude 37.05^{o}E and latitude of 1.19^{o}S, Temperatures ranges between a maximum of 26.1^{o}C and a minimum of 13.6^{o}C and the annual mean temperature is 18.9^{o}C (Ronoh et al., 2010). The relative humidity of JKUAT ranges between 15% and 80% (Uluko et al., 2006). JKUAT experiences a tropical highland climate with bimodal rainfall patterns and moderate temperatures. Rainfall occurs in two seasons: the short rains from October to December and long rains from March to May. The annual temperature ranges between 18 °C and 25 °C, while annual rainfall averages 900 mm. The relative humidity at JKUAT area varies (60%–90%) and is influenced by the seasonal rainfall patterns. The JKUAT study site was chosen because it hosts the previously developed evaporative cooling systems, a pumice padded evaporative cooler with a vegetation on its roof that has been experimentally evaluated under similar climatic conditions Sow et al. (2020).

3.2 Experimental Design

The study adopted full factorial design in the evaluation of the performance of the zero-energy cooler under varying conditions. Full factorial design arrangement was also used by Cherono and Workneh (2022) in a similar experiment and came up with authentic results. Figure 3.1 shows a diagram which represents the conceptual flow of how evaporative cooling influences the quality of tomatoes and kales, using a top-to-bottom sequence of processes. The diagram starts with ambient environmental conditions showing the high temperature and low relative humidity.

This section depicts that the system is influenced by the ambient condition

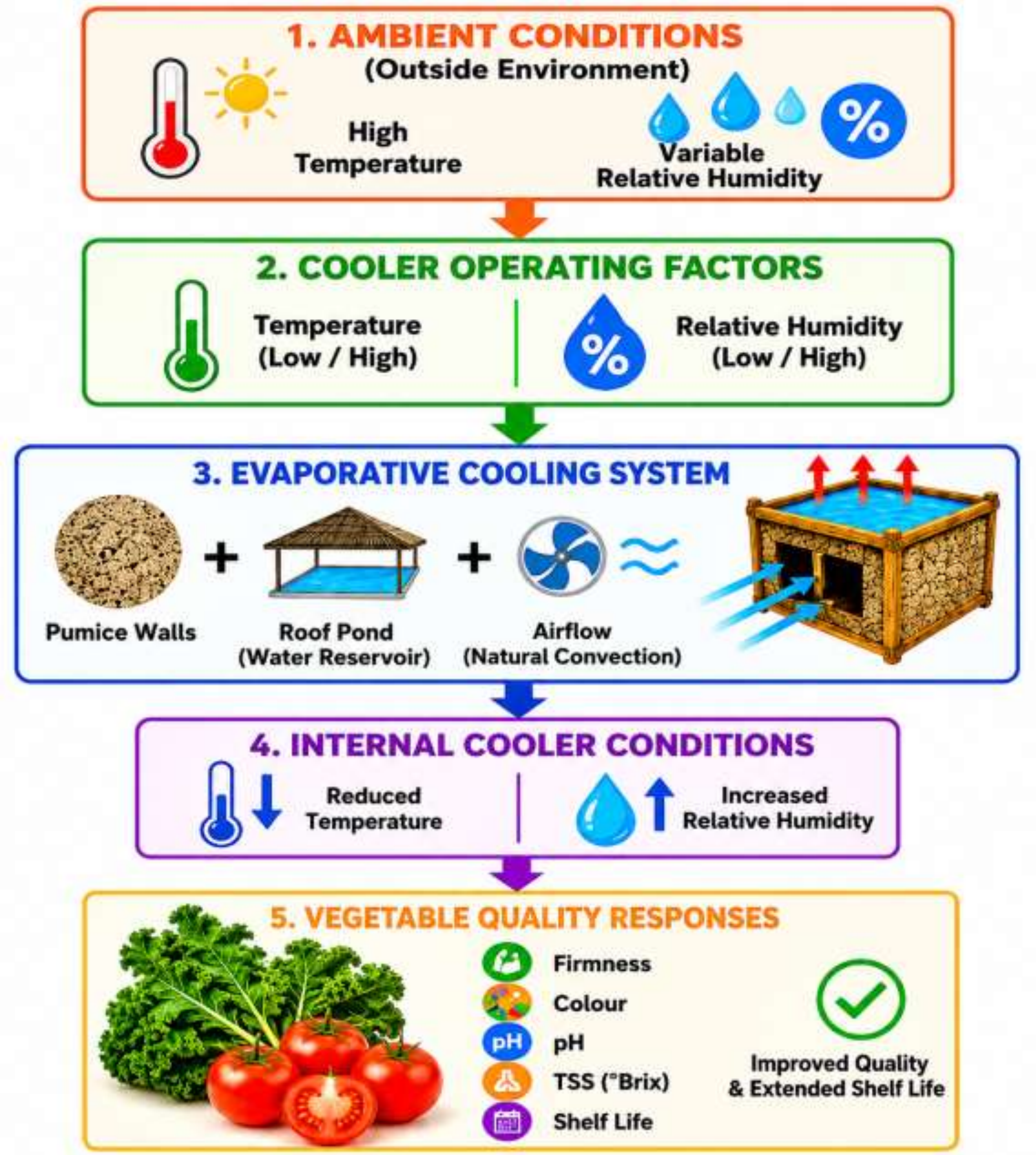

Figure 3.1: Cooler's Internal Environmental Conditions and its Effect on Vegetables Quality Parameters

The next level shows the cooler operating factors which are low temperature and high relative humidity which shows the independent variables in the experimental design. The figure also shows the working components of the cooler which are pumice wall, air flow and roof pond. The arrows indicate air movement and heat flow. The direct internal cooler condition is shown in the fourth stage (reduced temperatures and increased relative humidity). The fifth stage shows the vegetable quality TSS (°Brix), pH, Firmness, colour and shelf life). This diagram shows that the study design was a two-factor interaction (Temperature × Relative Humidity) with 4 treatment combinations (2×2 factorial design).

The experiment was conducted on kales and tomatoes by storing them in the cooler for 10 days and 30 days respectively. On each crop the process was repeated four times (runs). Figure 3.1 shows a diagram of the effect of the cooler on chamber's environmental conditions and on the quality parameters of the stored kales and tomatoes.

Starting from day 0, sampling of tomatoes was conducted weekly for 28 days while sampling for kales was done daily for ten days. All the experiments were replicated four times. Once all the data was collected, Multivariate Analysis of Variance (MANOVA) of variables, t-test were carried out to establish the effects of the conditions on the stored tomatoes and kales. The data collected was analysed using Statistical Packages for Social Scientists (SPSS) version 25 (IBM, USA) and Microsoft Excel, Version (2021). Separation of means was done using LSD (least significant difference) tests. MANOVA was carried out to establish the effects of the conditions on the storage of tomatoes and kales. Descriptive data analysis was employed in this study where tables and graphs for different parameters were used to describe the results of the experiment. Graphs showing trend of firmness, colour, pH and Brix, were used to describe the quality trend for crops stored in the cooler and the ones stored in the ambient condition. Table 3.1 shows the observations after interaction between cooler conditions and the ambient conditions.

Table 3.1: Interaction Between Cooler Conditions and the Ambient Conditions

		Cooler conditions	
		Temperature in the cooler	Relative humidity in the cooler
Ambient conditions	Temperature in ambient	Effect of the cooler on quality parameters of tomatoes and kales (firmness, TSS, pH, colour and Shelf life)	
	Humidity in the ambient		

3.3 Design of the Evaporative Cooler with Convective, and Roof Pond Cooling

The design of the evaporative cooler was based on scientific principles and previous research. The padding materials, design dimensions, roof pond incorporation and various controls are described in this section.

3.3.1 Selection of the Padding Material

The choice of the cooler's padding materials was pumice. The selection of pumice as the cooling medium was informed by its high porosity, which is reported to be approximately 85%, compared to about 75% for charcoal (Arenas et al., 2025; Elankumaran et al., 2024; Kitis et al., 2005). Higher porosity enhances water-holding capacity of the wall, which is critical in evaporative cooling systems. As water retained within the pumice pores evaporates, absorbing latent heat of evaporation and thereby increasing the relative humidity and reducing the temperature within the cooler chamber.The proposed study reduced the cooling load by ensuring that the cooler was well insulated by sealing all air entry points so that air could only get in through the pumice wall, secondly, the cooler door was kept closed and always insulated and minimizing the durations the researcher was in the cooler. The data loggers used could be read using blue tooth technology hence there were minimum incidences when the cooler was opened.

3.3.2 Determination of the Most Effective Mode of Cooling

The evaporative cooler had a wall thickness of 150 mm, the thickness was informed by a study conducted by Gunhan et al. (2007) who experimented on three thicknesses; 50 mm, 100 mm and 150 mm, and found the most efficient thickness as 150mm. Sow et al. (2020) designed a cooler with 150mm thickness which they termed as having the highest efficiency (93.1%). The internal dimensions were of the cooler in the current study were 1000mm by 1000mm, these dimensions were informed by maximization of area, by second derivative, the maximum area is found to be a square; Gunhan et al. (2007) and Sow et al. (2020) also used square based cooler with dimensions 500 mm and 2400 mm respectively. The prototype cooler maximised the volume based on first and second derivative. Assuming the length and width of the cooler to be x and y respectively, the cross-section area (A), the perimeter (p) of the horizontal cross section is given by the equation 3.1 and the derivation in equations 3.2 and 3.3

$$p = 2x + 2y \tag{3.1}$$

$$y = \frac{p-2x}{2} \tag{3.2}$$

$$A = xy \tag{3.3}$$

First derivative of area in respect to x at the maximum area. The cross-sectional area of the cooler is hence given by equation 3.4.

$$A = \frac{pX-2x^2}{2} \tag{3.4}$$

The first derivative of the area is given by the equation 3.5 and the resultant dimension of the cross section is given by equation 3.6.

$$\frac{dA}{dx} = \frac{p}{2} - 2x = 0 \tag{3.5}$$

$$x = \frac{p}{4} \tag{3.6}$$

The second derivative has a negative value (equation 3.7) which implies that at $x = \frac{p}{4}$, and $y = \frac{p}{4}$, the area of the cross-section is maximum (maximum area the cross section for any chosen perimeter should be a square).

$$\frac{d^2A}{dx^2} = -2 \tag{3.7}$$

Therefore, for maximization of volume and for efficient utilization of cooler fabrication materials the length and width was 1000 mm x 1000 mm, the height of the cooler was informed by the cooler designed by Sow et al. (2020) which had 2000 mm. The study shows that for maximum utilization of solar radiation in the evaporative cooler the long side should face east west, for the case of the study at hand the orientation of the cooler didn't matter because it was square. The outer and the inner side of the pumice wall was covered with wire mesh (5 mm x 5 mm). Compared with iron sheet Eltawil et al. (2006) found that wire mesh has better cooling efficiency. Table 3.2 shows the summary of all assumptions and design parameters for the evaporative cooler.

Table 3.2: Design Conditions and Assumptions for Pumice Padded/Roof Pond Evaporative Cooler

Specifications	Dimensions	Citation
Dimensions of the cooler	1000 mmX1000 mm	Derivative, maximization of area/volume. Sow et al. (2020) and Gunhan et al. (2007)
Height of the cooler	2000 mm	Sow et al. (2020)
Thickness of pumice wall	150 mm	(Ariyaratne et al., 2025; Rashwan et al., 2025)
Evaporative pad	Pumice porosity of 85% Environmentally friendly, locally available and durable	(Kumarasinghe et al., 2026; Rashwan et al., 2025) Sow et al. (2020)
Wire mesh on the outer and inner side of cooler wall	Wire mesh size 10mm X 10mm. Wire mesh is more effective in cooling than metal sheet	Eltawil et al. (2006)
The cooler reservoir	300 mmX1000 mm=0.3 m^3 Air flow on the water in the reservoir picked moistures and increased RH in the chambers	Sow et al. (2020)
Average windspeed for JKUAT-Juja	5.04 m/s	Saoke (2013)
Water flow rate from PPR	1.7 l/min	(Gunhan et al., 2007)
Roof pond role	Roof pond reduce cooling load	Kharrufa and Adil (2008) and Nahar et al. (1999)
Fans used at the roof pond	12V, increased rate of evaporation. Air flow rate 1.0m/s	Gunhan et al. (2007)
Fans used in the cooler chamber	12V, created suction in the chamber. Air flow rate 1.0m/s	Gunhan et al. (2007) and Sow et al., (2020
Pump used at the cooler chamber	12 VDC, 0.22 kW solar pump,	
Level of roof pond water	50 mm -150 mm	(Almodóvar-Melendo & La Roche, 2025),(Zghaib et al., 2024),Runsheng et al. (2003), Sodha et al. (1980), and Sodha et al. (1981)
Evaporative cooer Location	Juja (37.05ºE longitude, 1.19ºS latitude)	
Porosity of pumice	85%	Kitis et al., 2005

Figure 3.2 shows the diagrammatic set up of the evaporative cooler with all design components.

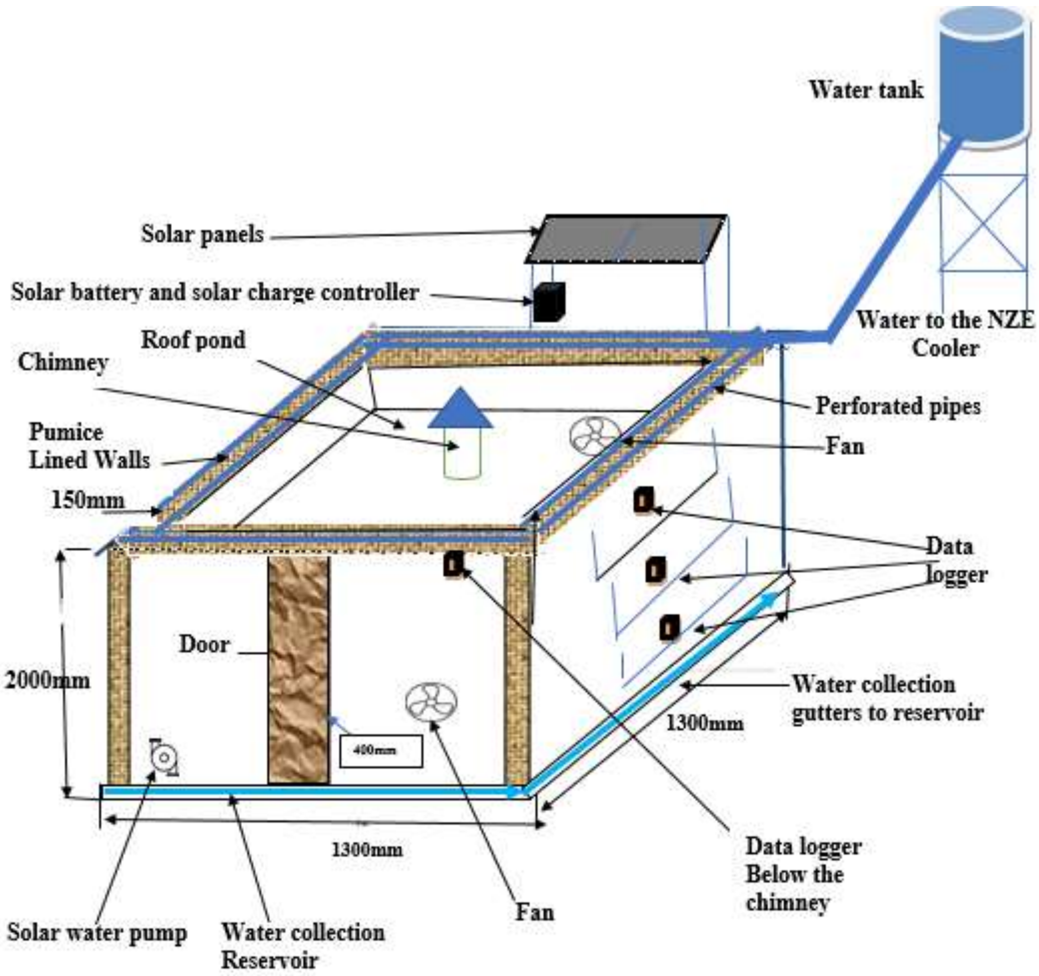

Figure 3.2: A schematic Diagram of the Pumice Evaporative Cooler with a Roof-Pond

Figure 3.2 illustrates a zero-energy evaporative cooling system designed for storage of fresh produce. The system is a combination of solar-powered water circulation with roof-pond and evaporative principle to maintain high relative humidity and low temperature inside the storage chamber. The two solar panels supply electrical energy to a battery, which powers the fans and a solar water pump used to circulate air and water within the cooler. Here, water flows by gravity to the perforated PPR pipes, the PPR pipes drips the water to the pumice wall. Water that drains from the cooler wall is collected in gutters and a reservoir for recirculation back to the tank, making the innovation water efficient (Appendix I). The cooled air is circulated by effect of internal fans and chimney, hence improving uniform cooling. Data loggers are installed to monitor temperature and humidity conditions at different points within the cooler. Overall, the design integrates evaporative cooling, solar energy, thermal mass materials (roof pond and pumice) to reduce post-harvest losses by maintaining appropriate storage conditions for perishable crops such as tomatoes and kale (Appendix II)

3.3.3 Determining the Most Effective Mode of Cooling

The environmental conditions (temperatures and relative humidities) were captured for various modes of the cooler namely, convective cooling, evaporative cooling, roof pond cooling and a combination of the three modes. The data was captured using a HOBO data logger (MX1104, Onset computer corporation, USA). The data from various modes were compared with the corresponding ambient conditions. The pairs of data were compared using MANOVA analysis and t-test, the mode which had the most cooling effect was chosen for the study. The mode selected based on cooling efficiency was the mode with combination of convective, roof-pond and evaporative cooling.

3.3.4 Evaluation of the Performance of the Cooler when Operating at no Load

After the cooler was designed, its performance (temperature drop and humidity increase) was determined while with no load (no vegetables in the evaporative cooler). The temperatures and relative humidities were taken from the upper and middle parts of the cooler chamber evaporative cooler. The two environmental conditions were captured using HOBO data loggers (MX1104, Onset computer corporation, USA). The loggers captured data every 5 minutes and recorded the average data every 30 minutes. Using SPSS and Microsoft Excel Version 21 the data was descriptively and graphically analysed to provide a comparison between the two environmental conditions (cooler and ambient environment).

3.4 Evaluation of the Performance of the Developed Cooler when Preserving Kales and Tomatoes

While loaded with tomatoes and kales (loaded at separate times), the quality parameters of the crops were determined for the crops in the ambient and in the cooler conditions. The quality parameters of the crops in the evaporative cooler were compared with resulting quality parameters of the crops stored in the ambient environment. The quality parameters in this study were: firmness, colour, pH, Brix and shelf life. To prevent effect of ethylene on kales, during the experiment in the current study, the kales and tomatoes were stored in the cooler at different times.

3.4.1 Sourcing and Sampling of Tomatoes and Kales

Freshly harvested tomatoes (*Lycopersicon esculentum cv. Anna F1*) at turning maturity were harvested from a greenhouse at Ng'undu Kamulu (1.252^{0}S 37.054^{0}E) 46 km from Jomo Kenyatta University of Agriculture and Technology (JKUAT). Tomatoes at turning stage have indications of about 10% to 50% of tomato being pink, tanning yellow or a combination (Cantwell, 2000). The Anna F1 are mainly grown in green house but can also be grown in the open field. The variety is not only firm but also deep red when ripe, these two attributes make them attractive to buyers. The crop matures early enough (75 days from transplanting). Its production is 185 tons/Ha. Anna F1 is tolerant to stem canker, fusarium wilt and nematode. Harvesting was done at 7 am to reduce on cooling load (Appendix IV). The harvesting time is backed up by the study conducted by Kader (2002) who stated that early morning harvesting of tomatoes after dew has dried and the temperature has not risen significantly preserves firmness of and helps in extending shelf life. The tomatoes were transported to JKUAT using a cooler box.

Fresh kales leaves *(Brassica oleracea var. ramose*) popularly known as thousand-headed kale was harvested at mature stage (leaves are bluish green). The choice of thousand headed variety was informed by its resilience, leaves can be picked over a long period of time including dry period and also produces many heads (Bvenura & Afolayan, 2015; Neugart et al., 2018). The field grown kales were harvested from

JKUAT farm (37°00'40.9" E,1°05'30.8" S). The harvesting was done at 60 days after transplanting as recommended by (Vilar et al., 2008).

Harvesting took place at 18:00 hrs, after which the kales were immediately placed in a cooler box, the crop was transported to the agricultural processing laboratory for sorting and labelling. Evening of harvesting kales (1800 hrs) is recommended in leafy vegetables because it minimises field heat there by preserving the crop quality (Elolu et al., 2023).

3.4.2 Tomatoes and Kales Preparation for Storage

The tomato fruits of uniform ripeness, uniform size and those without defects were washed with tap water and wiped with a cotton towel. The tomatoes were sorted based on size uniformity, level of ripeness and elements of defects. The tomatoes were then put into two plastic trays of 500 mm x 200 mm x 100 mm (high). The two trays were randomly assigned to control and experimental group. In each tray 80 tomatoes were put. Each tomato fruit was labelled with a sticker from number 1 to 80 for ease of test. The labelling of tomatoes for the experimental groups were assigned the letters EW before the numerical labelling number, for instance EW2-72 symbolized 'experimental group replication number two (second replication), tomato number 72, while the control group had CW before the numerical numbering, for instance CW2-78 represented the second replication of the control group tomato number 78 (Appendix III). The tomatoes were stored in 100 cm x 10000 mm x 20000 mm pumice/roof pond evaporative cooler for 28 days (four weeks).

The Kale leaves were cleaned using tap water and then sorted based on uniformity in the level of maturity, uniformity in size and free from defects. The kale leaves were then wiped with a cotton towel. 80 pieces of kales were put in each of the two plastic trays (500 mm x 200 mm x 100 mm. The two trays were randomly assigned to control and experimental group. Each kale leaf was labelled with a sticker from number 1 to 80 for ease of sampling. The labelling of kales for the experimental group was assigned the labels ER before the numerical labelling number, for instance letter ER1 symbolized 'experimental group replication number one' while the control group had CR before the numerical numbering, for instance CR2-10 represented the second replication of the control group leaf number ten. The kales were stored in the cooler for 10 days.

3.4.3 Sampling and Testing of Tomatoes and Kales

Using a random table for tomato sampling, four samples for each test (experimental group and control group) were taken after every 7 days (Ayantoyinbo & Adepoju, 2018). In total 8 samples were taken during each sampling. After measuring the quality parameters, the average in each test were determined. The quality parameters determined were firmness, colour, pH and Brix. In addition, the subjective quality parameters which were: rotting, spotted and wrinkled tomatoes were observed and eventually shelf life was determined.

On receiving the four samples of tomatoes from each group, the sampled tomatoes were weighed using a digital balance (Scout Pro SP202, OHAUS GmbH, Switzerland), Colour determination was conducted using a calorimeter (BCM 200, Biobase group, China), then the firmness of the tomatoes was determined using a penetrometer (GY-3, Laboratory instruments, China). Finally, juice from each tomato was squeezed for pH and TSS determination. TSS (^{0}Brix) was determined using a refractometer (3810 PAL-1, Atago, Japan). PH was determined using a pH meter (model 201-TF, Apera instruments, USA). The data for all the tests were recorded in both Microsoft Excel, Version (2021) sheet and hard copy. Besides the quality data records, the ambient, cooler temperatures and corresponding relative humidities were recorded using a HOBO data logger (MX1104, Onset computer corporation, USA). The percentage marketability of tomatoes was determined by calculating the percentage of the marketable tomatoes (ones which are not shrunk, not decayed and not overripe) in relation to the quality tomatoes. The calculation of percentage marketability was determined in relation to the remaining tomatoes during any sampling day. The subjective quality determination was determined before sampling. The data from the data logger was downloaded as Microsoft Excel, Version (2021) spread sheet at the end of the test period.

In sampling kales for testing, four leaves (samples) were taken randomly from each group. In total 8 samples were taken during each sampling (four from experimental group and four from the control group). The samples were taken every day at 8:00 am for 10 days. The quality parameters determined were firmness, colour, pH and TSS. At the end of the storage period and by observing the subjective quality factors, the shelf life of kales was determined (Appendix VI). The average quality of each parameter measured was recorded on Microsoft Excel, Version (2021) spread sheet. The temperature and relative humidity in the cooler and ambient environment were recorded for the whole period of storage using HOBO data loggers (MX1104, Onset computer corporation, USA). To determine the shelf life of kales, the following visual qualities were observed during each sampling: yellowing, decay and saleability (Albornoz & Cantwell, 2015). The visual quality according to Albornoz and Cantwell (2015) changes with increase in temperature and with leaf maturity.

The harvested kales in this study were at the mature stage. Recent postharvest literature indicates that leafy vegetables can be harvested at different maturity stages depending on use; immature, mature (marketable stage), and over-mature stages (Anjali et al., 2024).

3.5 Determination of the Cost-Benefit Ratio and Cost Effectiveness of Using the Cooler for Preservation of Kales and Tomatoes

3.5.1 Cost Benefit Analysis

All the costs and the benefits were calculated and the ratios of benefits to costs were also calculated. For a ratio greater than 1 the venture or project is termed as commercially beneficial and vice-versa. In determination of the cost benefit analysis (CBA) equation 3.8 was used (Habibzadeh-Bigdarvish et al., 2019).

$$\text{Benefit Cost Ratio} = \frac{\sum \text{Present Value of all expected Benefits}}{\sum \text{Present value of all expected costs}} \tag{3.8}$$

The cost-benefit analysis was based on annual usage of the cooler in comparison with the ambient storage. The financial gain and the costs associated with the use of the cooler were calculated. Examples of the financial gains when using the cooler are; prolonged shelf life, which reduces spoilage, safety of the crop against theft and reduction of physical contamination. The costs of the cooler labour costs, installation costs, maintenance of the cooler and water usage in running the cooler. On the other hand, the costs of storage of vegetables under ambient weather condition were determined. The costs of ambient storage included loss of crop due to spoilage, physical contamination and environmental effect of the rotting of vegetables. The benefits of the conventional storage under consideration will be: low labour cost and low equipment installation cost.

CBA borrowed heavily from the procedure by Boardman and Vining (2010) who described the steps of CBA as; specification of options, describing costs and benefits, monetizing the impacts, computation of net present value, determination of CBA and finally making a decision.

In determination of net present value (NPV), the equation 3.3 was employed.

$$NPV = \frac{P}{(1+i)^n} \tag{3.9}$$

Where;

P is Principal amount

i is discount rate

n is time in years

3.5.2 Determination of Accounting Rate of Return (IRR) of the Cooler

Internal rate of return (IRR) and payback period were calculated to ascertain the value of CBA attained. The IRR is a metric which evaluates how profitable a venture is. It is a discount rate which corresponds to NPV of zero. The higher the IRR the higher the expected profitability and vice versa. Equation 3.10 shows the equation used in determination of IRR (Ross et al., 1998). Lower IRR (lower than prevailing cost of capital) leads to rejection of the project and higher IRR consequently means that the project is viable.

$$0 = \sum_{t}^{n} \frac{C^{t}}{(1+r)^{t}}$$
(3.10)

where:

C^t = Cash flow at time t

r= Internal rate of return (IRR)

n = Total number of periods

3.5.3 Determination of Accounting Rate of Return (ARR) of the Cooler

Accounting rate of return (ARR) is a ratio of average profit and the initial project profitability. The equation 3.5 was used in determination of ARR (Gitman & Zutter, 2012).

$$ARR = \frac{Average\ annual\ profit}{Initial\ investiment} X100 \quad (3.11)$$

3.5.4 The Payback Period of the Cooler

Payback period is the time taken for a project to pay back the initial investment, projects with shorter payback periods are preferred compared with the ones with longer payback period. Equation 3.6 shows the formular used in determination of payback period

$$Payback\ period = \frac{Initial\ cost\ of\ the\ evaporative\ cooler}{Initial\ average\ annual\ profit\ from\ the\ cooler} X100 \quad (3.12)$$

3.5.5 Components of Cost Benefit Analysis (CBA) of the Cooler

Table 3.3 shows the components used in cost benefit analysis. The CBA determined the financial worth of the designed cooler in storage of kales and tomatoes. The storage of the vegetables in the cooler was compared with those stored in the ambient environment. Table 3.3 shows the main costs and benefits of the cooler.

Table 3.3: Cost-Benefit Analysis Indicators for the Evaporative Cooler Compared with the Ambient Storage for Tomatoes and Kales

Criteria	Evaporative Cooler	Ambient Environment	Expected results
Lifetime of the cooler	An evaporative cooler can last for up to 20 Years (Rashwan et al., 2025)	20 years	The cooler with proper maintenance can serve for 20 years.
Investment Cost	Cost of materials and construction (e.g., metals, pumice, fans)	The cost of the shelter for direct sun prevention	Initial cost for the cooler is high while the initial cost for the shelter in the ambient environment is low.
Cost of Operation	Water for evaporation, cost of tomatoes, cost of kales, checking water level in the tank.	Cost of tomatoes and kales, security of stored products especially at night	Cost of operation is expected to be high in the ambient storage than in the cooler because of the need for security in ambient storage.
Cost of Maintenance	Minor and major maintenance (cleaning, water refilling, replacing worn parts) which is 5% of the cooler cost (Ndukwu & Manuwa, 2015)	Minimal cost of cleaning the storage.	Cooler will require basic maintenance of fans, pump, batteries and PPR pipes.
Duration of Storage-shelf life	For tomatoes it is 28 days (Ngotho et al., 2025), for kales it is 9 days for kales .	For tomatoes it is 14 days (Ngotho et al., 2025) for kales it is 5 days for kales.	Cooler extends shelf life
Postharvest Loss (%)	Expect about 5% loss in a 28 days storage tomatoes and 10 days storage of kales (Jain, 2007)	Expect about 50% loss in a 28 days and 10 days storage of tomatoes and kales respectively (Jain, 2007)	The increment of storage of the cooler is 27% above the crop stored in the ambient environment (Jain, 2007)
Potential Income per batch	Higher income due to preservation of quality	Lower income due to high rate of deterioration.	Cooler stored vegetables fetch higher prices
Labor Requirement	Labor requirement is low for instance requires monitoring of tomatoes condition.	High labor requirement	Slightly higher labor input for ambient storage management
Retention of the market value	Appealing appearance maintained during storage	Deterioration of crops expected to be high	The cooler will maintain the freshness of the vegetables

3.5.5.1 Components of Costs of the Cooler

Among the costs will be maintenance of the cooler, which entails water pump and pipes cleaning if they are clogged with dirt and algae, replacing the cooling pads when they are clogged with dirt, flushing the water nozzles with water to clean them. In addition, the fans will need regular cleaning and lubrication to increase their efficiency.

The costs related to operation and maintenance of the cooler arise from day to day servicing, repair, cleaning, and replacement of system components for efficient operation. Timely maintenance is highly essential because evaporative coolers depend on clean airflow, continuous water circulation and efficient mechanical operation. Inadequate maintenance can reduce cooling efficiency and shorten the lifespan of the cooler (Mehrabi et al., 2023).

One of the costs is the maintenance of the water circulation system, especially the water pump and connecting pipes. During operation, mineral deposits, dirt and algae accumulate within the pipes and pump. These blockages limit water flow to the cooler, thereby increasing the workload on the pump. Therefore, regular cleaning is therefore necessary to maintain expected water flow and and prevent damage. Study on evaporative cooling have identified scaling, and biological contamination as the major maintenance challenges and cooler performance (Singh et al., 2025).

CHAPTER FOUR

RESULTS AND DISCUSSION

This chapter focuses on the description of results and the discussions of the environmental conditions in the cooler under different cooling modes.

4.1 Environmental Conditions of the Cooler Operating on Different Cooling Modes Under no Load

4.1.1 Changes in Temperature in the Cooler Under Different Cooling Modes

The cooler was tested under convective cooling mode, evaporative cooling, roof pond cooling and a combination of the three cooling modes under no load. A comparison of the temperature under the different cooling modes was done. Temperature under ambient conditions was used as the control.

Figure**s** 4.1 a, b, c and d show the mean temperature of the four modes of cooling which are convective cooling, evaporative cooling, roof pond cooling and combined cooling modes respectively.

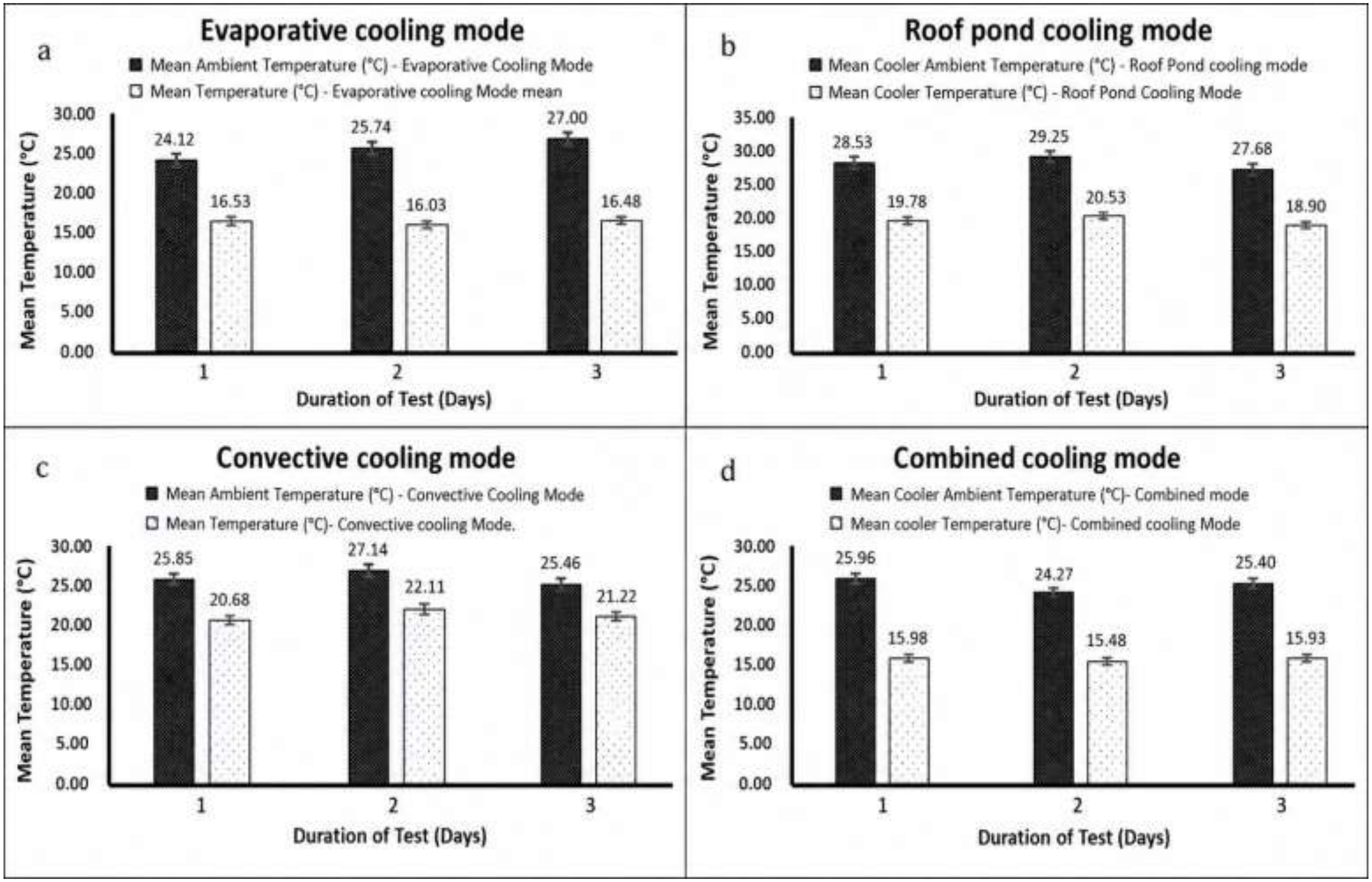

Figure 4.1: Temperature Variation in the Evaporative Cooler Under Different Modes. Error Bars Are Means±SEM

Figure 4.1 shows that temperatures under the four cooling modes (inside the cooler) were consistently lower than the ambient conditions. This was expected because the cooler under any mode reduced the temperature of the incoming air through convective cooling, evaporative cooling roof pond and water evaporation effects. The average temperature reductions, which were calculated as the difference between the average ambient temperature and the average cooler temperature, were 8.75°C, 9.27°C, 9.42°C, and 4.81°C, for roof pond, evaporative, combined cooling modes, and convective respectively.

The one-way ANOVA results showed that there were significant differences among all four cooling modes ($p \leq 0.05$). The combined cooling system produced the most effective cooling performance compared to the other three modes. This suggests that the combined cooling mode was the most suitable for maximizing vegetable/fruit cooling efficiency, followed closely by the evaporative mode, while the roof pond mode ranked third.

The combined cooling mode realized the highest reduction in ambient temperature, with a temperature drop of 9.42°C. This performance was higher than that observed in studies involving evaporative cooling mode alone. Furthermore, the mean cooler temperature during the combined cooling mode was 15.8°C (Figure 4.1d), which is considered ideal for the storage of both tomatoes and kales. The reduction in temperature achieved under combined cooling demonstrates the potential for improving cold storage of fruits and vegetables. Lower storage temperatures enable slow physiological deterioration and prolonged shelf life of stored produce. As shown in Table 4.1, the average temperature drops for the four cooling modes were 9.42°C for combined cooling 4.81°C for convective cooling, 9.27°C for evaporative cooling, 8.75°C for roof pond cooling.

Table 4.1: A Summary of Environmental Conditions in the Pumice Padded Evaporative Cooler Under No Load and Under Different Cooling Modes

Cooling Mode	Mean temperature drop (°C)	Mean relative humidity rise (%)	Maximum temperature drop (°C)	Mean relative humidity (%)	Mean temperature in the cooler (°C)
Combination cooling	9.42 ± 1.09	39.24±2.04	14.80±1.50	90.88±1.89	15.80±1.22
Evaporative cooling	9.27 ±1.19	32.59±2.23	11.36±1.31	75.63±1.67	16.35±1.12
Roof pond cooling	8.75 ±1.28	21.84±1.82	8.00±1.48	80.77±1.58	19.74 ±1.32
Convective cooling	4.81 ±1.04	14.53±1.71	7.35±1.27	88.77±1.67	21.34±1.32

All Results are Mean±SEM

The mean separation using Fisher's Least Significant Difference (LSD) test indicated that the difference between the temperature drops of 9.27°C (ambient) and 7.42°C (cooler) was statistically significant ($p \leq 0.05$) because the observed mean difference (1.85°C) exceeded the calculated LSD value (1.68).

Doğramacı et al. (2019) recorded a temperature reduction of 8.90 °C in their study. The slight variation between their finding and those of the present study may be attributed to differences in the evaporative padding materials used, as Doğramacı et al. (2019) utilized eucalyptus fibres, whereas the current study employed pumice media in combination with a roof pond cooling. Similarly, Camargo et al. (2005) observed a lower temperature drop of 7.4 °C under laboratory-simulated evaporative cooling conditions. In contrast, Nada et al. (2019) reported a significantly higher temperature reduction of 18 °C using cellulose paper as the cooling pad material. This disparity may be explained by differences in both the evaporative materials used and the environmental conditions under which the studies were conducted.

Furthermore, the current study recorded a lower temperature reduction compared to the findings of Linsley and Franzini (1979), who achieved a temperature difference of 16.50 °C using a roof pond system. This variation can also be attributed to differences in environmental conditions between the two studies experimental settings.

4.1.2 Changes in the Relative Humidity in the Pumice Evaporative Cooler Under Different Cooling Modes

Figure 4.2 a, b, c and d show a comparison of the mean Relative humidity of the ambient environment with the relative humidities in the pumice cooler under the evaporative cooling mode, roof pond cooling, convective and combined cooling modes, respectively.

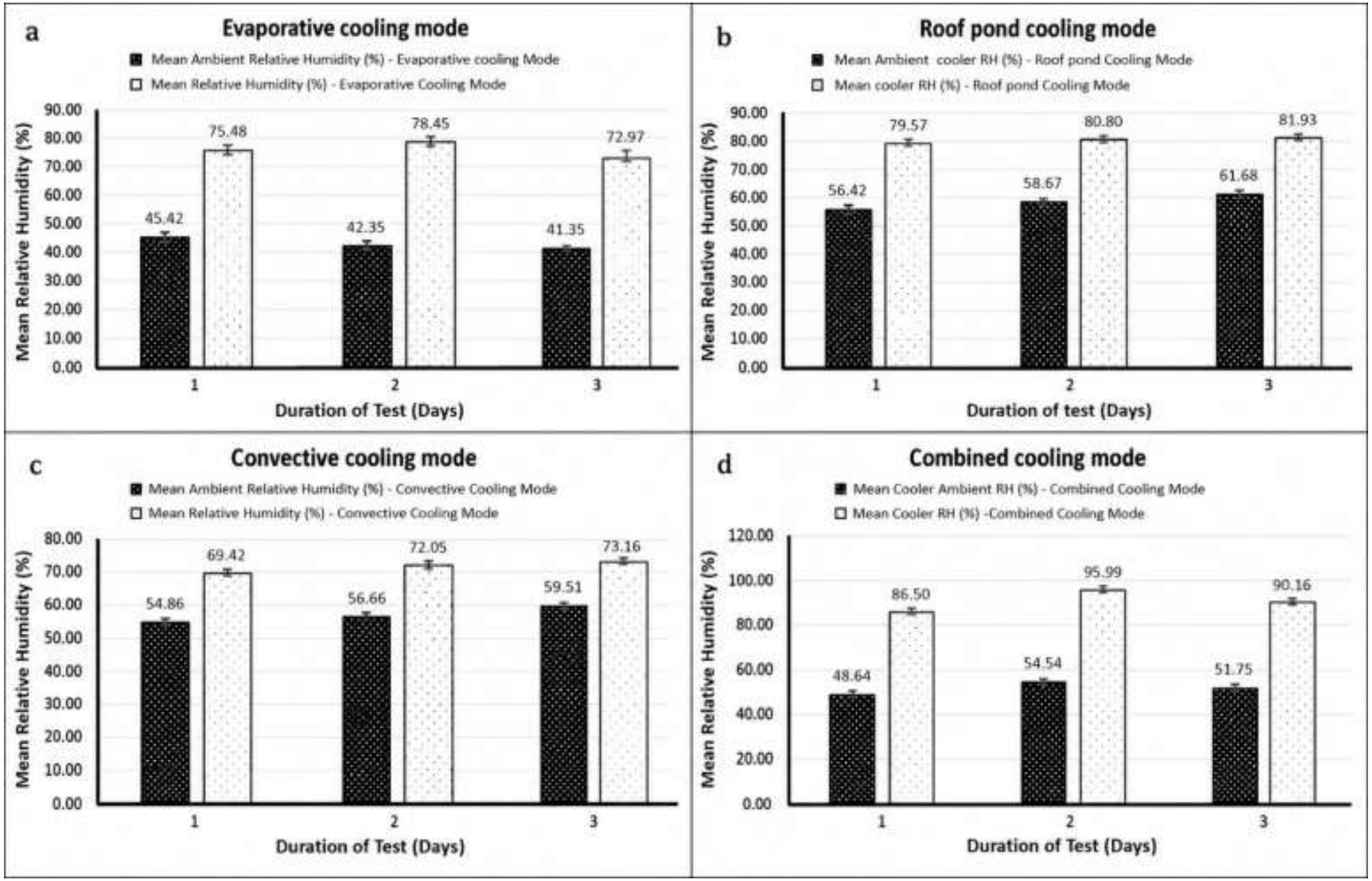

Figure 4.2: Relative Humidity of the Cooler under Convective, Poof Pond, Evaporative and Combined Cooling Modes (Error Bars +/- 1 SE)

The mean relative humidities shown in figure 4.2 (differences between ambient and cooler relative humidities) gave the result that the ambient relative humidity was lower than the cooler relative humidity in all the four cooling modes. The average relative humidity in the cooler was the highest at the combined cooling modes recording 86.50%, 95.99%, and 90.16% during the three test days respectively while the lowest was at convective cooling which registered 69.42%, 72.05% and 73.16% during the 1st, 2nd and 3rd test days respectively. The analysis of variance (ANOVA) revealed a significant effect of cooling mode on relative humidity ($p \leq 0.05$), revealing that the relative humidity during combined mode cooling was significantly higher than the relative humidity observed during convective cooling. Mean separation using Fisher's Least Significant Difference (LSD = 8.27) indicated that the combined cooling mode had a significantly higher relative humidity (90.88%) than the convective cooling mode (71.54%).

Table 4.1 shows mean rise in relative humidity and drop in temperature for the various cooling modes tested in this study. The analysed data showed the potential of the cooler in preserving Kales and tomatoes (Rutledge, 2005).The rise in relative humidity was 39.24%, 32.59%, 21.84% and 14.53% for combined cooling, evaporative cooling, roof pond cooling and convective cooling, respectively. The average rise in relative humidity for the present study is lower than that reported by Jha (2008) that observed a 52.5% as the maximum rise in relative humidity of when using river bed sand. Ronoh et al. (2010) also reported a relative humidity rise of 38.07% when using a charcoal evaporative cooler.

Figure 4.3 shows the temperature and relative humidity variation among the four modes of cooling

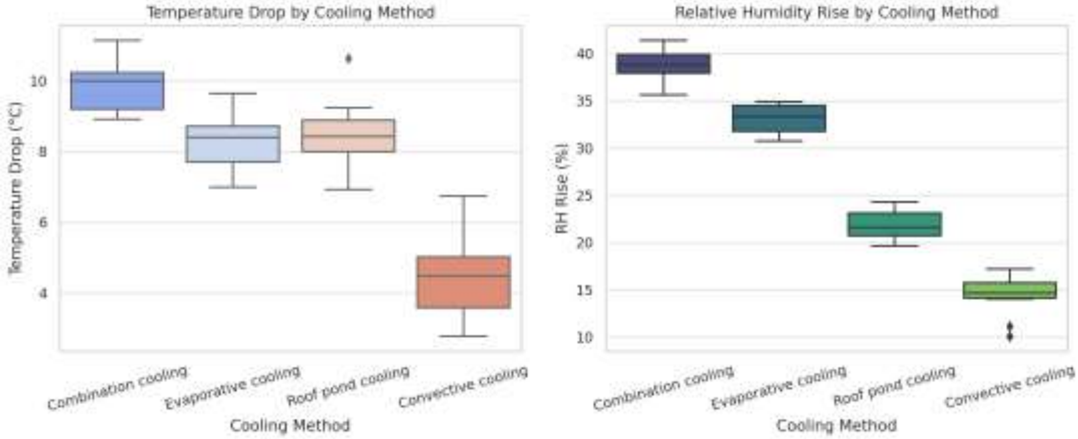

Figure 4.3: Distribution of Temperature Drops and Relative Humidity Rise for the Four Cooling

The results of the combination cooling were the best in crop preservation most likely because the cumulative cooling from convective, evaporative and roof pond cooling contributed to overall best cooling. The fact that the ranges in relative humidities did not overlap, this is an indication of distinct difference in the four cooling modes. This can be compared to the results of Sow et al (2020) whose evaporative cooling was a combination of evaporative, convective and roof vegetation and their research yielded reliable results.

Table 4.2: A Summary of Environmental Conditions in the Pumice Padded Evaporative Cooler Under No Load and Under Different Cooling Modes (mean±SEM)

Comparison	Parameter	Combined Value	Other Mode Value	Difference	Interpretation
Combined vs Roof Pond	Mean Temperature Drop (°C)	9.42	8.75	0.67	Combined higher
Combined vs Roof Pond	Mean RH Rise (%)	39.24	21.84	17.4	Combined much higher
Combined vs Roof Pond	Max Temperature Drop (°C)	14.8	8	6.8	Combined much higher
Combined vs Roof Pond	Mean RH (%)	90.88	80.77	10.11	Combined higher
Combined vs Roof Pond	Cooler Temperature (°C)	15.8	19.74	-3.94	Combined significantly cooler
Combined vs Evaporative	Mean Temperature Drop (°C)	9.42	9.27	0.15	Very small difference
Combined vs Evaporative	Mean RH Rise (%)	39.24	32.59	6.65	Combined higher
Combined vs Evaporative	Max Temperature Drop (°C)	14.8	11.36	3.44	Combined higher
Combined vs Evaporative	Mean RH (%)	90.88	75.63	15.25	Combined much higher
Combined vs Evaporative	Cooler Temperature (°C)	15.8	16.35	-0.55	Combined slightly cooler
Combined vs Convective	Mean Temperature Drop (°C)	9.42	4.81	4.61	Combined much higher
Combined vs Convective	Mean RH Rise (%)	39.24	14.53	24.71	Combined much higher
Combined vs Convective	Max Temperature Drop (°C)	14.8	7.35	7.45	Combined much higher
Combined vs Convective	Mean RH (%)	90.88	88.77	2.11	Slightly higher
Combined vs Convective	Cooler Temperature (°C)	15.8	21.34	-5.54	Combined far cooler

From table 4.2, the combined cooling mode consistently produced the highest increase in relative humidity, highest temperature reduction across all parameters. While its temperature drop was comparable to evaporative cooling, it achieved significantly higher humidity levels and lower internal temperatures. Compared to roof pond and convective cooling, the combined system demonstrated markedly superior performance. These differences were statistically significant at the 95% confidence level (Tukey HSD, $p \leq 0.05$), that is comparing each cooling mode against all others. The slight difference in observations between the current study and the studies by Ronoh et al. (2010) might be because of the differences in solar radiation or difference in the evaporative materials used. High relative humidity in the cooler under combined mode is advantageous for fruits and vegetable storage, as it slows down the physiological deterioration and reduces moisture loss, thereby prolonging the shelf life of vegetables (Hoffmann et al., 2023).

The result of the Tukey HDS test revealed that combination cooling causes the highest rise in humidity and hence it is the best cooling method for effective cooling of crops. Figure 4.4 shows the four methods of cooling and their relative rises in the relative rise in relative humidity. The combination cooling had highest rise in relative humidity ranging between 38.0% to 40.0%. The lowest of the three cooling modes was convective cooling with a relative humidity rise range (14.6% to16.0%).

4.1.3 Comparison and Selection of the Best Cooling Mode

The rise in relative humidity was 39.24%, 32.59%, 21.84% and 14.53% for combined cooling, evaporative cooling, roof pond cooling and convective cooling, respectively. the average rise in relative humidity for the present study is lower than that reported by Jha (2008) that observed a 52.5% as the maximum rise in relative humidity of when using river bed sand. Ronoh et al. (2010) also reported a relative humidity rise of 38.07% when in a charcoal evaporative cooler. The slight difference between in observations between the current studies and the studies by the two researchers might be because of the differences in solar radiation or difference in the evaporative materials used. The high relative humidity for the cooler under combined mode is advantageous for crop storage in that high relative humidity increases the shelf life of the stored crop (Rutledge, 2005). The result of the Tukey HDS test revealed that combination cooling causes the highest rise in humidity and hence it is the best cooling method for effective cooling of crops. Figure 4.3 shows the graph of the relative rise in relative humidity in the four methods of cooling. The combination cooling had highest rise in relative humidity ranging between 38.0% to 40.0%. The lowest of the three cooling modes was convective cooling with a relative humidity rise range (14.6% to16.0%).

The results of the combination cooling were the best in crop preservation most likely because the cumulative cooling from convective, evaporative and roof pond cooling contributed to overall best cooling. The fact that the ranges in relative humidities did not overlap, this is an indication of distinct difference in the four cooling modes. This can be compared to the results of Sow et al (2020) whose evaporative cooling was a combination of evaporative, convective and roof vegetation and their research yielded good results.

From figure 4.3, the drop in temperature when comparing the ambient and cooler environments shows that the combination mode had the best results (9^{o}C to 11.6^{o}C), followed by evaporative cooling, roof pond cooling and convective cooling respectively. Figure 4.3 also shows the variation in relative humidity between the cooler and ambient environments where the highest increase in temperature was realised in the combined cooling, followed by evaporative cooling, roof pond cooling and convective cooling respectively. The combined cooling modes achieved relatively lower temperatures and higher relative humidities compared with individual cooling strategies. As a result of this superior performance, combined cooling mode was selected for subsequent on evaluation of quality parameters of tomatoes and kales.

4.2 Environmental Conditions during Storage of Kales under Combination Cooling Mode

The combined cooling mode was chosen based on its comparative good results. The combined system achieved a lower temperatures, highest relative humidity and reduced cooling load, resulting into the best environment for the stored kales and tomatoes. Using the combined cooling mode, Figure 4.4 shows the temperatures at two positions (middle and upper part of the cooler) during the 10 days storage of kales under combined mode of cooling.

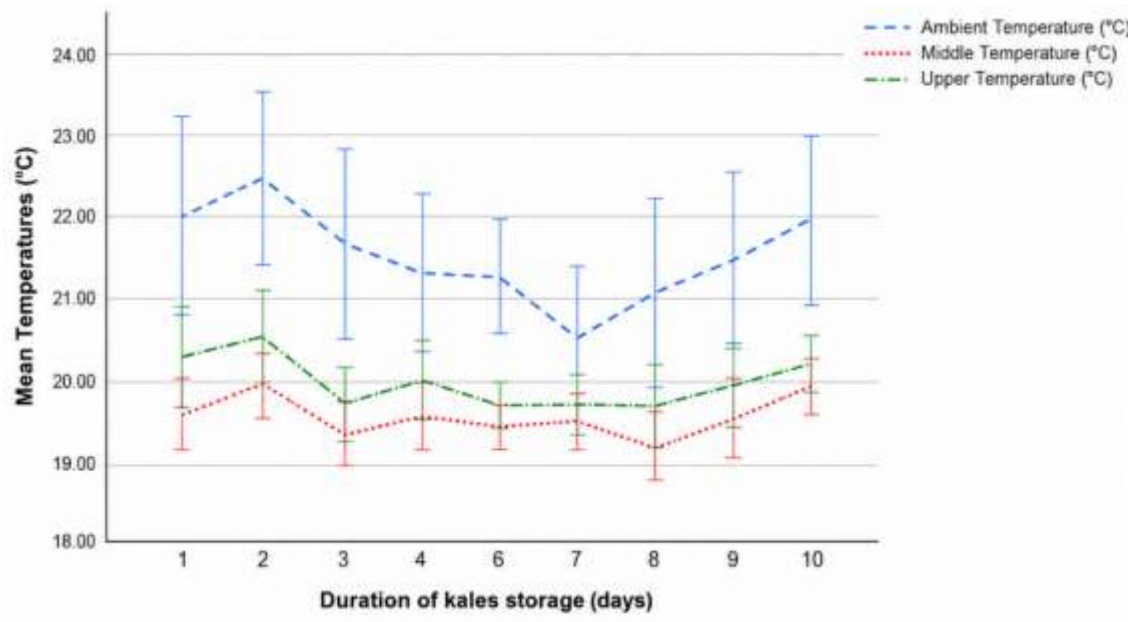

Figure 4.4: Variation of Ambient, Upper and Middle Mean Temperatures (°C) during 10 Days of Kale Storage in the Evaporative Cooling System Under Combined Cooling Mode. (Error Bars Are Means±SEM)

Figure 4.4 shows that the mean ambient temperature was higher than the mean temperatures in the two main storage areas (upper and middle) of the cooler. In addition, the middle of the cooler recorded lower mean temperatures than the upper section of the cooler, this was similar to the difference in mean temperatures at the same two levels recorded by Ngotho et al. (2025) while storing tomatoes in the same cooler. The difference between the mean temperatures at the middle of the cooler and mean ambient temperature was highest on the second day (2.4^{0}C). When the ambient temperature was high evaporation of the water on the cooler wall was high too which led to increased temperature difference.

A t-test (two tail, assuming nonequal variance) revealed that the difference between mean ambient temperature and mean cooler temperature was significant ($p \leq 0.05$). This is an indication that the evaporative cooler had a notable reduction in temperature compared to the ambient conditions, resulting in a suitable microenvironment for increased shelf life of kales. The results suggest that, if crop is stored in this cooler while operating under combined mode will provide a cooler environment to the crop leading to extension of shelf life and eventually lead to greater profitability for kale vendors and value for money to consumers.

Figure 4.5 shows the relative humidity conditions of the ambient environment and the evaporative cooler (upper and middle of the cooler) while storing kales.

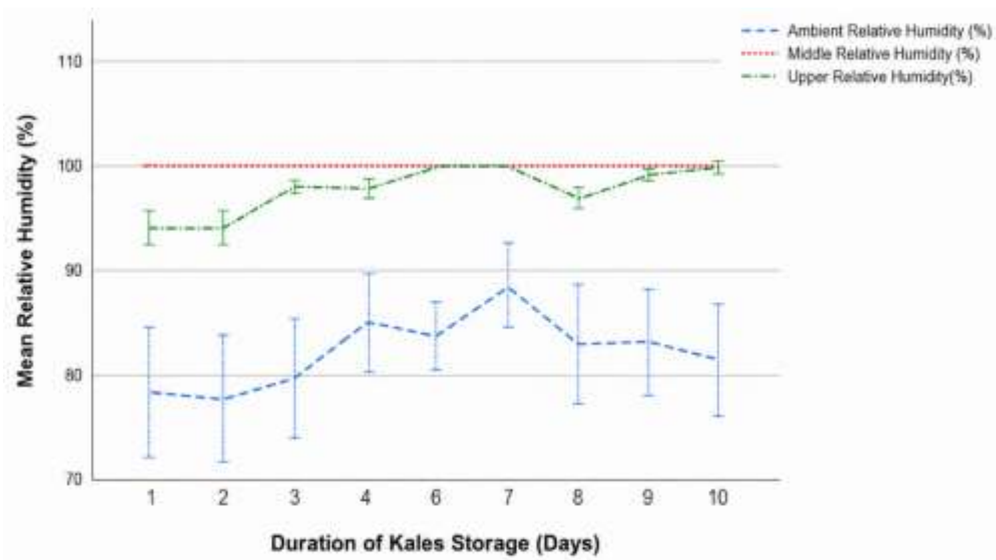

Figure 4.5: The Mean Relative Humidities for the Cooler and Ambient Temperatures during Ten-day Storage of Kales (Error Bars are means±SEM)

Figure 4.5 shows the mean relative humidity averaged over 24hr hours for storage conditions in the cooler and ambient environment. From figure 4.5, the mean relative humidity in the middle of the cooler was almost 100%, while the mean relative humidity in upper part cooler was lower than that of the middle section of the cooler. The figure shows that the mean ambient relative humidity was generally lower than that of the evaporative cooler. A high relative humidity is a desirable environment for the storage of vegetables as a high humidity environment reduces the rate of evapotranspiration from the produce resulting in increased shelf life. A similar trend on variation in relative humidity in relation to height within the cooler was also recorded by (Ngotho et al., 2025). The upper part of the cooler recorded lower relative humidity when compared with the middle part of the cooler. Similar differences in temperature and relative humidity between an evaporative cooler and the ambient environment is also reported by (Sow et al., 2020). Their study investigated the use of ANN (artificial neural networks) to make prediction internal climate conditions of a pumice padded evaporative coolers. The study found out that the ANN model accurately predicted cooler's internal climate. In the study at hand, it was expected that the upper part of the cooler registers the lowest relative humidity and the highest temperature based on density of the air in relation to temperature, but the study revealed an opposite result which is attributable to heat transfer, and air movement dynamics forced by a fan in the cooler chamber.

Figure 4.6 shows the mean daily temperature variation with time of the day averaged over the 10 days of kale storage in the cooler. Figure 4.7 shows the daily relative humidity variation over time for the 10 days of storage of kales in the cooler.

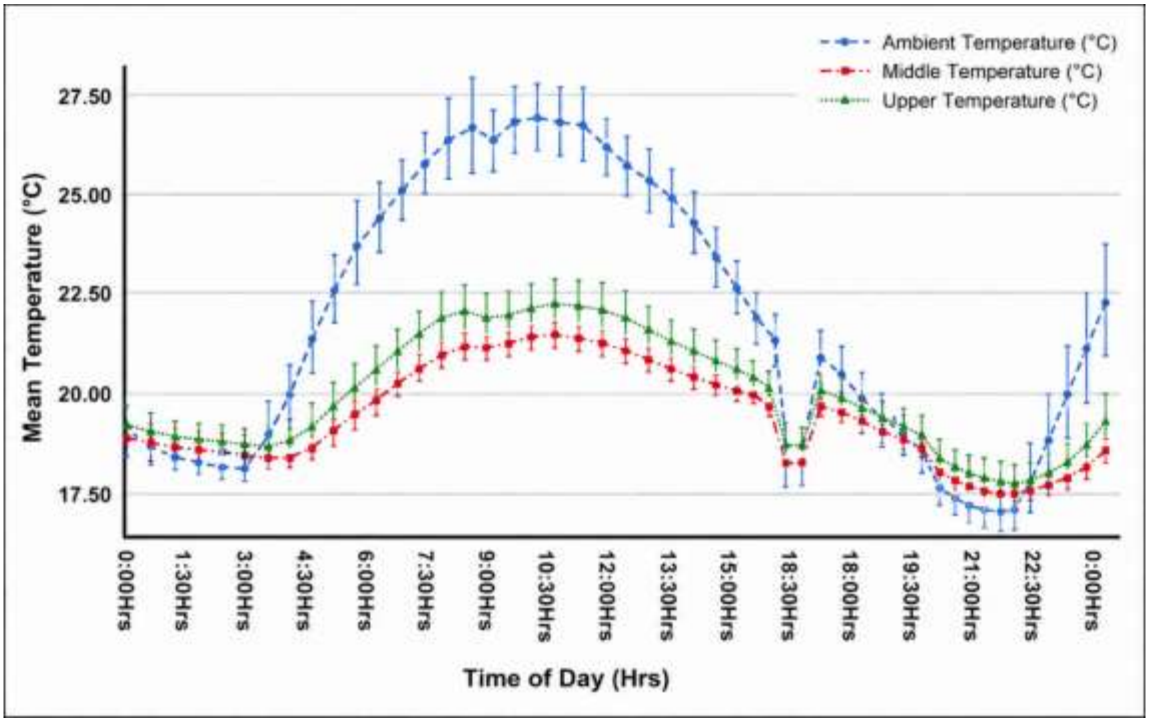

Figure 4.6: The Mean Temperatures at the Upper and Middle Cooler Chamber Compared with the Ambient Temperature during Storage of Kales Averaged Over Time. Error Bars are Means±SEM

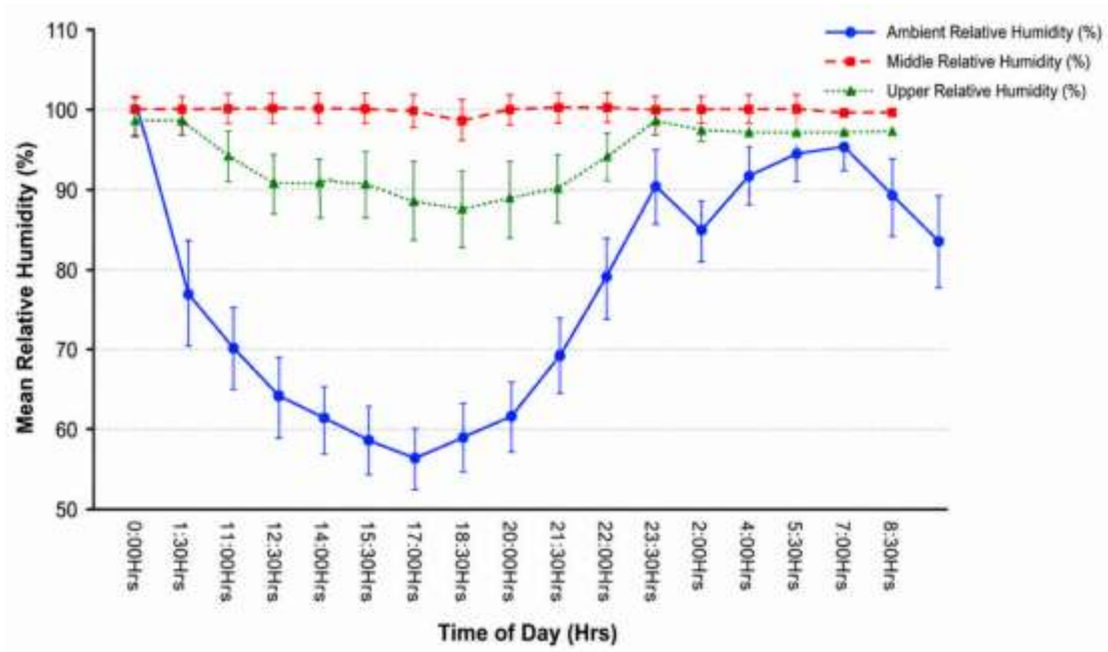

Figure 4.7: Changes in the Mean Relative Humidity with Time at the Upper and Middle Cooler Sections Then Compared to Ambient Relative Humidity Conditions. Error Bars are Means±SEM

According to results shown figure 4.6, the ambient temperatures were generally higher than the temperatures inside the cooler (both upper and middle temperatures). The mean temperatures in the cooler and in the ambient was the lowest at midnight (figure 4.6). The highest mean temperature was recorded at 1400hrs as 21.0^{0}C, 22.0^{0}C and 26.5^{0}C for middle section of the cooler, upper part of the cooler and ambient environment, respectively. The mean cooler temperatures ranged between 18.0^{0}C and 21.5^{0}C , these temperatures are conducive for kale storage as recommended by (Albornoz & Cantwell, 2015).

Figure 4.7 shows changes in the mean relative humidity in the ambient environment and in the evaporative cooler. The relative humidity was also highest at midnight (was 100% in all the three measurements) and decreased to attain the lowest level at 1400hrs (solar noon) measured to be 55%, 95% and 100% for ambient environment, upper part of the cooler and middle section of the cooler, respectively. The mean relative humidity was 55%, 92% and 100% for ambient, cooler upper and cooler middle respectively. The reported relative humidity at the middle and at the upper part of the cooler is associated to air movement caused by the fan in the cooler chamber. The difference between the graphs in figures 4.6 and 4.7 also show that the cooler's mean temperature and mean relative humidity ranged between 17^0C to 22^0C and 90% to 100%, respectively. Similarly, an independent study recorded that highest temperature and lowest relative humidity is experienced at solar noon at 1400hrs (Jones Jr & Burkhart, 1981). Although the solar noon is around 12:00 noon, the time lag, in this case is the delay between a change in ambient conditions (temperature or humidity) and the corresponding change inside the cooler which is about 1 to 3 hours The cooler was effective in maintaining a sufficiently high relative humidity (close to 100%) which is suitable for maintaining the quality and shelf life of kales (Rutledge, 2005).

Two tailed t-tests (assuming nonequal variance) showed that there was a significant difference ($p \leq 0.05$) between the ambient environment and evaporative cooler's relative humidity. In addition, t-test also revealed that there was a significant difference ($p \leq 0.05$) between the ambient and evaporative cooler's temperatures. In addition, a one-way ANOVA revealed that the difference between the upper temperature and relative humidity were significantly different ($p \leq 0.05$) compared with the same parameters recorded at the middle of the cooler. This shows that the cooler had suitable conditions for storage of fresh kales experienced through increased relative humidity and reduced the temperature compared to ambient conditions. Low temperature and high relative humidity reduce the rate of ripening and senescence hence increasing shelf life of kales ($p<0.05$). The high relative humidity in the evaporative cooler would potentially confer economic benefits to the kale vendors. The results show that, storing crop in a typical evaporative cooler tested in this study operating under combined cooling mode provide an environment with high humidity which led to extension of shelf life of crops stored in it and the result is that farmers and vendors reap high profit due to reduced PHL. Low temperature in the cooler acts as a slowing agent for metabolic activity like respiration, thus delaying ageing, ripening and reducing the chemical reactions as well as physiological processes. Similarly, high relative humidity which is a characteristic of the cooler under study reduces respiration which maintains the turgor, visual quality and texture of the stored crop—which delays ripening and aging too. Hence wilting and yellowing of vegetables is controlled by the cooler conditions. (FAO, 2024) backs the results by recording that kales and tomatoes exposed to relative humidity above 90% prolongs their shelf life at an average 12 and 21 days respectively. This slightly disagrees with the results at hand because the kale shelf life in the cooler was 9 days and the tomatoes shelf life was 28 days. The difference can be attributed to the type of variety and the stage of maturity for the two sets of tests.

4.3 Quality Attributes of Kales Stored in the Evaporative Cooler while Operating Under Combined Cooling Mode

4.3.1 *a and b* Colour Parameters of Kales

Figure 4.8 shows a* and b* colour parameters observed during storage of kales in the ambient environment and in the cooler over a period of 10 days. The kales were stored in the cooler while operating under combination mode of cooling.

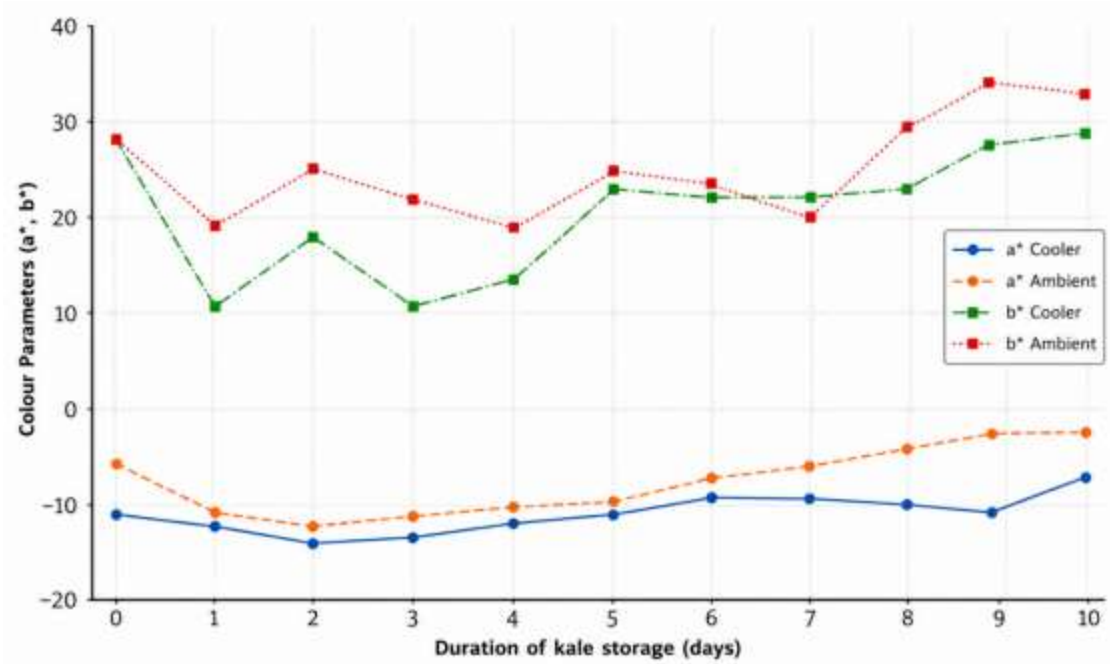

Figure 4.8: Changes in a* (Greenness-Redness) and b* (Blueness-Yellowness) Colour Parameters of Kales Stored in a Pumice Padded Evaporative Cooler Under No Load and at Different Cooling Modes (±SEM)

Generally, figure 4.8 shows that the a* (greenness-redness) colour parameter of kales increased from -12.57 to -6.53 and -11.38 to-2.36 for the evaporative cooler and ambient environment, respectively. This shows that, in the 10th day the kales in the cooler had more green parameters (less a*) compared with the kales stored at the ambient environment. The average a* colour parameter was -10.56 for kales stored in the cooler and -7.6 for kales stored in the ambient environment (control). From Figure 4.7 since a* depict green colour the low or negative a* depicts a large green component, the results imply that the kales stored in the evaporative cooler remained greener compared to those stored in the ambient environment. This phenomenon is expected as low temperature and high humidity conditions in the evaporative cooler reduces moisture loss and the rate of biological reactions such as respiration and transpiration that are responsible for quality reduction in fresh fruits and vegetables (Kader & Rolle, 2004; Shezi et al., 2024).

The colour changes of the b* colour parameter (blueness-yellowness) increased from low values of 11.23 to 33.58 and 11.16 to 29.15 for kales stored in the ambient environment and the evaporative cooler, respectively. This demonstrates the fact that yellowing of kales increased with storage duration. Since the kales did not have a negative b* during harvesting Figure 4.8, it shows that the kales were stored with very faint yellow pigmentation and progressed towards deep yellow as they continually lost chlorophyll over time (Wang & Zhang, 2020). The study revealed than the kales in the cooler degraded slower (less b*) than the kales in the ambient environment (larger b*). This shows that the cooler is ideal for kales storage based on green loss and gaining yellow.

A two-tail t-test (assuming an unequal variance) of the b* parameter of the kale samples stored in the evaporative cooler was not statistically significantly different ($p>0.05$) from the samples taken from the kales stored in the ambient environment. Since b* depicts yellowing, it shows that the evaporative cooler had insignificant effect ($p>0.05$) on the preservation of the chlorophyll content of kales. From the results of the b* colour parameter between the kales stored in the two environments (Figure 4.8), also demonstrate that the evaporative cooler environment had a minor effect in suppressing the yellowing of kales. On the other hand, the evaporative cooler had significant ($p<0.05$) effect on the a* colour parameter. The capacity of the cooler to keep the kales green imply that the kales stored in the evaporative cooler remained in their appealing state to consumers for a relatively longer time compared to kales stored in the ambient environment leading to extension of shelf life and improved earnings to farmers and vendors.

4.3.2 Total Soluble Solids (TSS) of Kales

Figure 4.9 shows the changes in TSS of kales during storage in the evaporative cooler and the ambient environment. The observed TSS for kales was 5.88 ± 0.31 °Brix and 5.66 ± 0.27 °Brix.

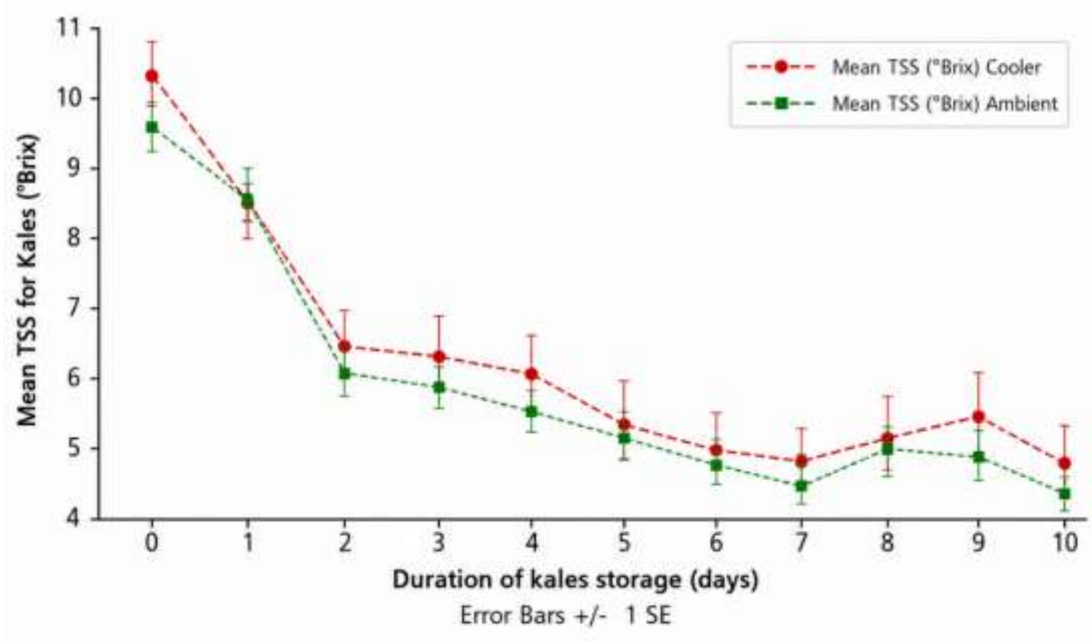

Figure 4.9: The Mean total soluble solids (TSS) for Kales at the Cooler and Ambient Environment Averaged for the Ten Days. Error Bars are Means±SEM

Figure 4.9 shows that the TSS decreased rapidly in the first two days (from 10^0 brix to 6^0 brix, then TSS reduced at a slower rate to record about 4.50 ^{0}brix on the 10^{th} day.

A two tailed t-test of the TSS data showed that the conditions in the evaporative cooler and the ambient environment had no significant ($p>0.05$) effect on the TSS content of the kales. From the results in Figure 4.9, it can be deduced that the evaporative cooler environment slightly maintained the TSS of the kales compared to the ambient environment and is an indication that the evaporative cooler maintains the TSS at higher level compared to the ambient storage. Hence the breakdown of carbohydrates which result into rotting of vegetables is delayed while kales are stored in the cooler (Ait-Oubahou, 2012). In most instances, the TSS of the kales kept in the evaporative cooler was slightly higher than that of the kales stored in the ambient environment. Scientifically, the drop in TSS can be traced from the breakdown of carbohydrates in kales which takes place as days of kale storage advances resulting in loss of quality (Ait-Oubahou, 2012). The results in this study is similar to the findings by Kader (2002) who found out that low temperature at the cooler slows the process of water loss and rate of respiration, hence the crop maintains the initial component of TSS.

4.3.3 pH of Kales

Figure 4.10 shows the mean pH of kales over the 10 days storage period. From figure 4.10, the pH of kales increases with storage duration. However, generally, the mean pH of the kales stored in the ambient environment was higher than that of kales stored in the evaporative cooler. At harvest the average pH of kales ranged between 6.0 ± 0.09 and 6.35 ± 0.09. During storage, the highest pH was 6.95 and 6.85 for the kales in the ambient environment and in the cooler respectively. Low pH (more acidic) is appropriate for kales storage because microbial effect is hampered by kale's acidity leading to longevity of storage and high profit for kale vendors.

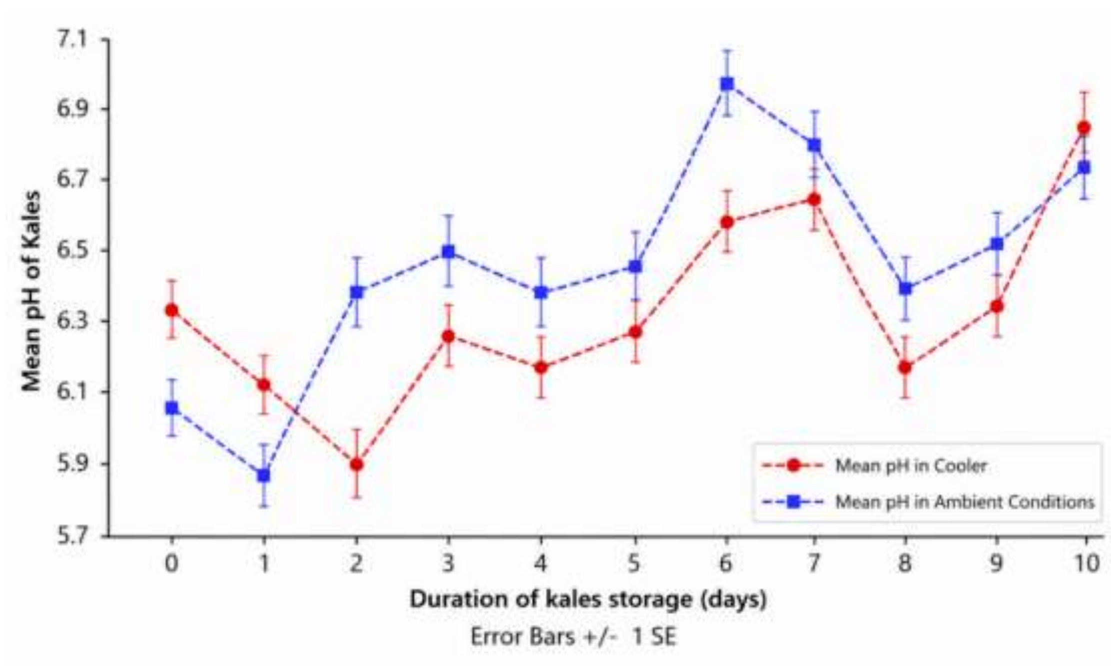

Figure 4.10: The Mean pH of Kales at the Ambient and Cooler Environment Averaged Over Time for Ten Days. Error Bars are Means±SEM

Early in storage, microbes (lactic acid bacteria) produce organic acids, hence lowering pH. By about a week, it is very likely that different microbes dominate (those that break down proteins and release ammonia), which raise pH (Tonto et al., 2023). This shift can cause a noticeable peak in in day 6 and 7 (Figure 4.10).

A two tailed t-test of the pH values of kales during storage to test the difference in the mean pH level between the kales stored in the cooler and in the ambient environment showed no significant difference ($p>0.05$). The average pH for kales stored in the cooler and ambient environment was 6.36±0.02 and 6.38±0.03, respectively. The kales in the cooler, however, maintained the pH levels of the kales compared with those stored in the ambient environment. In this case, the kales stored in the evaporative cooler were reported to have lower pH than kales stored in the ambient environment. Low pH (high acidity) is preferred in canned vegetables because they hinder microbial growth which would otherwise lead to deterioration of these vegetables. The application of the evaporative cooler in this study in the storage of kales resulted in the maintenance of the pH at comparatively a lower level, meaning that product was appropriate for a range of consumer uses, would potentially have a prolonged shelf life and would confer improved earnings to kale farmers and vendors. The difference between pH of kales in the cooler and in the ambient environment can be explained by the fact that cooler storage leads to a gradual drop in pH because of low metabolic activity while the crops stored in the ambient condition have a relatively higher pH due to high respiration and organic acid metabolism. The results in this study is similar to the findings by (Schmitzer et al., 2021).who found out that refrigeration storage preserves acidity and quality in vegetables while high temperature leads to synthesis of acid.

4.3.4 Chroma of Kales

Figure 4.11 shows the mean chroma (C*) of kales stored in ambient environment and evaporative cooler. Chroma refers to colour intensity which is a sensory quality which consumers use to make a judgement on freshness of kales (Barrett et al., 2010) From figure 4.11, the mean chroma increased with the storage duration and had a maximum value of 45.2 and 39.1 for in the ambient and cooler storage, respectively. (Toivonen & Brummell, 2008).

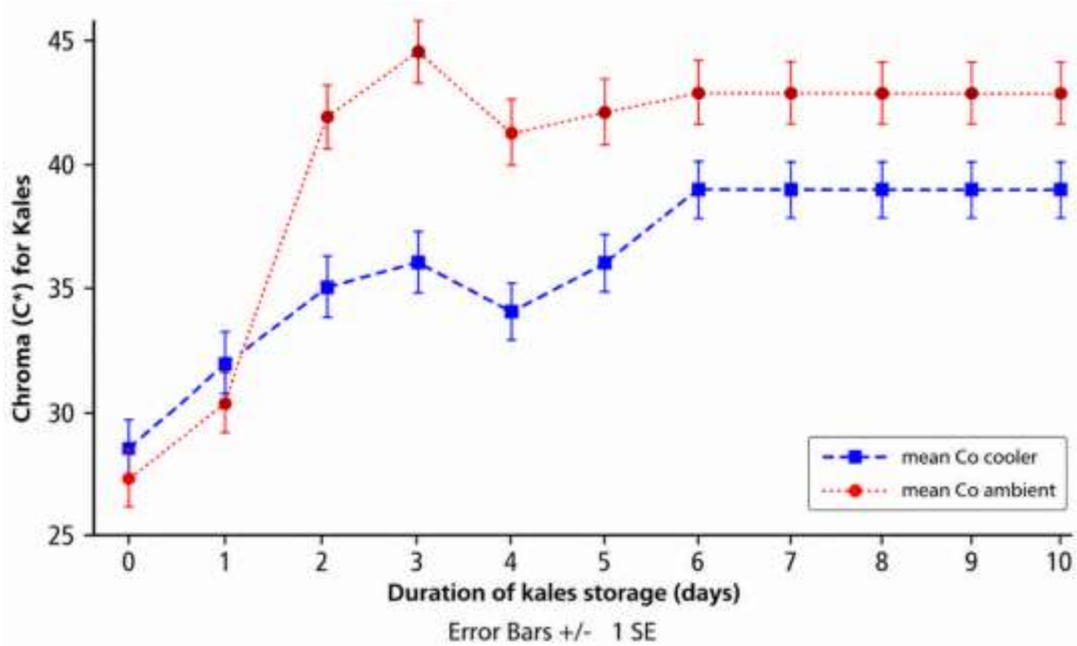

Figure 4.11: The Mean Chroma for Kales at the Cooler and at the Ambient Environment for ten Days. Error Bars are Means±SEM

Figure 4.11 shows that the chroma of kales was about 28.5 when the kales were harvested and increased to attain a maximum chroma of 45.2 and 39.1 for kales stored in the ambient and cooler environment respectively. After the day 6, the chroma of kales remained constant 39 and 42.5 for kales stored in the cooler and in the ambient environment respectively (Figure 4.11).

A two-tail t-test of the data revealed no significant difference ($p>0.05$) in C* between kales that were stored in the evaporative cooler and those stored in the ambient environment. The overall mean C* of kales stored in the evaporative cooler and ambient conditions was 36.03±1.01 and 40.23±0.03, respectively. This demonstrates the fact that the evaporative cooler has minimal effect on chroma of kales.

4.3.5 Hue Angle (h^o) of Kales

Figure 4.12 shows changes in the mean hue angle (h^o) of kales with storage in the evaporative cooler and in the ambient environment.

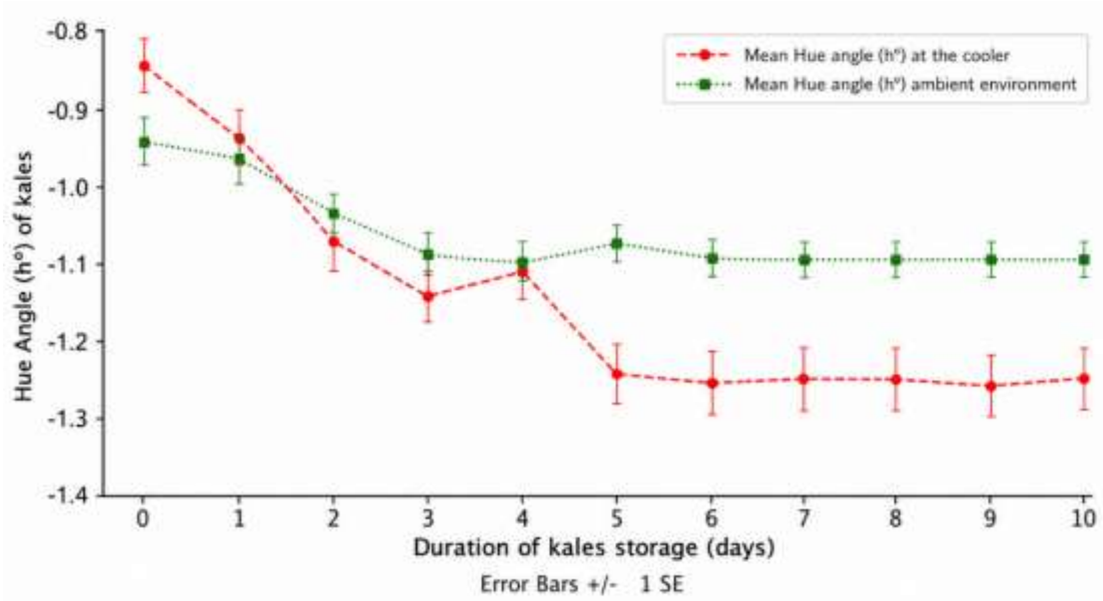

Figure 4.12: The Hue Angle of Kales at the Cooler and at the Ambient Environment Averaged Within Ten Days of Storage. Error Bars are Means±SEM

From figure 4.12, the h° showed a decrease in kale samples stored in the evaporative cooler and the ambient environment from -0.85 to -1.28 and -0.94 to -1.1 for kales stored in the cooler and the kales stored in the ambient environment respectively. Generally, the value of kale h° at the ambient environment was higher than the kale h° for the kales stored in the cooler during the storage. Lower hue angle depicts pure green colour while high hue angles represent degraded chlorophyl (red). This observation shows that the evaporative cooler preserved the green colour of the kales compared the ambient environment. However, a t-test (two tail) conducted to test the difference between mean h° for kale samples stored in the evaporative cooler and those in the ambient environment showed no significant difference ($p>0.05$). This shows that there was a comparatively marginal improvement by the evaporative cooler on the h° of kales. Generally, just as was the case with b* parameters, the evaporative cooler appeared to have a significant effect in maintaining the green colour of kales. Therefore, the evaporative cooler will potentially maintain the selling quality of kales leading to improved profits to farmers and kale vendors. It has been recorded that evaporative cooling reduces quality deterioration and help maintain colour and prolongs shelf life of leafy vegetables.

4.3.6 Total Colour Change (ΔE*) of Kales

Figure 4.13 shows the variation in total colour difference (ΔE*) for the kales stored in the evaporative cooler and in the ambient environment over the 10 days of storage. The mean values of (ΔE*) ranged between 38.1±1.02 to 8.1± 1.00 and 38.1± 1.12 to 27.5± 2.11 for the kales stored in the ambient environment and in the evaporative cooler, respectively. In both storage conditions, the value of (ΔE*) generally decreased. It is notable that the (ΔE*) decreased more rapidly for the kales stored in the ambient environment than the kales stored in the evaporative cooler.

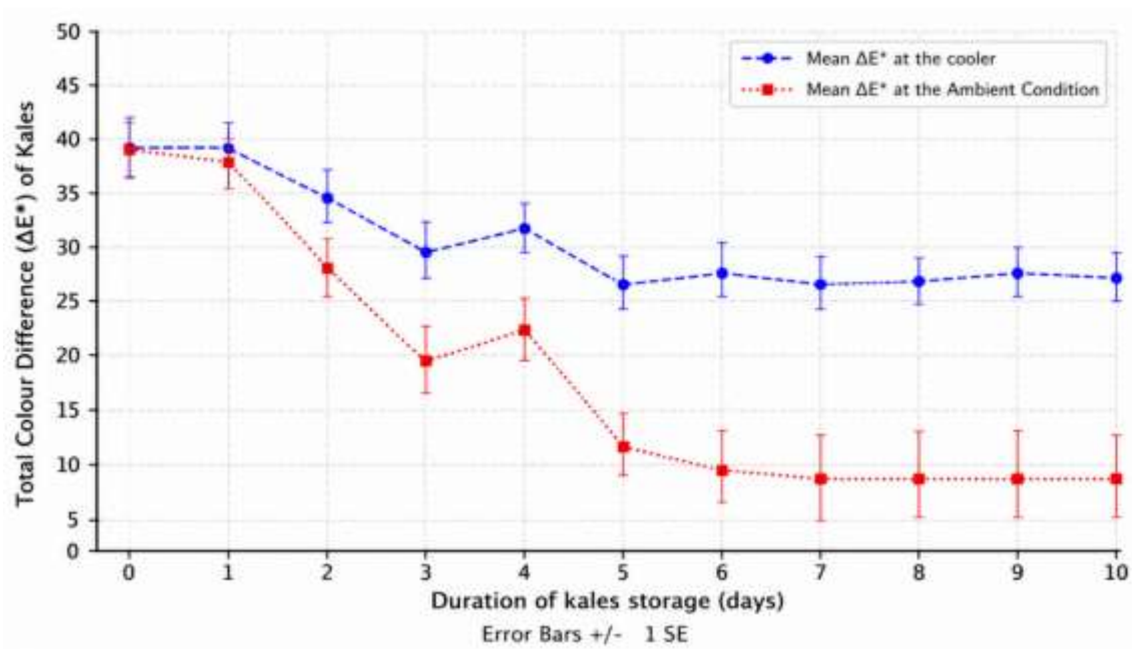

Figure 4.13: The Comparison of Colour Differences of Kales Stored in the Ambient and the Cooler Environments for Ten Days. Error Bars are Means±SEM

This observation suggests that the kales lost the green colour faster while being stored in the cooler as opposed to the case when stored in the ambient cooler.

A t-test of the ΔE* data resulted in a significant difference ($p \leq 0.05$) in ΔE* values between kales stored in the evaporative cooler and in the ambient environment. The overall mean of ΔE* was 30.41±0.31 and 18.41±0.31 for the kales stored in the evaporative cooler and in the ambient environment, respectively. It is apparent therefore, that kales stored in the ambient environment generally remained greener over a longer period compared to the kales stored in the cooler. The results show that the cooler was deficient in maintaining the original green colour, the results are backed up by result of the study by Ambuko et al. (2016) who found out that leafy vegetables has high colour change while stored in a poorly ventilated and oversaturated humid condition. The result in this study might have deviated from the expectation that the cooler would have lower change in kale colour compared with kales in the ambient environment. The implication of the results is that the cooler may not be ideal in maintaining kale colour. Gil and Garrido (2020) found a similar trend while studying leafy vegetables, when they exposed the leafy vegetables to humid environment for a long period, the vegetables showed faster yellowing than expected.

4.3.7 Kale Shelf-life

Table 4.3 shows the trend of subjective quality parameters of kales over 10 days of storage in the evaporative cooler and ambient environment. The subjective quality parameters observed during storage were rotten kales, spotted kales and yellow kales. In addition, the marketability was assessed based on level of kales senescence.

Table 4.3: The Progressive Subjective Quality of Kales during Storage

Quality Parameters	Days of Storage																			
	1		2		3		4		5		6		7		8		9		10	
	Cooler	Ambient	Cooler	Ambient	Cooler	Ambient	Cooler	Ambient	Cooler	Ambient	Cooler	Ambient	Cooler	Ambient	Cooler	Ambient	Cooler	Ambient	Cooler	Ambient
Rotten (n)	0±0.00	0±0.00	0±0.00	0±0.00	0±0.00	0.00	0±0.00	0±0.01	0±0.00	0±0.01	0±0.00	2±0.01	0±0.00	3±0.01	0±0.00	4±0.01	1±0.00	4±0.01	2±0.00	4.00
Spotted (n)	0±0.00	0±0.00	0±0.00	0±0.00	0±0.00	0.00	0±0.00	1±0.01	0±0.00	2±0.00	0±0.00	2±0.01	0±0.00	1±0.01	1±0.01	0±0.01	1±0.00	0±0.01	0±0.00	0±0.01
Yellow (n)	0±0.00	0±0.00	0±0.00	0±0.00	0±0.00	0.00	0±0.00	0±0.00	0±0.00	±0.00	0±0.00	0±0.01	0±0.00	0±0.01	0±0.00	0±0.01	0±0.00	0±0.01	0±0.00	0±0.01
Marketability (%)	100	100	100	100	100	100	100	75	100	50	100	0	100	0	75	0	50	0	0	0

All figures in the table are means±SEM

From table 4.3, all the samples under storage remained in marketable condition up to 3rd day in both for the kales stored in the ambient environment and evaporative cooler. To determine the marketability of the kales, the trends of defects (spotted, yellow and rotten leaves) were used as visual quality indicators because consumers use the same indicators to determine the freshness of the kales, However, the kales in the ambient environment deteriorated comparatively faster than in the evaporative cooler such that in the sixth day, kales in the ambient environment had 0% marketability.

The kales under storage in the evaporative cooler maintained 100% marketability condition up to the 7th day, while in 8th and 9th day the marketability was 75% and 50%, respectively. Therefore, the shelf-life of kales stored in the ambient environment and in the evaporative cooler was 5 days and 9 days, respectively. It has been reported by Gitau (2011) that on average, the shelf-life of cold room stored kales is 10 days while kales stored ambient environment is about 5 days. Ambuko et al. (2016) used the defects: rotting, wilting and yellowing as indicators which consumers use to reject kales. The results reported in this study show that there are less postharvest losses of the kales when stored in the evaporative cooler as compared to ambient storage, translating to higher profits to kale farmers and vendors.

4.4 Quality Characteristics of Tomatoes Stored in the Cooler while Operating Under Combination Cooling Mode

4.4.1 Cooler's environmental conditions during storage of tomatoes

Figure 4.14 and 4.15 show trends in the mean temperature and the relative humidity in the evaporative cooler and the ambient environment during storage of tomatoes averaged over 24hrs. In figure 4.14, the ambient temperature conditions are generally higher than the temperatures in the evaporative cooler. At 1400hrs (Figure 4.14), the temperature in ambient conditions had a mean of 10^{o}C higher than the temperatures in the cooler environment, with the maximum temperature in the ambient environment being approximately 31^{o}C. The temperature difference of 10^{o}C between the evaporative cooler and ambient conditions reported in this study, was lower than the temperature difference of 20^{o}C recorded by Jha (2008). This difference can be explained by the different environmental conditions where the two studies were conducted.

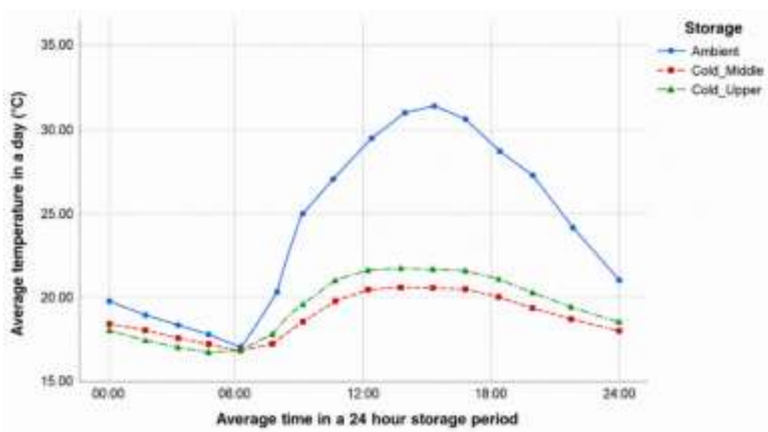

Figure 4.14: The Trend of Mean Temperature in the Ambient and Cooler Conditions over the Tomato Storage Period

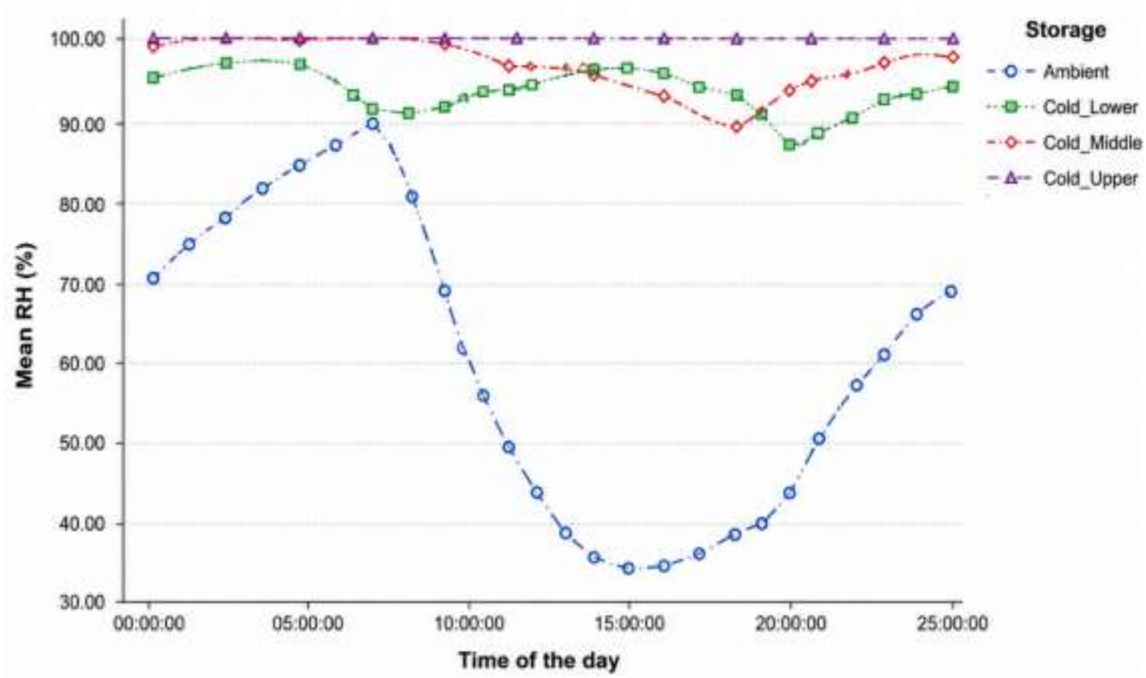

Figure 4.15: The Trend of Mean Relative Humidity in the Ambient and Cooler Conditions Over the Tomato Storage Period. Error Bars are Mean±SEM

The study by Jha (2008) was conducted at Delhi, India where the average temperature is higher than average temperature at JKUAT, the location where the present study was undertaken. When the ambient environment has low humidity and high temperature, evaporative coolers perform at its optimum level because the dry air has high affinity to absorb moisture on the wet cooler wall. High evaporation from the cooler wall lowers temperature from the cooler (due to phase change of moisture to vapor). The higher the difference between the wet bulb and dry bulk of the ambient air temperature the more efficient the cooling effect in the cooler (Kitinoja et al., 2011; Tejero-González & Franco-Salas, 2021).

The lowest ambient temperature during storage was 16^{o}C. The temperatures and relative humidity in the cooler are within the optimum conditions for storage of tomatoes and ranged from 18^{o}C to 21^{o}C and relative humidities of 90 to 95%. Storage temperature lower than 9^{o}C causes chilling injury and uneven ripening in tomatoes (Habibzadeh-Bigdarvish et al., 2019) Therefore, the evaporative cooler temperature conditions are suitable for storage of tomatoes.

In Figure 4.15, the relative humidity in the evaporative cooler was generally higher than the ambient environment. Under ambient conditions, the lowest relative humidity was recorded between 1200 hrs and 1400 hrs, this being at around the solar noon (Jones Jr & Burkhart, 1981; Sun et al., 2021) It is an expected phenomenon at the equatorial region. On the other hand, the relative humidity in the evaporative cooler was between 90 % and 100 % during the storage period. The highest relative humidity in the cooler was attained between 1300hrs and 1400hrs.

Figures 4.16 and 4.17 show the mean daily temperatures and humidity averaged over the 24-hour storage over the 28-day storage period, respectively.

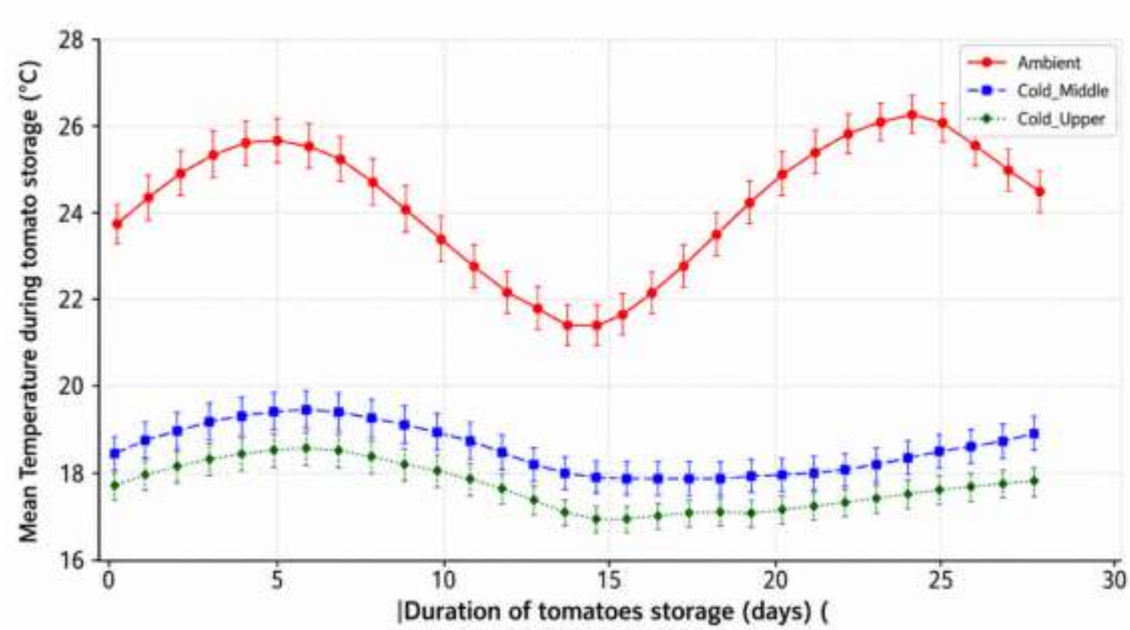

Figure 4.16: Mean Daily Temperatures Averaged over the 28 Days Storage Tomatoes Storage Period. Error Bars are Means ±SEM

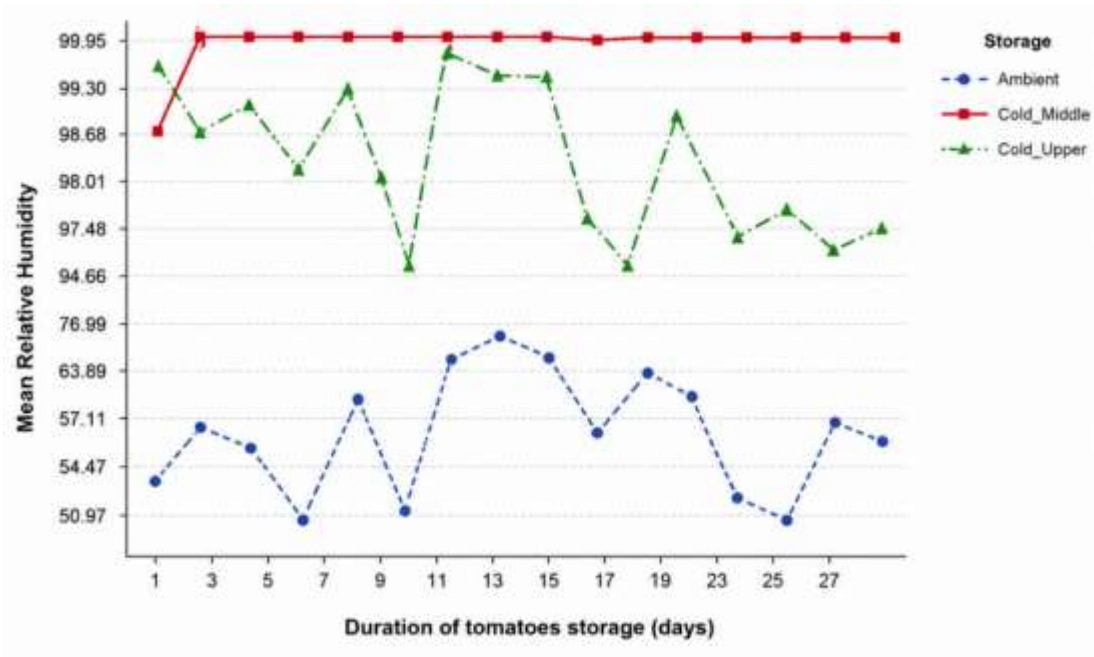

Figure 4.17: Mean Daily Relative Humidity Averaged over the 24-Hour Storage Period during the Storage of Tomatoes

It was observed from Fig. 4.16 that temperatures in the evaporative cooler ranged from 16.1ºC to 21.2ºC during the 28 days of storage. The temperatures reported in the cooler are suitable for storage of fresh tomatoes and in agreement with those established by Cantwell (2000), where it was demonstrated that a mean temperature of 17.5ºC is optimal not only for ripening and colour development, but also for tomato storage because they result in firm tomatoes with good red colour. The temperature in the ambient environment ranged between 21ºC and 25ºCand had a mean of 22.5±1.2ºC. The intersection of the cold middle and the cold upper in figure 4.16 might have been caused by through mixing of air by the forced air fan, this reduced and eliminated the vertical temperature gradients.

The maximum temperature drop (10ºC) was recorded on the 11th day (Figure 4.16). For the ambient conditions, the lowest temperatures occurred on 14th, 15th and 16th day. The maximum ambient temperature was observed on 11th day. It is also well documented in the literature that a temperature below 10 ^{o}C causes chilling to tomatoes (Cantwell, 2000), a phenomenon that was not observed in the evaporative cooler. The mean temperature reported in this study for the ambient environment is unsuitable for storage of tomatoes, as Cantwell (2000) reported that storage temperatures of 25 ^{o}C and above result into poor ripening, as it results in tomatoes that are soft and poorly coloured. In addition, such high temperatures hinder ethylene production, a bio-hormone required for synthesis and accumulation of lycopene in fresh tomatoes (Cantwell et al., 2009). The developed evaporative cooler tested in this study, established a colder temperature compared to that reported by Jha (2008), who, using river sand as the evaporative media, got an average temperature of 23 ^{o}C. The variation between the average cooler temperature (18.65 ^{o}C) in this study compared to the results by (Jha, 2008) which was 23 ^{o}C may be due to differences in environmental conditions or the evaporative material used. The results obtained in this study (high relative humidity) show that the evaporative cooler is appropriate for storage of tomatoes as it will result in extended shelf life and improved income to tomato farmers and vendors.

In Figure 4.17, it is apparent that the relative humidity of the evaporative cooler was higher than the relative humidity of the ambient environment. The relative humidity reported in this study is within the range of optimum storage for tomatoes which is above 92% according to Chilson et al. (2011a). Chilson et al. (2011b) reported that a relative humidity of 92% and above was best for the overall tomato quality in terms of fruit colour, freshness, firmness, decay and shrivelling as a relative humidity above 88% tend to be lower red colour development compared to those above 88%. Nunes et al. (2012) also recorded that firmness of pepper (Cv. Revolution) decreased as the pepper was subjected to a relative humidity of 40% to 95%. The coherence in the findings with the optimum tomatoes storage condition is an indication that the cooler has relative humidity conditions for tomato storage. Jha (2008) in the study that used river sand as a cooling media found the relative humidity to be 85% in the cooler chamber. The difference in relative humidity in this study and the finding by Jha (2008) might be attributed to differences in the evaporative material used and the incorporation of a roof pond in the current evaporative cooler. The evaporative cooler in this study appears to be the ideal for the storage of tomatoes.

A MANOVA of the data showed a significantly ($p \leq 0.05$) difference in the relative humidity between the cooler (higher) compared with the ambient environment condition (lower). Similarly, temperatures in the ambient environment were significantly ($p \leq 0.05$) higher than those in the cooler conditions. This effect is attributable to the cooling effect of evaporative systems where latent heat of vaporization is absorbed as water in the cooler walls evaporates reducing air temperature while increasing moisture content. These findings are consistent with established principles by the Defraeye et al. (2023) which recorded that evaporative cooling systems can highly lower air temperature while raising relative humidity, thereby improving storage conditions for fruits and vegetables. Similarly, Yeneneh and Walle (2025) highlighted that evaporative coolers create environments with higher relative humidity and lower temperatures and compared to ambient air, and in so doing enhances the storage life vegetables and fruits.

There was a significant ($p \leq 0.05$) two-way interaction between the storage environment and days of storage. This means that as storage condition depended on the duration of storage. Separation of means using LSD tests showed that, the relative humidity within the cooler chamber differed significantly ($p \leq 0.05$) in relation to vertical levels, a similar relationship was observed for temperatures recorded by sensors at the middle and upper part of the cooler. The present study also showed that the temperature at the middle (100cm from the cooler floor) of the cooler was significantly ($p \leq 0.05$) lower than the temperature at the upper part of the cooler chamber. Similarly, the relative humidity at the middle of the cooler was significantly ($p \leq 0.05$) lower than the relative humidity at the upper part of the cooler. Although scientifically, warm air is lighter than cold air, and hence the upper chamber is expected to be at a higher temperature than the lower part of the cooler. The middle may be cooler (closer to shaded pumice and bulk air from the reservoir at the base of the cooler may have caused the unexpected results. In addition, at the chimney of the cooler (upper part area), the air from the ambient environment may have mixed with the moist air from the cooler raising the temperature at the top of the cooler. The roof-pond surface which by design is cooled by evaporation, but if the pond is exposed to sun for a long period, surface water may be warmer especially during daytime and by so doing increase the temperature at the upper part of the cooler in relation to the middle part of the cooler. There was no significant ($p>0.05$) difference in ambient environmental conditions (temperature and relative humidity) over the storage period. This was expected because the experiments were conducted on the same period with not much deviation in weather conditions. From the statistical analysis, the cooler had significantly ($p\leq0.05$) better temperature and relative humidity conditions compared to the ambient environment. As expected, the temperature in the cooler was generally lower that the temperature in the ambient conditions while the relative humidity inside the cooler was higher than the relative humidity of the ambient conditions. These results agree with Sow et al. (2020) who reported that evaporative coolers significantly increases relative humidity and reduces temperature of the cooler chambers. The results of the current study also show that the incorporated roof-pond to the evaporative cooler seems to further improve the storage conditions of the evaporative cooler and to be ideal for storage of tomatoes potentially leading to increased shelf life and improved profits to fresh tomato farmers and vendors.

4.4.2 Changes in Tomato fruit Quality Attributes during Storage

4.4.2.1 pH of Tomatoes

Figure 4.18 shows the mean pH of tomatoes stored for 28 days in the evaporative cooler and in the ambient environment. From Figure 4.18, the pH of fresh tomatoes stored in the ambient environment was generally higher than the pH of fruit stored in the evaporative cooler.

Tomato fruit pH decreased in the first 7 days and then increased to the 21^{st} day, after which the pH in the cooler decreased while the pH of the tomatoes in the ambient environment further increased to a pH of about 4.4 (Figure 4.18).

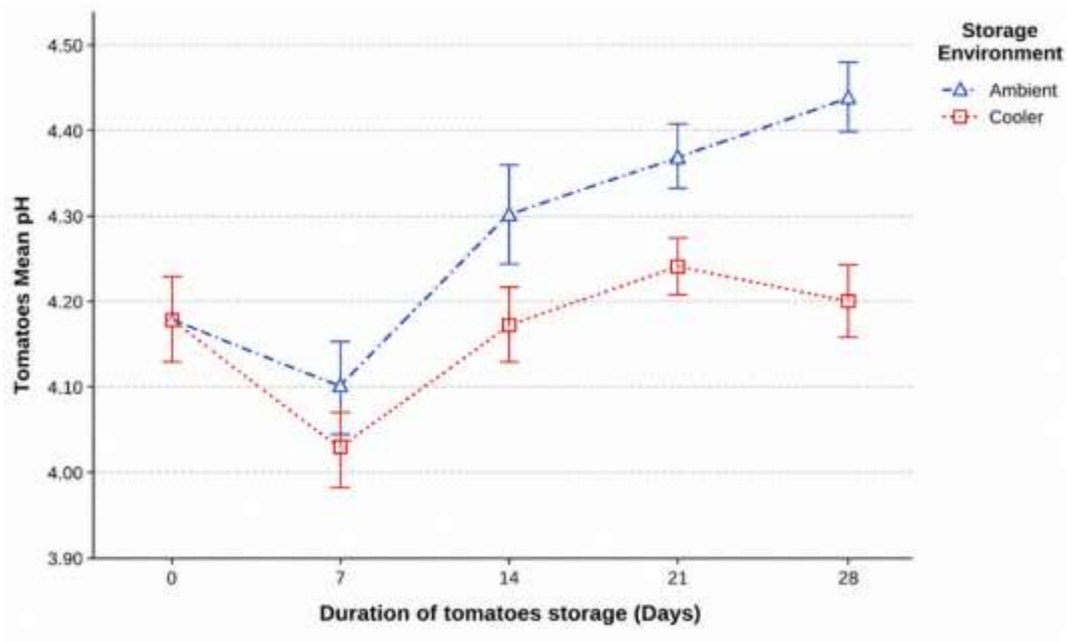

Figure 4.18: The Mean pH Values for Tomatoes Stored in the Cooler and in the Ambient Environment. Error Bars are Means±SEM

The tomatoes stored in the evaporative cooler maintained a lower pH compared to the tomatoes in the ambient environment. Low pH in tomatoes is highly preferred during processing of tomatoes (Tigist et al., 2013). Tomato fruit pH values that are higher than 4.4 encourage microbial growth in processed tomatoes (Abbott, 1999; Arah, Kumah, et al., 2015; Mundt & Norman, 1982). In fresh tomatoes higher pH signals deterioration and senescence conditions which correlated with lower shelf life and poorer flavour (Cherono et al., 2018a). The pH of tomatoes in the present study was remained at a level lower than 4.3 and may be considered as an ideal storage for tomatoes to be processed. The tomatoes at lower pH are appropriate for canned tomatoes leading to longevity of storage and hence increased profitability. PH of fresh tomato pH is determined by a balance between sugars and acids (mainly citric and malic acids). As tomato fruit ripen during storage there are dynamic metabolic changes where organic acids are synthesised and respired and by so doing their concentration changes in relation soluble solids (Etienne et al., 2013; Tang et al., 2020). The high temperatures at storage leads to increase in metabolism and respiration which increases the pH of stored tomatoes while low temperature slows down the metabolism and by so doing maintains the pH of tomatoes (Thole et al., 2021). High relative humidity in the cooler maintains the turbidity of the tissues and reduces the process that change acid levels. Water loss can change the concentration of solutes and hence alter pH (El-Mesery et al., 2024). Anthon et al. (2011) reported that daily increase in tomatoes pH is about 0.01 to 002 while under storage. Aykas et al. (2020) reported that the pH of tomatoes range of tomato pH to be 4.0 to 4.6, while in the study at hand reported a range of 4.05 to 4.22 (in the cooler) and 4.10 to 4.42 (in the ambient storage). The results of the current study is withing the ranges reported by (Aykas et al., 2020). Tigist et al. (2013) reported a pH of 4.0 to 4.5. The results of the current study is within the ranges reported by Tigist et al. (2013) and (Aykas et al., 2020). The variation in pH may be caused by variety and level of maturity (Tigist et al., 2013). Gonçalves et al. (2020) Reported a pH value of 4.02 to 4.63 after storing tomatoes for 21 days. The results of the current study is within the ranges reported by Aykas et al. (2020), Tigist et al. (2013) and (Gonçalves et al., 2020). Variation in pH may be caused by variety and level of maturity (Tigist et al., 2013).

4.4.2.2 Total Soluble Solids (TSS) of Tomatoes

Figure 4.19 shows changes in the total soluble solids (TSS) content of tomatoes stored in the evaporative cooler and in the ambient environment over a 28-day storage period. Generally, the TSS of the tomatoes in the ambient environment was higher that the TSS of the tomatoes stored in the cooler. TSS compared with the ambient condition. The delayed ripening of tomatoes in the cooler is beneficial for tomato storage because it means a prolonged shelf life and increased profit for tomato farmers and vendors. Figure 4.19 shows that the error bars have a lot of overlaps implying that the difference in TSS between cooler and ambient environments is statistically not significant. One way

ANOVA confirmed that, there is no significant (p>0.05) difference between TSS for the tomatoes stored in the cooler and the tomatoes stored in the ambient environment.

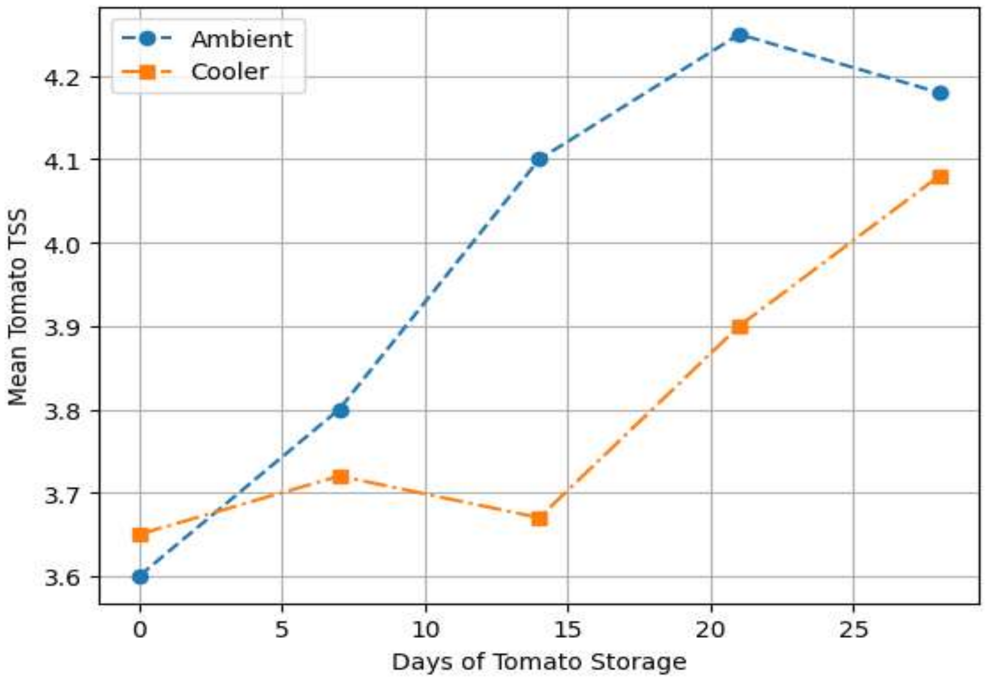

Figure 4.19: The Mean Total Soluble Solid (TSS) for Tomatoes Stored in the Cooler and at the Ambient Condition. Error Bars are Means±SEM

Similar to the study at hand, Christodoulou et al. (2025) found out that TSS of tomatoes in the cooler and at the ambient environment significantly increased between 3rd and 7th while at 7th to 10th day the TSS decreased and on 10th to 14th day TSS increased again before declining to the end of storage. According to Li et al. (2025) contrary to the study at hand TSS of tomatoes in cooler were significantly higher that for the tomatoes stored in temperatures above 24°C. Similar to the study at hand, (Arah, Amaglo, et al., 2015) reported that tomatoes stored in the ambient condition can lose water and concentrate sugars leading to increase in TSS.

4.4.2.3 Firmness of Tomatoes

Figure 4.20 shows changes in the firmness of tomatoes stored in the evaporative cooler and in the ambient environment. Figure 4.20 shows changes in the firmness of tomatoes stored in the evaporative cooler and in the ambient environment. Generally, throughout the study period, the tomatoes stored in the cooler remained firmer than the tomatoes stored in the ambient environment. In addition, both categories of tomatoes registered a continuous decrease in firmness as storage period progressed. During the study, the mean firmness of tomatoes in the ambient condition reduced from 3.20 kg/cm^2 to near 0 kg/cm^2, while the mean firmness of tomatoes in the cooler decreased from 3.20 kg/cm^2 to about 0.2 kg/cm^2 (Appendix IV). The largest difference in firmness between tomatoes stored under ambient environment and the evaporative cooler was about 1.1 kg/cm^2 registered on the 7th day of storage.

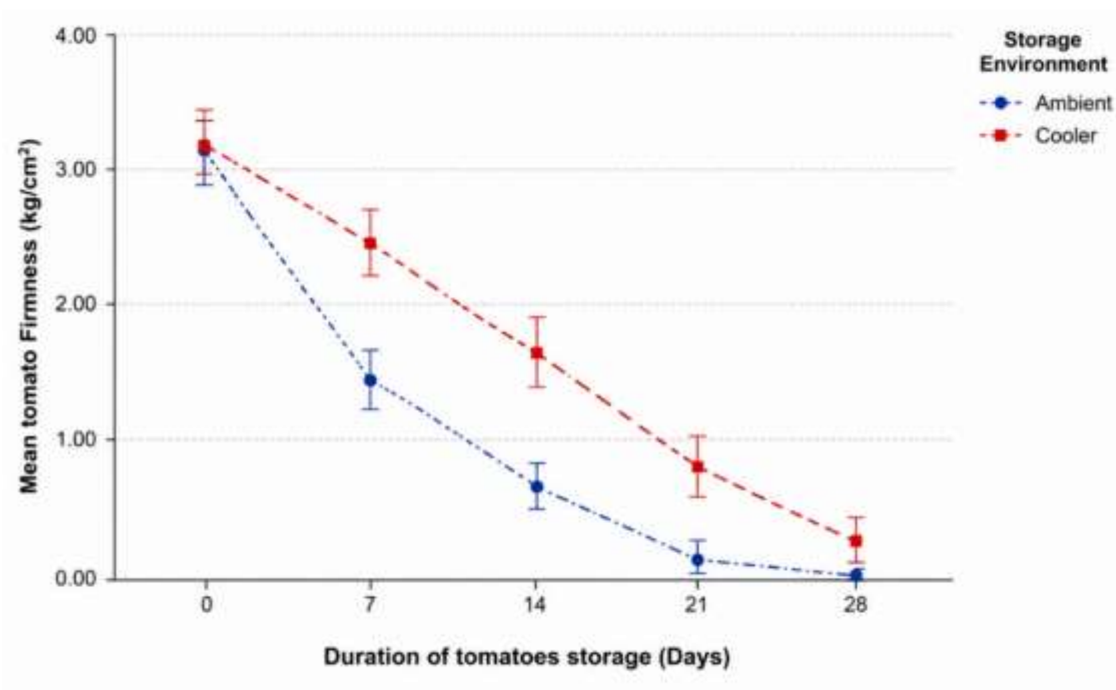

Figure 4.20: The Mean Firmness of Tomatoes Stored in the Ambient Environment and in the Evaporative Cooler. Error Bars are Means±SEM

Since consumers check freshness of tomatoes by touching and pressing, it is apparent from the findings of this study that the tomatoes stored in the evaporative cooler will comparatively be more appealing to the consumers over a long period of time compared to the tomatoes stored in the ambient environment resulting into higher profits for tomato vendors (Gormley & Egan, 1978; Mugwaneza et al., 2024). The results of the study are in agreement with Chilson et al. (2011a) who recorded that tomatoes stored in higher humidity (88% to 92%) maintained higher firmness compared with tomatoes stored in lower relative humidity. These results shows that the storage of tomatoes in the evaporative cooler results in tomatoes which are firm and appealing to buyers and hence sellers will potentially make higher profits.

4.4.2.4 Tomato Fruit Hue Angle

Figure 4.21 shows changes in the hue angle of tomatoes stored in the ambient environment and in the evaporative cooler. Hue angle measures colour of agricultural products where angle of 270^0 is associated with blue colour, 180^o is for green, 90^o is assigned to yellow and 0^o is assigned to red.

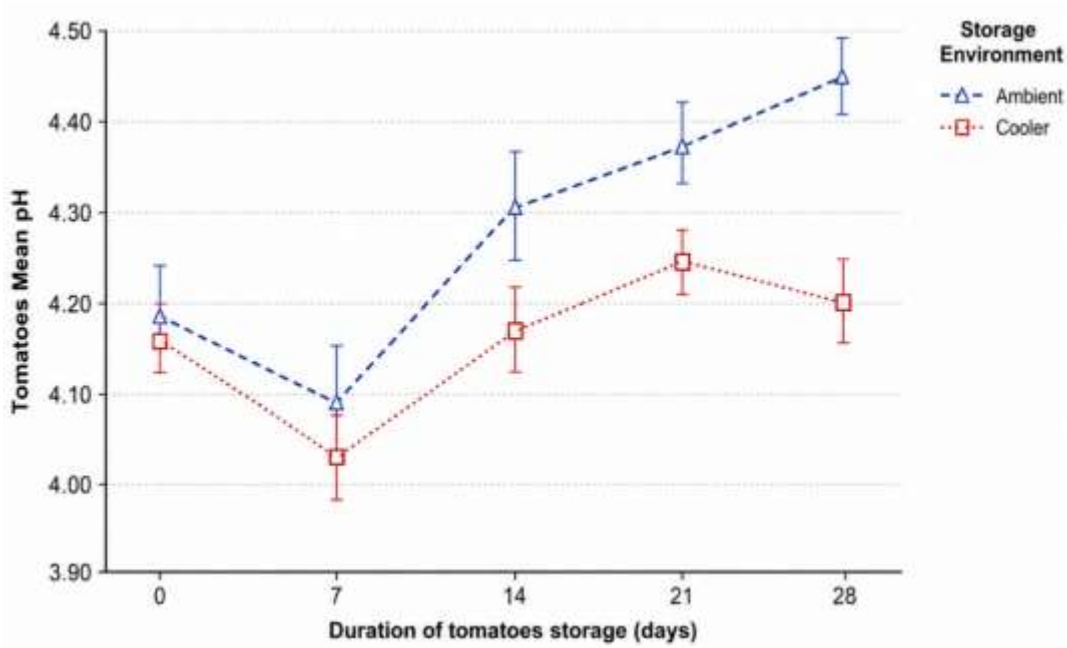

Figure 4.21: The Mean Hue Angle of Tomatoes stored in the Ambient Environment and Evaporative Cooler. Error Bars Designate Mean±SEM

This shows the process of ripening from green to red. It is apparent from figure 4.20 that tomatoes stored in the evaporative cooler were greener and took longer to fully ripen to reach a red colour (designated by a hue angle of 0^o. This is in relation to the colour change as described by Carrillo-López and Yahia (2014) that colour of tomatoes can be classified in to six stages: green, breaker, turning, pink, light red and deep red). Throughout the experimental period, the hue angle decreased to 10^0 in both the tomatoes stored in the cooler and in the ambient environment. The largest difference in hue angle (about 30) was observed between the 7^{th} day and the 14^{th} day of storage. There was no significant difference (p>0.05) between the hue angle values of tomatoes stored in the ambient storage and the evaporative cooler. The slight difference in the hue angle value between the ambient environment and the evaporative cooler can be associated with the high temperature in ambient environment which is associated with increased bioreaction in the stored tomatoes Cherono et al. (2018b, 2018c). The results agree with those reported by Chilson et al. (2011b) who demonstrated that tomato hue angle (h) was not a significant factor when the tomatoes are stored at a the relative humidity of 41% to 88% and a constant temperature of 15^0C. The comparatively low colour change in tomatoes stored in the cooler is an indication of preservation colour and the overall quality of fruit resulting in improved consumer appeal and profits from these tomatoes.

4.4.2.5 Tomato Subjective Quality Characteristics

Table 4.4 shows the trend of the visual subjective quality parameters of tomatoes during storage. From Table 4.4, the number of shrunk tomatoes, decayed tomatoes and overripe tomatoes duration the storage of tomatoes.

Table 4.4: The Progressive Subjective Quality of Tomatoes during Storage

Subjective quality parameters	Day 0		Day 7		Day 14		Day 21		Day 28	
	Cooler	Ambient	Cooler	Ambient	Cooler	Ambient	Cooler	Ambient	Cooler	Ambient
Decayed samples (n=40)	0±0.00	0±0.00	0±0.00	0±0.00	0±0.00	4.25±0.25	4.25±0.48	14.25±0.47	7.25±0.25	11±1.08
Shrunk samples (n=40)	0±0.00	0±0.00	0±0.00	2±0.41	8±1.47	12±0.41	6.25±0.25	13±0.41	7.75±0.75	13±0.41
Overripe samples (n=40)	0±0.00	0±0.00	0±0.00	4.5±0.50	2±3.56	5.75±0.85	12±0.41	17.5±1.19	30.25±0.25	15.75±1.60
Marketability (%)	100.0±0	100.00±0.0	100.0±0.0	91.45±0.84	85.07±3.56	69.44±0.77	66.91±0.40	34.19±0.93	41.80±2.03	6.9±2.12

From table 4.4, the tomatoes in the ambient environment started showing signs of shrinkage on the 7th day while the tomatoes in the cooler started shrinking on the 14th day. The quality deterioration increased further on the 21st and 28th day. On the 28th day, the average marketability was 41.8% and 6.9% for the tomatoes stored in the evaporative cooler and ambient conditions, respectively. The results show that the evaporative cooler maintains tomatoes' marketable quality longer compared with the ambient condition storage. The cooler increased the shelf life of tomatoes from 14 days to 28 days. The shelf life is determined by the duration when 40% of the fruits are in marketable condition.

These results agree with the report which showed that the effect of evaporative cooler increased the shelf life of amaranths from 3 to 9 days (Ronoh et al., 2010). The storage conditions provided by the evaporative cooler potentially results to less post-harvest loss and hence improved profits to farmers and tomato fruit vendors.

4.5 Determination of the Cost-Benefit Analysis (CBA) when the Cooler is used for the Preservation of Kales and Tomatoes

This section describes the cost–benefit analysis of the cooler, which is a determinant of the economic viability of the cooler. The section also gives an analysis of the key financial indicators which are Internal Rate of Return (IRR), payback period (PBP) and accounting rate of return (ARR), which are important in confirming the reliability of the calculated figures. The four analyses provide a detailed measure of profitability and the time required to get back the initial investment of the cooler, in addition, the cost-benefit analysis incorporates various cost components like installation costs, maintenance, operational expenses and capital costs. The benefits considered are reduced postharvest losses, higher market prices, increased revenue and prolonged shelf-life as shown in table 4.5. The method of determining the CBA is borrowed from (Hayes, 2001) who described the 5 steps determination of CBA which includes determination of project scope, determining costs, determining benefits, determination of CBA and finally deciding on whether to implement the project or not. The financial analyses together with the costs and benefit analysis offer a balanced assessment of the cooler's financial worth and gives an indication its potential in improving post-harvest management.

4.5.1 Components of the Benefits Accrued from Storage of Kales and Tomatoes in the Cooler

The size of the cooler in this study was 2m^3, leaving space for the pump that occupied 0.0142 m3 and leaving clearance between crop crates for air circulation. The remaining space for crop storage is 1.958 m^3 which is based on the density of kales which is 120 kg/m^3 according to Samson et al. (2001) while the density of tomatoes is ranges between 810kg/m^3 and 1070kg/m^3 (Ilori & Raji, 2013). For the sake of this study and the calculations of CBA, the density of tomatoes is taken to be 1000 kg/m³. Using the above stated densities and the stated volume of cooler's storage space, the cooler can store 1958 kg of tomatoes and 234.96 kg of kales. Since tomatoes are stored for 28 days and kales are stored for 10 days, it means that tomatoes will have 13 (365 days/28 days) batches and kales will have 36.5 (365 days/10 days) batches per annum which results to 8576.04 kg (13x1958) and 25454 kg (36.5 x 234.96) of kales and tomatoes respectively. The prices of kales and tomatoes in Nairobi are taken to be 261.54 KES and 280.56 KES respectively. Table 4.4 shows the vegetables stored in an ambient environment annually. For ease of comparison, the amount stored in the evaporative cooler and in the ambient environment was assumed to be equal. The volume of the crop that can be stored in the cooler is 1.958 m³. Table 4.4 shows the annual amounts in kilograms(kg) and the annual income in Kenya shillings (KES) as proceeds from sale of tomatoes and kales. The calculations of the amount of kales and tomatoes stored in a year are calculated using equation 4.1.

$$\text{Kales stored in the cooler per annum} = \text{Volume of the cooler X kale density x batches per year} \quad (4.1)$$

$$\text{Amount of kale } stored \text{ per annum } = 1.958m^3\ X\ 120\,\frac{\text{kg}}{\text{m}^3}\text{x}36.5 \text{ batches}$$

$$\text{Amount kales stored per annum} = 8{,}576.04kg$$

$$\text{Tomatoes stored per annum} = \text{Volume of the cooler X tomatoes density x batches(per annum)}$$

$$\text{Tomatoes stored per annum} = 1.958\text{m}^3 \text{ X } 1000\,\frac{\text{kg}}{\text{m}^3}\text{x}13 \text{ batches}$$

$$\text{Tomatoes stored per annum} = 25{,}454.00\text{kg}$$

Table 4.5 shows both the cost of purchasing kales and tomatoes and the profit made after selling them.

Table 4.5: Cost of Purchasing Kales and Tomatoes and the Profit Made After Selling

Crop	Amount stored per month (kg)	Amount stored per annum (kg)	Price of vegetables per kg (KES)[1]	Annual income (assuming 5% loss)	Buying price (per kg)	Cost of vegetable purchase per annum (assuming 5% loss)	Net income per annum (KES)
Kales	234.96	8,576.04	280.56	2,285,789.09	100.00	857,604.00	1,428,185.09
Tomatoes	1,985.00	25,454.00	261.54	6,324,377.20	100.00	2,545,400.00	3,536,388.66

Table 4.6 shows the calculated net income from kales and tomatoes as 1,428,185.09 KES and 3,536,388.66 KES.

Table 4.6: A Comparison of Annual Income from Kales and Tomatoes Stored in the Cooler and in the Ambient Environment

Crop	Net annual income (KES) from kales and tomatoes vegetables stored in the cooler at 6% loss2 .	Net annual income (KES) from vegetables stored in the ambient environment (50% loss[2])
Kales	1,428,185.09	799,783.65
Tomatoes	3,536,388.66	1,980,377,65

[1] Agri market review, featuring Nairobi and Mombasa markets, as of April 2025

[2] Jain, D. (2007). Development and testing of two-stage evaporative cooler. *Building and Environment*, *42*(7), 2549-2554

The total net income from kales and tomatoes stored in ambient environment storage was 714,092.55 KES and 1,768,194.33 KES respectively. This shows that the net income from cooler storage was 50% higher than the income from ambient storage.

4.5.2 Monetized Environmental Benefits of the Cooler

Table 4.6 shows the monetized benefits of the evaporative cooler while storing kales and tomatoes, (Goodwin, 2023) described the environmental saving which takes place when post-harvest loss is prevented Methane production is reduced as well as reduction of the cost of handling wastes. When kales and tomatoes are prevented from rotting by the evaporative cooler, there is reduction of methane gas production which is produced during anaerobic decomposition. Methane, being a greenhouse gas has the potential of causing global warming. Through extension of shelf-life of the kales and tomatoes, the cooler contributes in mitigating climate change. According to Robertson and Waite (2021) decomposition of tomatoes and kales produce 2.49 kg CO_2equivalent per kg of waste tomatoes and kales. Table 4.4 shows the total vegetables stored in the cooler per year, 8,576.04 kg and 25,454.00 kg for kales and tomatoes respectively. According Jain (2007), half of the crop goes to waste if the cooler is not used, therefore the cooler saves half of the crop from waste amounting to 4,288.02 kg and 12,727 kg of kales and tomatoes respectively. Every kilo gram of decayed (wasted) kales or tomatoes produces 2.94 kg of methane (Howarth, 2024). Table 4.7 shows the benefits of using the cooler because it reduced production of methane as well as reducing the cost of handling wastes (Howarth, 2024).

Table 4.7: Monetized Environmental Benefits of the Evaporative Cooler while Storing Tomatoes

Benefit	Amount of waste and methane reduced while using the cooler		Benefit of the cooler/ annum ($1=126KES)	
	Tomato storage	Kale storage	Tomato storage	Kale storage
Reduced methane emissions (carbon value)	12,727kg x 2.49=31,690.23kg =31.69 tons	4,288.02x2.49=10677.16kg =10.677tons	31.690 tons x $1,163= $1267.60 = 15,9717.60 KES	10.67872x$1,163= $427.08 53812.08 KES
Reduced food waste disposal costs (4000 KES/ton of waste)	31.6931.tons	10.677 tons	31.69 tons X 4000 KES= 126,760.00 KES	10.677 tons x 4000 KES= 42,708.00 KES

A modelling study by Colbert et al. (2020) estimated the social cost of a ton of methane (CH_4) approximately $1,163 for each ton of methane. The cost of handling waste is 4000 KES per ton[3]

[3] 404 Nairobi Online 0770029959 › Professional Services in Nairobi & Kenya - Professional Services in Nairobi & Kenya

4.5.3 The Investment, Operation and Maintenance Cost of the Cooler

Table 4.8 is the tabulated investment cost of the cooler, with a comprehensive description of the cost of the cooler.

Table 4.8: Cost of investment, Maintenance Cost and the Operation Cost of the Evaporative Cooler

Item	Cost (USD/KES)
Cooler fabrication and tank metallic stand materials (2m^3)	75,000.00
Labor for cooler fabrication	30,000.00
Two 12 VDC, 0.22 kW Solar pump	11,050.00
Two Solar panels (550W)	20,000.00
Two 12V motor fans	2,400.00
Two trays of 500mm x 200mm x 100mm (high).	980.00
One padlock (tri-circle 65)	400
PPR Pipes ½’’	550
One solar charge controller (12V,10A)	1,500.00
Making reservoir of the cooler (300mmX1000mm)	4,680.00
Amount of pumice (one ton)	3,000.00
Plastic roto tank (2000 liters)	19,000.00
Two 12V batteries	8,000.00
Total cost of investment (installation)	176,560.00
Cost of maintenance (5% of cost of investment)[4] per annum	9,078.00
Salary of cooler operator per annum (13,069.80[5] x 12)	156,837.60
Total	342,475.60

[4] Ndukvu, M., & Manuwa, S. (2015). Impact of evaporative cooling preservation on the shelf life of fruits and vegetable in South Western Nigeria. *Research in Agricultural Engineering*, *61*(3), 122-128. 5% x 176,560=9,078.00
[5] Kenya Gazette in October 2024

The table also shows the initial capital expenditure as well as the maintenance cost of the cooler which entails servicing, repair and preplacement of materials which are consumable like pads, pumps and fans. Operation costs are detailed as costs of electricity, water and labor. Table 4.8 shows the complete view of the financial requirements in construction of the cooler, maintenance and cost of running the cooler hence forming the bases for the establishment of the cost benefit analysis. From table 4.8, the cost of investment which includes the fabrication cost and environmental controls was estimated to be KES 176,560.00. The cost of maintenance is 5% of the investment which was calculated to be KES 9,078.00 (Ndukwu & Manuwa, 2015). The maintenance cost of the evaporative cooler involved estimating the monthly maintenance cost from repair and replacement of all parts that are inspected for damage and wear. Kapilan et al. (2023) also reported that evaporative coolers use substantially less energy compared to energy used by refrigerated systems including air conditioners. The operation cost of the evaporative cooler was calculated based on the water used, where the 2000 litres tank ran the cooler for 7 days because it was recirculated back to the tank after use. This translates to 8000 litres ($8m^3$) per month, therefore, annually the evaporative cooler uses $92m^3$ (8 x 11.5) where 15 days are set aside for maintenance of the cooler. ie servicing should be done once a monthly which translate to half a month per year. The operating expenses per year was KES 156,837.60 (table 4.7). The operating expenses was based on the wages of cooler attendant (based on labour institution act) Other operating costs includes water consumed (table 4.9), routine maintenance, business license and repairs whose costs are also considered. The cooler attendant is required daily to ascertain the flow of water and the functioning of the accessories like fans, pumps and refill the roof pond water if need be. The estimated wages of attendant per day was KES 411, (KES 8,109.90 per month and KES 75.95 per hour). This is based on labour institutions act, legal notice No. 125 of 2022 (for wages in areas which are neither cities nor municipalities). Considering the update by the president of Kenya H.E Dr. William Ruto and published in the Kenya Gazette in October 2024 he announced an implementing of a 6% increase in salary effective from 1st November 2024. So, the monthly salary was KES 13,069.80 (considering that the attendant will work for the whole month).

Table 4.9 shows the water rates (tariffs) according to RUJWASCO (Thika water and sewerage company limited). The evaporative cooler in this study used 8m^3 of water per month.

Table 4.9: Domestic and Residential Water and Sewer Tariff for RUJWASCO (Government of Kenya, 2024)

Water Monthly Consumption (m^3)	Water cost (Tariff) in KES/ m^3	Sewer Tariff (KES/m^3)	Total cost (KES)	Annual cost of water (KES)
1–6	104.00	55.00	159.00	1,908.00
7–20	110.00	64.00	174.00	2,088.00
21–50	130.00	72.00	202.00	2,424.00
51–100	150.00	78.00	228.00	2,736.00
101–300	155.00	84.00	239.00	2,868.00
Above 300	170.00	89.00	269.00	3,228.00

From table 4.9, the cost of water per month is 174.00 KES and hence per year it is 2,088.00 KES. Amount of water used per month is 8m^3, therefore, the cost of water for running the cooler per year 2088.00 x 8= 16,704KES. The cost of water for operating the cooler appears relatively low, from the point of view of the CBA, the low water consumption enhances the suitability of the cooler even in areas with water scarcity.

4.5.4 Rent, Legal and Regulatory Costs of Running the Cooler

During the process of running the evaporative cooler, there are expected legal, rent and regulatory costs that are incurred because it is assumed that the cooler will be placed at a suburban (Juja town). The major costs are described in table 4.6, based on WASREB (water services regulatory board) report and report by Wanjohi (2024).

Table 4.10 and 4.11 shows a compilation of all the costs and benefits associated with running the evaporative cooler for the storage of kales and tomatoes, respectively

Table 4.10: Cost and Benefits Associated with the Application of the Evaporative Cooler for Kale Storage

Costs and benefits	Annual cost (KES)[6]	Net benefits of using cooler (KES)	Net benefits of using ambient environment (KES)
Net income from kale in storage		1,428,185.09	799,783.65
Rent for Business Premises	120,000		
Single Business Permit-small trader shop	4,000.00		
Health certificates	2,000.00		
Water bills	1,776.00		
Internet	12,000.00		
Garbage collection fee	6,000.00		
Insurance	6,000.00		
Communication expenses	12,000.00		
Reduced food waste disposal		42,708.00	
Reduced methane emission		53,812.08	
Total		1,524,705.00	
	163,776.00		799,783.65

[6] **Source capital news.** Relief for Traders as Governor Kimani Wamatangi Slashes License and Inspection Fees - Kenyans.co.ke

Table 4.11: Cost and Benefits Associated with the Application of the Evaporative Cooler for Storage of Fresh Tomatoes

Costs and Benefits	Estimated cost /Annum[6]	Benefits of using the cooler	Benefits of using ambient environment
Net income from tomatoes storage		3,536,388.66	1,980,377,65
Rent for Business Premises	120,000.00		
Single Business Permit-small trader shop	4,000.00		
Health certificates	2,000.00		
Water bills	1,776.00		
Internet	12,000.00		
Garbage collection fee	6,000.00		
Insurance	6,000.00		
Communication expenses	12,000.00		
Reduced food waste disposal		126,760	
Reduced methane emission		159,717.6	
Total	163,776.00	3,822,866.00	1,980,377,65

Table 4.10 and 4.11 shows the business running cost and benefits in areas which are not cities or municipalities as reported by capital news (Wanjohi 2024). Table 4.9 and table 4.10 shows the total rent, legal and regulatory costs as KES 163,776.00 for both kales and tomatoes. The total benefits while storing kales and tomatoes was KES 1,524,705.00 (table 4.10) and KES 3,822,866.00 (table 4.11) respectively. The benefits accrued from ambient storage for kales and tomatoes was 799,783.65 KES (table 4.9) and 1,980,377.65 KES (table 4.10).

4.5.5 The Cost Benefit Analysis, Payback Period, Internal Rate of Return (IRR), and Accounting Rate of Return (ARR) of the Cooler

Evaluation of the economic and financial viability of the designed evaporative cooler entails the use of standard investment appraisal methods. In this section the methods of determining the financial worthiness of the cooler described are IRR, ARR, CBA and payback periods. Together these methods provide a solid prove of the financial robustness of the cooler.

4.5.5.1 Cost Benefit Analysis (CBA)

The NPV was calculated using the equation 4.1 (Jones & Smith, 1982).

$$NPV = \sum_{t=1}^{t=n} \left(C^t \frac{1}{(1 + \mathrm{r})^t} \right) - C^0 \qquad (4.1)$$

Where:

n= time period

r = Discount rate

C^t = Cash flow at time t

t = Time period (1 to n)

C^0 = Initial investment

Table 4.12 shows the analysis of present value (PV) of cooler's cost and cooler's benefits while storing kales and tomatoes.

Table 4.12: Year on Year Calculation of the Net Present Value for Benefits and Costs while Storing Kales and Tomatoes

Year	Annual total cost of running the cooler[7] under kales and tomatoes	PV (present value) of the total annual cost of running the cooler (at 6% discount rate)	Annual Cash inflow of cooler while storing tomatoes	PV of cash inflow from stored tomatoes at 6% discount rate	Annual Cash flow of the cooler while storing kales	PV of cash inflow from stored kales at 6% discount rate.
1	346,395.60	326,788.30	3,822,866.00	3,606,477.36	1,524,705.00	1,438,400.94
2	346,395.60	308,290.85	3,822,866.00	3,402,337.13	1,524,705.00	1,356,982.02
3	346,395.60	290,840.43	3,822,866.00	3,209,752.01	1,524,705.00	1,280,171.72
4	346,395.60	274,377.76	3,822,866.00	3,028,067.93	1,524,705.00	1,207,709.17
5	346,395.60	258,846.94	3,822,866.00	2,856,667.86	1,524,705.00	1,139,348.27
6	346,395.60	244,195.23	3,822,866.00	2,694,969.68	1,524,705.00	1,074,856.86
7	346,395.60	230,372.86	3,822,866.00	2,542,424.23	1,524,705.00	1,014,015.91
8	346,395.60	217,332.88	3,822,866.00	2,398,513.42	1,524,705.00	956,618.78
9	346,395.60	205,031.02	3,822,866.00	2,262,748.51	1,524,705.00	902,470.55
10	346,395.60	193,425.49	3,822,866.00	2,134,668.41	1,524,705.00	851,387.31
11	346,395.60	182,476.88	3,822,866.00	2,013,838.12	1,524,705.00	803,195.57
12	346,395.60	172,148.00	3,822,866.00	1,899,847.28	1,524,705.00	757,731.67
13	346,395.60	162,403.77	3,822,866.00	1,792,308.76	1,524,705.00	714,841.20
14	346,395.60	153,211.11	3,822,866.00	1,690,857.32	1,524,705.00	674,378.49
15	346,395.60	144,538.78	3,822,866.00	1,595,148.41	1,524,705.00	636,206.12
16	346,395.60	136,357.34	3,822,866.00	1,504,856.99	1,524,705.00	600,194.46
17	346,395.60	128,639.00	3,822,866.00	1,419,676.41	1,524,705.00	566,221.19
18	346,395.60	121,357.55	3,822,866.00	1,339,317.37	1,524,705.00	534,170.93
19	346,395.60	114,488.25	3,822,866.00	1,263,506.95	1,524,705.00	503,934.84
20	346,395.60	108,007.79	3,822,866.00	1,191,987.69	1,524,705.00	475,410.23
Total	6,927,912.00	3,973,130.24	76,457,320.00	43,847,971.85	30,494,100.00	17,488,246.23

[7] Cost of running the cooler under kales and under tomatoes maintenance cost-table 4.7 (9078.00), salary of the cooler operator per year 156837.00 +cost of water (16,704.00 KES) + legal costs table 4.9 (163,776.00) = 346395.6. Investment (fabrication, accessories and its labour which is a cost at the first year =176560.00

The figures in table 4.12 shows the total annual cost which comprise of, water, servicing and labour. Table 4.12 also displays the present values (PV) of the total cost of running cooler, PV of benefits (income) form the kales and tomatoes over 20 years life time of the cooler (Rashwan et al., 2025). This table is playing a central role in in determination of the Cost-benefit-analysis and allows for comparison of the benefits and costs over time. In addition, table 4.12 shows the annualised cash out flow of (324,395.60 KES annually) comparing with cash inflow (benefits) from the sale of kales and tomatoes which were 1,524,705.00 KES and 3,822,866.00 KES respectively. With the separation of costs and benefits it was possible to judge the profitability and the CBA of the cooler while storing each of the crops. Table 4.12 shows that the discount rate of 6% is applied to reflect the aspect of the time value of money thus, ensuring that the present cash is easily compared with future cash of the project. By displaying the separate PV of kales and tomatoes, it allowed the determination of the financial worthiness of the cooler in kales and tomatoes storage.

Table 4.12 shows the CBA figures (KES) for the cooler while operating under kales at 6% discount rate. The total PV (present value) of benefits (income) from kales is 17,488,246.23 KES, the total of PV for the total running cost while operating the cooler under kales was 3,973,130.24 KES while the cost of initial investment was 176,560.00 KES. Therefore, the analysis for CBA for the cooler while storing kales is as calculated below (Babaremu et al., 2019; Bidzakin et al., 2022; Gittinger, 1982).

$$\text{Total cost (PV) of running the cooler under kales} = \text{PV of cost} + \text{Initial cost} \quad (4.2)$$

$$\text{Total cost (PV) of running the cooler under kales} = 3{,}973{,}130.24 + 176{,}560.00$$

$$= 4{,}149{,}690.24 \text{ KES}$$

$$\text{Cost benefit ratio (CBR) of the cooler under kales} = \frac{Total\ PV\ income\ of\ kales}{Total\ cost\ (PV)\ (\ kales} \quad (4.3)$$

$$\text{CBR of the cooler under kales storage } = \frac{17{,}488{,}246.23}{4{,}149{,}690.24}$$

$$\text{CBR of the cooler under kales storage } = 1{:}\ 4.21$$

The interpretation of this analysis is that with the NPV of 13,338,555.99 KES ($17{,}488{,}246.23 - 4{,}149{,}690.24$) and a CBR of 4.21, The cooler while used to store kales is a viable project at 6% discount rate. There is a resemblance of the CBR realised in this study and the one found by Mujuka et al. (2020) of 4.29 while storing mangoes in an evaporative cooler While Langat (2024) found a CBR of a evaporative cooler with stored avocado fruits to be 2.88 which is lower than the one realised in this study. The difference might be because of the durability of pumice (in current study) and charcoal in the study by Langat (2024) or the difference in the crops stored in the cooler. Mishra et al. (2020) recorded a CRB of 2.9 in a zero-energy cooler.

Table 4.12 also shows the CBA figures (KES) for the cooler while operating under tomatoes at 6% discount rate. The total PV (present value) of benefits (income) from tomatoes is 43,847,971.85KES, the total of PV for the total running cost while operating the cooler under tomatoes was 3,973,130.24 KES while the cost of initial investment was 176,560.00 KES. Therefore, the analysis for CBA for the cooler while storing tomatoes is as calculated below:

$$\text{Total cost (PV)of running the cooler under tomatoes } = \text{PV of cost } + \text{Initial cost} \quad (4.4)$$

$$\text{Total cost (PV) of running the cooler under tomatoes } = 3{,}973{,}130.24 + 176{,}560.00$$

$$= 4{,}149{,}690.24 \text{ KES}$$

$$\text{CBR of the cooler under tomatoes storage } = \frac{Total\ PV\ income\ (kales)}{Total\ cost\ (PV)(kales)} \quad (4.5)$$

$$\text{CBR of the cooler under tomatoes storage } = \frac{43{,}847{,}971.85}{4{,}149{,}690.24}$$

$$\text{CBR of the cooler under tomatoes storage } = 1{:}\ 10.6$$

The interpretation of this analysis is that with the NPV of 39698281.6 KES 43847971.85-4,149,690.24 and a CBR of 10.6, The cooler while used to store tomatoes is a viable project at 6% discount rate. Mujuka et al. (2020) recorded a CBR of 7.1 in maize preservation project.

4.5.5.2 Payback Period of the Cooler while Storing Kales and Tomatoes

Payback period is defined as the time required for the cooler to realise an amount equivalent to the cost of investment. The annual cost of running the cooler was 346,395.60 KES (table 4.12) and the initial cost of installation was 176,560.00 KES (table 4.8), The total annual income from stored kales is 1,428,185.09 KES Table 4.4) The total cost of preserving kales in the cooler, the annual net saving (S) and payback period of cooler under kales is calculated using equation 4.5, 4.6 and 4.7 respectively(Gitman & Zutter, 2012).

$$\text{Total annual cost} = \text{Total annual running cost} + \text{installation cost} \qquad (4.6)$$

$$\text{Total annual cost} = 346{,}395.60 + 176560.00$$

$$\text{Total annual cost} = 522{,}955.60 \text{ KES}$$

$$\text{Annual net saving } (S) = \text{Total annual income (kales)} - \text{Total annual cost} \qquad (4.7)$$

$$\text{S} = 1{,}428{,}185.09 - 522{,}955.60$$

$$\text{S} = 905{,}229.50 \text{ KES}$$

$$\text{Payback period during kale storage} = \frac{\text{Initial cost}}{\text{Annual net savings}} \qquad (4.8)$$

$$= \frac{522,955.60}{905,229.50} = 0.6 \text{ years} = 7.2 \text{ months.}$$

Therefore, the payback period is about Seven months when the evaporative cooler is used to store kales. This means that when the cooler is used for kale storage the income from the cooler will pay back the investment cost within the first six months. The study by Tilahun (2010) reported a payback period of less than 1.2 years with eight stored fruits and vegetables and among them was tomatoes, all stored in a wood shaving padded evaporative cooler. The difference between the present study and the study by Tilahun (2010) may be due to the material used, type of crop stored in the cooler or the cooling pads used.

On the other hand, the payback period when the evaporative cooler is used for storage of tomatoes was calculated. The annual cost of running the cooler was 346,395.60 KES and the initial cost of installation was 176560.00 KES, the total annual income from stored tomatoes was 3,822,866.00 KES

While storing kales was 1,524,705.00KES. The annual net saving (S) is calculated using equation 4.5

$$\text{Total annual cost} = \text{Total annual running cost} + \text{installation cost}$$

$$\text{Total annual cost} = 346,395.60 + 176560.00$$

$$\text{Total annual cost} = 522,955.60 \text{ KES}$$

$$\text{Annual net saving (S)} = \text{Total annual income (tomatoes)} - \text{Total annual cost}$$

$$\text{Annual net saving (S)} = 3,822,866.00 - 522,955.60$$

$$\text{Annual net saving (S)} = 3,299,910.40 \text{ KES}$$

$$\text{Payback period during tomatoes storage} = \frac{\text{Initial cost}}{\text{Annual net savings}} \qquad (4.9)$$

$$= \frac{522,955.60}{3,299,910.40} = 0.16 \text{ years} = 1.9 \text{ months.}$$

Therefore, the payback period is about two months when the evaporative cooler stored tomatoes.

The payback period of 1.9 months for the evaporative cooler under tomato storage shows that the cooler will pay back the initial investment within less than two mouths of storing fresh tomatoes. This result shows that the evaporative cooler is profitable within a short time frame when used for tomato storage as compared to storage of kales. The payback period for the evaporative cooler under the storage of tomatoes in the present study is lower than the payback period reported by (Tilahun, 2010) who reported a payback period of 1 year while storing tomatoes in an evaporative cooler. This difference might be attributed to the differences in the value of the crop stored in the coolers or the costs of maintenance. The low pay back period means that the project will pay back quickly and is worthwhile as a profitable investment. Wittkamp et al. storing tomatoes and using agricultural waste pads for the evaporative cooler realised a payback period (PBP) of 2.6 months which compares well with the study at hand. The difference in the PBP values might be because of the type of cooler and the padding materials used.

4.5.5.3 Accounting Rate of Return (ARR)

Accounting rate of return is a quick way of determining the rate of return on investment. The ARR role is to measure the projects return based on profits expected from the venture rather than cash flows. ARR is expressed in percentage of the profit in relation to the initial investment Equation 4.6 is used for the determination of ARR (Gitman & Zutter, 2012).

$$Accounting\ rate\ of\ return\ (ARR) = \frac{\text{annual cash flow} - \text{Depreciation}}{Initial\ investment} \tag{4.10}$$

From table 4.4, the annual cash inflow of the cooler was 1,428185.09 KES and 3,536388.66 KES for cooler under kales and tomatoes respectively. The initial investment was KES 176,560.00.

$$Depreciation\ = \frac{\text{initial investment}-\text{Salvage value}}{useful\ life} \tag{4.11}$$

Assuming the salvage value for the cooler after 20 years will be KES 8828.00, Roy and Khurdiya (1986) records a salvage value of 5% of cost of investment (176560,00 x 5% =8828.00 KES). Therefore, the depreciation is:

$$Depreciation\ = \frac{176{,}560.00 - 8828.00}{20} = 8386.60 \text{ KES}$$

$$ARR\ kales = \frac{1{,}428185.09 - 8{,}386.60}{176{,}560.00} = 2899\%$$

$$ARR\ tomatoes = \frac{3{,}536388.66 - 8{,}386.60}{176{,}560.00} = 1998\%$$

During the cooler's useful life time, the two values of ARR show that the evaporative cooler (2899% for kales and 1998% for tomatoes) is a profitable venture. Brigham (2016) reported at a rate of 2095% and 440% when tomatoes and kales are stored in it respectively. In the case of the project at hand, both values are high above 100%, meaning that the project will generate income greater than the initial cost of investment, for instance when kales are stored there will be an income of over 28 times higher than the capital invested, while using the cooler in storage of tomatoes it is expected that the income will me more than 19 times higher than the investment. This depicts that the evaporative cooler is a highly profitable project. Therefore, it is profitable to implement such a project in storage of kales and tomatoes since the evaporative cooler will lead to improved earnings to fruit and vegetable vendors while under kale or tomatoes and by extension even when storing other perishable crops.

4.5.5.4 Cooler's Internal Rate of Return (IRR)

The internal rate of return (IRR) is the value of discount rate when the NPV = the investment (Tilahun, 2010). IRR is calculated by interpolating between two NPVs. The higher the value of IRR the safe it is to invest in the Project (Tilahun, 2010). The formular of IRR as described by equation 4.12.

$$IRR_{Tomatoes} = r_1 + \frac{NPV_1}{NPV_1 - NPV_2} X \ (r_1 - r_2) \qquad (4.12)$$

Where:

r_1 is the lower trail discount rate with a positive NPV

r_1 is the higher trail discount rate with a negative NPV

NPV_1 is the net present value of the project discounted at r_1

NPV_2 is the net present value of the project discounted at r_2

r_1 is 4% (assumed)

r_2 is 70% (assumed)

NPV_1 = 47,069,807.26 KES

NPV_2 = -71172,77723 KES (loss)

$$IRR_{Tomatoes} = 0.04 + \frac{47{,}069{,}807.26}{47{,}069{,}807.26 - (-71{,}172.777.23)} X \ (0.04 - (-0.7))$$

$IRR_{Tomatoes}$ = 30.27%

The value of the IRR was estimated by getting the sum of NPV for income at 4% and at 70%, by extrapolation the value of IRR when the cooler is used for storing tomatoes was determined as 30.27%. The study by Odeyemi and Ikegwuonu (2021) found a slightly higher IRR (36-48%) for a solar cold room under tomatoes while Obanubi et al. (2021) reported an IRR of 28% which is almost similar to the one for the study at hand. At this IRR (for current study), the investment will be equal to present value of the project (Ross et al., 1998). Assuming the cost of capital (interest rate) is 12%, since the IRR is greater than 12% the project is financially viable

Using equation 4.8, the IRR of kales is calculated as follows:

r_1 is 4% (assumed)

r_2 is 70% (assumed)

NPV_1 is 16,571,548.29 KES

NPV_2 is -1,971,593.84 KES (loss)

$$IRR_{kales} = 0.04 + \frac{16{,}571{,}548.29}{16{,}571{,}548.29-(-71{,}172.777.23)} X\ (0.04-(-0.7))$$

IRR_{kales} = 17.98%

The value of the IRR of the cooler under kales was estimated by getting the sum of NPV for income at 4% and at 70%, by extrapolation the value of IRR when the cooler is used for storing kales was determined as 17.98%. An almost similar IRR (17%) was realised by Global (2019) having stored kales and leafy vegetables in a solar cooler. At the current study IRR, the investment will be equal to present value of the project (Ross et al., 1998). Assuming the cost of capital (interest rate) is 12%, since the IRR is greater than 12% the project is financially viable when kales are stored in the cooler.

These figures of IRR imply that the evaporative cooler project can only incur losses only if the country's inflation surpasses the respective thresholds. This rate of inflation is too high and very rare in a stable country (Macklem, 1984). Therefore, following from these findings that the cost of borrowing will always be lower than the ARR and hence the project has very high chances of making long term profits. The cost of borrowing is below the IRR. The high value of IRR is an indication that the project on construction of an evaporative cooler is economically viable with high expectation of huge profits.

4.5.5.5 Summary of Findings from the Cost Benefit Analysis, ARR, IRR and Payback Period

Table 4.13 shows the tabulation and calculation of three financial indicators in cost benefit analysis which are ARR, IRR and payback period. The three are used to appraise ventures and assess the level of risk, efficiency and profitability.

Table 4.13: Summary of the Cost Benefit Analysis, ARR, IRR and Payback Period of the Evaporative Cooler when Used for Storing Kales and Tomatoes

Test	Evaporative cooler used to store tomatoes	Evaporative cooler used to store kales	General comments
Payback period (months)	1.9 months	7.2 months	Under kales or under tomatoes the cooler will payback within the first year of usage
Cost benefit ratio (CBR)	1:10.6	1:4.21	While storing kales or tomatoes, the cooler is profitable and worthy implementation because CBR> 1
Accounting rate of return (ARR)	2899%	1998%	In its lifetime the cooler will be profitable when kales or tomatoes are stored in it because it will earn a profit of 2899% (tomatoes) and 1998% (kales)
Internal rate of return (IRR)	30.27%	17.98%	The risk of making loss is very too low

Table 4.13 shows that the values of payback period, IRR, ARR and CBR are favourable for the implementation of the project, the four tests act as confirmation of the results from the foregoing analysis. The findings show that the cooler has a short payback period, high return on investment and a favourable benefit cost ratio. Therefore, the evaporative cooler is cost effective and profitable in the long term when used for storage of kales and tomatoes.

The study developed a highly efficient cooler and used the cooler to evaluate the changes in qualities of kales and tomatoes. In addition, the costs and benefits of using the developed cooler for preservation of kales and tomatoes was determined. In the study, the cooler's environment was compared with ambient conditions in relation to crop preservation. The determination of the microenvironment of the cooler under different modes (convective, roof pond, evaporative and combination of the three modes) is beneficial to users in that it provided data which shows the mode which provide optimum cooling hence enabling users to select the mode that is suitable for their application.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

5.1 Conclusion

This study addressed the three key objectives: the design/development of a pumice-padded evaporative cooler and evaluation of its environmental performance under no-load conditions. The study also assessed the cooler's effectiveness in preserving the quality of tomatoes and kales. The determination of the cooler's economic viability was successfully achieved too.

Firstly, the study achieved the design and fabrication of the zero-energy evaporative cooler optimized for both thermal performance and material efficiency. The use of pumice as a cooling medium, based to its high porosity and high-water retention capacity, proved effective compared to other conventional padding materials. The study established the optimal structural parameters as a pumice wall thickness of 0.15 m and a roof pond water depth of less than 0.10 cm, which enhanced evaporative cooling efficiency while minimizing material use. Secondly, under no-load conditions, the cooler demonstrated a favourable environmental performance, maintaining relative humidity levels of 80–100% and temperatures within the range of 15–22°C, these conditions fall within the recommended range for storage of fresh agricultural produce hence indicated the system's ability to create a modified microclimate suitable for reducing post-harvest losses. Thirdly, the evaporative cooler effectively preserved the quality of stored tomatoes and kales. For tomatoes, significant maintenance was observed in pH, total soluble solids (TSS) and firmness, with shelf life extending from 14 days under ambient conditions to 28 days in the evaporative cooler. For kales, although no significant differences ($p>0.05$) were observed in TSS, pH and overall colour change (ΔE), there were significant differences ($p\leq 0.05$) in specific colour parameters (a^* and b^*), indicating reduced quality degradation. The shelf life of kales was extended from 5 days to 9 days, this demonstrated that the cooler was effective in slowing senescence and maintaining post-harvest quality.

Finally, the economic analysis conducted confirmed the financial viability of the cooler. The cost-benefit ratios of 10.6 for tomatoes and 4.21 for kales indicate strong returns relative to investment costs. The high accounting rates of return (1998% for kales and 2899% for tomatoes), coupled with internal rates of return of 30.27% (tomatoes)and 17.98% (kales), demonstrate the financial attractiveness of the technology. Additionally, the short payback periods of 7.2 months for kales and 1.9 months for tomatoes highlight the quick recovery of initial investment costs.

In conclusion, the developed pumice-padded/roof pond evaporative cooler is both economically viable and technically effective for the storage of perishable agricultural produce. Its adoption offers a low cost, practical and energy-efficient solution for improving produce quality, reducing post-harvest losses and hence enhancing profitability for small-scale farmers who are off grid and resource constrained environments.

5.2 Recommendations

5.2.1 Recommendations from the Study

Based on the findings of this study, the following are the recommendations; the use of the pumice-padded/ roof pond evaporative cooler is recommended for small-scale farmers as a low cost, effective, energy efficient and low-cost technology for maintaining the quality and extending the shelf-life perishable crops such as kales and tomatoes. Secondly, farmers should adopt the combined cooling mode (evaporative, convective, and roof pond), as it offers a superior performance in maintaining higher relative humidity and lower temperatures which are critical for preserving fresh crop quality. Thirdly, agricultural extension services, non-governmental organizations and government agencies should promote and support the adoption of zero-energy evaporative cooling technologies through subsidies, training and integration into post-harvest management programs to enhance food security through reduced post-harvest losses. Finally, the evaporative cooler design developed in this study can be used as a baseline model for on-farm storage systems, especially for resource-constrained and off-grid environments.

5.2.2 Recommendations for Future Research

Further studies are necessary to expand and improve the findings of this research. To start with, research should be conducted on the storage quality performance of other perishable crops such as carrots, cabbages, mangoes, spinach and lettuce to evaluate the versatility of the cooler. secondly, studies should investigate the performance of the cooler under different climatic conditions with varying relative humidity and temperature conditions to enhance its adaptability. Thirdly, further research is needed to optimize the cooler design by varying parameters such as pumice particle size, pumice wall thickness and water circulation rates. Finally, additional economic analyses should be carried out across different crops and different seasons to validate the cost-benefit performance of the cooler.

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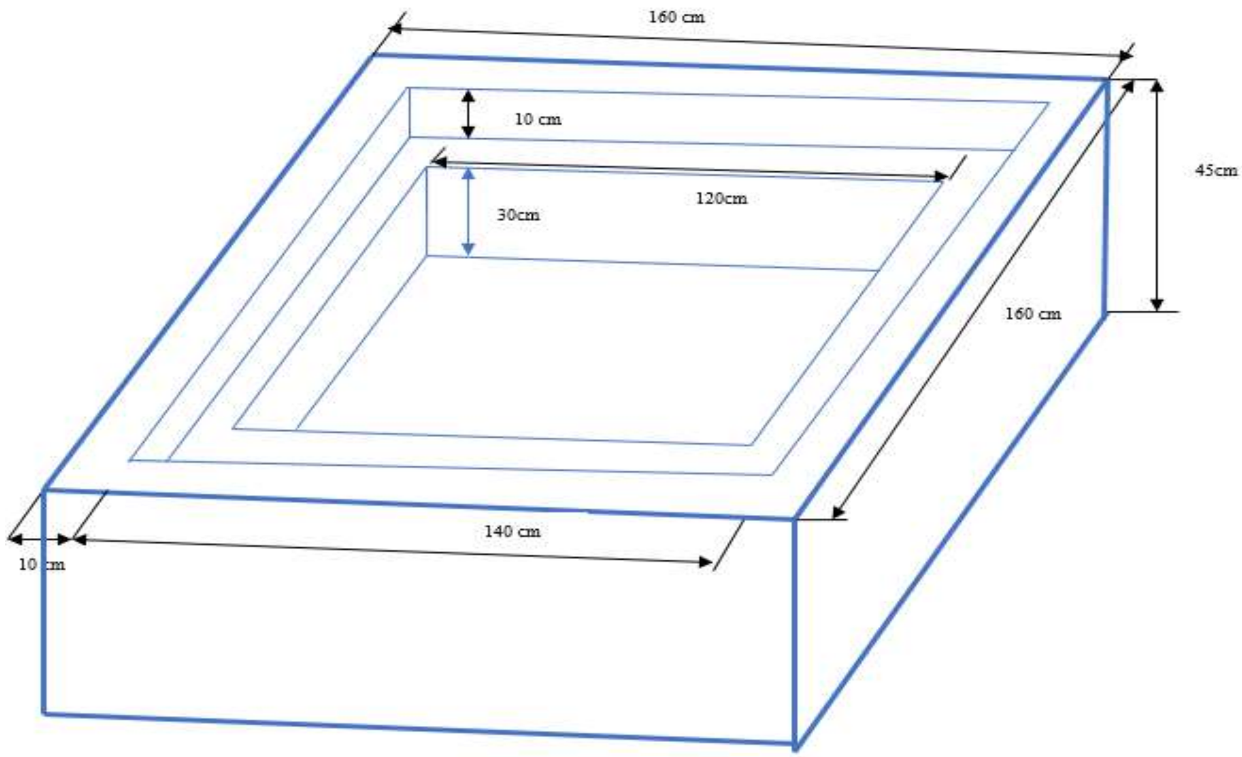
APPENDICES

Appendix I: Design and Dimensions of the Cooler's Reservoir



Appendix II: The Photographic Representation of the Cooler

Appendix III: Labelling Tomatoes Before Storage

Appendix IV: Labelled Tomatoes Ready for Storage

Appendix V: Testing Tomatoes Firmness Using a Penetrometer

Appendix VI: Freshly Harvested Kales

Appendix VII: Kales in the 10th Day of Storage