EFFECTS OF DIFFERENT PACKAGING MATERIALS AND STORAGE CONDITIONS ON THE QUALITY ATTRIBUTES OF TOMATO FRUITS

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DISCLAIMER

As the candidate's Supervisor, I have approved this thesis for submission.

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Professor TS Workneh

PREFACE

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RESEARCH OUPUT

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ABSTRACT

Tomatoes come second to potatoes as one of the most cultivated crops worldwide. In South Africa, tomato production contributes 24% of the country's vegetable production. As the industry is faced with many challenges, integrated post-harvest technologies are required. This study aimed to evaluate the effects of different packaging materials and storage conditions on the quality attributes of the tomatoes used in the South African supply chain. The study consisted of two experiments: Experiment I evaluated the effects of the different packaging materials on the round "Nema-Netta" tomato fruit stored under ambient and cold storage conditions. Experiment II evaluated the effects of the different packaging materials on the "Romanita" cherry tomatoes stored under ambient and cold storage conditions. A Randomized Complete Block Design with six different packaging materials [Experiment I: the Stamped Paper (SP) Tray + Polyvinyl Chloride (PVC) wrap, the Expandable Polystyrene Sheet (EPS) Tray + Polyvinyl Chloride (PVC) wrap, the Stamped Paper (SP) Tray + Flow wrap, the Expandable Polystyrene Sheet (EPS) Tray + Flow wrap, the Polypropylene bag (PP) and the Unpackaged tomatoes; Experiment 2: the Zibo Punnet PET + Flow wrap, the Old Polypropylene (PP) bag, the Zibo Punnet PET + Zibo PET Lid, the Glued Paper Tray + Flow wrap, the Pulped Paper Tray + Zibo PET Lid, as well as Open storage] and two storage conditions (cold and ambient) for 28 days. The colour (L*, a* and b*), firmness, Physiological Weight Loss (PWL), Total Soluble Solids (TSS), pH, Titratable Acidity (TA), total sugars, Total Phenolic Content (TPC) and microbial analysis were evaluated. The cold storage conditions were recorded in the range of 8-2°C, 78–80% RH and the ambient storage conditions were in the range of 22-26°C, 68–72% RH. The packaging and storage conditions significantly ($P<0.05$) affected the quality attributes that were evaluated in both experiments. Packaged cherry tomatoes under cold storage conditions displayed the least significant changes in quality. The lowest decrease in L* and hue angle, the firmer fruits, the lowest PWL, and the lowest increase in the TSS content and pH value paralleled with the lowest decrease in TA, total sugars and TPC, as well as the low microbial growth. The EPS Tray, combined with PVC wrap, maintained the quality of the tomatoes better than the other packaging. The relative difference in the other evaluated quality attributes was less pronounced in EPS Tray + PVC wrap (non-degradable) and SP Tray + Flow wrap . The Glued Paper Tray + Flow wrap package, together with cold storage conditions, was the most beneficial combination for preserving the quality of cherry tomatoes, as they prevented excessive microbial growth and deterioration, hence extending their shelf-life. The use of biodegradable packaging materials and storage techniques

in post-harvest handling in the food industry could be of great value for providing a holistic approach to environmentally-friendly materials and minimising post-harvest losses. Hence, more practical investigations and comparisons of the varying temperatures and relative humidity are required. The study of more environmentally-friendly packaging techniques can be beneficial for the South African supply chain.

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1. INTRODUCTION

The tomato crop (*Solanum Lycopersicum)* is one of the most important agricultural commodities in the world. Tomatoes are consumed mainly for their high nutritional value in the human diet and for good health (Tigist *et al.*, 2013; Azeez *et al.*, 2019). Globally, tomato production accounts for approximately 4.5 to 5 million hectares of the cultivated land, with production being estimated at 170.8 million tons (Costa and Heuvelink, 2018; Gatahi, 2020). China is the leading producer and accounts for nearly 31% (50 million tons) of the world's tomato production, followed by India, with an estimated production of 11% (17.5 million tons) (FAO, 2019b).

Many studies have indicated that there is a correlation between tomato consumption and their protective effects against various cancer diseases. Their protective effects may be one of the reasons why there has been an increase in the consumption of tomatoes (Stahl and Sies, 2005; Pinheiro *et al.*, 2013). Tomatoes are an essential product in fresh markets (Fagundes *et al.*, 2015). According to Ahmed and Tariq (2014), they can be consumed in their fresh form, as a fruit or a salad, and they can be processed into soups, sauces and pastes. Due to their biochemical, microbiological and physiological properties, tomatoes have a short shelf-life of two to three weeks after harvest (Karam *et al*., 2016; Zewdie, 2017); therefore, these properties need to be controlled within an optimum range (Tigist *et al.*, 2013; Zewdie, 2017).

The loss in quality after harvesting is attributed to their continuous respiration (Zewdie, 2017), as well as the production of ethylene, a ripening hormone. Hence, the post-harvest management of tomatoes is centred upon reducing the respiration rate and controlling the ethylene production (Martínez-Romero *et al.*, 2007; Fagundes *et al.*, 2015; Zewdie, 2017). Post-harvest tomato losses in the range of 20–50% have been reported in Africa (Pila *et al.*, 2010; Ahmed and Tariq, 2014). These losses are associated with poor handling techniques and the failure to meet climatic requirements (Tigist *et al.*, 2013). The use of packaging has also been reported to reduce post-harvest losses in the fresh produce supply chain (Zewdie, 2017). A controlled environment, combined with improved packaging, can extend the shelf-life of most fruits and vegetables (Marsh and Bugusu, 2007; Patanè *et al.*, 2019).

Fresh tomatoes are climacteric, with a shelf-life of two to three weeks (Sibomana *et al.*, 2015). This short life-span requires careful handling, in order to maintain their quality and to preserve their marketable value after harvest. The quality of tomatoes is measured or determined by their nutritional value, as well as their firmness, flavour and appearance. These quality measures are influenced by many different factors; for example, the agronomic practices, the harvesting period and harvesting methods, post-harvest handling, the packaging materials, pest infestation, as well as the storage facilities and conditions (Zewdie, 2017). Packaging protects and preserves the quality of fruit and vegetables. The different packaging materials that are used to pack food and beverage products include metal, plastic, paper, paper board and glass.

The use of polymer packaging has increased exponentially as the human population has increased (Lv *et al.*, 2018; Patanè *et al.*, 2019). This is consistent with South African statistics, which show that half of all the plastic produced in the country is used for packaging (Vermaak, 2017). These packaging materials are predominantly plastic polymers produced from petroleum monomers, which are non-biodegradable. Petrochemical-based packaging materials are considered to be pollutants in the environment and detrimental to human health. These concerns have led to the production of alternative renewable and biodegradable packaging materials (Zhou *et al.*, 2019). However, there is limited information on the effects of biodegradable packaging material on the physiological, biochemical and microbial quality of the tomatoes during storage. The packaging has increased their shelf-life and market value (Sammi and Masud, 2009; Zewdie, 2017), and it can prevent the contamination of the product, which results in improved freshness and thus meets the consumers' demand for quality. Some reports have shown that tomatoes packaged in polyethene bags experience an approximately 10% loss in weight, while an approximately 32% weight loss was observed in those packaged in grease-free papers for 35 days (Shahnawaz *et al.*, 2012; Zewdie, 2017).

Several integrated technologies have been studied to evaluate the beneficial influence of post-harvest treatments for maintaining the quality and prolonging the shelf-life of tomatoes. Workneh *et al.* (2009) assessed the influence of Modified Atmospheric Packaging (MAP), ComCat® treatments and evaporative cooling on the marketability of tomatoes that are stored for 24 hours in an evaporative cooler. It was found that the packaging helps to preserve the quality attributes of tomatoes. However, some of these new integrated technologies have not been tested on a commercial scale. Presently, the scale of tomato production has increased, mainly because of a wide range of sensory and morphological studies in the tomato industry, which seek to determine the post-harvest life of tomatoes. A few studies have been conducted on the influence of packaging; however, they are not a representative of the whole African continent, since there are a wide variety of geographic factors and cultivars. Most tomato and packaging studies resonate mainly from the northern African region, such as Egypt (Asem *et al.*, 2016b) and Ethiopia (Mekonnen, 2017a). Not many studies on tomatoes and packaging have been conducted in the southern Africa region, particularly under the sub-Saharan weather conditions and by using the local tomato varieties. The literature review of this study will focus on an overview of tomato production in South Africa, the physiological and biochemical characteristics of tomatoes, the challenges affecting tomato production, the importance of food packaging and the methods that are used to measure the quality of tomatoes. This proposed work focuses on evaluating the effects of the different packaging materials and storage conditions on the quality attributes of tomatoes by evaluating and analysing the physical and biochemical properties of the tomato fruit, microbial developmentwithin the packaging material, comparing the performance differences of the packages, particularly non-biodegradable vs biodegradable materials, and selecting based on the performance from each experiment the most suitable biodegradable packaging for potential new sustainable packaging development.

2. LITERATURE REVIEW

In the southern Africa region, South Africa is the dominant producer of tomatoes, with the Limpopo Province being the primary producer in the country. The round and cherry tomatoes are the common varieties that are produced. However, the industry is not without its challenges, as high post-harvest losses have been recorded throughout the country.

2.1 History and Origin of the Tomato Fruit

According to D'Angelo *et al.* (2019), tomatoes are indigenous to the South American Andes, particularly in the Peru and Ecuador regions, where they grow naturally as a wild crop. They are believed to have evolved from *Lycopersicon esculentum var*. c*erasiforme*, the cherry form (Naika *et al.*, 2005; di Paola Naranjo *et al.*, 2016). It was then taken and domesticated by European explorers, who planted them as a decorative plant (Arah *et al.*, 2015). Tomatoes were originally thought to be poisonous; however, in the 18th century, they were accepted as a food crop (Paran and van der Knaap, 2007; Tan *et al.*, 2010).

2.2 General Overview of Tomato Production in South Africa

Tomatoes are among the most cultivated crops, and they rank second to potatoes in South Africa. The Limpopo Province is the largest producer of tomatoes, with a cultivated area of approximately 3 590 ha. (DAFF, 2010; Beckles, 2012; DAFF, 2017). South Africa's annual tomato production is estimated at 600 000 tons, with an estimated net value of USD 210 million (Sibomana *et al.*, 2016b). According to The Farmers' Weekly (2017), depending on the climatic conditions and seasons, the annual yield ranges between 65 to 70 t/ha. In 2018, tomatoes accounted for 24% of the overall production of vegetables on the South African market (DAFF, 2019). They have a relatively short shelf-life and are grown mainly for domestic use. Between 83% and 87% of the annual crop is sold through the national and regional fresh produce markets, with a limited quantity being delivered directly to supermarket chains (DAFF, 2019). A small percentage of South African tomatoes is bought by cross-border traders who sell the produce in Lesotho, Swaziland, Mozambique, Botswana and Namibia (DAFF, 2017; van Lin *et al.*, 2018). Africa produces about 18 million tons of tomatoes per year, with Egypt ranking the highest on the continent, with a production of 8.5 million tons. Southern Africa accounts for nearly 4% of the total tomato production (FAOSTAT, 2017). Over the years, tomato production has grown in the Southern African Democratic Corporation (SADC) (Malherbe and

Marais, 2015). Despite ranking 35th globally, South Africa is the dominant producer, with 54% of the total tomato production grown on 11% of the total cropped area in the SADC region (Figure 2.1). According to Sibomana *et al.* (2016b), post-harvest technology has improved in southern Africa, compared to other regions, with South Africa being the most improved country. South Africa produces more tomatoes on the same area of land than any other African country, and the tomato losses in the northern regions of the country are lower because of the innovative technology structures that are employed (Sheahan and Barrett, 2017).

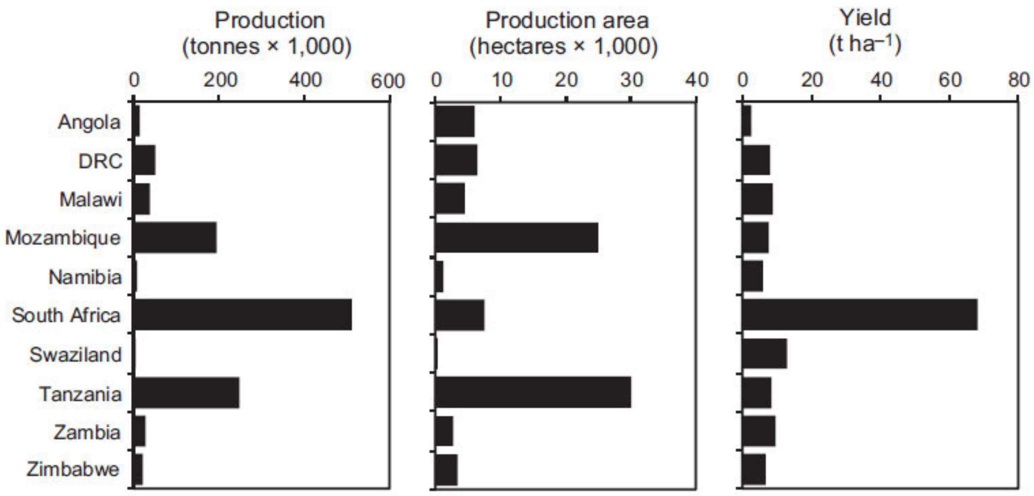

Figure 2.1 Tomato production, production area and yield in the SADC region (FAO, 2019b)

The commercial production of tomatoes is private sector-driven and a company called ZZ2 is the largest tomato producer in the southern hemisphere (Sibomana *et al.*, 2017). Sibomana *et al.* (2016b) reported that the value of tomatoes along the value chain has increased significantly, compared to potatoes and citrus. In 2015, the monthly tomato value at production and consumption was USD 263.30 and USD 1053 ton^{-1}, respectively (Sibomana *et al.*, 2016b). These values were higher than those of potatoes, which were valued at USD 157.96 and USD 616.79 ton^{-1} at production and consumption. At the same time, citrus was reported to be valued at USD 278.91 and USD 445.24 ton^{-1} at production and consumption, respectively (Directorate Marketing, 2015). South Africa is regarded as a leader in the use of best practices in tomato production; however, the industry is not without its challenges. The high input costs, fluctuating market prices, the shortage of good quality irrigation water, an unreliable electricity supply, poor post-harvest handling, labour issues and a poor road infrastructure are among the top challenges that need to be addressed. Several reports have shown that post-harvest losses occur between production and consumption (Aba *et al.*, 2012; Cronjé *et al.*, 2018). Nearly 50%

of all tomato losses occur post-harvest, while 25% occur during processing and packaging, 20% during supply and marketing, and 5% at consumer level (DAFF, 2017; The Farmer's Weekly, 2017). Spearheaded by the tomato producer's organisation, programs are run to improve the sustainability and competitiveness of the local industry.

The country grows three main types of tomatoes, namely, round or fresh tomatoes, *Roma* tomatoes that are destined for processing, and cherry tomatoes. Most tomatoes are grown in open fields under irrigation. These common varieties are cultivated based primarily on their fruit quality, their low vulnerability to pests and diseases, their suitability to the growing season and growing habits, as well as on the available market. In South Africa, cherry production by commercial and small farmers is still rare. They are mainly grown in the Western Cape, Eastern Free State, and KwaZulu-Natal. The cherry type is not popular, compared to the classic round, while the Bamby, Giant Heidelfinger, Early Red and Bing, which are bred from PRUNUS avium and Josephine, are the most widely-grown cherry tomatoes for the South African fresh market. They are cultivated from spring to summer (DAFF, 2014). The germplasm of tomatoes is different all over Africa, which can be attributed to the growing conditions, the geographic location, the maturity stage and the storage conditions. It is difficult to associate the South African varieties with the information gathered in the literature, which focuses mainly on popular varieties and cultivars that are grown in other countries under subjective growing conditions that are very different to those grown in the sub-Saharan African region.

2.3 Physiological and Biochemical Characteristics of Tomatoes

Tomatoes are an integral part of the human diet and an essential industrial cash crop (Arah *et al.*, 2015). They are a nutrient-dense food, which means that they are rich in nutrients, but do not contain many calories. Their primary constituent is water, with the moisture content being between 91-95% for cherry and round tomatoes, respectively, which makes them highly perishable (Hedges and Lister, 2005; Hussein *et al.*, 2016). Although they do have trace elements of fats and protein, the primary macronutrient in tomatoes is carbohydrates. They are low in carbohydrates, when compared to other nutritious fruits and vegetables, ranging between 3.67-8,00% for raw fresh tomatoes and 1-3% for cherry tomatoes, respectively (Hedges and Lister, 2005; Jafari *et al.*, 2017). Cherry tomatoes are a good source of fibre, with about 1.13-1.60% in an averaged-sized tomato, whereas the round tomato type ranges between 0.14-1.50%. The dietary fibres are associated with improving the human digestive system and controlling the blood cholesterol levels (Hedges and Lister, 2005; Guil-Guerrero and

Rebolloso-Fuentes, 2009). The fibre of fresh tomatoes is insoluble and come in the form of cellulose, lignin and hemicellulose (Claye *et al.*, 1996). Fresh tomatoes contain very little fat, with less than 0.2% for round tomatoes and 0.3% for the cherry variety (Guil-Guerrero and Rebolloso-Fuentes, 2009; Pinela *et al.*, 2012). The compositional nutrients of the tomato fruit may vary, depending on the cultivar, the geographic growing conditions, the maturity stage and the storage conditions. The moisture, crude protein, carbohydrates, fats, fibre and ash content of tomatoes are shown in Table 2.1.

2.4 The Importance of Tomato Production

Tomatoes are a primary dietary source of lycopene, Vitamin C, beta carotene, naringenin, potassium, Vitamin K1 and folate (Arab and Steck, 2000; Bergougnoux, 2014; Campestrini *et al.*, 2019). Vitamin C is an antioxidant and is linked with the prevention of degenerative diseases (Frusciante *et al.*, 2007; Pinela *et al.*, 2012). Compared to other fruits, tomatoes contain high levels of carotenoids (Weisburger, 1998; Mekonnen, 2017a), which are mainly produced in the ripening stage of the tomato and are grouped into two groups. The first and most abundant form of carotenoid is lycopene, which represents more than 80% of the carotenoids in fully-matured tomatoes. About 7-10% is represented by β-carotene, the second carotenoid form. Lycopene is the one of actual interest, since it is only available in relatively few foods, yet it is available in reasonable quantities in tomatoes (Maria *et al.*, 2015; Hernández *et al.*, 2020). Several studies have provided evidence that tomatoes may reduce the risk of cancer and other cardiovascular diseases (Freeman and Reimers, 2011; Arah, 2015). Lycopene is the most abundant carotenoid in tomatoes, and its highest concentration is in the skin (Viuda-Martos *et al.*, 2014). Clinical evidence has linked lycopene consumption to the reduced incidence of generative cancer diseases, namely, breast, cervical, bladder, oral, colorectal, stomach, lung and pancreatic cancer (Pohar *et al.*, 2003; Fiedor and Burda, 2014; Linnewiel-Hermoni *et al.*, 2015). The relationship between consuming large quantities of tomatoes and decreasing prostate cancer cell proliferation has been linked to the presence of lycopene in tomatoes (Bommareddy *et al.*, 2013; Arah, 2015). Naringenin, which is also found in the tomato skin, reduces skin inflammation (Bharti *et al.*, 2014).

Table 2.1 The moisture, crude protein, lipid, fibre, ash and carbohydrate content of the tomato varieties

Variety	Moisture (%)	Crude protein (%)	Carbohydrates (%)	Fat (%)	Fibre (%)	Ash (%)	Author
Cherry pera	92-95	1.05	2.18	0.42	1.60	1.41	Guil-Guerrero and Rebolloso-Fuentes (2009)
Roma VF	92-95	1.0	4.7	0.2	1.5	-	Arah *et al*. (2015)
Comprido	93-95	0.4	5.14	0.17	-	0.59	Pinela *et al.* (2012)
Batateiro	91-93	0.41	6.63	0.11	-	0.63	Pinela *et al.* (2012)
Amarelo	90-92	0.61	7.99	0.03	-	0.72	Pinela *et al.* (2012)
Coracao	92-94	0.42	6.14	0.13	-	0.54	Pinela *et al.* (2012)
Mongal F1	95	0.25	-	-	-	0.25	Oboulbiga *et al.* (2017)
Hausa	94	0.56	5.72	0.10	0.15	0.22	Garuba *et al.* (2018)
Yoruba	94	0.79	5.23	0.13	0.14	0.17	Garuba *et al.* (2018)
Tropimech	94.40	0.55	3.65	0.14	1.14	0.14	Garuba *et al.* (2018)
Cherry	93-95	0.78	1.27	0.49	1.13	0.90	Guil-Guerrero and Rebolloso-Fuentes (2009)

Pro-vitamins A and C are essential for improving eyesight and reducing the rate of muscular degeneration (Arah *et al.*, 2015; Hussein *et al.*, 2016). The availability of potassium in tomatoes enhances blood refinement and cleans up urinary tract contagions (D'Elia *et al.*, 2011). Another essential mineral, folate (Vitamin B9), promotes tissue growth and enhances cell function. This compound is significant for pregnant women, in particular (Fekete *et al.*, 2012). Some have reported that the consumption of tomatoes enhances fertility in men by enhancing the quality, production and swimming speed of the male sperm (Arah, 2015; Yamamoto *et al.*, 2017). Freeman and Reimers (2011) also reported that consuming large amounts of tomatoes can reduce old-age diseases like Alzheimer's, dementia and osteoporosis. The antioxidant compounds that are present in tomatoes have led to an increased interest in more studies on their consumption as a raw crop with many medicinal properties (Arah, 2015; Campestrini *et al.*, 2019). These nutrients are susceptible to loss during post-harvest handling. Vitamin C, in particular, is sensitive to packaging and storage conditions. These conditions also relate to the stability of other nutrients (Sablani *et al.*, 2006). However, the emphasis in the literature has been on processing, in order to preserve the nutritional qualities, while not much research has focused on post-harvest handling and retail packaging, which seems to be the most important factor before the processing stage.

2.5 Challenges Affecting Tomato Production in Southern Africa

Post-harvest losses occur along the supply chain, from the on-farm operations to the last consumer of the product. These losses originate from the harvesting, handling, storage, processing and supply stages and contribute to the global food security challenge by simply decreasing the local and global availability of food. FAO (2019) reported that, in order to reduce the severity of these post-harvest losses, researchers must first identify where the losses occur and where the most impactful interventions can be made. The climacteric and delicate nature of the fruit or vegatable gives an indication status of which post-harvest technologies and practices can be employed, in order to reduce the loss of quality and to extend its shelf-life.

2.5.1 On-farm post-harvest operations

Poor agricultural practices are one of the challenges that smallholder farmers face in sub-Saharan Africa (Arah *et al.*, 2015; Sibomana *et al.*, 2017). For example, the over- or under-application of pesticides to the crop, harvesting an immature crop or delayed harvesting

(Beckles, 2012; Arah, 2015) may result in the quicker deterioration and higher susceptibility of the crop to mechanical damage and injury (Watkins, 2006; Toivonen, 2007). Sibomana *et al.* (2016) reported the inadequate use of quality standards in the tomato supply chain, which has led to the rejection of tomatoes in the South African market. Pre-harvest factors, such as fertilization, irrigation, water quality, light intensity, harvesting time, harvesting methods and conditions, as well as pests and diseases, are significant influencers of the post-harvest quality deterioration of crops on farms. According to DAFF (2017), all tomatoes in South Africa are harvested manually, in order to minimize mechanical injury; however still most of the post-harvest losses emanate from poor handling during harvest and across the supply chain.

2.5.2 Transportation and storage facilities

In Africa, the transportation and storage facilities fall far behind those of the rest of the world, and a good transportation infrastructure is scarce (Arah *et al.*, 2015; FAO, 2019a). Smallholder farmers in remote areas are forced to harvest most of their crops later than usual and to sell them at nearby markets at lower prices (Sibomana *et al.*, 2017). Another factor is that the roads are poor, which makes transportation to the markets very difficult. There is too much vibration in the traditional modes of transport, which results in the fruit being physically damaged, due to the impact of the vibrations. This negatively influences its shelf-life (Idah *et al.*, 2007; Arah, 2015; Arah *et al.*, 2015). The storage facilities that can maintain temperature and humidity, particularly in vehicles, are limited. A few are used in some countries like South Africa, but they are still not of the best standard for maintaining the temperature variations that occur in the country (Sibomana *et al.*, 2016b; Sibomana *et al.*, 2017).

2.5.3 Handling methods and processing

Processing losses result from inefficient and the lack of mechanical processing facilities, processing factories and the redundancy of those that are available (Arah *et al.*, 2015; FAO, 2019a). Most of the smallholder agricultural operations are completed manually, and sacks and traditional baskets are used for packaging (Sibomana *et al.*, 2016b). These materials have rough internal surfaces that cause bruising and chilling injuries (Arah, 2015; Kitinoja, 2016). Even if the tomatoes reach the market, sanitation in sub-Saharan Africa is still a problem (Mashau *et al.*, 2012; Sibomana *et al.*, 2016b). The sanitary conditions are deplorable; for example, in the local open-air markets markets on the South African streets. This leads to people rejecting the fruit because they are regarded as being not consumable (Asem *et al.*, 2016a; FAO, 2019a).

Training and a desire to improve and do the task well is fundamental for improving production, for marketing and for maintaining food production. Sibomana *et al.* (2016b) reported that although there are fewer post-harvest losses in tomato production in South Africa than in other African regions, it still lags far behind other developed countries, like America and Europe. Nevertheless, it has the potential to offer the appropriate technology and facilities, hence more studies need to be conducted on post-harvest technology, which is what this study attempts to do.

2.6 Overview of Food Packaging Materials

Plastics are the most used material in the food industry. However, serious concerns have been raised about the waste that is accumulated and produced by such plastic packaging. Biodegradable packaging films produced from biopolymers have been established as a lucrative solution for reducing the environmental pollution crisis.

The packaging of food is the last process that is used to ensure that the product is protected and distributed safely to customers. Packaging prolongs the shelf-life of fresh and processed food commodities, including fruit and vegetables (Mekonnen, 2017a; Aduri *et al.*, 2019), and it conserves the aroma, colour, firmness and flavour of the product (Asem *et al.*, 2016a). The extension of its shelf-life is in the interaction between packaging material and the properties of the fruit or product.

Plastic is the dominant material that is used for food packaging in South Africa (Dikgang *et al.*, 2012; Rensburg *et al.*, 2020). It offers simple recyclability and requires relatively less energy to manufacture than other packaging materials, hence its dominance (Hopewell *et al.*, 2009). Plastic bags require 40% less energy and have a solid waste output of 80% less than paper. They are relatively cheap, making them an attractive packaging easy to access, even for small retailers. Plastic can endure harsh weather conditions and keep the product contents intact. Shahnawaz *et al.* (2012) reported that the packaging of tomatoes slows down their weight loss, compared to unpackaged tomatoes. Packaging fruit in polyethylene bags provides a modified atmosphere and reduces fruit decay, softening and the loss of soluble solids during storage. Controlling respiration and the loss of water through transpiration increases the shelf-life and retains the quality of the fruit. In China, polyethylene bags were reported to extend the shelf-life of tomatoes from a life-span of 14 days to over 28 days (Zhu *et al.*, 2018). Tomatoes wrapped with grease-free paper and newspaper were reported to last up to 14 days longer than expected (Shahnawaz *et al.*, 2012; Mekonnen, 2017a). Gebeyehu (2018) reported that packaging tomatoes preserved the fruit's quality by almost twice the shelf-life of unpackaged tomatoes. Other related studies on the effects of packaging treatments on tomatoes have reported that some treatments maintain the Vitamin C content and fruit firmness, compared to the unpackaged tomatoes in ambient and cold storage conditions (Asem *et al.*, 2016a). The packaging industry changes now and then; hence different packaging materials are used for fresh tomatoes across the supply chain and in retail stores. The effects of these different packaging materials need to be studied, in order to determine their suitability for the tomato varieties grown under South African geographic conditions.

Consequently, there is a growing demand to eliminate plastic packaging and to transition from petrochemical-based products to sustainable ones (Youssef and El-Sayed, 2018; Aduri *et al.*, 2019). It has been suggested that biodegradable packaging material be used in food packaging, rather than plastic materials (Zhong *et al.*, 2020), because they degrade naturally into organic compounds once they come into contact with the natural environment. Recent interventions have looked at biopolymers e.g. polyhydroxy-butyrate (PHB) (Puppi *et al.*, 2019; McAdam *et al.*, 2020), a biodegradable thermoplastic with semi-crystalline properties, hydrophobic polymers, as well as starch and polylactic acid-based packaging (PLA) (Lv *et al.*, 2018; Zhou *et al.*, 2019). According to Cyras *et al.* (2007) and McAdam *et al.* (2020), the low water permeability properties of PHB makes it an interesting material for use in food packaging (see Table 2.2). However, it is brittle and some retailers consider it to be quite expensive, which has stunted its popularity (Lv *et al.*, 2018). Industrial endeavours and research activities have focused on exploring PHB for a variety of purposes. However, the high manufacturing cost of PHB has limited its wide application as a biodegradable plastic (Zhao *et al.*, 2019).

Moreover, the PHB films are weak, which restricts their application in circumstances where a high elastic quality is required. In this way, materials with better mechanical properties can be set up at a lower cost by promoting bioplastic with natural fibres or different environmentally friendly polymers (Zhou *et al.*, 2019). Polylactic acid (PLA) containers have been reported to preserve the quality of fruit better in controlled temperatures between 10˚ and 23°C (Almenar *et al.*, 2008). Kantola and Helen (2001) reported that the quality of tomatoes remains good when they are packaged in biodegradable packages for weeks. Koide and Shi (2007) also reported no significant difference in the physicochemical qualities of peppers between PLA and Low-density polyethylene (LDPE) packaging. However, PLA packages have a high water vapour transmission rate, compared to LDPE (Table 2.2), which produces an ideal environment for bacterial growth.

Paper and corrugated cardboard is the most commonly-used biodegradable packaging material for horticultural products. They are made from cellulose, which is the most abundant renewable polymer on the planet (Cyras *et al.*, 2007; Aduri *et al.*, 2019), and they protect the products against mechanical shock and damage along the supply chain, particularly during transportation (Fadiji *et al.*, 2018). The mechanical properties of paper are excellent, but the vapour permeability is too high for some applications; hence the hydrophilic nature of the paper-based packaging materials is a significant issue, when used for foods (Cyras *et al.,* 2007). The water penetrability of polymers is a significant trademark when utilised for the protection and packaging of food and beverage materials. Information on the gas permeability and water absorption of these polymers is still required, when choosing a good packaging material and foreseeing the lifespan of fruit in humid conditions (Raj, 2020). It should be noted that most of the comparable results found in literature are based on their material strength and that these recent studies originate in Asian countries. Africa still lags far behind in terms of research into such standards. Biodegradable packages are fast becoming a reality in South Africa and, currently, applications focus mainly on food containers. Even though the volumes are relatively low at this stage, the consumer management of these packages requires proactive consideration. Hence, evaluating the effect of biodegradable packaging requires more study.

Table 2.2 The barrier properties of flexible packaging material polymers

Biodegradable polymer	Material thickness (mm)	Young modulus of elasticity ($kN.mm^{-2}$)	Permeability		Strength ($N.mm^{-2}$)	Light transmission (%)	References
			O_2 [cc/(mm.m^{-2}.24h^{-1}.0.21atm O_2)]	H_2O (g.m^{-2}.24h^{-1} at 100% RH)			
Oriented polylactic acid (OPLA)	20	1.9-2.5	56.33	3.48	60-65	90	Auras *et al.* (2005)
Polylactic acid (PLA)	0.1	3.5-5	200	66	48-53	90	(Auras *et al.*, 2005)
Polylactic acid average molecular weight (PLA-M)	0.25	-	84-99	210		90	Ivonkovic *et al.* (2017)
Polyhydroxy butyrate (PHB)	1.0	3.5-4.5	183	1.16	25-40	-	McAdam *et al.* (2020)
Polyhydroxy butyrate and hydroxy valerate (PHBV)	1.0	0.6-1.0	-	1.39	25-30	-	Puppi *et al.* (2019)
Polyethylene terephthalate (PET)	4.6	2.8-4.0	9.44	3.48	48-72	88	Ivonkovic *et al.* (2017)
Oriented polystyrene (OPS)	18	1.6-2.0	532	5.18	60-65	-	Auras *et al.* (2005)
Low density polyethylene (LDPE)	0.025	0.2-0.5	7000-8000	14-18	1.5-5	65	Raj (2020)
Polypropylene (PP)	0.25	0.3-0.5	2000-3000	7-9	30-40	80	Raj (2020)

2.7 Influence of Storage Conditions on Tomatoes

After harvesting, tomatoes are subjected to storage. The storage conditions, i.e. the temperature and relative humidity, have a significant effect on the quality attributes of the tomatoes in storage (El-Ishaq and Obirinakem, 2015; Sualeh *et al.*, 2016), and the outcome of these conditions within a storage facility is crucial for extending their shelf-life.

Temperature is an environmental factor that plays a vital role in the quality and shelf-life of horticultural crops. It influences the enzyme activity and increases the chance of spoilage (Lee and Kader, 2000; Wu, 2010; Mekonnen, 2017a). It is the sole factor that controls the metabolic processes; hence, it is a significant contributor to food deterioration (Mekonnen, 2017a). If stored at an ambient temperature, tomatoes have a short life-span of about 10 to 14 days (Shezi, 2016a; Haile and Safawo, 2018). Ambient temperatures activate the production of ethylene, which intensifies the respiration rate and consequently affects the metabolic rate of the fruit (Asem *et al.*, 2016a). González-Casado *et al.* (2018) showed that there is a direct correlation between the surrounding temperature and the ripening and decay rate of the fruit. Wu (2010) reported that, where there is a 10ºC temperature increment, the respiration rate in the fruit is doubled. Kader (2008) also reported that the effect of temperature on the respiration rate might go as far as to triple, or even quadruple. Most fresh fruits are stored at relatively low temperatures to satisfy the customer requirements for a high-quality product. Žnidarčič and Požrl (2006) observed that the development of colour in stored tomatoes is related to the surrounding temperature and that the enzymatic activity is decreased at a low temperature, and hence the colour changes. Mekonnen (2017a) reported that, fresh tomatoes should be kept at temperatures that are as low as possible, from off-field to consumption. Other studies have reported that a temperature of around 12°C is the best storage temperature for tomatoes (Žnidarčič and Požrl, 2006; González-Casado *et al.*, 2018). However, the ideal temperature for storing freshly-harvested tomatoes will vary according to the geographic region, the cultivar, the packaging type and the pre-treatments before packaging.

Most horticultural crops must be stored in storage facilities that maintain a high relative humidity. If the relative humidity is high, the vapour pressure deficit decreases and less water is lost into the atmosphere (Workneh and Osthoff, 2010; Getinet *et al.*, 2011). An unfavourable variance in the vapour pressure deficit between the stored commodity and the storage environment results in the movement of water molecules from the fresh product into its surroundings, which causes a loss in weight (Workneh and Osthoff, 2010; Shezi, 2016a). In general, the relative humidity in the surrounding environment should always be above 90% for horticultural crops. These conditions reduce the transpiration rate of the fresh product, hence minimising the weight loss and wilting (Kola *et al.*, 2015). A relative humidity of 85% is optimum for tomatoes. If the relative humidity in the atmosphere is too high, it can result in the development of fungi due to water condensation on the surface of the tomato (Pinheiro *et al.*, 2013). The importance of packaging goes hand-in-hand with the storage conditions; therefore, there is a need to evaluate the tomato quality attributes that are affected by different packaging materials and storage.

2.8 The Quality Measurements of the Tomato Fruit

The quality indices of fruit and vegetables are significant, as they influence the preferences of consumers. Many factors, both good and bad, influence the quality attributes of tomatoes. However, this project will focus on the colour, firmness, Total Soluble Solids (TSS), titratable acidity (TTA), pH, total sugars, total phenolic content and microbial growth.

2.8.1 Colour change

Colour is the primary quality attribute that consumers use for selecting tomatoes in the marketplace. The pigments responsible for colour include chlorophyll for green, carotenoids for yellow, orange and red, as well as gelatins for red and flavonoids for yellow (Barrett *et al.*, 2010). The ratio of chlorophyll to carotenoids determines the colour of the tomatoes. The synthesis of carotenoids supersedes the degradation of chlorophyll during ripening. The two critical carotenoids in tomatoes are β-carotene and lycopene (van Roy *et al.*, 2017), which are strongly associated with orange and red colour, respectively. Colour changes in tomatoes result from the skin pigments that vary with the level of maturity and ripening (Maftoonazad and Ramaswamy, 2008; Kassim, 2013; Takahashi *et al.*, 2013). To a farmer, the colour is a significant sign of the maturity of a tomato (Kerkhofs *et al.*, 2005; Tilahun *et al.*, 2017b). Colour has been used to determine its ripeness, firmness and nutritional status (Sharma *et al.*, 2020a), it influences consumers in the market and is perceived to be a measure of quality (Asem *et al.*, 2016b; Mekonnen, 2017a). The colour change can be qualitatively monitored by using visual colour rating charts or sensing platforms (Kola *et al.*, 2015; Kasampalis *et al.*, 2020). A colourimeter and a chromameter are commonly used to measure the colour of tomatoes (Tilahun *et al.*, 2017b). Mekonnen (2017a) reported that the lightness (L*) and hue angle (h°) values are influenced by the storage period and temperature. Gebeyehu (2018) reported that the storage period and packaging materials affect the colour change. According to Kasampalis *et al.* (2020), the parameters connected to colour change estimation are as follows: L^* = brightness or lightness, a^* = greenness or redness, and b^* = blueness or yellowness.

Table 2.3 Ripening stages of the tomato fruit (Mekonnen, 2017a)

Ripening stage	Class	Description
1	Mature green	Appear completely light to dark-green, but mature
2	Breaker	Pink, red or greenish-yellow starts to appear; less than 10%
3	Turning	More than 10% of greenish-yellow colour, red less than 30%, orange-yellow or pink
4	Pink	Between 30-60% of the external surface appears pink or red
5	Light-red	Between 60-90% of the external surface appears pinkish-red or red
6	Red	More than 90% of the surface is red; complete ripeness and aggregate red

2.8.2 Tomato firmness

The firmness of a tomato is a textural property that relates to its solidness, and it is a significant quality characteristic that is used by consumers when selecting tomatoes (Aked, 2002; Batu, 2004; Chaïb *et al.*, 2007). In addition, the firmness is a surface quality that can be associated with its storage life and deformation (Yurtlu and Erdoğan, 2005; Brashlyanova *et al.*, 2014). The softness of the tomato tissue is associated with the respiratory rate and the subsequent loss of turgor pressure and degradation of polysaccharides (Brashlyanova *et al.*, 2014). The changes in pH during softening is a function of storage conditions (Spagna *et al.*, 2005). Temperature is the primary factor that influences the texture of tomatoes (Chiesa *et al.*, 1998; Lee *et al.*, 2008), and a higher storage temperature yields a decreased firmness (Brackmann *et al.*, 2007; Lee *et al.*, 2008; Brashlyanova *et al.*, 2014). There is limited information on the effects of the interaction between the storage temperature and packaging materials on the firmness of tomatoes.

2.8.2.1 Puncture test

The puncture test is one of the most effective procedures for determining the quality of tomatoes. It is a destructive method and is regarded as the most precise method for evaluating their firmness and quality (Kassim, 2013; Zewdie, 2017). It is a force evaluating technique that involves mass, length and time (Barrett *et al.*, 2010; Li *et al.*, 2015), which measures the force and deformation required to punch or penetrate a probe into the fruit to a displacement that causes failure. Horticulturists have used many measurement forms, which vary from a hand-held puncture in the fields to laboratory-based Texture Analyzers (Aguilar-Méndez *et al.*, 2008). The Universal Instron is widely used to measure the firmness of fruit and vegetables (Ali, 1998; Li *et al.*, 2015). The texturometer is another standard tool that is applied to measure the firmness of the whole fruit or uniformly-sliced materials (Aurand *et al.*, 2012). The exturometer uses a cylindrical pressure probe, the size of which ranges from 2-6 mm in diameter. The cylindrical probe is placed perpendicular to the axis of the tomato and allows a 6 to 8 mm displacement of the fruit (Zewdie, 2017). The resulting force, or displacement, that is necessary to punch the cuticle and epidermis layer of the fruit is directly linked to its elasticity, stiffness and firmness (Aurand *et al.*, 2012). During a puncture test, the material or fruit's peak force is considered to be representative of the material, or the hardness of the fruit. The puncture test was applied to apple fruit studies by Harker *et al.* (2002) and to tomatoes by Biswas *et al.* (2014).

2.8.2.2 Compression test

The compression test measures the force at the break, the deformation, theenergy at the break, the degree of elasticity and the modulus of elasticity that is needed to compress a fruit or vegetable between two separate steel sheets, until its initial diameter has decreased by 3% (Aurand *et al.*, 2012). These textural properties are a response of the whole fruit. There are many applications of flat-plate compression for fruit and vegetables. Li *et al.* (2012) applied flat-plate compression to test the mechanical properties of the tomato exocarp, mesocarp and locular gel tissues and to accurately predict the distribution of the internal stress of tomatoes when they are subjected to external forces. Sirisomboon *et al.* (2012) also evaluated the textural mechanical properties of tomatoes by using the flat-plate compression test to detect the firmness and rigidity of the whole tomato. Flat-plate compression can be conducted by using a texture analyzer or a universal testing machine. The peak compressive load, deformation and elasticity are used to determine the textural class pattern that is related to its maturity and storage period.

2.8.2.3 Kramer shear or shear press

The Kramer shear test is also a texture evaluation technique that is used chiefly for fruit and vegetables (Kassim, 2013). It simulates biting small food pieces. The Kramer shear test uses a shear-compression cell and the shear occurs on the measured fruit. The sample weight is measured and loaded to a test cell that has horizontal plates at the bottom. A set of five blades (3 mm) that are equally spaced passes through the test cell, which presses and shears the sample material. As the blades of the Kramer cell moves down, the food specimen is compressed. As the shearing continues, the food is extruded upwards between the blades and down through the slots at the bottom of the cell. As the blades reach the bottom slots, the specimen is sheared. The force required to move the blades relates to the texture. The force at various test stages (compression, extrusion and shear) provides additional information about the texture properties. The result obtained is a force-time curve, which shows how the specimen reacts to the chewing motion. The Kramer shear can be applied to a range of raw, canned and cooked fruit and vegetables. Barret *et al.* (1998) reported that it is also an effective tool for measuring the force of tomato products.

2.8.3 Physiological weight loss

Tomatoes have a high moisture content, which makes water a significant component of their weight (Pinheiro *et al.*, 2013). Weight loss is a process related to the post-harvest loss of moisture, which results in the softening of tissues and turgor loss (Mekonnen, 2017a). Weight loss is a percentage of the initial sample weight. Misra *et al.* (2014) reported that around 3 to 5% of post-harvest fruit losses are attributed to the loss of carbon dioxide escaping from the fruit's cells. Water vapour loss and the circulation of gases on the surface of the fruit occur through the gaseous pores and cause a loss in weight (Haile and Safawo, 2018). The water loss causes the appearance of shrinkage, softening and drying and is significantly influenced by the storage conditions, such as the relative humidity and temperature (Gebeyehu 2018). Workneh *et al.* (2009) explained that storing tomatoes under high temperature and low relative humidity conditions increases the rate of respiration in the fruit, thus enhancing the loss of water through transpiration, which results in a loss of weight in the fruit. In the work of Gebeye (2018), weight loss resulted from post- and pre-harvest treatments, such as packaging and storage conditions.

2.8.4 Total titratable acidity and pH

The Titratable Acidity (TA) is the volume of a base that is required to neutralize the acidity of the fruit sample juice. It brings the pH to its neutral point (pH=7) or a considerably alkaline value below pH 8, as quantified by the International Standard Organisation (ISO) (Anthon *et al.*, 2011; Kassim, 2013). TA of the fruit is associated with fruit acid and yields the perception of sweetness and sourness (Tilahun *et al.*, 2017b). The titratable acidity is the most commonly-used method for determining sweetness and sourness. Sodium hydroxide (0.1 N of NaOH) is used as a chemical reagent base; it is added to the fruit juice in controlled incremental amounts (Kola *et al.*, 2015). During the addition of the base, hydrogen ions are exchanged with cations, which leads to an increased pH. Anthon *et al.* (2011) reported that the titratable acidity and maturity stage are highly correlated. The titratable acidity decreases with the increased maturity stage of tomatoes (Cocetta *et al.*, 2020). The pH is increased in fully-ripe tomatoes. Dhall and Singh (2013) also investigated the effects of ethaphon and ethylene on tomatoes and reported that their acidity is decreased with increased ripening. The decrease can be attributed to the utilization of organic acids during a pyruvate decarboxylation reaction, which occurs during the ripening stage of the tomato (Pool *et al.*, 1972; Dhall *et al.*, 2009; Dhall and Singh, 2013). The pH of tomatoes differs according to the type, variety and cultivar, but not by much. It is measured by using a pH scale and ranges from 0 to 14, with 7 being regarded as a neutral pH state (Dufera *et al.*, 2021). The tomato pH varies between 3.5 and 4.9, at most; hence there is not much difference between them (Gebeyehu 2018).

2.8.5 Total soluble solids

The Total Soluble Solids (TSS) is a significant parameter that is used for evaluating the maturity of fruit (Li *et al.*, 2016; Shezi, 2016a). It measures the sum of the sugar content (hexoses and sucrose: 65%), the acids (malate and citrate: 13%) and other trace elements of flavour (Salunkhe *et al.*, 2002; Kola *et al.*, 2015; Liu *et al.*, 2020). A TSS of between 4.8 to 8.4°Brix characterizes high-quality tomatoes (Nasrin *et al.*, 2008). There are many ways of to measuring TSS, but the most common is the digital refractometer, which gives a reading in the degree Brix (°Brix) (Kader, 2008; Beckles, 2012; Floren *et al.*, 2016). The °Brix is an indicator of the percentage of TSS, and it expresses the amount of total soluble solids to water in the fruit juice. Salunkhe *et al.* (2002) explained that the sugar content increases uniformly, from small green tomatoes to large, red-ripened tomatoes; hence, the TSS is expected to increase with the ripening stage. Coyago-Cruz *et al.* (2019) reported that in a variety of cherry tomatoes, the TSS ranged from 3.3 to 5.7°Brix. However, these values were lower than the TSS values recorded in round tomatoes, which ranged from 5.2 to 8.8°Brix (Figàs *et al.*, 2015; Flores *et al.*, 2017b) (Table 2.4). In other studies, a TSS range of 5.5 to 7.4°Brix was defined for the cherry pera varieties (Figàs *et al.*, 2015; Flores *et al.*, 2017b; Coyago-Cruz *et al.*, 2019). Recent studies have focused more on the non-destructive methods of TSS measurements, which vary from Hyperspectral Imaging (HSI), Nuclear Magnetic Resonance (NMR), X-rays, as well as sonic radiation and vibrations (Teerachaichayut and Ho, 2017; Cakmak, 2019). These methods are less time-consuming and are considered to be more accurate than the traditional digital refractometer. Since the TSS content in tomatoes is subjected to post-harvest handling, the effects of packaging and storage conditions on the TSS need to be evaluated, in order to identify the trends in the post-harvest handling processes.

2.8.6 Total phenolic content

Phenols have been widely reported as the bioactive, cytotoxic activities in vitro and they are antimutagenic in fresh tomatoes. Their chemical composition varies, depending on the tomato tissue, the type of tomato, the cultivar and the geometric region, and it is vastly affected by the handling and storage methods (Barros *et al.*, 2012; Perea-Domínguez *et al.*, 2018). They may exist in a free, conjugated soluble and insoluble-bound form in fruit. Phenols have become the current subject matter amongst food scientists. The analysis and evaluation of phenolic compounds allows a complete bioactivity characterisation (Barros *et al.*, 2012; Ambigaipalan *et al.*, 2016; Ayoub *et al.*, 2016). Perea-Domínguez *et al.* (2018) mentioned that although the interest in phenols has grown, there is still no detailed information on conjugated, soluble and bound phenolic compounds, which therefore intensifies the need for comprehensively analysing these bioactive activities, as they are affected by packaging and storage methods.

2.9 Microbial Analysis (Bacterial and Fungal Growth Count)

The higher water content (~95%) in tomatoes makes them progressively susceptible to decay, due to the activity of different microorganisms (Ghosh, 2009). Microbial infestations occur during harvesting, post-harvest handling, in storage facilities, transportation and processing. These infestations are primarily recorded in developing countries (Chinakwe *et al.*, 2019). Exposing tomatoes in open baskets and benches in the markets is a major contributing factor to bacterial contamination in most African countries (Bello *et al.*, 2016). The infected and damaged tomatoes can harm human health (Baiyewu *et al.*, 2007; Bello *et al.*, 2016; Obeng *et* *al.*, 2018). Identifying micro-organisms on the surface of tomatord requires that the micro-organism be isolated from its host surface and be allowed to grow under specific controlled conditions, such as agar or fungal media (Ghosh, 2009; Agbabiaka, 2015; Ogwu, 2019). Isolation media are then prepared and plated, by using the serial dilution method of 10^0 up to 10^{-6}, depending on the sensitivity of the solution. The plates are then incubated at an ambient temperature to allow the microorganisms to grow. Ghosh (2009) reported that the media should be stored for 48 hours for bacterial growth and up to five days, for fungal growth. A bacterial and fungal count can be determined by using the standard pour plate technique method, in which counts of the colonies can be made after 24 hours for bacteria, and after 72 hours for fungal growth (Agbabiaka, 2015; Ogwu, 2019).

Table 2.4 Titratable acidity, pH, TSS, total sugars, lycopene and Vitamin C in tomatoes

Variety	Acidity (mg/100g)	pH	TSS (°Brix)	Total sugars (g/FW)	Lycopene (mg/100g)	Vitamin C (mg/100g)	Authors
Cherry Pera	0.22	-	5.5-7.4	-	2.8-35	0.90	Flores *et al.* (2017a)
Cher Ami	0.41	-	5.35	-	6.64	-	Dobrin *et al.* (2019)
Roma VF	0.74-0.76	4.0-4.6	4.2-4.48	2.7	0.9-18.1	11.6	(Akanbi and Oludemi, 2004; Frusciante *et al.*, 2007)
Sakura	0.5	-	6.58	12.6	5.4-42.2	-	Duma *et al.* (2016)
Sunstresm	0.49	-	5.26	14.1	16.7	-	Duma *et al.* (2016)
Amarelo	-	-	-	6.62	5.02	16.03	Pinela *et al.* (2012)
Batateiro	-	-	-	5.83	9.49	10.86	Pinela *et al.* (2012)
Comprido	-	-	-	3.91	8.10	16.5	Pinela *et al.* (2012)
Coracao	-	-	-	4.95	9.22	18.56	Pinela *et al.* (2012)
Mongal F1	0.55	3.71	5.51	4..7	-	-	Oboulbiga *et al.* (2017)
Topacio	0.5	3.71	5.02	4.8	-	-	
Heinz 1350	0.84	4.25	4.5	5.4	-	13.9	Tigist *et al.* (2013)
Bishola	0.84	4.36	5.0	5.8	-	14.3	Tigist *et al.* (2013)

2.10 Discussion and Summary

Due to the physiological and biochemical post-harvest changes during storage, tomatoes are highly perishable and are subjected to a rapid quality loss after harvest. Their high water content makes them susceptible to degradative reactions that are biochemical, microbial and enzymatic in nature. As a result, the tomatoes have a shorter shelf-life. The continuous supply of fresh tomatoes to meet the high demand can be achieved by using post-harvest preservation strategies along the supply chain. The strategies include cold chain distribution, as well as storage and packaging treatments. Plastic materials derived from non-biodegradable materials degrade the environment, which poses safety and health concerns. Biodegradable packaging materials can be decomposed by microorganisms in the soil and can be physically degraded by radiation from the sun. Thus, the use of biodegradable materials has stirred up great interest in the food industry (Rensburg *et al.*, 2020). The quality and shelf-life of tomatoes can be described as the function of various factors, such as the packaging treatments, the storage temperature and the storage time. The quality parameters that are commonly used to characterize tomatoes include their colour, firmness, physiological weight loss, total soluble solids, total sugars and phenolics.

A few findings have proved that the temperature and relative humidity significantly affect the quality attributes of tomatoes and can shorten their life-span. The packaging influences their colour, firmness, weight loss, pH and TSS. Generally, fresh products are stored in low-temperature environments to preserve their quality. Given the possibility of chilling injuries, the relative temperature remains a mystery to many researchers. Some have reported the ideal storage temperature as 10°C and 11°C, while others have reported it as 12°C. However, the temperature will vary with the treatments and ripeness. Lycopene and Vitamin C are the two most important antioxidants found in tomatoes. Lycopene represents 80% of the total carotenoids found in tomatoes, and the quantity of lycopene in fresh tomatoes ranges between 0.9-42mg.100g^{-1} of their fresh weight (Duma *et al.*, 2016). Phenols participate in the essential metabolic functioning of the human body. Phenols are susceptible to the tomato's surroundings and are most often used to measure other chemical compounds (Sablani *et al.*, 2006). The reported quantities lie in the range of 0.4-19 mg.100g^{-1} fresh weight of tomatoes (Frusciante *et al.*, 2007). The accumulation of nutrients in a tomato depends on several factors, such as the harvesting time, the cultivar, the post-harvest handling processes, like the packaging and storage conditions, and the geographic growing conditions. However, post-harvest handling, such as packaging and storage, seems to be the focal point. Therefore, controlling these processes is vital in the quest for providing fresh market produce to consumers.

The above overview has discussed tomato production in South Africa, their importance to human health, their packaging and storage conditions. The most crucial points that have been discussed are the post-harvest handling technologies that are employed by the industry to preserve the quality and shelf-life of tomatoes. However, despite these innovative technologies in the fruit industry, there are still knowledge gaps regarding their impact on the quality attributes of tomatoes, particularly under South African geographic conditions. There is insufficient knowledge about their physical, physiological and physicochemical properties, as well as the microbial development within the different tomato packaging materials that are used across the South African supply chain. Therefore, this study aims to evaluate the effects of the different packaging materials and storage conditions on the quality attributes of tomatoes.

2.11 References

Aba, IP, Gana, YM, Ogbonnaya, C and Morenikeji, O. 2012. Simulated transport damage study on fresh tomato (Lycopersicon esculentum) fruits. *Agricultural Engineering International: CIGR Journal* 14(2):119-126.

Aduri, P, Rao, KA, Fatima, A, Kaul, P and Shalini, A. 2019. Study of Biodegradable Packaging Material Produced from Scoby. *Research Journal of Life Sciences, Bioinformatics, Pharmaceutical and Chemical Sciences* 5(3):389-405.

Agbabiaka, T. 2015. Microbial deterioration of tomato fruit (Lycopersicon esculentum) sold in three popular markets in Ilorin, Kwara State, Nigeria. *Fountain Journal of Natural and Applied Sciences* 4(1):10-18.

Aguilar-Méndez, MA, Martín-Martínez, ES, Tomás, SA, Cruz-Orea, A and Jaime-Fonseca, MR. 2008. Gelatine–starch films: Physicochemical properties and their application in extending the post-harvest shelf-life of avocado (Persea americana). *Journal of the Science of Food and Agriculture* 88(2):185-193.

Ahmed, M and Tariq, M. 2014. Enhancing post-harvest storage life of tomato (Lycopersicon esculentum Mill.) cv. Rio Grandi using calcium chloride. *American-Eurasian Journal of Agricultural and Amp; Environmental Sciences* 14(2):143-149.

Akanbi, C and Oludemi, F. 2004. Effect of processing and packaging on the lycopene content of tomato products. *International Journal of Food Properties* 7(1):139-152.

Aked, J. 2002. Maintaining the post-harvest quality of fruits and vegetables. In: ed. Jongen, W, *Fruit and Vegetable Processing. Improving Quality* Woodhead Publishing Ltd, Cambridge, United Kingdom.

Ali, B. 1998. Some factors affecting on determination and measurement of tomato firmness. *Turkish Journal of Agriculture Forestry* 22(4):411-418.

Almenar, E, Samsudin, H, Auras, R, Harte, B and Rubino, M. 2008. Postharvest shelf-life extension of blueberries, using a biodegradable package. *Food Chemistry* 110(1):120-127.

Ambigaipalan, P, de Camargo, AC and Shahidi, F. 2016. Phenolic compounds of pomegranate by-products (outer skin, mesocarp, divider membrane) and their antioxidant activities. *Journal of Agricultural and Food Chemistry* 64(34):6584-6604.

Anthon, GE, leStrange, M and Barrett, DM. 2011. Changes in pH, acids, sugars and other quality parameters during extended vine holding of ripe processing tomatoes. *Journal of the Science of Food Agriculture* 91(7):1175-1181.

Arab, L and Steck, S. 2000. Lycopene and cardiovascular disease. *The American Journal of Clinical Nutrition* 71(6):1691-1695.

Arah, I. 2015. An Overview of Post-Harvest Losses in Tomato Production in Africa: Causes and Possible Prevention Strategies. *Journal of Biology, Agriculture and Healthcare* 5(1):78-88.

Arah, IK, Kumah, E, Anku, E and Amaglo, H. 2015. An overview of post-harvest losses in tomato production in Africa: causes and possible prevention strategies. *Journal of Biology, Agriculture Healthcare* 5(16):78-88.

Asem, A, Arisha, H, Bardisi, A and Ibraheim, SKA. 2016a. Effect of some Packaging Materials on Quality Attributes of Tomato Fruits (Solanum Lycopersicum L.) During Cold Storage and after Shelf-Life Period. *Middle East Journal of Agriculture Research* 5(4):687-700.

Aurand, R, Faurobert, M, Page, D, Maingonnat, J-F, Brunel, B, Causse, M and Bertin, N. 2012. Anatomical and biochemical trait network underlying genetic variations in tomato fruit texture. *Euphytica* 187(1):99-116.

Auras, RA, Singh, SP and Singh, JJ. 2005. Evaluation of oriented poly (lactide) polymers vs existing PET and oriented PS for fresh food service containers. *Packaging Technology and Science: An International Journal* 18(4):207-216.

Ayoub, M, de Camargo, AC and Shahidi, F. 2016. Antioxidants and bioactivities of free, esterified and insoluble-bound phenolics from berry seed meals. *Food Chemistry* 197(1):221-232.

Azeez, L, Adebisi, SA, Oyedeji, AO, Adetoro, RO and Tijani, KO. 2019. Bioactive compounds' contents, drying kinetics and mathematical modelling of tomato slices influenced by drying temperatures and time. *Journal of the Saudi Society of Agricultural Sciences* 18(2):120-126.

Baiyewu, R, Amusa, N, Ayoola, O and Babalola, O. 2007. Survey the postharvest diseases and aflatoxin contamination of marketed Pawpaw fruit (Carica papaya L.) in South-Western Nigeria. *African Journal of Agricultural Research* 2 (4): 178-181.

Barrett, DM, Beaulieu, JC and Shewfelt, R. 2010. Colour, flavour, texture, and nutritional quality of fresh-cut fruits and vegetables: desirable levels, instrumental and sensory measurement, and the effects of processing. *Critical Reviews in Food Science and Nutrition* 50(5):369-389.

Barros, L, Dueñas, M, Pinela, J, Carvalho, AM, Buelga, CS and Ferreira, IC. 2012. Characterization and quantification of phenolic compounds in four tomatoes (Lycopersicon esculentum L.) farmers' varieties in north-eastern Portugal home gardens. *Plant Foods for Human Nutrition* 67(3):229-234.

Batu, A. 2004. Determination of acceptable firmness and colour values of tomatoes. *Journal of Food Engineering* 61(3):471-475.

Beckles, DM. 2012. Factors affecting the postharvest soluble solids and sugar content of tomato (Solanum Lycopersicum L.) fruit. *Postharvest Biology Technology* 63(1):129-140.

Bello, OB, Ullah, H, Olawuyi, O and Adebisi, O. 2016. Microorganisms causing post-harvest tomato (Solanum Lycopersicum L.) fruit decay in Nigeria. *Scientia* 13(2):93-96.

Bergougnoux, V. 2014. The history of tomato: From domestication to biopharming. *Biotechnology Advances* 32(1):170-189.

Bharti, S, Rani, N, Krishnamurthy, B and Arya, DS. 2014. Pre-clinical evidence for the pharmacological actions of naringin: a review. *Planta Med* 80(6):437-51.

Biswas, P, East, AR, Hewett, EW and Heyes, JA. 2014. Interpreting textural changes in low temperature stored tomatoes. *Postharvest Biology and Technology* 87:140-143.

Bommareddy, A, Eggleston, W, Prelewicz, S, Antal, A, Witczak, Z, Mccune, DF and Vanwert, AL. 2013. Chemoprevention of prostate cancer by major dietary phytochemicals. *Anti-cancer Research* 33(10):4163-4174.

Brackmann, A, Steffens, CA, Andriolo, JL and Pinto, JAV. 2007. Storage of tomato cultivar Cronus as a function of ripening stage and temperature. *Ciência Rural* 37(5):1295-1300.

Brashlyanova, B, Zsivánovits, G and Ganeva, D. 2014. Texture quality of tomatoes as affected by different storage temperatures and growth habits. *Emirates Journal of Food and Agriculture* 26(9):750-756.

Cakmak, H. 2019. 10 - Assessment of fresh fruit and vegetable quality with non-destructive methods. In: ed. Galanakis, CM, *Food Quality and Shelf Life*. Academic Press, Cambridge, Massachusetts, United States.

Campestrini, LH, Melo, PS, Peres, LEP, Calhelha, RC, Ferreira, ICFR and Alencar, SM. 2019. A new variety of purple tomato as a rich source of bioactive carotenoids and its potential health benefits. *Heliyon* 5(11):e02831.

Chaïb, J, Devaux, M-F, Grotte, M-G, Robini, K, Causse, M, Lahaye, M and Marty, I. 2007. Physiological relationships among physical, sensory and morphological attributes of texture in tomato fruits. *Journal of Experimental Botany* 58(8):1915-1925.

Chiesa, L, Diaz, L, Cascone, O, Panak, K, Camperi, S, Frezza, D and Fraguas, A.1998. Texture changes on normal and long shelf-life tomato (Lycopersicon esculentum Mill.) fruit ripening. *International Postharvest Science Conference Postharvest* 96(464):488-489.

Chinakwe, E, Ibekwe, V, Nwogwugwu, U, Onyemekara, N, Ofoegbu, J, Mike-Anosike, E, Emeakaraoha, M, Adeleye, S and Chinakwe, P. 2019. Microbial Population Changes in the Rhizosphere of Tomato Solanum Lycopersicum Varieties during Early Growth in Greenhouse. *Malaysian Journal of Sustainable Agriculture (MJSA)* 3(1):23-27.

Claye, SS, Idouraine, A and Weber, CW. 1996. Extraction and fractionation of insoluble fibre from five fibre sources. *Food Chemistry* 57(2):305-310.

Costa, JM and Heuvelink, E. 2018. The global tomato industry. In: ed. Heuvelink, E, *Tomatoes*. CAB, Boston, USA.

Coyago-Cruz, E, Corell, M, Moriana, A, Mapelli-Brahm, P, Hernanz, D, Stinco, CM, Beltrán-Sinchiguano, E and Meléndez-Martínez, AJ. 2019. Study of commercial quality parameters, sugars, phenolics, carotenoids and plastids in different tomato varieties. *Food Chemistry* 277(1):480-489.

Cronjé, N, van der Merwe, I and Müller, I-M. 2018. Household food waste: A case study in Kimberley, South Africa. *Journal of Consumer Sciences* 46(1):1-9.

Cyras, VP, Commisso, MS, Mauri, AN and Vázquez, A. 2007. Biodegradable double-layer films based on biological resources: Polyhydroxybutyrate and cellulose. *Journal of Applied Polymer Science* 106(2):749-756.

D'Elia, L, Barba, G, Cappuccio, FP and Strazzullo, P. 2011. Potassium intake, stroke, and cardiovascular disease a meta-analysis of prospective studies. *Journal of the American College of Cardiology* 57(10):1210-1219.

D’Angelo, M, Zanor, MI, Burgos, E, Asprelli, PD, Boggio, SB, Carrari, F, Peralta, IE and Valle, EM. 2019. Fruit metabolic and transcriptional programs differentiate among Andean tomato (Solanum Lycopersicum L.) accessions. *Planta* 250(6):1927-1940.

DAFF. 2010. A Profile of The South African Tomato Market Value Chain. [Internet]. Available from: www.nda.agric.za/docs/amcp/tomatomvcp2010-11.pdf. [Accessed: 23 January 2019].

DAFF. 2013. *South African varieties list as maintained by the registrar of plant improvement* (p. 25). Pretoria, RSA. National Department of Agriculture.

DAFF. 2014. *Production guidelines for tomato* (p. 22). National Department of Agriculture. Pretoria, South Africa

DAFF. 2017. A profile of the South Africa tomato market value chai. [Internet]. Available from: www.nda.agric.za/doaDev/sideMenu/Marketing/Annual%20Publications/Commodity%20Profiles/field%20crops/Tomato%20Market%20Value%20Chain%20Profile%202017.pdf [Accessed: 23 January 2020].

DAFF. 2019. *Directorate Plant Production*. Department of Agriculture, Forestry and Fisheries, Pretoria, RSA.

Dhall, R, Mahajan, B and Dhatt, A.2009. Effect of ethephon and ethylene gas on ripening and quality of detached winter tomato. *VI International Postharvest Symposium* 877:1025-1030.

Dhall, R and Singh, P. 2013. Effect of ethephon and ethylene gas on ripening and quality of tomato (Solanum Lycopersicum L.) during cold storage. *Journal of Nutrition Food Sciences* 3(6):1-7.

Di Paola Naranjo, RD, Otaiza, S, Saragusti, AC, Baroni, V, Carranza, AdV, Peralta, IE, Valle, EM, Carrari, F and Asis, R. 2016. Hydrophilic antioxidants from Andean tomato landraces assessed by their bioactivities in vitro and in vivo. *Food Chemistry* 206:146-155.

Dikgang, J, Leiman, A and Visser, M. 2012. Analysis of the Plastic Bag Levy in South Africa. *Resources, Conservation and Recycling* 66(1):59–65.

Directorate Marketing. 2015. *A profile of the South African tomato market value chain.* Department of Agriculture, Forestry and Fisheries, Pretoria, South Africa.

Dobrin, A, Nedelus, A, Bujor, O, Mot, A, Zugravu, M and Badulescu, L. 2019. Nutritional Quality Parameters of the Fresh Red Tomato Varieties Cultivated in Organic System. *Scientific Papers. Series B, Horticulture* 63(1):1-5.

Domínguez, I, Ferreres, F, del Riquelme, FP, Font, R and Gil, MI. 2012. Influence of preharvest application of fungicides on the postharvest quality of tomato (Solanum Lycopersicum L.). *Postharvest Biology and Technology* 72(1):1-10.

Dufera, LT, Hofacker, W, Esper, A and Hensel, O. 2021. Physicochemical quality of twin layer solar tunnel dried tomato slices. *Heliyon* 7(5):e07127.

Duma, M, Alsina, I, Dubova, L and Erdberga, I. 2016. Chemical composition of tomatoes depending on the stage of ripening. *Chemical Technology* 66(1):24-28.

El-Ishaq, A and Obirinakem, S. 2015. Effect of Temperature and Storage on Vitamin C Content in Fruits Juice. *International Journal of Chemical and Biomolecular Science* 1(2):17-21.

Fadiji, T, Berry, TM, Coetzee, CJ and Opara, UL. 2018. Mechanical design and performance testing of corrugated paperboard packaging for the postharvest handling of horticultural produce. *Biosystems Engineering* 171:220-244.

Fagundes, C, Moraes, K, Pérez-Gago, MB, Palou, L, Maraschin, M and Monteiro, A. 2015. Effect of active modified atmosphere and cold storage on the postharvest quality of cherry tomatoes. *Postharvest Biology and Technology* 109:73-81.

FAO. 2019a. *The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction*. Rome, Italy.

FAOSTAT. 2017. Food and agriculture data. [Internet]. Available from: http://www.fao.org/faostat/en/#data/QC. [Accessed: 12 May 2020].

Farmer's Weekly. 2017. The cost of South Africa's food loss and waste. [Internet]. Caxton Magazines. Available from: https://www.farmersweekly.co.za/opinion/by-invitation/cost-south-africas-food-loss-waste/. [Accessed: 23 January 2019].

Fekete, K, Berti, C, Trovato, M, Lohner, S, Dullemeijer, C, Souverein, OW, Cetin, I and Decsi, T. 2012. Effect of folate intake on health outcomes in pregnancy: a systematic review and meta-analysis on birth weight, placental weight and length of gestation. *Nutritional Journal* 11(1):75-84.

Fiedor, J and Burda, K. 2014. Potential role of carotenoids as antioxidants in human health and disease. *Nutrients* 6(2):466-488.

Figàs, MR, Prohens, J, Raigón, MD, Fita, A, García-Martínez, MD, Casanova, C, Borràs, D, Plazas, M, Andújar, I and Soler, S. 2015. Characterization of composition traits related to organoleptic and functional quality for the differentiation, selection and enhancement of local varieties of tomato from different cultivar groups. *Food Chemistry* 187:517-524.

Floren, HK, Sischo, WM, Crudo, C and Moore, DA. 2016. Technical note: Use of a digital and an optical Brix refractometer to estimate total solids in milk replacer solutions for calves. *Journal of Dairy Science* 99(9):7517-7522.

Flores, P, Sánchez, E, Fenoll, J and Hellín, P. 2017a. Genotypic variability of carotenoids in traditional tomato cultivars. *Food Research International* 100:510-516.

Flores, P, Sánchez, E, Fenoll, J and Hellín, P. 2017b. Genotypic variability of carotenoids in traditional tomato cultivars. *Food Research International* 100 (1):510-516.

Freeman, BB and Reimers, K. 2011. Tomato consumption and health: emerging benefits. *American Journal of Lifestyle Medicine* 5(2):182-191.

Frusciante, L, Carli, P, Ercolano, MR, Pernice, R, Di Matteo, A, Fogliano, V and Pellegrini, N. 2007. Antioxidant nutritional quality of tomato. *Molecular Nutrition Food Research International* 51(5):609-617.

Garuba, T, Mustapha, O and Oyeyiola, G. 2018. Shelf-life and proximate composition of tomato (Solanum Lycopersicum L.) fruits as influenced by storage methods. *Ceylon Journal of Science* 47(4):387-393.

Gatahi, DM. 2020. Challenges and Opportunities in Tomato Production Chain and Sustainable Standards. *International Journal of Horticultural Science and Technology* 7(3):235-262.

Gebeyehu, AS. 2018. The Effects Packaging Materials on Post-harvest Quality of Tomato (Solanum Lycopersium). *Journal of Natural Sciences Research* 8(11):97-103.

Getinet, H, Workneh, TS and Woldetsadik, K. 2011. Effect of maturity stages, variety and storage environment on the sugar content of tomato stored in multiple pads evaporative cooler. *African Journal of Biotechnology* 10(80):18481-18492.

Ghosh, A. 2009. Identification of microorganisms responsible for spoilage of tomato (Lycopersicon esculentum) fruit. *Journal of Phytology* 1(6):414-416.

González-Casado, S, Martín-Belloso, O, Elez-Martínez, P and Soliva-Fortuny, R. 2018. Induced accumulation of individual carotenoids and quality changes in tomato fruits treated with pulsed electric fields and stored at different post-treatments temperatures. *Postharvest Biology and Technology* 146:117-123.

Guil-Guerrero, J and Rebolloso-Fuentes, M. 2009. Nutrient composition and antioxidant activity of eight tomato (Lycopersicon esculentum) varieties. *Journal of Food Composition Analysis* 22(2):123-129.

Haile, A and Safawo, T. 2018. Shelf life and quality of tomato (Lycopersicon esculentum Mill.) fruits as affected by different Packaging Materials. *African Journal of Food Science* 12(2):21-27.

Harker, FR, Stec, MG, Hallett, IC and Bennett, CL. 1997. Texture of parenchymatous plant tissue: a comparison between tensile and other instrumental and sensory measurements of tissue strength and juiciness. *Postharvest Biology and Technology* 11(2):63-72.

Hedges, J and Lister, C. 2005. *Nutritional attributes of tomatoes*. Veg-Fed, Christchurch, New Zealand.

Hernández, V, Hellín, P, Fenoll, J and Flores, P. 2020. Impact of nitrogen supply limitation on tomato fruit composition. *Scientia Horticulturae* 264:109173.

Hopewell, J, Dvorak, R and Kosior, E. 2009. Plastics recycling: challenges and opportunities. *Philosophical transactions of the Royal Society of London. Series B, Biological Sciences* 364(1526):2115-2126.

Hussein, J, Sanusi, M and Filli, K. 2016. Evaluation of drying methods on the content of some bio-actives (lycopene,-carotene and ascorbic acid) of tomato slices. *African Journal of Food Science* 10(12):359-367.

Idah, P, Ajisegiri, E and Yisa, M. 2007. Fruits and vegetables handling and transportation in Nigeria. *Journal of Technology* 10(3):175-183.

Ivonkovic, A, Zeljko, K, Talic, S and Lasic, M. 2017. Biodegradable packaging in the food industry. *Journal of Food Safety and Food Quality* 68(2):26-38.

Jafari, SM, Jabari, SS, Dehnad, D and Shahidi, SA. 2017. Effects of thermal processing by nanofluids on Vitamin C, total phenolics and total soluble solids of tomato juice. *Journal of Food Science and Technology* 54(3):679-686.

Kader, AA. 2008. Flavour quality of fruits and vegetables. *Journal of the Science of Food and Agriculture* 88(11):1863-1868.

Kantola, M and Helen, H. 2001. Quality changes in organic tomatoes packaged in biodegradable plastic films. *Journal of Food Quality* 24(2):167-176.

Karam, MC, Petit, J, Zimmer, D, Djantou, EB and Scher, J. 2016. Effects of drying and grinding in production of fruit and vegetable powders: A review. *Journal of Food Engineering* 188:32-49.

Kasampalis, DS, Tsouvaltzis, P and Siomos, AS. 2020. Chlorophyll fluorescence, non-photochemical quenching and light-harvesting complex as alternatives to colour measurement, in classifying tomato fruit according to their maturity stage at harvest and in monitoring postharvest ripening during storage. *Postharvest Biology and Technology* 161:111036.

Kassim, A. 2013. Evaluating the effects of pre-packaging, packaging and varying storage environment treatments on the quality of avocados (Persea Americana mill.). Unpublished thesis, School of Engineering, College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Kerkhofs, N, Lister, C and Savage, G. 2005. Change in colour and antioxidant content of tomato cultivars following forced-air drying. *Plant Foods for Human Nutrition* 60(3):117-121.

Kitinoja, L. 2016. *Innovative Approaches to Food Loss and Waste Issues. Frontier Issues Brief submitted to the Brookings Institution's Ending Rural Hunger project.* Frontier Issues Brief, submitted to the Brookings Institution's Ending Rural Hunger Project

Koide, S and Shi, J. 2007. Microbial and quality evaluation of green peppers stored in biodegradable film packaging. *Food Control* 18(9):1121-1125.

Kola, O, Simsek, M, Duran, H and Bozkir, H. 2015. HPLC determination of carotenoid, organic acid, and sugar content in Pepino (Solanum Muricatum) fruit during the ripening period. *Chemistry of Natural Compounds* 51(1):132-136.

Law, KL. 2017. Plastics in the marine environment. *Annual Review of Marine Science* 9(1):205-229.

Lee, SK and Kader, AA. 2000. Preharvest and postharvest factors influencing Vitamin C content of horticultural crops. *Postharvest Biology and Technology* 20(3):207-220.

Lee, Y, Kim, J and Chung, D-S. 2008. The effect of 1-MCP (1-Methyl cyclopropane) treatment methods on the ripening process of tomato fruit during postharvest storage. *Horticulture Environment and Biotechnology Advances* 49(3):175-181.

Li, JL, Sun, DW and Cheng, JH. 2016. Recent advances in nondestructive analytical techniques for determining the total soluble solids in fruits: a review. *Comprehensive Reviews in Food Science and Food Safety* 15(5):897-911.

Li, Z, Li, P, Yang, H, Liu, J and Xu, Y. 2012. Mechanical properties of tomato exocarp, mesocarp and locular gel tissues. *Journal of Food Engineering* 111(1):82-91.

Li, Z, Lv, K, Wang, Y, Zhao, B and Yang, Z. 2015. Multi-scale engineering properties of tomato fruits related to harvesting, simulation and textural evaluation. *LWT-Food Science and Technology* 61(2):444-451.

Linnewiel-Hermoni, K, Khanin, M, Danilenko, M, Zango, G, Amosi, Y, Levy, J and Sharoni, Y. 2015. The anti-cancer effects of carotenoids and other phytonutrients reside in their combined activity. *Archives of Biochemistry and Biophysics* 572(1):28-35.

Liu, D, Yang, L, Zhang, J-z, Zhu, G-t, LÜ, H-j, LÜ, Y-q, Wang, Y-l, Cao, X, Sun, T-s, Huang, S-w and Wu, Y-y. 2020. Domestication and breeding changed tomato fruit transcriptome. *Journal of Integrative Agriculture* 19(1):120-132.

Lv, S, Zhang, Y, Gu, J and Tan, H. 2018. Physicochemical evolutions of starch/poly (lactic acid) composite biodegraded in real soil. *Journal of Environmental Management* 228(1):223-231.

Maftoonazad, N and Ramaswamy, H. 2008. Effect of pectin-based coating on the kinetics of quality change associated with stored avocados. *Journal of Food Processing Preservation* 32(4):621-643.

Malherbe, S and Marais, D. 2015. Economics, Yield and Ecology: A Case Study from the South African Tomato Industry. *Outlook on Agriculture* 44(1):37-47.

Maria, AG, Graziano, R, Nicolantonio, D. 2015. Carotenoids: potential allies of cardiovascular health? *Food and Nutrition Research* 59(1):26762.

Marsh, K and Bugusu, B. 2007. Food packaging—roles, materials, and environmental issues. *Journal of Food Science* 72(3):39-55.

Martínez-Romero, D, Bailén, G, Serrano, M, Guillén, F, Valverde, JM, Zapata, P, Castillo, S and Valero, D. 2007. Tools to maintain postharvest fruit and vegetable quality through the inhibition of ethylene action: a review. *Critical Reviews in Food Science Nutrition* 47(6):543-560.

Mashau, M, Moyane, J and Jideani, I. 2012. Assessment of post-harvest losses of fruits at Tshakhuma fruit market in Limpopo Province, South Africa. *African Journal of Agricultural Research* 7(29):4145-4150.

McAdam, B, Brennan Fournet, M, McDonald, P and Mojicevic, M. 2020. Production of Polyhydroxybutyrate (PHB) and Factors Impacting its Chemical and Mechanical Characteristics. *Polymers* 12(12):2908.

Mekonnen, Z. 2017. The Influence of Retailing Packaging on Tomato Quality. *Journal of Nutritional Food Science* 7(604):1-14

Misra, NN, Keener, KM, Bourke, P, Mosnier, J-P and Cullen, PJ. 2014. In-package atmospheric pressure cold plasma treatment of cherry tomatoes. *Journal of Bioscience and Bio-engineering* 118(2):177-182.

Naika, S, de Jeude, J, de Goffau, M, Hilmi, M and van Dam, B. 2005. Cultivation of tomato. In: *Production, Processing Marketing. Revised Edition*, Agromisa/CTA.

Nasrin, T, Molla, M, Hossaen, MA, Alam, M and Yasmin, L. 2008. Effect of postharvest treatments on shelf life and quality of tomato. *Bangladesh Journal of Agricultural Research* 33(4):579-585.

Obeng, FA, Gyasi, PB, Olu-Taiwo, M and Ayeh-kumi, FP. 2018. Microbial Assessment of Tomatoes (Lycopersicon esculentum) Sold at Some Central Markets in Ghana. *BioMed Research International* 1(1):1-7.

Oboulbiga, EB, Parkouda, C, Sawadogo-Lingani, H, Compaoré, EW, Sakira, AK and Traoré, AS. 2017. Nutritional composition, physical characteristics and sanitary quality of the tomato variety Mongol F1 from Burkina Faso. *Food and Nutrition Sciences* 8(4):444-455.

Ogwu, MC. 2019. Effects of storage methods and duration on the microbial composition and load of tomato (Solanum Lycopersicum [L.], Solanaceae) fruits. *Bitlis Eren University Journal of Science and Technology* 9(1):1-7.

Paran, I and van der Knaap, E. 2007. Genetic and molecular regulation of fruit and plant domestication traits in tomato and pepper. *Journal of Experimental Botany* 58(14):3841-3852.

Patanè, C, Malvuccio, A, Saita, A, Rizzarelli, P, Siracusa, L, Rizzo, V and Muratore, G. 2019. Nutritional changes during storage in fresh-cut long storage tomato as affected by bio compostable polylactide and cellulose-based packaging. *LWT-Food Science and Technology* 101:618-624.

Perea-Domínguez, XP, Hernández-Gastelum, LZ, Olivas-Olguin, HR, Espinosa-Alonso, LG, Valdez-Morales, M and Medina-Godoy, S. 2018. Phenolic composition of tomato varieties and an industrial tomato by-product: free, conjugated and bound phenolics and antioxidant activity. *Journal of Food Science and Technology* 55(9):3453-3461.

Pila, N, Gol, NB and Rao, TR. 2010. Post-harvest treatments on physicochemical characteristics and shelf-life of tomato (Lycopersicon esculentum Mill.) fruits during storage. *Journal of Agriculture and Environmental Science* 9(5):470-479.

Pinela, J, Barros, L, Carvalho, AM and Ferreira, ICFR. 2012. Nutritional composition and antioxidant activity of four tomatoes (Lycopersicon esculentum L.) farmer' varieties in north-eastern Portugal home gardens. *Food and Chemical Toxicology* 50(3):829-834.

Pinheiro, J, Alegria, C, Abreu, M, Gonçalves, EM and Silva, CL. 2013. Kinetics of changes in the physical quality parameters of fresh tomato fruits (Solanum Lycopersicum, cv.'Zinac') during storage. *Journal of Food Engineering* 114(3):338-345.

Pohar, KS, Gong, MC, Bahnson, R, Miller, EC and Clinton, SK. 2003. Tomatoes, lycopene and prostate cancer: a clinician's guide for counselling those at risk for prostate cancer. *World Journal of Urology* 21(1):9-14.

Pool, R, Weaver, R and Kliewer, W. 1972. Effect of growth regulators on changes in fruits of Thompson seedless grapes during cold storage. *Amer Soc Hort Sci Journal* 97:67-70.

Puppi, D, Pecorini, G and Chiellini, F. 2019. Biomedical Processing of Polyhydroxyalkanoates. *Bioengineering* 6(4):108.

Rensburg, M, Nkomo, L and Dube, T. 2020. The 'plastic waste era'; social perceptions towards single-use plastic consumption and impacts on the marine environment in Durban, South Africa. *Applied Geography* 114:102132.

Sablani, S, Opara, L and Al-Balushi, K. 2006. Influence of bruising and storage temperature on vitamin C content of tomato fruit. *Journal of Food Agriculture Environment* 4(1):54-60.

Salunkhe, D, Jadhav, S and Yu, M. 2002. Quality and nutritional composition of tomato fruit as influenced by certain biochemical and physiological changes. *Qualitas Plantarum* 24(1-2):85-113.

Sammi, S and Masud, T. 2009. Effect of different packaging systems on the quality of tomato (Lycopersicon esculentum var. Rio Grande) fruits during storage. *International Journal of Food Science Technology* 44(5):918-926.

Sawicka, B. 2019. Post-harvest Losses of Agricultural Produce. *Sustainable Development* 1(1):1-16.

Shahnawaz, M, Sheikh, SA, Soomro, AH, Panhwar, AA, Khaskheli, SG 2012. Quality characteristics of tomatoes (Lycopersicon esculentum) stored in various wrapping materials. *African Journal of Food Science and Technology* 3(5):123-128.

Sharma, L, Ramesh, K, Paul, V and Pandey, R. 2020. Ripening index: a better parameter for colour based assessment of ripening behaviour of tomato fruits. *Plant Physiology Reports* 25(1):171-177.

Sheahan, M and Barrett, CB. 2017. Food loss and waste in Sub-Saharan Africa: A critical review. *Food Policy* 70:1-12.

Shezi, S. 2016. Evaluation of the effects of supply chain routes and pre-storage treatments on the postharvest quality of stored 'Nemo-Netta' tomatoes. Unpublished thesis, School of Engineering, College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Sibomana, CI, Opiyo, AM and Aguyoh, JN. 2015. Influence of soil moisture levels and packaging on postharvest qualities of tomato (Solanum Lycopersicum). *African Journal of Agricultural Research* 10(2):1392-1400.

Sibomana, M, Workneh, T and Audain, K. 2016. A review of postharvest handling and losses in the fresh tomato supply chain: a focus on Sub-Saharan Africa. *Journal of Food Security* 8(2):389-404.

Sibomana, M, Ziena, L, Schmidt, S and Workneh, T. 2017. Influence of transportation conditions and postharvest disinfection treatments on the microbiological quality of fresh market tomatoes (cv. Nemo-Netta) in a South African supply chain. *Journal of Food Protection* 80(2):345-354.

Sirisomboon, P, Tanaka, M and Kojima, T. 2012. Evaluation of tomato textural mechanical properties. *Journal of Food Engineering* 111(4):618-624.

Spagna, G, Barbagallo, RN, Chisari, M and Branca, F. 2005. Characterization of a tomato polyphenol oxidase and its role in browning and lycopene content. *Journal of Agricultural and Food Chemistry* 53(6):2032-2038.

Stahl, W and Sies, H. 2005. Bioactivity and protective effects of natural carotenoids. *Biochimica et Biophysica Acta (BBA)-Molecular Basis of Disease* 1740(2):101-107.

Sualeh, A, Daba, A, Kiflu, S and Mohammed, A. 2016. Effect of storage conditions and packing materials on the shelf life of tomato. *Food Science and Quality Management* 56(1):65-67.

Takahashi, N, Maki, H, Nishina, H and Takayama, K. 2013. Evaluation of Tomato Fruit Color Change with Different Maturity Stages and Storage Temperatures using Image Analysis. *IFAC Proceedings Volumes* 46(4):147-149.

Tan, H-L, Thomas-Ahner, JM, Grainger, EM, Wan, L, Francis, DM, Schwartz, SJ, Erdman, JW and Clinton, SK. 2010. Tomato-based food products for prostate cancer prevention: what have we learned? *Cancer Metastasis Reviews* 29(3):553-568.

Teerachaichayut, S and Ho, HT. 2017. Non-destructive prediction of total soluble solids, titratable acidity and maturity index of limes by near-infrared hyperspectral imaging. *Postharvest Biology and Technology* 133:20-25.

Tigist, M, Workneh, TS and Woldetsadik, K. 2013. Effects of variety on the quality of tomato stored under ambient conditions. *Journal of Food Science and Technology* 50(3):477-486.

Tilahun, S, Taye, AM and Jeong, CS. 2017. Effects of storage duration on physicochemical and antioxidant properties of tomato (Lycopersicon esculentum Mill.). *Journal of Horticultural Science and Technology* 35(1):88-97.

Toivonen, PM. 2007. Fruit maturation and ripening and their relationship to quality. *Stewart Postharvest Review* 3(2):1-5

van Hille, R, Zietsman, G and Hille, N. 2020. *Biodegradable and Compostable Packaging: A review of the South African landscape*. The Moss Group, Cape Town, South Africa.

van Lin, M, van den Bos, A and Sterra, N. 2018. *The Current State of Fruit and Vegetable Agro-Processing in South Africa* RVO-203-1801/RP-INT. Commission by Netherlands Enterprise Agency Ministry of Foreign Affairs, South Africa.

van Roy, J, Keresztes, J, Wouters, N, de Ketelaere, B and Saeys, W. 2017. Measuring the colour of vine tomatoes using hyperspectral imaging. *Postharvest Biology and Technology* 129:79-89.

Vermaak, V. 2017. 2017 Plastics Recycling Figures Released. [Internet]. Plastic SA. Available from: https://www.plasticsinfo.co.za/wp-content/uploads/2019/09/2017-PLASTICS-RECYCLING-FIGURES-RELEASED_FINAL.pdf. [Accessed: 20 January 2020].

Viuda-Martos, M, Sanchez-Zapata, E, Sayas-Barberá, E, Sendra, E, Pérez-Álvarez, JA and Fernández-López, J. 2014. Tomato and tomato byproducts. Human health benefits of lycopene and its application to meat products: a review. *Critical Reviews in Food Sciences and Nutrition* 54(8):1032-49.

Watkins, CB. 2006. The use of 1-Methyl cyclopropane (1-MCP) on fruits and vegetables. *Biotechnology Advances* 24(4):389-409.

Weisburger, JH. 1998. Evaluation of the evidence on the role of tomato products in disease prevention. *Proceedings of the Society for Experimental Biology Medicine* 218(2):140-143.

Workneh, T and Osthoff, G. 2010. A review on integrated agro-technology of vegetables. *African Journal of Biotechnology* 9(54):9307-9327.

Wu, C-T.2010. An overview of postharvest biology and technology of fruits and vegetables. *Technology on Reducing Post-harvest Losses and Maintaining Quality of Fruits and Vegetables: Proceedings of 2010 AARDO Workshop*, 2-11.

Yamamoto, Y, Aizawa, K, Mieno, M, Karamatsu, M, Hirano, Y, Furui, K, Miyashita, T, Yamazaki, K, Inakuma, T and Sato, I. 2017. The effects of tomato juice on male infertility. *Asia Pacific Journal of Clinical Nutrition* 26(1):65-71.

Youssef, AM and El-Sayed, SM. 2018. Bionanocomposites materials for food packaging applications: Concepts and future outlook. *Carbohydrate Polymers* 193(1):19-27.

Yurtlu, YB and Erdoğan, D. 2005. Effect of storage time on some mechanical properties and bruise susceptibility of pears and apples. *Turkish Journal of Agriculture Forestry* 29(6):469-482.

Zewdie, TM. 2017. Tomato quality as influenced by different packaging materials and practices. *Journal of Scientific Agriculture* 1(1): 91-99.

Zhao, X, Ji, K, Kurt, K, Cornish, K and Vodovotz, Y. 2019. Optimal mechanical properties of biodegradable natural rubber-toughened PHBV bioplastics intended for food packaging applications. *Food Packaging Shelf Life* 21:100348.

Zhong, Y, Godwin, P, Jin, Y and Xiao, H. 2020. Biodegradable polymers and green-based antimicrobial packaging materials: A mini-review. *Advanced Industrial and Engineering Polymer Research* 3(1):27-35.

Zhou, X, Yang, R, Wang, B and Chen, K. 2019. Development and characterization of bilayer films based on pea starch/polylactic acid and use in the cherry tomatoes packaging. *Carbohydrate Polymers* 222:114912.

Zhu, J-Y, Tang, C-H, Yin, S-W and Yang, X-Q. 2018. Development and characterization of novel antimicrobial bilayer films based on Polylactic acid (PLA)/Pickering emulsions. *Carbohydrate Polymers* 181(1):727-735.

Žnidarčič, D and Požrl, T. 2006. Comparative study of quality changes in tomato cv.'Malike'(Lycopersicon esculentum Mill.) whilst stored at different temperatures. *Acta Agriculturae Slovenica* 87(2):235-243.

3. EVALUATION OF THE EFFECTS OF DIFFERENT PACKAGING MATERIALS ON THE QUALITY ATTRIBUTES OF THE ROUND TOMATO FRUIT IN SOUTH AFRICA

3.1 Abstract

Tomatoes are a climacteric fruit with a limited shelf-life and high post-harvest losses, due to poor handling. Packaging is one of the post-harvest technologies that is used to extend the shelf-life of tomatoes. This study was carried out to evaluate the effects of the packaging materials and storage conditions on the quality attributes of the round "Nema-Netta" tomatoes. The treatments consisted of a Stamped Paper (SP) Tray + Polyvinyl Chloride (PVC) wrap, an Expandable Polystyrene Sheet (EPS) Tray + Polyvinyl Chloride (PVC) wrap, a Stamped Paper (SP) Tray + Flow wrap, an Expandable Polystyrene Sheet (EPS) Tray + Flow wrap, a polypropylene (PP) bag, and Unpackaged tomatoes (the Control), as well as two storage conditions (cold and ambient), by using a randomized block design with three replications. The colour, firmness, Physiological Weight Loss (PWL), Total Soluble Solids (TSS), pH value, Titratable Acidity (TA), and total sugars were evaluated at seven-day intervals, over 28 days. The cold storage conditions were recorded in the range of 8-12°C, 78–80% RH, and the ambient storage conditions were in the range of 22-26°C, 68–72% RH. The packaging and storage conditions had a significant effect ($P<0.001$) on the colour changes, PWL, firmness, TSS, pH, TA and total sugars. Tomato samples in the EPS Tray combined with the PVC wrap at cold storage maintained the quality of the tomatoes better than the other packages, showing the lowest reduction in L* of 13.4% and hue angle of 14.7%, the lowest PWL of 1.78%, firmer fruits, with a puncture, Kramer shear and compression of 30.3%, 41.6% and 28%, respectively, the lowest increase in TSS and pH value of 18.1%, and 5.7% and the lowest decline in TA of 25.5%, reduction in total sugars of 31.7%, and the lowest reduction in total phenolic content of 21.2%. The observations of this study prove that differences in the construction of the packaging and cover result in the interplay of gaseous exchange (CO_2 and O_2) and water vapour, with minimal quality changes and losses. A combination of packaging and cold storage creates an ideal environment for maintaining the quality of tomatoes. The differences between the EPS Tray + PVC wrap (non-biodegradable) and SP Tray + PVC wrap (biodegradable) are less than 5% in the multiple tests, hence the SP

Tray is a recommended biodegradable package that has become a viable package to use. It can also be concluded that the packaging is beneficial for tomatoes.

3.2 Introduction

Tomatoes (*Solanum Lycopersicum*) are a large considereable product on the South African market. They supply most of the daily nutritional requirements for human health, and they contain nutrients, such as Vitamin C and lycopene, in abundance (Nasir *et al.*, 2015; Mior Azmai *et al.*, 2019). They contain the two most essential nutrients for human health, compared to other fruit and vegetables, and they can be consumed as a raw crop or as a processed product in many forms (Hövelmann *et al.*, 2020). However, they are climacteric in nature, and ripening remains active long after they are harvested. They undergo changes in their colour, flavour and texture, as well as biochemical changes, throughout their life-span (Bertin and Génard, 2018; Osorio *et al.*, 2020). These changes are associated with various metabolic processes, including the accumulation of organic acids, organic compounds and sugars (Wang *et al.*, 2018).

Post-harvest losses have continually been reported in the tomato industry, mainly in developing countries (Abera *et al.*, 2020). According to FAOSTAT (2014), post-harvest losses of tomatoes in South Africa are estimated at 10.2% of the total production, and the severity of these losses is similar in sub-Saharan Africa (Sibomana *et al.*, 2016b; Cherono *et al.*, 2018). This has been attributed to various factors, such as the lack of packaging materials and suitable storage conditions. In order to reduce these losses, a systematic knowledge of the post-harvest physiology, handling and storage of tomatoes is required (Azene *et al.*, 2014a; Sibomana *et al.*, 2016a). Although packaging materials have been used in the tomato industry for a long time, their effects on the quality attributes of tomatoes are still debatable.

A rapidly-growing population requires the matching quick production of food and other nutritional needs. Hence, improving the quality of tomato-handling is a pending and interesting issue that is reflected in the consumers' behaviour in the market across the globe (Bertin and Génard, 2018; Paolo *et al.*, 2018). Quality has multiple traits and it is dependent on the stakeholders (Dobrin *et al.*, 2019). However, commercially, tomatoes rely primarily on their external appearance (e.g. colour, size and form), their storage life and firmness, their organoleptic quality, such as texture, and their biochemical traits, such as their sugar content, which defines their flavour (Bertin and Génard, 2018; Garuba *et al.*, 2018). However, even under the best conditions, the life-span of tomatoes is relatively short and they require careful handling and management (Oboulbiga *et al.*, 2017). Despite the growing familiarity with the molecular regulations and metabolic pathways of the tomato fruit, understanding their qualities changes is a global challenge (Abera *et al.*, 2020). This has been overlooked for far too long, and there are still many knowledge gaps and much room for research. This is evident from the breeding programs in the 1990s and 2000s that sought to integrate the nutritional taste and quality of tomatoes. Recently, tomato growers have had to tackle the challenging constraints brought about by climate change. Innovative technologies have been developed; however, environmental storage conditions and packaging treatments are still the underlying factors in the establishment of an innovatiove and long-lasting post-harvest process.

3.3 Sampling Site and Transportation

Fresh tomatoes (*Solanum Lycopersicum* cv. "Nema-Netta" Mill) were harvested from ZZ2 farm in Limpopo, South Africa, at the pinkish-red maturity stage. The tomatoes were grown on open fields in the Mooketsi area (23.5992 S, 30.1424 E). The region receives an average annual rainfall of less than 600 mm, which peaks between January and February. The summers in Limpopo are warm, with mean daily temperatures between 18-22°C, and the winters are relatively mild, with mean daily temperatures of between 8-14°C. The tomatoes were harvested manually during the summer season on 23 January 2020 and transported to the nearby packhouses. The fruits were cooled, cleaned and packaged in the different packaging treatments and loaded into transportation crates on 24 January 2020. Their size and colour were kept uniform, in order to avoid experimental prejudice, and the crates were marked with storage and packaging codes, to avoid contamination. The tomato samples that were to be stored under ambient temperature conditions were transported by using a truck with no cooling system. Those that were to undergo cold storage treatment were transported to Pietermaritzburg, using a refrigerated truck. The selection of the tomatoes at the pinkish-red maturity stage coincided with the South African fresh market retail requirements of consumers.

3.4 Experimental Design

A Randomized Complete Block Design was selected. A three-factor factorial experiment consisting of six different packaging treatments (the Stamped Paper Tray + PVC Cling wrap, the EPS Tray + PVC Cling wrap, the Stamped Paper Tray + Flow wrap, the EPS Tray + Flow wrap, the 1 kg PP bag and the Unpackaged tomatoes), under two storage treatment conditions (ambient and cold) over a 28-day storage period, with five data collection points, starting from the first day of arrival (Day 0) and repeated at seven-day intervals (0, 7, 14, 21 and 28). The packaging treatment and storage conditions were the main factors, whilst the storage period was a sub-factor.*

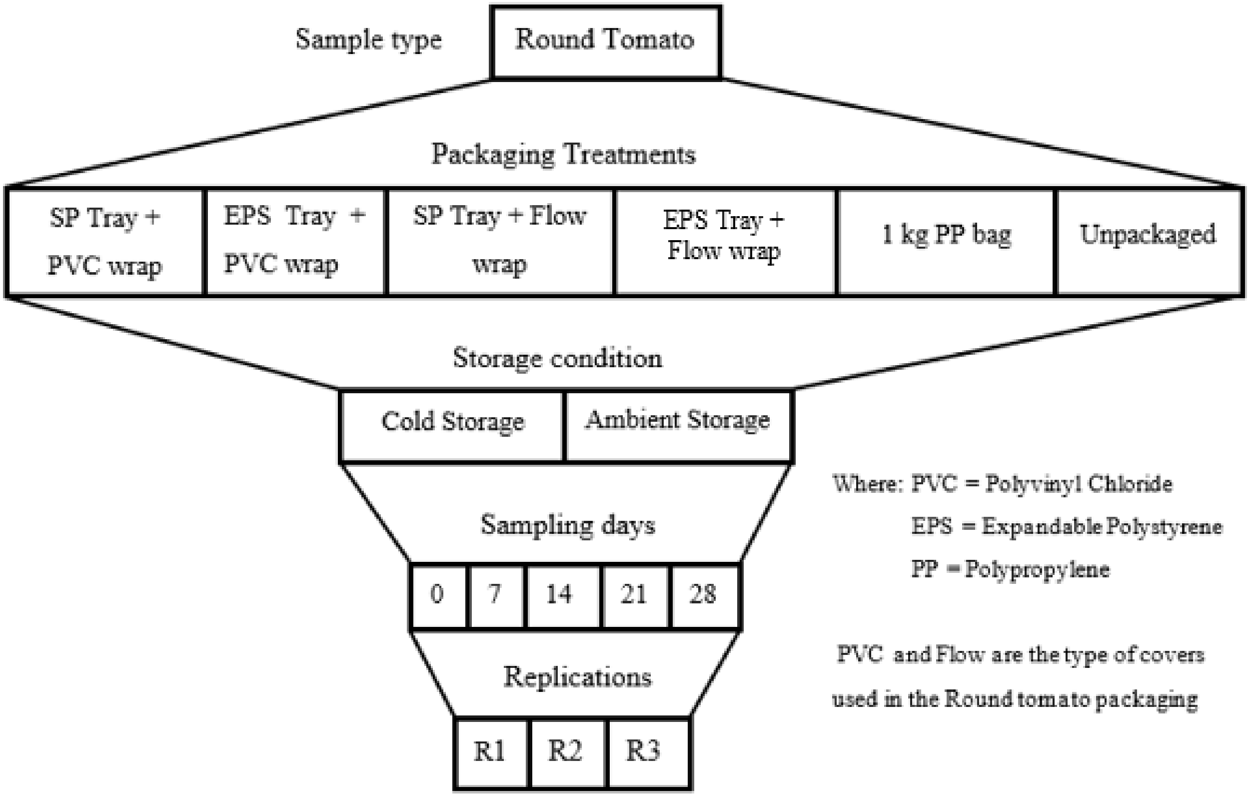

Figure 3.1 Schematic representation of the round tomato experimental design

3.5 Packaging Treatments

a) Stamped Paper Tray

A Stamped Paper Tray (Mpact Operation (Pty) Ltd., Johannesburg, South Africa) is made of a biodegradable solid bleached sulphate and cross-linked coated paperboard. It is formed by turning fibrous materials from wood and recycled paper into pulp, which is then bleached and coated with Kraft paper. A Stamped Paper Tray has three layers: an inside Kraft liner, an outside Kraft liner and a corrugated fluting medium, which gives it strength and rigidity. It is lightweight, yet strong. The paperboard is cut and folded into a rectangular shape, which is then stamped to become a Stamped Paper Tray package with dimensions of 150 mm×130 mm×30 mm and a thickness of 1 mm.

b) Expandable Polystyrene Tray

An Expandable Polystyrene (EPS) Tray (Mpact Operation (Pty) Ltd., Johannesburg, South Africa) is a thermoplastic film. It is manufactured from General Purpose Polystyrene, master batch and a nucleating agent. Pentane is used as an expandable agent. The amount of styrene monomer present in the raw materials is below 500 ppm. The EPS Tray is a brittle and poor barrier against gases and water vapour. The EPS Tray had dimensions 135 mm ×130 mm ×30 mm, and a thickness of 3.5 mm.

c) PVC cling wrap

The PVC cling film (Mpact Operation (Pty) Ltd., Johannesburg, South Africa) is manufactured from PVC resin, which is mainly plasticised with DEHA (Bis(2-Ethylhexyl) adipate) and stabilised by using ESBO (Epoxidized soybean oil) and CaZn (Calcium Zinc) heat stabilisers. PVC has a water vapour transmission rate of 750-15700 g.µm.m^{-2}day^{-1}, and a permeability of O_2 and CO_2, 154-10000 and 939-61000 g.µm.m^{-2}h^{-1}.atm^{-1} at 25°C.

d) Flow wrap

The Flow wrap used for the cover is a PP film. The make-up of the PP film contains an outer layer, a PP core acrylic-coated layer to prevent friction on the contact surface and an interior sealant layer. The Flow wrap film has 12 perforated holes with a diameter of 10 mm, which are spaced 30 mm apart.

e) Polypropylene bag

Polypropylene (PP) (Mpact Operation (Pty) Ltd., Johannesburg, South Africa) is a non-biodegradable addition to the propylene polymer, and the resins used are mainly isotactic. PP has the lowest density of 0.89–0.91 g.cm^{-3} of all the commodity plastics. It is elastic, more transparent, more effective at bearing water vapour and it has a good chemical resistance. PP has a water vapour transmission rate of 100-300 g.µm.m^{-2} day at 37.8°C and 90% RH, with a permeability of O_2 and CO_2 of 2083-3916 and 11706-22008 g.µm.m^{-2}h^{-1}.atm^{-1} at 25°C. The dimensions of the PP bag (1 kg) are 195 mm × 300 mm, with 32 perforated air vents with a diameter of 12 mm and that are spaced 30 mm apart.

f) Unpackaged (Control)

The tomato fruit open corrugated cardboard box (Mpact, Johannesburg (Pty) Ltd., South Africa) has a 6 kg capacity, with dimensions 390 mm×240 mm×20 mm. The corrugated box has four air vents on the side and bottom panels.

The tomato samples were treated with the six different packaging combinations that are currently used in the South African supply chain, as shown in Figure 3.2.

(A)

(B)

(C)

(D)

(E)

(F)

Figure 3.2 Round tomato packaging treatment (A) SP Tray + PVC wrap, (B) EPS Tray + PVC wrap, (C) EPS Tray + Flow wrap, (D) SP Tray + Flow wrap, (E) 1 kg PP bag, and (F) Unpackaged (Control)

3.6 Storage Temperature and Relative Humidity Measurement

As described in the experiment design in Section 3.4, the tomatoes were divided into those under ambient storage conditions, with an estimated temperature and relative humidity ranging between 22-24°C, 75-85% RH, and a cold storage facility that was set at 11°C, 85% RH. A data logger (HOBO® pro v2, U23-001, USA) was placed inside each storage facility to monitor and record the fluctuations in temperature and relative humidity.

3.7 Data Collection and Analysis

The dataset involved the quality assessment of colour, firmness (Puncture, Kramer and compression), physiological weight loss, total soluble solids, acidity, pH, total sugars and phenolic content, which were measured on Days 0, 7, 14, 21 and 28, respectively.

3.7.1 Colour analysis

The colour change of each sample was measured, with three replications. It was measured across the equatorial surface of the fruit, as described by Dominguez *et al*. (2012). The measurements of colour L*, a* and b* were measured by using a Konica Minolta chromameter (Model-CR-300, Ramsey, NJ, USA). L* was used to analyse the rate of change of lightness, whilst a* and b* were used to calculate the hue angle (h°), based on the individual model formula (h° = tan-1 (b* / a*)).

3.7.2 Firmness analysis

3.7.2.1 Puncture test

As described by Sirisomboon *et al*. (2012), the puncture test was measured by using a Texture Analyzer (TA-XT Plus, Texture Technologies Company, USA). The tomato samples were aligned horizontally on the plate, as shown in Figure 3.3. The analyser was calibrated with a 10 kg (100 N) load cell to transfer the data to Easy-Match-QC software. It was equipped with a 2 mm diameter probe. The equipment settings were set at a speed of 3 mm.sec^{-1} and a 7.5 mm insertion depth into the tomato. Firmness is defined as the maximal force (N) needed to penetrate the tomatoes at a constant depth in each sample, with three replications.

Figure 3.3 Illustration of the puncture force experiment

3.7.2.2 Kramer shear test

The Kramer shear was determined by using a method adopted by Harker *et al.* (1997), and it was measured by using a Texture Analyzer (TA-XT Plus, Texture Technologies Company, USA). However, the load cell was changed from a puncture probe fitting to a shear press-fitting, with a 30 kg load (300 N). The tomatoes were cut into 10 mm disk slices by using a Vanier calliper and a knife for each sample. The disks were weighed and then positioned in a sample chamber (as shown in Figure 3.4), where the shear press plate pressed the sliced disk at a speed of 10 $mm.min^{-1}$. The maximum force applied was recorded and divided by the weight of the tomato sample disk, to accommodate for the difference in the area of the tissue that was cut by the plates. The data were recorded for the three sample replications.

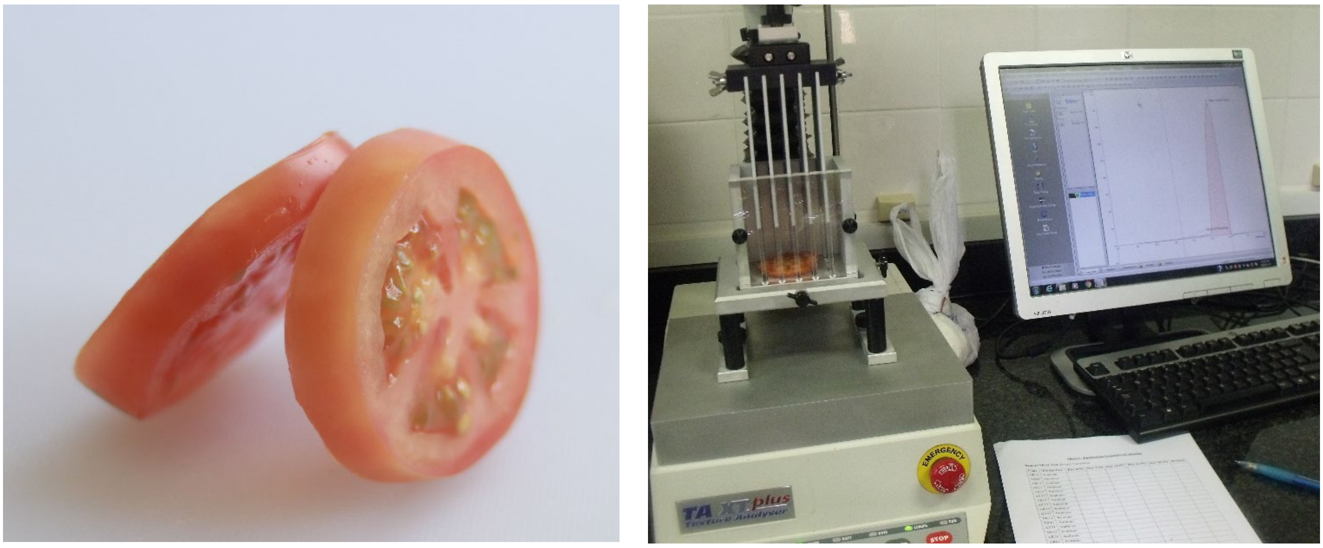

Figure 3.4 Illustration of the 10 mm disk slice and Kramer shear chamber

3.7.2.3 Compression test

As described by Sirisomboon *et al.* (2012), the compression was measured by using a Texture Analyzer (Instron Universal Testing Machine, Model-3345, Buck, United Kingdom). The analyser was calibrated with a 5 kg weight. It was equipped with a 55 mm diameter plate probe, with a speed setting of 10 $mm.min^{-1}$. Each tomato fruit was aligned vertically, from the stem end to the top apex (as shown in Figure 3.5), on a smooth surface and pressed by the moving parallel probe until the fruit ruptured. The firmness was defined by the compressive load (N) at the breaking point. The measurements were recorded in triplicate, by using the Bluehill Instron 2, Version 2.5 data acquisition software.

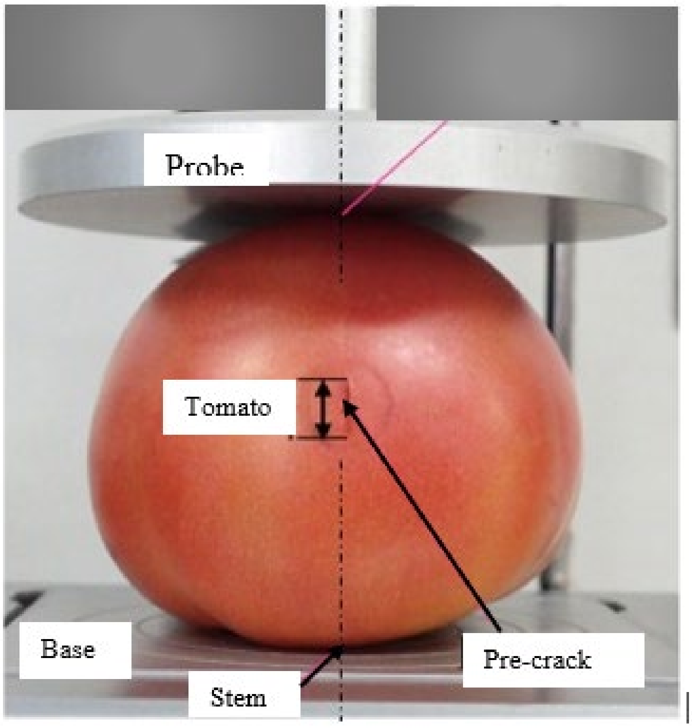

Figure 3.5 Flat-plate compression test of the round tomato fruit

3.7.3 Physiological weight loss

The physiological weight loss of the tomato samples was measured on Day 0 (upon arrival) and labelled for consistent measurement. The total weight loss was taken as the difference between the initial and the final weight, during each storage interval. The percentage of weight method followed the description of the AOAC (1984). The formula for calculating the percentage weight loss is presented in Equation 3.1. Each measurement was recorded in triplicate, for each sampling day.

$$\%Weight\ loss\ = \frac{W_0 - W_f}{W_o} \times 100 \tag{3.1}$$

where

W_o = the average weight of the tomato sample at Day 0

W_f = the average weight tomato of the tomato sample on the final day

3.7.4 Biochemical analysis

3.7.4.1 Total Soluble Solids

The Total Soluble Solids (TSS) were measured by using the method of Jafari *et al.* (2017). Three replicates of each treatment were blended and liquified in a blender. The tomato juice was extracted and filtered by using a muslin cloth. A hand refractometer (Atago Palette-PR32, Tokyo, Japan) was used to determine the TSS by placing two to three drops of extracted clear juice three times on the refractometer prism. Between each sampling, the refractometer prism was washed with alcohol and distilled water, and it was then dried with tissue paper before being used. Before experimentation, the digital refractometer was standardized with distilled water containing 0 % TSS, and it was adjusted to room temperature.

3.7.4.2 Titratable Acidity

The total titratable acidity was determined, as described in Domínguez *et al.* (2012). Three randomly-selected tomatoes from the sample replications were blended by using a fruit blender (Philips Model, HR2103, Makro Pty, PMB, South Africa) for one minute. An aliquot of juice was extracted and filtered by using a muslin cloth, which was then transferred to a sterilized conical flask. The titratable acidity was determined by titrating 25 ml of the sample tomato juice with 0.1 mol.l^{-1} of sodium hydroxide (NaOH). The titration procedure was repeated three times, and the readings were recorded.

3.7.4.3 pH Value

The pH of the tomatoes was measured by using a method described by Tigist *et al*. (2013). A glass electrode pH meter was used, which was standardized each time before use with a neutral buffer pH 7.0 and pH 4.0. Three randomly-selected tomatoes from the sample replications were blended by using a fruit blender (Philips Model, HR2103, Makro Pty, PMB, South Africa) for one minute. The juice was filtered by using a muslin cloth and an aliquot of the juice sample was transferred into a sterile beaker, into which the pH meter was inserted. The procedure was repeated three times and the readings on the pH meter were recorded.

3.7.4.4 Total Sugars

The total sugars were determined by using a method used by Pinela *et al.* (2012), with slight modifications. A tomato fruit sample was blended for two minutes, and 5 mL of the juice was extracted into centrifuge tubes. Then 2 mL of deionized water was added and centrifuged (Avanti J-26S XP; Beckman Coulter, United States of America) at 10,000 rpm for 15 minutes at 4°C. All solutions of the samples were filtered through a 0.45µm nylon syringe filter and 2 mL was injected into High-Performance-Liquid-Chromatography (HPLC) vials. The HPLC system (LC-20AT; Shimadzu, Japan) column was set at 85°C, with ultra-pure water as the mobile phase (RID-10A; Shimadzu, Japan) flowing at 0.6 $ml.min^{-1}$. The chromatographic comparisons identified the sugar compounds with authentic standards of glucose and fructose (the sucrose was negligible). A quantification was performed by using the standard internal method and the sugar content was expressed in mg per 100 g of fresh weight ($mg.100^{-1}g^{-1}$ FW).

3.7.4.5 Total Phenolic Content

The total phenolic content in the tomatoes was determined by using a Folin-Ciocaltean (FC) reagent, which is a method used by Dufera *et al.* (2021). A 0.1 mL of the sample fruit juice from each replication was extracted and mixed with 0.5 mL of the FC reagent and 1.5 mL of the 7% sodium carbonate solution. Distilled water was added to make a final solution volume of 10 mL. The solution was then incubated at 90°C for two hours in a shaking water bath (Faithful FWS-30; Huanghua Faithful Instruments Co.,Ltd, China). The absorbance was then measured by using a UV-Vis spectrophotometer (Shimadzu UV-Spectrophotometer, UV-1800, Japan) at 750 nm, against a blank. The final results were expressed in mg of Gallic acid, which is equivalent to 100 g of the fresh weight (mg.GAE.100g FW).

3.7.5 Microbial analysis

The microbial development was determined by using a method adopted by Shezi (2016b). Briefly, a randomly-selected tomato (single) was taken from each treatment for sampling. 30 mL of sterile peptone water (0.85% NaCl and 0.1% peptone, pH 7) was added as an initial solution to the selected sample in a sterile plastic bag containing the sampled tomato. The tomato was gently massaged for five minutes to rinse off and collect the micro-organisms from its surface. The aerobic mesophilic micro-organisms on the tomato surface were determined and enumerated by extracting 0.1 mL of the appropriate serial dilutions, from the first sample to the sixth (10^{-6}) sample. The dilutions were mixed thoroughly for one minute in a Whirlmixer (Model CM-1, Fisher Scientific, Massachusetts, USA) and spread onto the ready-to-use plate count agar plates, followed by an incubation period of 48 hours at 28°C. The counts were given as colony-forming units per tomato (whole surface area). The determination and enumeration of the fungal flora (yeast and mould) present on the tomato surface was done by extracting 0.1 mL of the appropriate decimal solutions, from the first to sixth (10^{-6}) and spread onto ready-to-use Rose-Bengal-chloramphenicol agar plates (RBC-agar), followed by an incubation period of up to seven days at 25°C. The differentiation between the bacterial and fungal colonies was confirmed via microscopy (Kern OBT 102, 4/10/40 Magnification, Germany). The difference were determined by counting the number of Colony Forming Units (CFU's) per cm^{-2} of tomato surface.

3.7.6 Statistical data analysis

Significance tests were conducted by the Analysis of Variance (ANOVA) in a completely randomized design arrangement by using the GenStat® 18th Edition (VSNI, Hempstead, UK). The performance level of the treatment's means was carried out by considering a statistical significance level of 5% and Duncan's multiple range comparison tests.

3.8 Results and Discussion

This section discusses the results and effects of the packaging and storage conditions, over a 28-day storage period, on the physical and chemical changes, as well as the microbial development of the classic round tomatoes.

3.8.1 Temperature and relative humidity

The temperature and relative humidity varied significantly ($P<0.05$) during the storage period. The ambient storage temperatures fluctuated between 22℃ at night and 26℃ during the day, whereas the cold storage temperatures fluctuated between 8°C at night and 12℃ during the day (Figure 3.6). The Relative Humidity (RH) was higher under cold storage, fluctuating around 78-80%, while that of the ambient storage fluctuated between 68-72% (Figure 3.6). The tomatoes responded differently to these storage environments. Tomatoes under cold storage conditions had a longer storage life than those under ambient storage conditions. The surrounding temperature is a substrate for metabolic processes, such as transpiration, respiration and ethylene production. A low temperature slows down these metabolic processes, and therefore, the rate of deterioration (Workneh *et al.*, 2012). Shezi (2016b) also reported similar observations, where tomatoes stored under cold storage conditions were of a better quality after 32 days than those stored under ambient conditions at different harvesting times.

Workneh and Osthoff (2010) stated that temperature is the most critical post-harvest factor, and if it is not maintained, it can have a significant impact on the quality of fruit and vegetables.

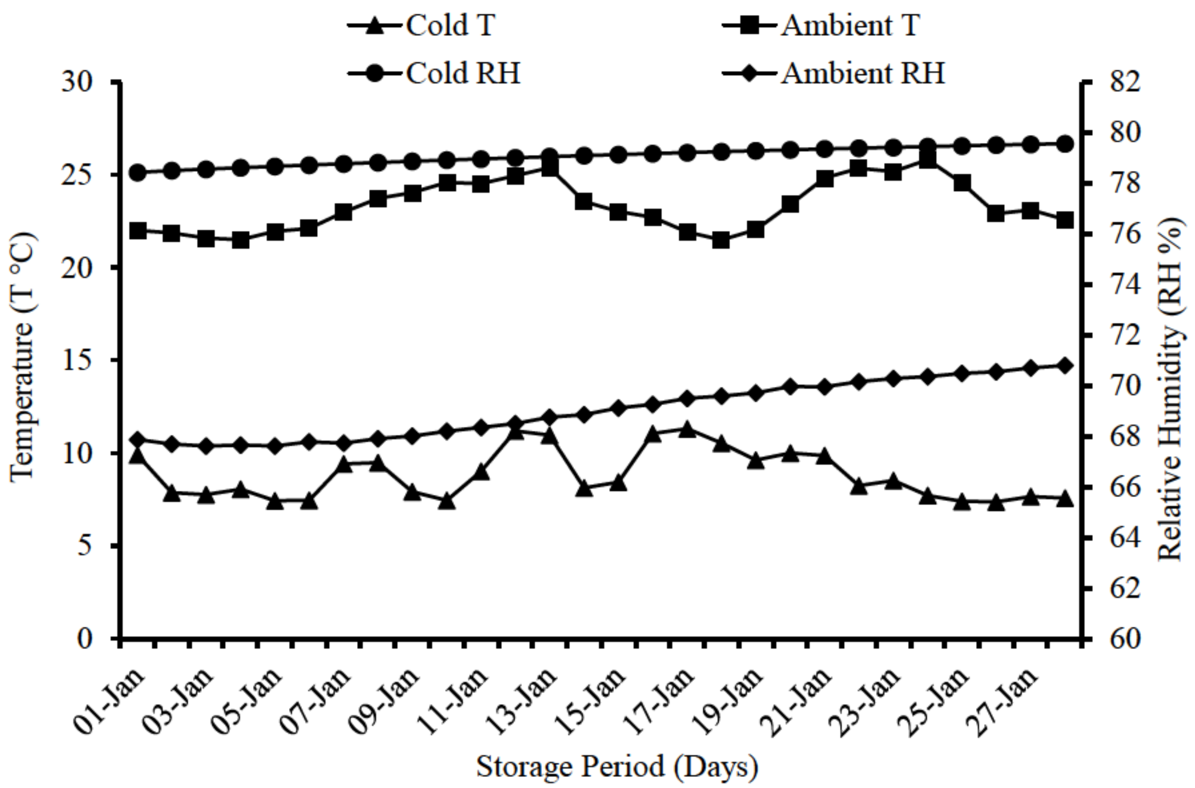

Figure 3.6 Variations in temperature (a) and relative humidity (b) under the cold and ambient storage conditions

3.8.2 Colour analysis

The results of lightness (L*) and hue (H) angle are discussed in this section, as well as the effects of the storage period, storage conditions and different packaging on the colour attributes of tomatoes.

3.8.2.1 Lightness

Table 3.1 shows the mean lightness (L*) values of the tomatoes affected by the packaging and storage conditions over a period of 28 days. The L* values ranged between 45.90 to 37.10 during the 28-day storage period. This range is similar to the range (46.5 to 36.5) at the pink-light red stage, as reported by Khairi *et al.* (2015a). The packaging treatment had a significant ($P<0.001$) influence on the L* changes in the tomatoes. Unpackaged (control) tomatoes tend to decline faster in the L* colour index than tomatoes in packaging treatments. Tomatoes packaged in the EPS tray + PVC wrap had a slower L* change. The results agree with those of Gebeye (2018), which showed that packaging tomatoes helps to retain perfect colour index (L*, a*, and b*) scores for nine days, compared to unpackaged tomatoes. Sharma *et al.* (2020b) explained that a decrease in lightness indicates the synthesis of pigments that darken the red colour (from pinkish-yellow to full red).

The storage conditions also influenced the L* of the tomatoes significantly (P<0.001). The results revealed that the average L* values under cold and ambient conditions were 43.87° and 41.19°, respectively. The difference indicates that the rate of change from pinkish-yellow to a red colour was slower under cold storage conditions than under ambient conditions. The slower rate of change in the L* colour under cold storage conditions also implied that the ripening process was slower than it was under ambient conditions, resulting in the extended shelf-life of the tomatoes.

The results showed that the L* values varied significantly (P<0.001) over the storage period. The L* values decreased from 45.90 on Day 0 to 38.72 on Day 28. Generally, as the storage period increased, the tomatoes lost their lightness, and as they matured, they became a full red colour, which is a sign of complete ripeness and that they are getting closer to the end of their life-span and not ideal for consumers. Similarly, Khairi *et al.* (2015b) reported that the L* decreases significantly with the storage time, as the tomatoes progress towards maturity. This result may be attributed to that ς-carotene that gives them a pale-yellowish colour and which reaches its highest concentration peak before full ripening, when the lycopene gives the tomato its red colour and the β-carotene gives the tomato its orange colour. Generally, as the tomatoes ripen further, they lose all the greenness of the chlorophyll, which is superseded by the accumulation of carotenoids and lycopene, which gives them their final colour. However, the colour development in tomatoes is also temperature-sensitive, which explains the much higher decrease of L* under ambient storage conditions, compared to tomatoes under cold storage conditions, which changed to a full red colour.

The interaction of packaging and storage conditions proved to have no significant (P>0.05) influence on the L* index of colour. The lowest reduction in the L* (13.3%) was observed in the tomato samples packaged in the EPS Tray + Flow wrap and stored under cold storage conditions. The interaction between the storage conditions and storage period also revealed a significant (P<0.05) influence on the changes in the L* values. The tomato samples subjected to cold storage conditions had the lowest reduction in L* values (14.5%), compared to the samples under ambient storage conditions, which experienced the highest reduction in L* values (16.5%) over the 28-day storage period. The lowest reduction can be attributed to the synthesis of pigments being slowed down, which enhances the storage life of tomatoes.

Table 3.1 The effects of the packaging and storage conditions on the Lightness (L*) of the tomatoes over the 28-day storage period (n=3)

Packaging Treatment	Storage Condition	Storage Period (days)				
		0	7	14	21	28
SP Tray + PVC wrap	Cold	45.90^{s}	$44.64\pm1.39^{l\text{-}q}$	$43.72\pm2.10^{i\text{-}p}$	$43.78\pm0.69^{j\text{-}p}$	$39.37\pm0.88^{a\text{-}f}$
	Ambient	45.90^{s}	$40.60\pm2.25^{b\text{-}j}$	$40.08\pm0.98^{a\text{-}f}$	$39.56\pm1.52^{a\text{-}f}$	$39.54\pm2.87^{a\text{-}f}$
EPS Tray + PVC wrap	Cold	45.90^{s}	45.88 ± 2.54^{rs}	$43.55\pm4.39^{h\text{-}p}$	$42.42\pm2.82^{f\text{-}m}$	$40.17\pm0.76^{a\text{-}g}$
	Ambient	45.85^{s}	$45.80\pm1.61^{o\text{-}r}$	$43.53\pm0.66^{g\text{-}p}$	$40.26\pm2.23^{a\text{-}h}$	$38.73\pm0.23^{a\text{-}d}$
SP Tray + Flow wrap	Cold	45.90^{s}	45.90 ± 0.54^{s}	$45.04\pm1.78^{l\text{-}q}$	$42.17\pm1.72^{e\text{-}m}$	$38.45\pm1.89^{a\text{-}d}$
	Ambient	45.90^{s}	$42.35\pm0.83^{e\text{-}n}$	$39.45\pm0.01^{a\text{-}f}$	$39.37\pm1.28^{a\text{-}f}$	$38.37\pm0.83^{a\text{-}f}$
EPS Tray + Flow wrap	Cold	45.90^{s}	45.14 ± 1.94^{pqr}	$44.12\pm2.56^{k\text{-}p}$	$42.13\pm1.54^{e\text{-}m}$	$39.79\pm0.97^{a\text{-}f}$
	Ambient	45.90^{s}	$41.07\pm1.43^{c\text{-}k}$	$40.40\pm0.94^{a\text{-}i}$	$40.10\pm2.72^{a\text{-}f}$	$39.57\pm0.64^{a\text{-}f}$
1 kg PP bag	Cold	45.90^{s}	$45.01\pm3.61^{l\text{-}q}$	$44.86\pm1.56^{l\text{-}q}$	$42.20\pm2.13^{e\text{-}m}$	38.70 ± 1.66^{abc}
	Ambient	45.90^{s}	$43.72\pm2.29^{i\text{-}p}$	$40.17\pm1.60^{a\text{-}g}$	38.28 ± 1.85^{abc}	37.65 ± 1.73^{ab}
Unpackaged (Control)	Cold	45.90^{s}	$45.22\pm1.72^{m\text{-}q}$	$42.53\pm1.62^{f\text{-}o}$	$41.79\pm1.90^{d\text{-}l}$	$39.03\pm0.13^{a\text{-}e}$
	Ambient	45.90^{s}	$41.75\pm1.26^{d\text{-}l}$	$40.25\pm1.53^{a\text{-}h}$	$38.47\pm0.87^{a\text{-}d}$	37.10 ± 0.88^{a}
Significance (P) level						
Package (A)		P<.001				
Storage condition (B)		P<.001				
Storage period (C)		P<.001				
A*B		P>0.05				
A*C		P<0.05				
B*C		P<.001				
A*B*C		P<0.05				

Values are means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). SP = Stamped Paper Tray: EPS = Expandable Polystyrene: PVC = Polyvinyl Chloride; PP = Polypropylene

The interaction of the packaging, storage condition and storage period was also shown to have a significant influence (P<0.05) on the L* changes in the tomatoes. The tomato samples packaged in the EPS Tray + PVC wrap and stored under cold storage conditions resulted in a reduction of 13.3% in L* from Day 0 to Day 28. The highest reduction in L* (20%) was observed in the unpackaged tomato samples stored under ambient storage conditions from Day 0 to Day 28. This indicates that the EPS Tray + PVC wrap and cold storage conditions were beneficial for preserving the colour characteristic (L* value) of the tomatoes. Comparing the EPS Trays and SP Trays under the same storage conditions, the differences in L* changes were under 2% over the 28-day storage period.

3.8.2.2 Hue angle

The hue angle (h°) records the colour index values of food in a 360° space. A 90° angle is given to yellow, a 270° angle to blue, a 180° angle to green and a 0° angle to the red hue. Table 3.2 shows the h° values of the round tomatoes that were affected by the packaging and storage conditions over the 28-day storage period. The h° values from this experiment ranged from 60.70 to 45.96, which is within the 85.95 to 36.57 range reported by Mekonnen (2017a). Domínguez *et al.* (2016) and Olveira-Bouzas *et al.* (2021) reported h° values of 72.27 and 42.12 in tomatoes at the light red and full red stages, respectively. Tomatoes that are harvested early are expected to have higher h° values than tomatoes harvested at the late stage of ripeness (Shezi, 2016b). The packaging treatment had a significant ($P<0.001$) effect on the h° values of the tomatoes. Those packaged in the EPS Tray + PVC wrap had the highest h° values, while unpackaged (control) tomatoes recorded the lowest h° values. According to Mekonnen (2017b), packaging forms a modified gas atmosphere that decelerates the synthesis of pigments, such as carotenoids and the formulation of lycopene, which gives the tomato its colour. The results revealed that a combination of the EPS Tray + PVC wrap and cold storage conditions is the most effective post-harvest treatment for delaying the metabolic processes that influence colour change.

The storage conditions also had a significant ($P<0.001$) influence on the h° values of the tomatoes. The h° values under cold storage conditions were higher than those under ambient storage conditions, namely 53.64 and 50.75, respectively, which indicates that the colour change was slower under cold storage conditions than ambient storage conditions. Similar observations were reported by Distefano *et al.* (2020), where tomatoes stored at 10℃ had lower changes in colour than those stored at 20℃ over time. According to Liu *et al.* (2015), the environmental conditions influence the metabolic and enzymatic reactions within tomatoes, and the rate of enzyme-catalysed reactions increase when the temperature increases. Hence, temperature is the underlying factor of post-harvest handling. This describes the higher h° in tomatoes stored under cold storage conditions, which results from a low metabolic rate and ripening process and slows down the colour change. The higher temperatures under ambient storage conditions influenced the biochemical processes that occur in tomatoes and enhanced their maturing process.

The results revealed a highly significant ($P<0.001$) difference in h° values during the 28-day storage period. The decline in h° values between Day 0 and Day 28 was from 60.70 to 48.93, respectively. The decline signifies the significant maturity changes and ripening that occurs in the tomatoes, causing a colour change from pinkish-yellow to red over the storage period (Olveira-Bouzas *et al.*, 2021). Generally, from a biochemical and physiological perspective, the declining trend revealed by the h° is expected in fruit, such as tomatoes, as it continues its ripening process. Similarly, Cherono *et al.* (2018) reported a decline in h° as the storage period progresses. This can be ascribed to the ripening process that occurs within the tomato fruit, which causes biochemical changes, which are mainly a build-up and synthesis of pigments and an accumulation of carotenoids and lycopene.

The interaction between the packaging and storage showed no significant ($P>0.05$) influence on the h° values. Tomatoes packaged and stored under cold storage conditions showed the lowest decline of h° values, with the highest decline in unpackaged fruits. The interaction between (a) the packaging and storage period and (b) the storage conditions and storage period have a significant ($P<0.05$) influence on the h° values. Tomatoes packaged in the EPS Tray + PVC wrap had the lowest reduction in h° values (15.8%), whilst the highest decline (22.3%) was observed in unpackaged tomatoes. Tomatoes stored under ambient storage conditions had the highest reduction in h° values (21.7%), compared to 16.1% under cold storage conditions, from Day 0 to Day 28.

The packaging, storage conditions and storage period also had a significant ($P<0.05$) influence on the tomato fruit. Samples packaged in the EPS Tray + PVC wrap and stored under cold storage conditions had the lowest reduction (14.7%) in h° values. The highest reduction in h° values (24.8%) was observed in unpackaged tomatoes under ambient storage conditions, from Day 0 to Day 28. The results of this experiment revealed that the EPS Tray + PVC wrap and cold storage conditions are beneficial for minimising the colour changes in tomatoes, hence they extend the shelf-life of the product.

Table 3.2 The effects of the different packaging materials and storage conditions on the colour changes (h°) in tomatoes over the 28-day storage period (n=3)

Packaging Treatment	Storage Condition	Storage Period (days)				
		0	7	14	21	28
SP Tray + PVC wrap	Cold	60.70[q]	54.13±2.49[g-p]	52.48±1.86[b-o]	50.22±1.09[a-l]	49.66±1.80[a-k]
	Ambient	60.70[q]	51.42±2.24[a-m]	50.98±3.79[a-m]	48.20±1.28[a-f]	47.66±1.82[abc]
EPS Tray + PVC wrap	Cold	60.70[q]	57.58±3.43[pq]	54.26±6.70[h-p]	51.01±3.30[a-m]	50.57±0.94[a-l]
	Ambient	60.70[q]	54.83±2.77[j-p]	53.81±2.10[e-o]	51.73±1.67[a-n]	49.31±2.45[a-j]
SP Tray + Flow wrap	Cold	60.70[q]	59.58±1.52[pq]	55.66±2.37[l-q]	49.63±2.57[a-k]	48.15±0.54[a-f]
	Ambient	60.70[q]	50.07±0.08[a-l]	49.77±1.22[a-k]	49.03±1.45[a-j]	47.42±2.36[ab]
EPS Tray+ Flow wrap	Cold	60.70[q]	56.37±3.81[m-q]	53.40±3.20[c-o]	49.61±2.46[a-k]	48.45±2.29[a-h]
	Ambient	60.70[q]	51.08±0.20[a-m]	50.92±2.02[a-m]	48.75±1.17[a-i]	46.57±2.18[a]
1 kg PP bag	Cold	60.70[q]	54.47±1.92[i-p]	52.48±3.52[b-o]	50.85±3.70[a-m]	48.08±2.45[a-e]
	Ambient	60.70[q]	51.33±1.10[a-m]	52.54±4.44[b-o]	47.62±0.97[abc]	47.40±3.21[ab]
Unpackaged (control)	Cold	60.70[q]	54.79±2.15[j-p]	50.52±0.83[a-l]	50.22±3.17[a-l]	47.67±0.72[abc]
	Ambient	60.70[q]	49.38±0.84[a-k]	48.42±1.09[a-g]	47.86±0.24[a-d]	45.96±1.65[a]

Significance (P) level	
Packaging (A)	P<.001
Storage condition(B)	P<.001
Storage period(C)	P<.001
A*B	P>0.05
A*C	P<0.05
B*C	P<.001
A*B*C	P<0.05

Values are means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). SP = Stamped Paper Tray: EPS = Expandable Polystyrene: PVC = Polyvinyl Chloride; PP = Polypropylene

3.8.3 Physiological weight loss

The effects of the packaging and storage conditions on the Physiological Weight Loss (PWL) of tomatoes are presented in Table 3.3. The PWL (%) ranged from 0.27% on Day 7 to 11.93% on Day 28, which is similar to the range reported by Gebeyehu (2018). The results showed that the packaging treatments had a significant (P<0.001) influence on the PWL of tomatoes. The EPS Tray + PVC wrap had the lowest PWL (%), with 0.70% on Day 7 and 3.94% on Day 28. Unpackaged (control) tomatoes had the highest PWL (%) of all the packaging treatments, averaging 1.30% on Day 7 to 8.98% on Day 28 (Figure 6.1, Appendix A). Similar results have been reported by Fawuyini *et al.* (2020) and Sammi and Masud (2009), where the weight loss in the uncontrolled ripening of unpackaged fruits caused a sudden increase in ethylene production and in the respiration rate, which degrades the nature of the fruit faster, while the packaging slows down these processes. The results of the SP Tray + PVC wrap revealed a rapid increase in weight loss within the first seven days of packaging, averaging 2.93% (Figure 6.1, Appendix A), compared to the other packaging treatments. This increase was the highest rapid PWL (%) in the first seven days of storage, compared to all the other packaging treatments, including the unpackaged tomatoes. Asem *et al.* (2016b) stated that the permeability properties of the packaging material generate a modified atmosphere inside the packaging, which might be positive or negative, depending on the response of the fruit to its new surroundings. The accumulation of water inside the SP Tray + PVC wrap packaging swells, which was not ideal for the tomatoes. Blossom end-rot was observed in the tomatoes after Day 28 at ambient storage (Figure 6.3, Appendix A).

The storage conditions also had a significant ($P<0.001$) influence on the PWL (%) of the tomatoes. Those stored under ambient conditions had a higher percentage weight loss than those under cold storage conditions, with average values of 3.99% and 2.05%, respectively. The same effects were reported by Gebeyehu (2018), where tomatoes stored under ambient storage conditions had a significantly higher PWL (%) than tomatoes stored under cold storage conditions.

The PWL (%) of tomatoes varied significantly ($P<0.001$) with the storage period. As the storage period progressed, the tomatoes tended to lose weight. The interaction between the packaging and storage conditions significantly ($P<0.001$) influences the PWL (%) of the tomatoes. The fruit packaged and stored under cold storage conditions had the lowest PWL (%), compared to those packed and stored under ambient conditions (Figure 6.2, Appendix A). Gebeyehu (2018) stated that high temperatures accelerate the rate of transpiration and enhance water loss. Subsequently, the fruit shrivels and softens. This explains the rapidly-increasing trend of water loss in the unpackaged tomato treatments. Tilahun *et al.* (2017b) stated that packaging retards the rate of transpiration and prevents excessive water loss. The SP Tray + Flow wrap had the second-lowest percentage of weight loss under both the ambient and cold storage conditions (3.02% and 1.82%). This proves that allowing for a small airflow allows the moisture to escape from the SP Tray and dries the packaging environment. However, the rapid increase observed in the SP Tray + PVC wrap results from the moisture being absorbed by the SP Tray, which keeps the environment dry and the samples shiny, hence reducing the chances of microbial growth.

Table 3.3 The effects of the packaging and storage conditions on the physiological weight loss (%) of tomatoes over a 28-day storage period

Package Treatment	Storage conditions	Storage Period (Days)				
		0	7	14	21	28
SP Tray + PVC Cling wrap	Cold	0.00^{a}	$2.42±0.36^{b-k}$	$3.23±0.14^{f-m}$	$4.22±0.20^{j-q}$	$5.45±0.60^{n-r}$
	Ambient	0.00^{a}	$3.44±0.13^{g-m}$	$4.80±0.24^{l-r}$	$5.67±1.49^{o-s}$	$8.64±0.07^{tu}$
EPS Tray + PVC Cling wrap	Cold	0.00^{a}	$0.23±0.03^{a}$	$0.77±0.04^{a-d}$	$1.28±0.08^{a-g}$	$1.78±0.11^{a-i}$
	Ambient	0.00^{a}	$1.17±0.67^{a-f}$	$3.20±1.13^{f-m}$	$3.58±0.32^{h-o}$	$6.11±1.19^{qrs}$
SP Tray + Flow wrap	Cold	0.00^{a}	$0.57±0.06^{ab}$	$1.79±0.20^{a-i}$	$2.84±0.39^{c-m}$	$3.92±0.50^{i-p}$
	Ambient	0.00^{a}	$0.88±0.08^{a-e}$	$2.90±0.20^{d-m}$	$4.56±0.28^{k-q}$	$6.74±0.38^{rst}$
EPS Tray + Flow wrap	Cold	0.00^{a}	$0.58±0.11^{ab}$	$1.83±0.43^{a-i}$	$3.03±0.64^{e-m}$	$4.29±0.91^{j-q}$
	Ambient	0.00^{a}	$1.44±0.95^{a-h}$	$3.11±0.31^{f-m}$	$4.97±0.44^{m-r}$	$7.48±0.89^{stu}$
1 kg PP bag	Cold	0.00^{a}	$0.62±0.12^{ab}$	$1.91±0.26^{a-i}$	$3.21±0.49^{f-m}$	$4.46±0.59^{k-q}$
	Ambient	0.00^{a}	$2.64±3.46^{b-l}$	$3.13±1.09^{f-m}$	$8.70±3.26^{tu}$	$9.34±3.37^{u}$
Unpackaged (Control)	Cold	0.00^{a}	$0.69±0.12^{abc}$	$2.19±0.37^{a-j}$	$4.14±0.80^{j-q}$	$6.00±1.14^{p-s}$
	Ambient	0.00^{a}	$1.91±0.46^{a-i}$	$4.86±1.75^{m-r}$	$8.51±2.80^{tu}$	$11.93±3.70^{v}$

Significance (P) level	
Packaging (A)	P<.001
Storage Conditions (B)	P<.001
Storage Period (C)	P<.001
A*B	P<0.05
A*C	P<.001
B*C	P<.001
A*B*C	P>0.05

Values are means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). SP = Stamped Paper Tray: EPS = Expandable Polystyrene: PVC = Polyvinyl Chloride; PP = Polypropylene

3.8.4 Firmness

The firmness of tomatoes is an enzymatically-related process that continues long after they have been harvested. A knowledge of the firmness properties may provide an understanding of the ripening and maturity stages of the fruit. The three objective texture measurements are puncture, Kramer shear (pulp firmness) and flat-plate compression tests.

3.8.4.1 Puncture

The effects of the packaging and storage conditions on the puncture force of tomatoes over a 28-day storage period are presented in Table 3.4. The puncture test results ranged from 9.97 N to 5.50 N, which is similar to the range reported by Alenazi *et al.* (2020) of tomatoes at the pink to light-red stage of maturity. The packaging treatments had a significant ($P<0.05$) influence on the puncture force of the tomatoes. Tomatoes packaged in the EPS Tray + PVC wrap were relatively firmer (8.20 N), while the unpackaged tomatoes were less firm (7.16 N) than the fruit in the packaging treatments (Figure 6.4c, Appendix A). Olveira-Bouzas *et al.* (2021) reported low puncture force values under modified atmospheric packaging, compared to unpackaged tomatoes. Domínguez *et al.* (2016) reported that packaging decreases the activity of polygalacturonase and pectinesterase enzymes, which are involved in the degradation of the cell walls.

The puncture force varied significantly ($P<0.05$) with the storage conditions. Tomatoes stored under cold storage conditions were firmer than those stored under ambient temperature conditions. The puncture force values for the cold and ambient storage conditions were 8.54 and 6.62 N, respectively (see Figure 6.4b, Appendix A). According to Cherono *et al.* (2018), the firmness is determined by using a puncture test which measures the integrity of the fruit pericarp with localised softening enzymes. The higher firmness under cold storage conditions might be due to the lower temperature and presence of a high relative humidity, which retards the transpiration and respiration rates of the tomatoes. Tigist *et al.* (2013) reported that the biochemical and enzymatic processes in tomatoes are temperature-dependent. Higher temperatures lead to rapid cell degradation, which affects the structure of the tomatoes (Workneh and Osthoff, 2010). The high loss of firmness under ambient storage conditions can be attributed to the increased loss of water through transpiration, respiration and enzymatic activities (Aurand *et al.*, 2012).

The puncture varied significantly ($P<0.001$) with the storage period. The puncture force decreased during storage, from about 8.80 N to 7.09 N between Day 0 and Day 28, respectively (Figure 6.4a, Appendix A). The rate of decline was more significant between Day 0 and Day 7; thereafter, it levelled out until Day 28. According to Kantola and Helen (2001) and Alenazi *et al.* (2020), the flesh of the whole tomato is expected to decrease within 7 to 12 days of storage, due to sudden changes in the fruit, which explains the massive decrease in the puncture force within the first seven days of storage. The same results were reported by Jackman *et al.* (1992), where the firmness of a whole tomato decreased massively within the first 12 days of storage.

Table 3.4 The effects of the packaging and storage conditions on the puncture force (N) of the tomatoes over the 28-day storage period (n=3)

Packaging Treatment	Storage condition	Storage period (days)				
		0	7	14	21	28
SP Tray + PVC wrap cover	Cold	9.97^{n}	9.02±0.11^{mn}	7.90±1.42^{f-m}	6.73±0.31^{a-g}	6.03±0.00^{a-e}
	Ambient	9.97^{n}	8.28±0.15^{g-m}	7.31±0.33^{b-l}	5.70±0.72^{abc}	5.51±0.54^{a}
EPS Tray + PVC wrap cover	Cold	9.97^{n}	8.96±0.00^{lmn}	8.22±1.10^{g-m}	7.38±0.00^{c-m}	6.95±0.00^{a-i}
	Ambient	9.97^{n}	8.70±0.13^{j-n}	8.01±1.24^{f-m}	7.21±0.68^{a-k}	6.08±0.00^{a-f}
SP Tray + Flow wrap cover	Cold	9.97^{n}	8.83±1.66^{k-n}	7.90±1.42^{f-m}	7.61±1.78^{d-m}	6.15±0.35^{a-e}
	Ambient	9.97^{n}	8.64±0.79^{i-n}	7.12±1.65^{a-j}	6.90±0.57^{a-h}	6.12±0.68^{a-e}
EPS Tray + Flow wrap cover	Cold	9.97^{n}	8.95±0.00^{lmn}	8.01±1.24^{f-m}	7.64±0.00^{e-m}	6.07±0.46^{a-e}
	Ambient	9.97^{n}	8.23±0.59^{g-m}	7.96±0.09^{f-m}	7.59±1.56^{d-m}	5.63±2.45^{ab}
1 kg PP bag	Cold	9.97^{n}	8.48±0.00^{h-n}	7.61±1.78^{d-m}	6.90±0.57^{a-h}	5.92±1.49^{a-d}
	Ambient	9.97^{n}	7.29±0.00^{b-l}	6.36±0.67^{a-f}	5.79±1.27^{abc}	5.85±1.62^{abc}
Unpackaged (Control)	Cold	9.97^{n}	8.17±0.42^{g-m}	7.38±0.00^{c-m}	6.42±0.00^{a-f}	5.62 ±1.71^{ab}
	Ambient	9.97^{n}	7.26±0.36^{b-}	6.03±0.00^{a-e}	5.85±0.00^{abc}	5.50±0.53^{a}

Significance (P) level	
Packaging (A)	P<.001
Storage Conditions (B)	P<.001
Storage Period (C)	P<.001
A*B	P<0.05
A*C	P<0.05
B*C	P<.001
A*B*C	P>0.05

Values are means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). SP = Stamped Paper Tray: EPS = Expandable Polystyrene: PVC = Polyvinyl Chloride; PP = Polypropylene

There was no significant (P>0.05) difference between the packaging and storage conditions, although the tomatoes stored under cold storage conditions were firmer than those packaged and stored under ambient temperature conditions (Figure 3.5d). The tomatoes in all packages softened during the storage period, which is attributed to the degradation of polysaccharides during the ripening process. According to Azene *et al.* (2014a), the texture changes in fruit are a result of the polysaccharides components that give rise to the disassembling of the cell walls and the middle lamella caused by enzyme activities. Hence, the variability in the decline of firmness of the tomatoes in the different packaging treatments may well be described by the differences in the packaging structure, which influence the respiration rate during the ripening process. Tomatoes in the packages without perforated holes were slightly firmer than those in packages with perforated holes. This difference is evident in those packed with the EPS Tray + PVC wrap and EPS Tray + Flow wrap under the same storage conditions. The perforated holes allow air movement in and out of the packaging system, which influences the rate of respiration.

3.8.4.2 Kramer shear

Table 3.5 presents the results of the Kramer shear of tomatoes as they are affected by the packaging and storage conditions over the 28-day storage period. The shear force values ranged from 8.63 to 3.17 $N.g^{-1}$, which is within the range reported by Gormley and Keppel (2006). The packaging treatments had no significant impact (P>0.05) on the shearing of the tomatoes. Tomatoes packaged in the SP Tray + PVC Cling had a higher shear force value (5.80 $N.g^{-1}$), while unpackaged fruits had a significantly low shear force value (5.16 $N.g^{-1}$). The Kramer shear results also varied significantly (P<0.05) with the storage conditions. The shear force of tomatoes stored under cold storage conditions was higher than those stored under ambient conditions. The shearing force values for cold and ambient storage conditions were 5.88 and 5.31 $N.g^{-1}$, respectively. The differences can be attributed to the high biochemical changes related to the ripening process that transpire under the high temperatures in ambient conditions.

The shear force varied significantly (P<0.05) with the storage period. The shear force of the tomatoes decreased with the storage time. Gormley and Keppel (2006) reported a decline in the tomato firmness, depending on the ripening stage and storage time. The decline was considerable within the first seven days of storage. The packaging and storage period results were not significant (P>0.05) with regrd to the shear force of the tomatoes. A significant decline was observed in all packages within the first seven days, with a slight increase on Day 21 and a decline on Day 28 across all packages. The first decline may be attributed to enzyme activity, in response to the packaging treatments (Ali, 1998). However, the slight increase may be due to a massive water loss in the tomatoes, resulting in muscle pulp stiffness (Banda *et al.*, 2015). Tomatoes consist of water; when they are harvested, they can no longer replace the water that is used up by biochemical activities and through transpiration, and this causes shrivelling. Hence, the fruit juice becomes thicker and the flesh becomes firmer (FAO, 2018).

Table 3.5 Effects of the packaging and storage conditions on the kramer shear ($N.g^{-1}$) of the tomatoes over the 28-day storage period (n=3)

Packaging Treatment	Storage Conditions	Storage Period (Days)				
		0	7	14	21	28
SP Tray + PVC wrap	Cold	8.63^{i}	$6.28\pm1.70^{c-i}$	$5.98\pm0.83^{a-i}$	$5.87\pm0.72^{a-i}$	$4.67\pm0.84^{a-f}$
	Ambient	8.63^{i}	$5.64\pm1.56^{a-h}$	$4.54\pm0.61^{a-f}$	$4.27\pm0.43^{a-f}$	$3.79\pm1.03^{a-c}$
EPS Tray + PVC wrap	Cold	8.63^{i}	$6.47\pm1.87^{c-i}$	$6.03\pm1.36^{a-i}$	$5.50\pm0.98^{a-h}$	$5.04\pm1.73^{a-h}$
	Ambient	8.63^{i}	$6.40\pm0.12^{c-i}$	$5.60\pm1.51^{a-h}$	$5.45\pm1.14^{a-h}$	$3.98\pm1.43^{a-d}$
SP tray + Flow wrap	Cold	8.63^{i}	$7.05\pm1.02^{e-i}$	$6.48\pm2.08^{c-i}$	$5.50\pm0.90^{a-h}$	$4.67\pm1.21^{a-f}$
	Ambient	8.63^{i}	$6.49\pm0.21^{c-i}$	$5.62\pm1.86^{a-h}$	$5.13\pm0.19^{a-h}$	3.80 ± 0.71^{abc}
EPS Tray + Flow wrap	Cold	8.63^{i}	7.82 ± 4.33^{hi}	$6.64\pm2.48^{c-}$	$5.37\pm2.24^{a-h}$	$4.40\pm0.95^{a-f}$
	Ambient	8.63^{i}	$6.61\pm1.84^{c-i}$	$5.07\pm1.66^{a-h}$	$5.01\pm1.43^{a-h}$	$4.37\pm1.05^{a-f}$
1 kg PP bag	Cold	8.63^{i}	$5.59\pm1.48^{a-h}$	$6.11\pm1.75^{a-i}$	$5.54\pm0.67^{a-h}$	$4.33\pm0.70^{a-f}$
	Ambient	8.63^{i}	$5.56\pm0.54^{a-h}$	$5.50\pm1.39^{a-h}$	$4.21\pm0.13^{a-f}$	3.75 ± 0.72^{abc}
Unpackaged (control)	Cold	8.63^{i}	$5.82\pm1.87^{a-i}$	$5.31\pm0.21^{a-h}$	$4.81\pm1.94^{a-g}$	3.31 ± 0.53^{ab}
	Ambient	8.63^{i}	$4.99\pm0.67^{a-h}$	$4.20\pm0.26^{a-f}$	$4.10\pm0.51^{a-e}$	3.17 ± 1.97^{a}

Significance (P) level	
Package (A)	P>0.05
Storage conditions (B)	P<.001
Storage period (C)	P<.001
A*B	P>0.05
A*C	P>0.05
B*C	P>0.05
A*B*C	P<.001

Values are means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). SP = Stamped Paper Tray: EPS = Expandable Polystyrene: PVC = Polyvinyl Chloride; PP = Polypropylene

3.8.4.3 Compression test

The flat-plate compression test results of tomatoes affected by the packaging and storage conditions over the 28-days storage period are presented in Table 3.6. The compression values of this experiment had a range of 155.5 to 72.8 N. These values are below the range reported by Albaloushi *et al.* (2012). The differences can be attributed to the difference in cultivars, the geographic location and the growing conditions of the cherry tomatoes. The packaging treatments had a significant (P<0.05) influence on the compressive load of the tomatoes. Tomatoes packed in the SP Tray + Flow wrap had a higher compressive load (130.1 N), whilst the Unpackaged (control) tomatoes had the lowest compressive load (119.7 N). According to Albaloushi *et al.* (2012), tissue failure under compression loading is a result of the cell wall rupturing, which is caused by extreme stress. The significant changes are related to the presence of pectin in the amorphous matrix of the fruit, where the cellulose microfibrils of the cell wall are rooted, and in the middle lamella. For rupturing to occur, the lining of these pectin in the amorphous matrix significantly influences tissue failure. The ripening stage determines these factors (Albaloushi *et al.*, 2012); hence, the compressive force was low in unpackaged fruits, which had ripened faster.

The storage conditions had a significant (P<0.05) influence on the compressive load of tomatoes. Those stored under cold storage conditions had a higher compressive load than those stored under ambient conditions. The compressive load values of cold and ambient storage conditions were 139.7 and 104.9 N, respectively, which means that tomatoes under cold storage conditions maintained their firmness better than those stored under ambient storage conditions. Workneh (2010) reported similar results, where tomatoes stored in a controlled cooling system remained firmer than those stored under ambient conditions.The compression force varied significantly (P<0.05) over the storage period. It decreased progressively as the storage time progressed, between Day 0 and Day 28, from 148.5 N to 104.1 N, respectively. Similar results were reported by Albaloushi *et al.* (2012), who found that the hardness, resilience and fracturability of the whole fruit decreased during ripening. According to Barrett *et al.* (1998), the firmness is expected to decline as the storage time increases, due to the maturity of the fruit. Similar findings were reported by Mekonnen (2017b), where the firmness of the tomatoes decreased as the length of the storage period increased.

The interaction of (a) the packaging and storage period, and (b) the storage conditions and storage period proved to have a significant (P<0.05) influence on the firmness of the tomatoes.

The results showed a decline in the compressive force amongst the packaging treatments, as the storage time progressed. The firmness was higher in packaged tomatoes, compared to unpackaged tomatoes, from Day 0 to Day 28. The cold storage conditions also reduced the loss in firmness. This is evident in the firmer tomatoes that were packaged under cold storage conditions, compared to those packaged under ambient storage conditions.

The interaction of the packaging and storage conditions also significantly ($P<0.05$) influenced the compressive load. Tomatoes packaged in the SP Tray + Flow wrap had the highest compressive load under both cold and ambient storage conditions. The effects of the packaging, storage conditions and storage period had a significant ($P<0.05$) influence on the firmness of the tomatoes. Those packaged and stored under cold storage conditions were firmer than those stored under ambient conditions. The differences show that the packaging and cold storage conditions maintained the structure, rigidity and solidness better than those under ambient storage conditions. Similar observations were reported by Mekonnen (2017b), where the loss of firmness occurred slowly in packages stored under cold conditions, compared to those stored under ambient temperature conditions for the same storage period. Asem *et al.* (2016b) also reported that the packaging had a significant effect on the firmness of the tomato fruit, where the packaging and cold storage conditions maintained the firmness better than under ambient conditions. Gebeyehu (2018) reported the exact effects of the packaging, storage conditions and storage period on tomatoes by showing that the differences in the packaging structure, the packaging design and the cover were the main influences on the quality of tomatoes.

All firmness tests (puncture, Kramer and compression) revealed that there was a softening of the tomato fruit during the storage period, from Day 0 to Day 28. According to Irtwange (2006), the loss of firmness can be attributed to the degradation of polysaccharides, such as cellulose, hemicellulose and pectin, during ripening. The modification of the polysaccharides disassembles the cell walls and the middle lamella structures due to enzyme activities (Albaloushi *et al.*, 2012). Hence, the significant differences in firmness in the tomatoes in this study can be ascribed partly to the differences in the structure of the packaging treatments, which give rise to differences in the respiration rate; these affect the depolarisation and solubility of pectin under the same storage conditions and over the same period. The results showed that packages without perforated holes maintained the firmness of the fruit better than packages with perforated holes. Tomatoes packaged in the EPS Tray + PVC wrap and SP Tray + PVC wrap remained firmer than all the other packages and showed the highest puncture and shear force test values. However, the indefinite differences between the biodegradable (SP Tray + PVC wrap) and non-biodegradable (EPS Tray + PVC wrap) packaging were marginal (4.6%). The relative difference might be attributed to the permeability of the packaging materials. Non-biodegradable materials are less permeable than the biodegradable materials; hence, the respiration rate might be slightly increased by the movement of particles through the porous spaces (Cyras *et al.*, 2007; Ivonkovic *et al.*, 2017).

Table 3.6 Compression (N) test of tomatoes influenced by the packaging and storage conditions over a 28-day storage period (n=3)

Packaging Treatment	Storage Conditions	Storage Period (Days)				
		0	7	14	21	28
SP Tray + PVC wrap	Cold	155.5^{v}	133.6±0.01^{n-t}	123.7±0.01^{j-q}	116.8±16.83^{f-n}	107.3±2.63^{c-i}
	Ambient	155.5^{v}	129.5±0.01^{m-t}	116.0±0.06^{f-m}	105.8±1.72^{c-h}	101.1±0.01^{c-g}
EPS Tray + PVC wrap	Cold	155.5^{v}	143.9±5.64^{s-v}	128.1±0.01^{m-t}	119.0±0.01^{g-p}	112.0±0.01^{e-l}
	Ambient	155.5	126.3±24.83^{k-r}	115.4±0.01^{f-m}	113.4±9.92^{e-m}	103.4±1.60^{c-g}
SP Tray + Flow wrap	Cold	155.5^{v}	135.6±0.01^{0-t}	127.0±0.01^{l-s}	124.2±0.01^{i-q}	106.6±0.01^{c-h}
	Ambient	155.5^{uv}	129.5±27.00^{m-t}	123.6±12.28^{j-q}	96.2±19.25^{b-e}	92.8±2.52^{bcd}
EPS Tray + Flow wrap	Cold	155.5^{v}	145.9±0.01^{tuv}	133.8±0.01^{n-t}	128.6±1.73^{l-s}	99.8±19.60^{c-f}
	Ambient	155.5^{uv}	136.1±0.01^{p-t}	126.1±0.01^{k-r}	116.6±0.01^{f-m}	103.4±12.61^{c-g}
1 kg PP bag	Cold	155.5^{uv}	129.9±8.87^{m-t}	129.5±0.01^{m-t}	112.9±4.41^{e-m}	108.6±0.01^{d-j}
	Ambient	155.5^{uv}	116.2±0.01^{f-m}	113.9±15.00^{f-m}	81.6±13.75^{ab}	93.7±0.64^{bcd}
Unpackaged (Control)	Cold	155.5^{uv}	138.8±3.46^{q-u}	124.7±6.01^{j-q}	110.9±5.06^{e-l}	105.5±13.20^{c-g}
	Ambient	155.5^{uv}	134.8±0.01^{0-t}	107.5±0.01^{c-j}	90.5±22.04^{bc}	72.8±21.53^{a}

Significance (P) level	
Packaging (A)	P<0.01
Storage Conditions (B)	P<0.01
Storage Period (C)	P<0.01
A*B	P<.001
A*C	P<0.01
B*C	P<0.01
A*B*C	P<0.05

Values are means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). SP = Stamped Paper Tray: EPS = Expandable Polystyrene: PVC = Polyvinyl Chloride; PP = Polypropylene

3.8.5 Total soluble solids

A complete layout of the effects of the packaging and storage conditions on the total soluble solids of the tomatoes over the 28-day storage period is presented in Table 3.7. The Total Soluble Solids (TSS) is one of the critical quality attributes of a tomato. In this experiment, the TSS ranges were between 3.70 and 4.87 °Brix, which were similar to the range (3.40 to 4.80 °Brix) reported by Murariu *et al.* (2021). The packaging treatment had a significant ($P>0.05$) influence on the TSS of tomatoes. Unpackaged (control) tomatoes showed the highest increase in TSS content (4.36 °Brix), while the SP Tray + PVC wrap had the lowest TSS content (4.09 °Brix). The results agree with those of Sualeh *et al.* (2016), who reported that the packaging significantly influenced the TSS of tomatoes. The different changes in the TSS can be attributed to the slower respiration rate, as well as the metabolic activities, which slow down the ripening process in packaged tomato fruits, compared to unpackaged tomato samples (Gharezi *et al.*, 2012; Sattar *et al.*, 2019).

The storage conditions also had a significant ($P<0.001$) influence on the TSS values of the tomatoes. Al-Dairi *et al.* (2021) reported similar results of where the storage conditions highly influenced the TSS of tomatoes. The most significant changes were observed in tomatoes under ambient storage conditions, with a significant increase from 3.70 to 4.24 °Brix, whilst minimum changes were found in tomatoes stored under cold conditions, where the TSS ranged from 3.70 to 4.13 °Brix. These results show that the ripening process was slow under cold storage conditions, and therefore, the accumulation of total soluble solids was slowed down.

The results revealed that the TSS varied significantly ($P<0.001$) with the storage period. The TSS increased between Day 0 and Day 28, from 3.8 to 4.5 °Brix. The results agree with those of Moneruzzaman *et al*. (2008) and Tolasa *et al.* (2021), who reported that the TSS increased constantly, as storage time progressed. Asem *et al.* (2016a) also reported that the TSS increases gradually with storage time, due to the maturity of the fruit. The interaction of the packaging and storage period also affected theTSS changes significantly ($P<0.05$). Higher TSS values were recorded in the Control tomatoes. From the early packaging stage, unpackaged tomatoes showed the highest increase in TSS content after Day 7 (4.21 °Brix), which indicates that rapid ripening occurred within the first seven days and that the highest TSS content (4.75 °Brix) was maintained throughout the 28-day storage period. Amongst the packaging treatments, the 1 kg PP bag showed the highest increase in TSS content (4.17) over the 28 days. According to Adhikari *et al.* (2020), the higher the TSS content in tomatoes, the riper they are. Tomatoes with a high TSS content are favoured for consumption. However, a rapid increase indicates a fast progression to maturity and it decreases the shelf-life, which is not ideal for a perishable fruit, such as tomatoes (Murariu *et al.*, 2021).

Table 3.7 The total soluble solids (°Brix) of tomatoes influenced by the packaging and storage conditions over a 28-day storage period (n=3)

Packaging Treatment	Storage Conditions	Storage Period (Days)				
		0	7	14	21	28
SP Tray + PVC wrap	Cold	3.70^{a}	3.83±0.06^{a-d}	4.17±0.06^{f-h}	4.30±0.10^{h-k}	4.37±0.06^{h-m}
	Ambient	3.70^{a}	3.97±0.06^{b-e}	4.33±0.06^{h-m}	4.53±0.06^{m-q}	4.70±0.10^{qr}
EPS Tray + PVC wrap	Cold	3.70^{a}	3.77±0.06^{ab}	4.23±0.12^{g-j}	4.37±0.06^{h-m}	4.43±0.12^{j-n}
	Ambient	3.70^{a}	3.87±0.15^{a-d}	4.27±0.05^{g-k}	4.50±0.10^{l-p}	4.83±0.06^{r}
SP Tray + Flow wrap	Cold	3.70^{a}	3.97±0.06^{b-e}	4.16±0.06^{f-h}	4.34±0.12^{h-m}	4.40±0.20^{i-m}
	Ambient	3.70^{a}	4.20±0.10^{g-i}	4.31±0.27^{h-l}	4.40±0.10^{i-m}	4.50±0.17^{l-p}
EPS Tray + Flow wrap	Cold	3.70^{a}	3.77±0.06^{a-c}	4.20±0.10^{f-i}	4.27±0.06^{g-k}	4.43±0.12^{j-n}
	Ambient	3.70^{a}	3.80±0.06^{a-c}	4.28±0.15^{h-k}	4.30±0.26^{h-l}	4.53±0.06^{m-q}
1 kg PP bag	Cold	3.70^{a}	3.83±0.06^{a-d}	4.27±0.15^{f-h}	4.35±0.17^{g-i}	4.48±0.06^{j-o}
	Ambient	3.70^{a}	3.90±0.01^{a-e}	4.33±0.06^{h-m}	4.47±0.15^{l-p}	4.73±0.25^{qr}
Unpackaged (control)	Cold	3.70^{a}	4.17±0.12^{f-h}	4.40±0.10^{j-o}	4.57±0.06^{k-n}	4.63±0.12 $^{n-q}$
	Ambient	3.70^{a}	4.25±0.06^{h-k}	4.47±0. 06^{k-p}	4.83±0.12^{r}	4.87±0.06^{r}

Significance (P) level	
Packaging (A)	P<0.05
Storage Conditions (B)	P<.001
Storage Period (C)	P<.001
A*B	P<0.05
A*C	P<.001
B*C	P<.001
A*B*C	P<0.05

Values are means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). SP = Stamped Paper Tray: EPS = Expandable Polystyrene: PVC = Polyvinyl Chloride; PP = Polypropylene

The combined effect of (a) the packaging and storage conditions and (b) the storage conditions and storage period also had a significant (P<0.05) influence on the TSS of tomatoes. Tomatoes packaged and stored under cold storage conditions had lower TSS values than those packaged and stored under ambient storage conditions. The results agree with those of Sualeh *et al.* (2016) and Mekonnen (2017a), who found that tomatoes packed and stored under cold storage conditions had lower TSS values than those stored under ambient storage conditions. The packaging provides a modified atmosphere that reduces the interplay of O_2 and CO_2; hence, a combination of the packaging and lower temperatures delayed the senescence of the tomato fruit, due to a low respiration rate (Gebeyehu 2018). The difference means that packaged tomatoes stored under cold storage conditions ripen slowly, compared to those stored under ambient storage conditions.

The combined effect of the packaging, storage conditions and storage period also significantly ($P \leq 0.05$) influenced the TSS values. The lowest was an increase of 18.1% in the TSS values of tomatoes packaged in the SP Tray + PVC wrap stored under cold storage conditions. The highest increase in TSS values was in the control tomatoes, which were subject to cold and ambient storage conditions (25% and 31.6%) between Day 0 and Day 28. According to Asem *et al.* (2016a), the TSS changes are a natural phenomenon that occurs due to ripening, and it is associated with the starch hydrolysis that occurs in the post-harvest period. The conversion of starch to sugar is an indication of the end of a tomato's lifespan, hence higher TSS values occur at the end of the storage period (Murariu *et al.*, 2021). Therefore, a slow increase in the TSS content is appropriate for extending the shelf-life of tomatoes. The TSS results revealed that the SP Tray + PVC wrap is the best packaging treatment for maintaining changes in the quality of TSS in the tomatoes.

3.8.6 pH value

A layout of the pH results affected by the packaging and storage conditions for the 28-day period are presented in Table 3.8. The pH values ranged from 4.20 to 4.60 over the 28-day storage period. Al-Dairi *et al.* (2021) found a similar pH range, from 4.15 to 4.55 over eight days of storage. The results revealed that the packaging had a highly significant ($P<0.001$) influence on the pH values of the tomatoes. Unpackaged (control) tomatoes had the highest pH value (4.48), while the EPS Tray + PVC wrap had the lowest average pH value (4.42). Similar results were reported by Olveira-Bouzas *et al.* (2021), where packaged tomato fruits had the lowest pH values, compared to unpackaged tomato fruits. According to Gebeyehu (2018), the lower pH values in packaged tomatoes can be attributed to the relatively reduced respiration rate that results from the changes brought about by the packaging environment. The differences mean that respiration occurs much faster in the unpackaged tomatoes than in the packaged treatments.

The storage conditions also had a highly significant ($P<0.001$) effect on the pH values of tomatoes. The pH value of tomatoes stored under cold storage conditions was lower (pH value=4.41) than those stored under ambient conditions (pH value =4.45). Generally, the normal tomato ripening process causes the pH to rise, as the fruit converts acids to sugars (Azene *et al.*, 2014b). The higher pH values of tomatoes under ambient storage conditions could be attributed to the faster conversion rate of acids to sugar, due to the faster respiration rate experienced by tomatoes during ripening (Azene *et al.*, 2014a). Hence, higher temperature conditions cause a faster respiration rate, which results in a loss of acidity (Tigist *et al.*, 2013).

The tomato pH results varied significantly ($P<0.001$) over the 28-day storage period. The pH values increased significantly as the storage time progressed, from 4.20 to 4.46 between Day 0 and Day 28, respectively. Similar observations have been reported by Anthon *et al.* (2011) and Cherono *et al.* (2018), where the pH continually increased with the storage time. Endalew (2020) explained that the pH value of tomatoes increases with the storage time, due to ripening and respiration.

The interaction of (a) the packaging and storage conditions, and (b) the packaging and storage period had no significant ($P>0.05$) influence on the changes in pH value. Packaged tomatoes stored under cold storage conditions had lower pH values than those stored under ambient storage conditions. The most significant changes were observed in the control samples under ambient storage conditions between Days 0 and 28. The storage conditions and storage period had a significant ($P<0.05$) influence on the tomato samples. This interaction showed that those samples stored under ambient conditions exhibited a faster increase in their pH values (7.6%) than (6%) those stored under ambient storage conditions between Day 0 and Day 28. This faster increase results from the high temperatures, which promote respiration and the ripening process. This is paralleled with a decrease in titratable acidity as a result of the loss of citric acid. (Anthon *et al.*, 2011).

The combined effect of the packaging, storage conditions and storage period also had a significant ($P<0.05$) influence on the pH values of the tomato samples after 28 days. The highest increase in pH values of 10% was observed for unpackaged samples under ambient storage conditions. Samples packaged in the EPS Tray + PVC wrap under cold storage conditions resulted in the lowest change in pH values, namely a 5.7% increase after 28 days. This experiment indicates that the packaging and cold storage are beneficial for maintaining the quality of tomatoes, in terms of slowing down the pH increase. Tomatoes packaged in the EPS tray + PVC and subjected to cold storage conditions exhibited the slowest increase in their pH value.

Table 3.8 pH values of the tomatoes affected by the packaging and storage conditions during storage (n=3)

Packaging Treatment	Storage Conditions	Storage Period (Days)				
		0	7	14	21	28
SP Tray + PVC wrap	Cold	4.20^{a}	$4.51\pm0.02^{d-j}$	$4.42\pm0.06^{b-f}$	$4.48\pm0.01^{d-j}$	$4.47\pm0.03^{c-j}$
	Ambient	4.20^{a}	$4.55\pm0.01^{f-k}$	$4.45\pm0.05^{b-i}$	$4.54\pm0.05^{e-k}$	$4.58\pm0.02^{i-k}$
EPS tray + PVC wrap	Cold	4.20^{a}	$4.47\pm0.23^{c-i}$	4.34 ± 0.01^{b}	$4.44\pm0.07^{b-g}$	$4.44\pm0.03^{b-f}$
	Ambient	4.20^{a}	$4.53\pm0.03^{e-j}$	$4.47\pm0.03^{c-j}$	$4.57\pm0.06^{g-k}$	$4.54\pm0.01^{e-k}$
SP Tray + Flow wrap	Cold	4.20^{a}	$4.42\pm0.02^{b-f}$	4.34 ± 0.01^{b}	4.35 ± 0.05^{bc}	$4.50\pm0.01^{d-j}$
	Ambient	4.20^{a}	$4.46\pm0.05^{b-i}$	$4.46\pm0.05^{b-i}$	$4.48\pm0.02^{d-j}$	$4.48\pm0.04^{d-j}$
EPS Tray + Flow wrap	Cold	4.20^{a}	$4.48\pm0.16^{d-j}$	$4.43\pm0.02^{b-f}$	$4.44\pm0.01^{b-g}$	$4.49\pm0.06^{d-j}$
	Ambient	4.20^{a}	$4.57\pm0.11^{h-k}$	$4.46\pm0.03^{b-i}$	$4.57\pm0.03^{g-k}$	$4.52\pm0.06^{e-j}$
1 kg PP bag	Cold	4.20^{a}	$4.44\pm0.06^{b-h}$	$4.44\pm0.04^{b-f}$	$4.50\pm0.02^{d-j}$	$4.49\pm0.04^{d-j}$
	Ambient	4.20^{a}	$4.53\pm0.03^{e-j}$	$4.46\pm0.05^{b-i}$	$4.53\pm0.09^{e-j}$	$4.55\pm0.03^{f-k}$
Unpackaged (control)	Cold	4.20^{a}	$4.50\pm0.06^{d-j}$	$4.47\pm0.18^{c-j}$	$4.53\pm0.01^{e-j}$	$4.58\pm0.02^{i-k}$
	Ambient	4.20^{a}	4.60 ± 0.01^{jk}	$4.50\pm0.03^{d-j}$	4.66 ± 0.19^{k}	4.60 ± 0.06^{jk}

Significance (P) level	
Packaging (A)	P<.001
Storage Conditions (B)	P<.001
Storage Period (C)	P<.001
A*B	P>0.05
A*C	P>0.05
B*C	P<0.05
A*B*C	P<0.05

Values are means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). SP = Stamped Paper Tray: EPS = Expandable Polystyrene: PVC = Polyvinyl Chloride; PP = Polypropylene

3.8.7 Titratable acidity

Table 3.9 presents the results of the titratable acidity that is affected by the packaging and storage conditions over a storage period of 28 days. The Titratable Acidity (TA) values ranged from 0.51 to 0.24%, which is similar to those of the field-grown tomatoes reported by Tolesa and Workneh (2017). The packaging had a significant (P<0.001) influence on the TA of the tomatoes. The EPS Tray + PVC wrap had the lowest reduction in TA (0.42%), while the Unpackaged (control) tomatoes had the highest (0.39%). Adhikari *et al.* (2020) reported that the packaging significantly affects the TA and that the TA decreases in the fruit, while the pH increases, as the fruit storage time progresses towards senescence.

The storage condition significantly (P<0.001) influenced the TA of the tomatoes. Those stored under cold storage conditions had higher TA values (0.42%) than the TA values (0.36%) of those stored under ambient storage conditions. TA values varied significantly (P<0.001) over the 28-day storage period. As the storage period progressed, the TA declined, with the highest mean TA values recorded on Day 0 (0.51%) and the lowest mean TA values recorded on Day 28 (0.30%). Similar results were reported by Tolasa *et al.* (2021), where the titratable acidity decreases with time. Shehata *et al.* (2021) reported that a reduction of the TA as the storage time progresses can be attributed to the use of titratable acids by the respiration processes and the metabolism of the tomatoes.

The interaction between the packaging and storage period, the packaging and storage conditions, and the storage period and storage conditions also significantly influenced (P<0.001) the TA. A highly significant (P<0.001) influence was also shown by the three-way interaction of the packaging, storage condition and storage period on the TA content of the tomatoes. Sualeh *et al.* (2016) also found that the packaging and storage conditions significantly influenced the TA of tomatoes. In this study, the lowest decline in TA of 25% was recorded in the EPS Tray + PVC wrap on the initial sampling day under cold storage conditions, and the highest decline in TA of 51% was recorded in the Control on the Day 28 under ambient storage conditions. Shehata *et al.* (2021) and de Castro *et al.* (2006) explained that the TA decreases with the storage time because it is a respiration substrate; hence, tomatoes stored under ambient storage conditions will have a relatively lower TA, since respiration is a temperature-dependent process. The lower TA values in the packaged tomatoes under cold storage conditions could result from the reduced respiration rate, which is central to the slow accumulation of titratable acids in the tomatoes, due to their metabolism. In contrast to the ambient storage conditions, the massive reduction in TA can result from the rapid depletion of organic acids that is caused by the faster respiration rate and ripening process, which are caused by the high temperature in the storage room (Dandago *et al.*, 2017; Kumar *et al.*, 2021).

Table 3.9 Titratable acidity (%) of the tomatoes influenced by the packaging and storage conditions (n=3)

Packaging Treatment	Storage Condition	Storage Period (Days)				
		0	7	14	21	28
SP Tray + PVC wrap	Cold	0.51^{r}	0.50 ± 0.08^{r}	$0.43\pm0.03^{k-n}$	$0.38\pm0.01^{g-j}$	$0.26\pm0.11^{a-c}$
	Ambient	0.51^{r}	$0.46\pm0.01^{n-q}$	$0.39\pm0.02^{h-k}$	$0.35\pm0.04^{e-g}$	0.24 ± 0.05^{a}
EPS Tray + PVC wrap	Cold	0.51^{r}	$0.45\pm0.02^{m-p}$	$0.40\pm0.01^{i-l}$	$0.36\pm0.01^{e-i}$	$0.38\pm0.02^{g-j}$
	Ambient	0.51^{r}	$0.43\pm0.01^{k-n}$	$0.35\pm0.02^{e-h}$	0.30 ± 0.02^{cd}	0.25 ± 0.02^{ab}
SP Tray + Flow wrap	Cold	0.51^{r}	$0.49\pm0.01^{p-r}$	$0.48\pm0.01^{0-r}$	$0.37\pm0.01^{e-i}$	$0.35\pm0.03^{e-g}$
	Ambient	0.51^{r}	$0.47\pm0.01^{n-r}$	$0.36\pm0.02^{e-i}$	0.30 ± 0.02^{cd}	0.24 ± 0.00^{a}
EPS Tray + Flow wrap	Cold	0.51^{r}	$0.46\pm0.01^{n-q}$	$0.43\pm0.01^{k-n}$	$0.38\pm0.01^{g-j}$	0.33 ± 0.02^{de}
	Ambient	0.51^{r}	$0.41\pm0.03^{j-m}$	$0.37\pm0.01^{f-j}$	0.29 ± 0.01^{cd}	$0.27\pm0.02^{a-c}$
1 kg PP bag	Cold	0.51^{r}	$0.45\pm0.00^{n-p}$	$0.37\pm0.01^{e-i}$	$0.35\pm0.01^{e-g}$	$0.33\pm0.03^{d-f}$
	Ambient	0.51^{r}	$0.45\pm0.01^{m-p}$	$0.38\pm0.00^{g-j}$	0.28 ± 0.01^{bc}	$0.28\pm0.02^{a-c}$
Unpackaged (Control)	Cold	0.51^{r}	$0.47\pm0.03^{0-r}$	$0.43\pm0.01^{l-n}$	$0.40\pm0.02^{i-l}$	$0.34\pm0.02^{e-g}$
	Ambient	0.51^{r}	$0.44\pm0.00^{m-o}$	$0.40\pm0.04^{i-l}$	$0.28\pm0.02^{a-c}$	0.25 ± 0.02^{ab}

Significance (P) level	
Packaging (A)	P<.001
Storage Conditions (B)	P<.001
Storage Period (C)	P<.001
A*B	P<.001
A*C	P<.001
B*C	P<.001
A*B*C	P<.001

Values are means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). SP = Stamped Paper Tray: EPS = Expandable Polystyrene: PVC = Polyvinyl Chloride; PP = Polypropylene

3.8.8 Total sugars

The results of the influence of the packaging and storage conditions on the total sugars over 28 days are presented in Table 3.10. The total sugar concentration values ranged from 8.95 to 3.43 mg.100^{-1}g of fresh weight. These results are in agreement with the range reported by Farooq *et al.* (2020). The packaging had a significant ($P<0.001$) effect on the changes in the total sugar concentration of the tomatoes. The unpackaged tomatoes (Control) showed a rapid decline in total sugars, compared to the packaged tomatoes. Sammi and Masud (2009) reported similar results with regard to the effects of different packaging systems, where the total sugars gradually decreased as the ripening progressed. The EPS Tray + PVC wrap had the minimum loss in total sugars (6.90 g.100^{-1}g FW), followed by the SP Tray + Flow wrap (6.56 mg.100^{-1}g FW), the EPS Tray + Flow wrap (6.25 mg.100^{-1}g FW) and the SP Tray + PVC cling wrap (6.40 mg.100^{-1}g FW). The Old PP plastic (6.23 mg.100^{-1}g FW) did poorly and was only exceeded by the unpackaged tomatoes (5.76 mg.100-1g of FW). The packaging potentially creates a modified atmosphere around the tomatoes, which helps to regulate the gaseous exchange influxes (Giannakourou and Tsironi, 2021). As the fruit respires inside the packaging, the O2 concentration levels decrease, while the CO_2 increases (Gebeyehu 2018). The interplay of these gases retards the consumption of respiratory substrates, such as sugars; hence, the quality of the fruit is maintained (Azene *et al.*, 2014b). However, as reported by Asem *et al.* (2016b), the permeable properties of the packaging materials play an essential role. One of the disadvantages of biodegradable materials is their high permeability rate (Ivonkovic *et al.*, 2017), which can explain the difference in sugars between the SP Tray and the EPS Tray packaging materials.

The storage conditions significantly ($P<0.001$) influenced the total sugar concentration of the tomatoes. For those tomatoes stored under ambient storage conditions (5.98 mg.100^{-1}g FW), it declined faster than in tomatoes stored under cold storage conditions (6.72 mg.100^{-1}g FW). Similar results were reported by Cantwell *et al.* (2009), where there was more than a 30% decrease in the total sugar concentration of tomatoes stored under ambient storage conditions, compared to those stored under cold storage conditions. Pinela *et al.* (2012) reported that total sugars are a significant source of metabolic energy. The higher loss of sugars under ambient storage conditions can be associated with high respiration rate and metabolic processes, which trigger the rapid hydrolysis of sugars. Similarly, Azene *et al.* (2014b) also reported that higher temperatures advocate the more rapid utilisation of sugars as a substrate for the ripening and metabolic processes. Cooler temperatures help to delay these processes, which results in the lower utilisation of sugars.

The total sugar concentration varied significantly ($P<0.001$) over the 28-day storage period. The relationship shows a decline in the total sugar concentration over the storage period, from 8.95 $mg.100^{-1}g$ on Day 0 to 4.77 $mg.100^{-1}g$ of fresh weight (FW) on Day 28, respectively. Farooq *et al.* (2020) also reported a decline in the total sugar concentration with the advancement of a 30-day storage period. According to Sammi and Masud (2009), the total sugars reach a peak concentration at the pinkish-yellow to red ripening stages. Thereafter, they begin to decrease as the fruit matures and changes to become entirely red. The results show that the highest total sugar concentration was at the initial stage of packaging, where the tomatoes were at their pinkish-yellow to red ripening stage. Charles *et al.* (2016) reported that sugars generally increase with the maturity of tomatoes. The fructose and glucose dominate, while the sucrose decreases up to 90% of its initial concentration and declines when the tomatoes start to deteriorate, which explains the decline in total sugars during storage, as they ripen to full red. Similar trends were reported in the papaya fruit by Azene *et al.* (2014b), where the fruit showed a slight increase in total sugars at the beginning and a decrease towards the end of its lifespan. Oms-Oliu *et al.* (2011) also reported that sugar phosphates are intermediate pathways of central metabolism; as the fruit begins to deteriorate, there is a high turnover rate of sugar concentration. As the tomatoes mature to become entirely red, more starch is lost due to respiration, which causes carbon influxes.

All the combined effects of (a) the packaging and storage conditions, (b) the packaging and storage period, (c) the storage conditions and storage period, and (d) the packaging, storage conditions and storage period had a significant ($P<0.05$) influence on the total sugar concentration. The highest decrease in total sugars of 61.7% was observed in the unpackaged tomato samples stored under ambient conditions. In contrast, samples packaged in the EPS Tray + PVC wrap and stored under cold conditions resulted in the lowest decline in total sugars of 31.7% after 28 days. From the results of this experiment, it can be concluded that a combination of the EPS + PVC wrap or packaging and cold storage conditions are the most effective for maintaining the decline of the total sugars in tomatoes.

Table 3.10 The total sugars (mg.100^{-1}g) of tomatoes influenced by the packaging and storage conditions over the 28-day storage period (n=3)

Packaging Treatment	Storage Condition	Storage Period (Days)				
		0	7	14	21	28
SP Tray + PVC wrap	Cold	8.95^{v}	7.69±0.09^{u}	6.58±0.30^{o-r}	5.96±0.06^{k-n}	5.06±0.16^{gh}
	Ambient	8.95^{v}	6.22±0.05^{m-p}	6.02±0.44^{k-n}	5.19±0.03^{g-j}	5.00±0.05^{gh}
EPS Tray + PVC wrap	Cold	8.95^{v}	7.564±0.08^{u}	6.67±0.19^{pqr}	6.57±0.06^{o-r}	6.11±0.06^{l-o}
	Ambient	8.95^{v}	6.40±0.06^{n-q}	6.01±0.35^{k-m}	6.04±0.18^{lmn}	5.76±0.28^{klm}
SP Tray + Flow wrap	Cold	8.95^{v}	6.02±0.44^{k-n}	5.88±0.35^{klm}	5.79±0.53^{klm}	5.64±0.01^{i-l}
	Ambient	8.95^{v}	5.64±0.23^{i-l}	5.63±0.29^{jkl}	5.52±0.32^{h-k}	4.43±0.33^{cde}
EPS Tray + Flow wrap	Cold	8.95^{v}	7.33±0.07^{tu}	6.95±0.26^{rst}	6.87±0.39^{q-t}	5.22±0.58^{g-j}
	Ambient	8.95^{v}	6.05±0.13^{lmn}	4.98±0.06^{fg}	4.41±0.04^{cde}	4.26±0.32^{bcd}
1 kg PP bag	Cold	8.95^{v}	6.94±0.21^{rst}	6.19±0.03^{m-p}	5.16±0.13^{ghi}	3.96±0.07^{bc}
	Ambient	8.95^{v}	4.86±0.69^{efg}	4.79±0.05^{efg}	4.38±0.02^{cde}	3.87±0.11^{b}
Unpackaged (Control)	Cold	8.95^{v}	7.26±0.22^{stu}	6.82±0.30^{qrs}	5.07±0.11^{gh}	4.56±0.00^{def}
	Ambient	8.95^{v}	6.26±0.72^{m-p}	6.01±0.08^{k-n}	4.55±0.79^{def}	3.43±0.13^{a}
Significance (P) level						
Packaging (A)		P<.001				
Storage Conditions (B)		P<.001				
Storage Period (C)		P<.001				
A*B		P<.001				
A*C		P<.001				
B*C		P<.001				
A*B*C		P<.001				

Values are means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). SP = Stamped Paper Tray: EPS = Expandable Polystyrene: PVC = Polyvinyl Chloride; PP = Polypropylene

3.8.9 Total phenolic content

A complete layout of the total phenolic content results affected by the packaging and storage conditions are tabulated in Table 3.11. This experiment showed that the Total Phenolic Content (TPC) ranged between 0.579 mg GAE.g^{-1} FW and 0.211 mg GAE.g^{-1} FW, which is in the same range as that reported by Singh *et al.* (2020). The TPC of the tomatoes was also significantly (P<0.001) influenced by the packaging materials; it was better retained in the EPS Tray + PVC wrap, averaging at 0.514 mg GAE.g^{-1} FW, while the unpackaged (control) tomatoes had the highest loss of TPC, averaging at 0.421 mg GAE.g^{-1} FW. This result agrees with that of Szabo *et al.* (2020), where the TPC significantly differed according to the biopolymer used. According to Rababah *et al.* (2011) and Tilahun *et al.* (2021a), a decrease in the total phenolics results from the oxidation and hydrolytic activities of phenolic compound enzymes in the presence of more oxygen.

The storage conditions were also found to have a significant ($P<0.001$) effect on the TPC of tomatoes, where those stored under ambient conditions had a lower TPC value than those stored under cold conditions. Parker and Maalekuu (2013) reported similar results, which showed that the polyphenols in tomatoes were continuously decreasing as the respiration and ripening process continued. Buta and Spaulding (1997) reported a similar continuous decline of TPC in the tomato pericarp, as the ripening process continues. According to Shezi (2016), the decrease in TPC, as the fruit ripens, is related to the reduction of 5-caffeoylquinic acid (CaQ), one of the three significant compounds that make up the phenolic compounds in tomatoes. CaQ has a protective function that dominates the pericarp tissue, while others dominate the pulp, hence it is a significant determinant of the phenolics in fruits. The low temperature under the cold storage conditions slows down respiration, which slows down the reduction of CaQ and the oxidation of phenolics, thus it increases the total phenolics in the fruit under cold storage conditions. The decline of TPC can be attributed to the polyphenols that are oxidized faster during respiration, due to the higher temperatures under ambient storage conditions.

The TPC of the tomatoes varied significantly ($P<0.001$) as the storage period progressed. The tomatoes had a higher TPC concentration (0.579 mg GAE.g^{-1} FW) on Day 0, and it decreased to about 40% (0.348 mg GAE.g^{-1} FW) of its initial concentration after the 28-day storage period. Similar trends were reported by Singh *et al.* (2020) and Baltacioğlu *et al.* (2011), who showed that the TPC decreased continuously as the storage time progressed. Similarly, the TPC peaks when the tomatoes are at the pinkish-yellow to red maturity stage, as with the sugars. As their maturity progresses to becoming entirely red, the tomatoes start to deteriorate by utilizing the polyphenols compounds (Tao *et al.*, 2020).

Table 3.11 Effects of the packaging and storage conditions on the quality of the total phenolic compounds (mg GAE.g^{-1} FW) of stored tomatoes over 28 days (n=3)

Packaging Treatment	Storage Condition	Storage Period (Days)				
		0	7	14	21	28
SP Tray + PVC wrap	Cold	0.579 ± 0.02^{vw}	$0.542\pm0.02^{o-v}$	$0.530\pm0.01^{n-u}$	$0.453\pm0.08^{j-m}$	0.339 ± 0.02^{cde}
	Ambient	0.579 ± 0.02^{vw}	$0.519\pm0.01^{n-s}$	0.435 ± 0.01^{hij}	0.371 ± 0.02^{efg}	0.298 ± 0.01^{bc}
EPS Tray + PVC wrap	Cold	0.579 ± 0.02^{uvw}	0.593 ± 0.03^{w}	$0.562\pm0.02^{r-w}$	0.492 ± 0.03^{lmn}	0.438 ± 0.03^{ij}
	Ambient	0.579 ± 0.02^{vw}	$0.555\pm0.02^{p-w}$	$0.518\pm0.03^{n-s}$	0.432 ± 0.02^{hij}	0.367 ± 0.00^{efg}
SP Tray + Flow wrap	Cold	0.579 ± 0.02^{vw}	$0.566\pm0.01^{s-w}$	$0.566\pm0.04^{t-w}$	$0.526\pm0.04^{n-t}$	0.449 ± 0.04^{jkl}
	Ambient	0.579 ± 0.02^{vw}	$0.560\pm0.01^{q-w}$	0.509 ± 0.03^{nop}	0.435 ± 0.00^{hij}	0.374 ± 0.02^{efg}
EPS Tray + Flow wrap	Cold	0.579 ± 0.02^{vw}	$0.565\pm0.03^{s-w}$	$0.559\pm0.02^{q-w}$	$0.528\pm0.05^{n-t}$	0.441 ± 0.03^{ijk}
	Ambient	0.579 ± 0.02^{vw}	$0.512\pm0.01^{n-q}$	$0.516\pm0.02^{n-r}$	0.496 ± 0.01^{mno}	0.365 ± 0.01^{efg}
1 kg PP bag	Cold	0.579 ± 0.02^{vw}	$0.554\pm0.03^{p-w}$	$0.519\pm0.00^{n-t}$	0.399 ± 0.02^{ghi}	0.306 ± 0.02^{bc}
	Ambient	0.579 ± 0.02^{vw}	$0.516\pm0.02^{n-r}$	$0.484\pm0.01^{k-n}$	0.370 ± 0.02^{efg}	0.279 ± 0.03^{b}
Unpackaged (Control)	Cold	0.579 ± 0.02^{vw}	$0.517\pm0.02^{n-r}$	$0.461\pm0.04^{j-m}$	0.351 ± 0.01^{def}	0.309 ± 0.00^{bc}
	Ambient	0.579 ± 0.02^{vw}	0.496 ± 0.02^{mno}	0.393 ± 0.03^{fgh}	0.318 ± 0.01^{bcd}	0.211 ± 0.01^{a}

Significance (P) level	
Packaging (A)	P<.001
Storage Conditions (B)	P<.001
Storage Period (C)	P<.001
A*B	P>0.05
A*C	P<.001
B*C	P<.001
A*B*C	P>0.05

Values are means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). SP = Stamped Paper Tray: EPS = Expandable Polystyrene: PVC = Polyvinyl Chloride; PP = Polypropylene

The combined effect of (a) the packaging and the storage period and (b) the storage conditions and storage period also had a significant (P<0.001) effect on the quality of the TPC. The samples packaged in the EPS Tray + PVC wrap had the lowest decline (28.9%) in TPC concentration after 28 days. The highest decline in TPC (55.1%) was observed in the unpackaged tomatoes after 28 days. Tomatoes under cold storage conditions had the lowest reduction in TPC concentration (34.4%), whilst those under ambient storage conditions had the highest reduction (46.5%) between Day 0 and Day 28. The longer the storage period, the more the packaging and storage conditions play an essential role in the changes in TPC concentration. The overall interaction of the packaging, storage condition and storage period showed no significant (P>0.05) influence on the TPC concentration. Tomato samples in the EPS Tray + PVC wrap that were subjected to cold storage conditions showed the lowest reduction (24.3%) in the TPC concentration, whilst the highest reduction (63.5%) was observed in unpackaged tomatoes under ambient storage conditions.

3.8.10 Microbial population

The effects of the packaging and storage conditions on the colony-forming units in the tomatoes that use APC and FC are presented in Table 3.12. The packaging had a significant (P<0.05) influence on the APC and FC units of the tomatoes. Those packaged in the EPS Tray + PVC Cling wrap had fewer APC units (5.17 log units), while those packaged in the SP Tray + PVC Cling wrap had fewer FC units (2.96 log units). The unpackaged (Control) tomatoes had more APC and FC units (5.78 and 3.73 log units, respectively). This is in agreement with a study by Min *et al.* (2018), who found that the packaging slows down the bacterial growth as an intended action. The introduction of a modified atmosphere slows down and averts aerobic growth. In this way, microbes that cause spoilage are prevented from reaching significant levels, which extends the safety and shelf-life of the product (Cutter, 2002).

The storage conditions had a significant (P<0.001) influence on the APC and FC units of the tomato fruit. Tomatoes under cold storage conditions had a low load of APC (3.75 log units) and FC (2.78 log units), compared to those stored under ambient storage conditions, which had high APC and FC units (7.17 and 3.92 log units). This result agrees with that of Min *et al.* (2018), where tomatoes stored at 10°C had a lower mesophilic plate count than those stored at 25°C. According to Berrueta *et al.* (2016), a high temperature and relative humidity hastens the microbial growth, which explains the high mesophilic count of microbes and fungus under ambient storage conditions.

Table 3.12 The effects of the packaging and storage conditions on the colony-forming units using APC and FC after a 14-day storage period (n=3)

Packaging Treatment	Storage condition	APC log cfu per tomato	FC log cfu per tomato	Microscopic Observation
SP Tray + PVC wrap	Cold	3.67±0.09[a]	1.93±0.37[a]	Yeasts and moulds
	Ambient	675±0.11[b]	3.99±0.12b	Mainly moulds, yeasts present but below LOD
EPS Tray + PVC wrap	Cold	3.81±0.09[a]	2.58±0.33[a]	Mainly yeasts
	Ambient	6.53±0.24[b]	3.81±0.47[b]	Only moulds
SP Tray + Flow wrap	Cold	3.74±0.38a	2.46±0.43[b]	Yeasts and moulds
	Ambient	7.61±0.29[c]	4.30±0.09[b]	Only moulds, yeasts positive but below LOD
EPS Tray + Flow wrap	Cold	3.71±0.25[a]	3.54±0.27[b]	Mainly yeasts, moulds also present
	Ambient	6.78±0.24[b]	3.92±0.40[b]	Moulds, yeasts present but below LOD
1 kg PP bag	Cold	3.80±0.13[a]	2.52±0.91[a]	Mainly yeasts
	Ambient	7.53±0.19[c]	3.78±0.43[b]	Moulds and yeasts
Unpackaged (Control)	Cold	3.76±0.27[a]	3.63±0.12[b]	Yeasts and moulds
	Ambient	7.80±0.47[c]	3.73±0.67[b]	Mainly moulds
Significance (P) level				
Packaging (A)		P<.001	P<0.05	
Storage Conditions (B)		P<.001	P<.001	
A*B		P<.001	P<0.05	

Values are means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). SP = Stamped Paper Tray: EPS = Expandable Polystyrene: PVC = Polyvinyl Chloride; PP = Polypropylene

3.9 Conclusion

The packaging and storage conditions significantly influenced the quality attributes of the round "Nema-Netta" tomatoes that were analysed in this experiment. A shortened shelf-life and massive quality changes were observed in all unpackaged tomatoes, while packaged tomatoes seem to have a slow quality change. Packaged tomatoes stored under cold storage conditions (8-12°C, 78–80% RH) were of a better quality, had a reduced colour change rate (L* and Hue angle), maintained firmer fruits (Puncture, Kramer shear and Compression), a lowered PWL, a reduced rate of increase in TSS and pH, together with a decreasing TA rate, a reduced decline rate in the total sugars and TPC, as well as low microbial growth on the surface of the tomatoes. The benefits of packaging and cold storage conditions were also shown by those tomatoes that were in storage for 28 days, which had a good shape and appearance. Tomato samples stored under ambient conditions (22-26°C, 68–72% RH) succumb to excessive shrivelling, softening, mould and yeast development and decay after 14 days of storage. The EPS Tray + PVC wrap was the most efficient packaging treatment for maintaining the quality of the tomatoes, followed closely by the SP Tray + PVC wrap, with a significant difference of less than 5%. Tomato samples in the EPS Tray + PVC wrap and the SP Tray + PVC wrap were the least affected by the APC and FC mesophilic bacterial growth, due to the enclosed packaging system, which allowed the depletion of O_2 inside the packaging, and created a non-conducive environment for microbial growth. A build-up of moisture and water droplets, the availability of oxygen and a high temperature were observed in the 1 kg PP bag, the EPS Tray + Flow wrap and the SP Tray + Flow wrap packages (with perforated holes), resulting in microbial growth and the rapid deterioration of these tomato samples under ambient conditions.

A summary of the effects of different packaging materials and storage conditions on the quality attributes of the round tomatoes are presented in Table 6.1, Appendix A. The combined use of packaging and cold storage conditions proved to be pivotal for maintaining the respiration rate and ripening process of the tomatoes over the 28-day storage period. The EPS Tray + PVC wrap and cold storage was the most beneficial treatment combination. This combination resulted in a low reduction in L* of 12.3%, a hue angle of 14.7% and a PWL of 1.78%, compared to unpackaged tomatoes, with the highest reduction in L* of 23.0% and a hue angle of 24.8% and PWL OF 11.9% between Day 0 and Day 28. The tomato samples in the EPS + PVC wrap resulted in the slightest softening of 30.3%, 41.6% and 28%, in terms of their puncture, Kramer and compression, compared to the highest softening of 44.8%, 63.3% and 53.2% observed in unpackaged tomatoes, under ambient storage conditions, after the 28-day storage period. The lowest increase in TSS values of 18.1% was in the tomatoes packaged in the SP Tray + PVC wrap and stored under cold storage conditions, while the highest increase in TSS values (31.6%) was from tomatoes in the Control group, which were subject to ambient storage conditions between Day 0 and Day 28. The highest increase in pH values (10%), together with the highest decline in TA (0.51%), was observed for unpackaged samples under ambient storage conditions, compared to samples packaged in the EPS Tray + PVC wrap under cold storage conditions, which resulted in the lowest increase in pH values of 5.7% and a decline in TA of 25% after 28 days. The highest decrease in total sugars (61.7%) was observed in the unpackaged tomato samples stored under ambient conditions. In contrast, samples packaged in the EPS Tray + PVC wrap and stored under cold conditions resulted in the lowest decline in total sugars of 31.7% after 28 days. Tomato samples in the EPS Tray + PVC wrap and which were subjected to cold storage conditions showed the lowest reduction (21.2%) in the TPC concentration, whilst the highest reduction (63.5%) was observed in unpackaged tomatoes under ambient storage conditions. From the results of this experiment, it can be concluded that the EPS Tray + PVC wrap and SP Tray + PVC wrap under cold storage conditions are beneficial for preserving the quality attributes of tomatoes by retarding the physiological and biochemical processes and therefore extending their shelf-life. However, since the differences between the EPS Tray + PVC wrap and SP Tray + PVC wrap are less than 5% in the multiple tests, the SP Tray is a biodegradable package that has become a viable package to use. It can also be concluded that the packaging is beneficial for tomatoes. The observations of this study prove that differences in the construction of the packaging and cover result in the interplay of gaseous exchange (CO_2 and O_2) and water vapour, with minimal quality changes and losses. Packaging treatments without perforated holes (the EPS and SP Tray + PVC wrap) were the most beneficial packages under cold storage conditions. Another factor is the permeable nature of the packaging; non-biodegradable materials are less permeable than biodegradable cardboard and paper-based packages. This was evident when comparing the EPS Trays and SP Tray's packages in all the measured parameters; hence the respiration rate might be increased slightly by the movement of particles through porous spaces in the SP Tray packages.

3.10 References

Abera, G, Ibrahim, AM, Forsido, SF and Kuyu, CG. 2020. Assessment on post-harvest losses of tomato (Lycopersicon esculentem Mill.) in selected districts of the East Shewa Zone of Ethiopia using a commodity system analysis methodology. *Heliyon* 6(4):e03749.

Adhikari, P, Dhakal, A, Pahadi, K, Adhikari, S, Ghimire, P, Subedi, S and Ghimire, D. 2020. Effect of Different Plastic Packaging on the Postharvest Quality of Tomatoes (Lycopersicon Esculentum Mill.). *Tropical Agroecosystems* 1(1):15-18.

Al-Dairi, M, Pathare, PB and Al-Yahyai, R. 2021. Chemical and nutritional quality changes of tomato during postharvest transportation and storage. *Journal of the Saudi Society of Agricultural Sciences* 20(6):401-408.

Albaloushi, N, Azam, M and Amer Eissa, A. 2012. Mechanical Properties of Tomato Fruits under Storage Conditions 1. *Journal of Applied Sciences Research* 8(1):3053-3064.

Alenazi, M, Shafiq, M, Alsadon, A, Ibrahim, M, Alhamdan, A, Solieman, T, Ibrahim, A, Shady, M and Al-Selwey, W. 2020. Improved Functional and Nutritional Properties of Tomato Fruit during Cold Storage. *Saudi Journal of Biological Sciences* 27(1):1467-1474.

Ali, B. 1998. Some factors affecting the determination and measurement of tomato firmness. *Turkish Journal of Agriculture Forestry* 22(4):411-418.

Anthon, GE, LeStrange, M and Barrett, DM. 2011. Changes in pH, acids, sugars and other quality parameters during extended vine holding of ripe processing tomatoes. *Journal of the Science of Food Agriculture* 91(7):1175-1181.

Asem, A, Arisha, H, Bardisi, A and Ibraheim, SKA. 2016a. Effect of Some Packaging Materials on the Quality Attributes of Tomato Fruits (Solanum Lycopersicum L.) During Cold Storage and after Shelf-Life Period. *Middle East Journal of Agriculture Research* 4(4):687-700.

Asem, A, Arisha, H, Bardisi, A and Ibraheim, SKA. 2016b. Effect of some Packaging Materials on the Quality Attributes of Tomato Fruits (Solanum Lycopersicum L.) during Cold Storage and after Shelf-Life Period. *Middle East Journal of Agriculture Research* 5(4):687-700.

Aurand, R, Faurobert, M, Page, D, Maingonnat, J-F, Brunel, B, Causse, M and Bertin, N. 2012. Anatomical and biochemical trait network underlying genetic variations in tomato fruit texture. *Euphytica* 187(1):99-116.

Azene, M, Workneh, TS and Woldetsadik, K. 2014a. Effect of packaging materials and storage environment on postharvest quality of papaya fruit. *Journal of Food Science and Technology* 51(6):1041-1055.

Azene, M, Workneh, TS and Woldetsadik, K. 2014b. Effect of packaging materials and storage environment on postharvest quality of the papaya fruit. *Journal of Food Science and Technology* 51(6):1041-1055.

Baltacioğlu, C, Velioğlu, S and Karacabey, E. 2011. Changes in total phenolic and flavonoid contents of rowanberry fruit during postharvest storage. *Journal of Food Quality* 34(4):278-283.

Banda, K, Caleb, OJ, Jacobs, K and Opara, UL. 2015. Effect of active-modified atmosphere packaging on the respiration rate and quality of pomegranate arils (cv. Wonderful). *Postharvest Biology and Technology* 109(1):97-105.

Barrett, DM, Garcia, E and Wayne, JE. 1998. Textural modification of processing tomatoes. *Critical Reviews in Food Science and Nutrition* 38(3):173-258.

Berrueta, MC, Giménez, G, Galván, GA and Borges, A. 2016. New sources of partial resistance to bacterial spot race T2 in processing tomatoes. *Horticultura Brasileira* 34(1):326-332.

Bertin, N and Génard, M. 2018. Tomato quality as influenced by pre-harvest factors. *Scientia Horticulturae* 233(1):264-276.

Buta, J and Spaulding, D. 1997. Endogenous levels of phenolics in tomato fruit during growth and maturation. *Journal of Plant Growth Regulation* 16(1):43-46.

Cantwell, M, Nie, X and Hong, G. 2009. Impact of storage conditions on grape tomato quality. *6th ISHS Postharvest Symposium, Antalya, Turkey.*

Charles, MT, Arul, J, Charlebois, D, Yaganza, E-S, Rolland, D, Roussel, D and Merisier, MJ. 2016. Postharvest UV-C treatment of tomato fruits: changes in simple sugars and organic acids contents during storage. *LWT - Food Science and Technology* 65(1):557-564.

Cherono, K, Sibomana, M and Workneh, TS. 2018. Effect of infield handling conditions and time to pre-cooling on the shelf-life and quality of tomatoes. *Brazilian Journal of Food Technology* 21:e2017016

Cutter, CN. 2002. Microbial control by packaging: a review. *Critical Reviews of Food Science and Nutrition* 42(2):151-61.

Cyras, VP, Commisso, MS, Mauri, AN and Vázquez, A. 2007. Biodegradable double-layer films based on biological resources: Polyhydroxybutyrate and cellulose. *Journal of Applied Polymer Science* 106(2):749-756.

Dandago, MA, Ilesanmi, J and Tamme, V. 2017. Effects of packaging and storage conditions on quality and storage life of tomato fruits (Lycopersicon esculentum Mill.) in Kura, Kano State, Nigeria. *Journal of Postharvest Technology* 5(4):71-82.

de Castro, LR, Cortez, LA and Vigneault, C. 2006. Effect of sorting, refrigeration and packaging on tomato shelf life. *Journal of Food Agriculture and Environment* 4(1):70-75.

Distefano, M, Arena, E, Mauro, RP, Brighina, S, Leonardi, C, Fallico, B and Giuffrida, F. 2020. Effects of genotype, storage temperature and time on quality and compositional traits of cherry tomato. *Foods* 9(12):1729.

Dobrin, A, Nedelus, A, Bujor, O, Mot, A, Zugravu, M and Badulescu, L. 2019. Nutritional Quality Parameters of the Fresh Red Tomato Varieties Cultivated in Organic System. *Scientific Papers. Series B, Horticulture* 63(1):1-5.

Domínguez, I, Ferreres, F, del Riquelme, FP, Font, R and Gil, MI. 2012. Influence of pre-harvest application of fungicides on the postharvest quality of tomato (Solanum Lycopersicum L.). *Postharvest Biology and Technology* 72:1-10.

Domínguez, I, Lafuente, MT, Hernández-Muñoz, P and Gavara, R. 2016. Influence of modified atmosphere and ethylene levels on quality attributes of fresh tomatoes (Lycopersicon esculentum Mill.). *Food Chemistry* 209(1):211-219.

Dufera, LT, Hofacker, W, Esper, A and Hensel, O. 2021. Physicochemical quality of twin layer solar tunnel dried tomato slices. *Heliyon* 7(5):e07127.

Endalew, E. 2020. Postharvest Loss Assessment of Tomato (Lycopersicon esculentum Mill)(Galilea Cultivar) along the Postharvest Supply Chain, North-west Ethiopia. Unpublished Master Thesis, Bahir Dar University, Ethiopia.

Farooq, S, A. Rather, S, Gull, A, Ahmad Ganai, S, Masoodi, F, Mohd Wani, S and Ganaie, TA. 2020. Physicochemical and nutraceutical properties of tomato powder as affected by pretreatments, drying methods, and storage period. *International Journal of Food Properties* 23(1):797-808.

Fawuyini, J, Patrick, OA and Sedara, A. 2020. Effect of maturity stage on quality and shelf life of tomato (Lycopersicon Esculentum mill) using the refrigerator storage system. *Eurasian Journal of Agricultural Research* 4(1):23-44.

Garuba, T, Mustapha, O and Oyeyiola, G. 2018. Shelf life and proximate composition of tomato (Solanum Lycopersicum L.) fruits as influenced by storage methods. *Ceylon Journal of Science* 47(4):387-393.

Gebeyehu, AS. 2018. The Effects Packaging Materials on Post-harvest Quality of Tomato (Solanum Lycopersium). *Journal of Natural Sciences Research* 8(11):97-103.

Gharezi, M, Joshi, N and Sadeghian, E. 2012. Effect of postharvest treatment on stored cherry tomatoes. *Journal of Nutrition and Food Sciences* 2(8):1-10.

Giannakourou, MC and Tsironi, TN. 2021. Application of Processing and Packaging Hurdles for Fresh-cut Fruits and Vegetable Preservation. *Foods* 10(4):830-853.

Gormley, T and Keppel, D. 2006. A method for measuring tomato fruit firmness using a modified shear press. *International Journal of Food Science and Technology* 11(1):607-617.

Harker, FR, Stec, MG, Hallett, IC and Bennett, CL. 1997. Texture of parenchymatous plant tissue: a comparison between tensile and other instrumental and sensory measurements of tissue strength and juiciness. *Postharvest Biology and Technology* 11(2):63-72.

Hövelmann, Y, Jagels, A, Schmid, R, Hübner, F and Humpf, H-U. 2020. Identification of potential human urinary biomarkers for tomato juice intake by mass spectrometry-based metabolomics. *European Journal of Nutrition* 59(2):685-697.

Irtwange, S. 2006. Application of modified atmosphere packaging and related technology in postharvest handling of fresh fruits and vegetables. *Agricultural Engineering International: CIGR Journal* 8(4):1-12.

Ivonkovic, A, Zeljko, K, Talic, S and Lasic, M. 2017. Biodegradable packaging in the food industry. *Journal of Food Safety and Food Quality* 68(2):26-38.

Jackman, RL, Gibson, HJ and Stanley, DW. 1992. Effects of chilling on tomato fruit texture. *Physiologia Plantarum* 86(4):600-608.

Jafari, SM, Jabari, SS, Dehnad, D and Shahidi, SA. 2017. Effects of thermal processing by nanofluids on vitamin C, total phenolics and total soluble solids of tomato juice. *Journal of Food Science and Technology* 54(3):679-686.

Kantola, M and Helen, H. 2001. Quality changes in organic tomatoes packaged in biodegradable plastic films. *Journal of Food Quality* 24(2):167-176.

Khairi, A, Falah, M, Suyantohadi, A, Takahashi, N and Nishina, H. 2015a. Effect of Storage Temperatures on Color of Tomato Fruit (Solanum Lycopersicum Mill.) Cultivated under Moderate Water Stress Treatment. *Agriculture and Agricultural Science Procedia* 3(1):178-183

Khairi, AN, Falah, MAF, Suyantohadi, A, Takahashi, N and Nishina, H. 2015b. Effect of Storage Temperatures on Color of Tomato Fruit (Solanum Lycopersicum Mill.) Cultivated under Moderate Water Stress Treatment. *Agriculture and Agricultural Science Procedia* 3(1):178-183.

Kumar, N, Ojha, A, Upadhyay, A, Singh, R and Kumar, S. 2021. Effect of active chitosan-pullulan composite edible coating enriched with pomegranate peel extract on the storage quality of green bell pepper. *LWT-Food Science and Technology* 138(1):110435.

Liu, L, Shao, Z, Zhang, M and Wang, Q. 2015. Regulation of carotenoid metabolism in tomato. *Molecular Plant* 8(1):28-39.

Mekonnen, Z. 2017a. The Influence of Retailing Packaging on Tomato Quality. *Journal of Nutrition and Food Sciences* 7(604):1-7.

Mekonnen, Z. 2017b. The Influence of Retailing Packaging on Tomato Quality. *Journal of Nutritional Food Science* 7(604):1-7

Min, SC, Roh, SH, Niemira, BA, Boyd, G, Sites, JE, Fan, X, Sokorai, K and Jin, TZ. 2018. In-package atmospheric cold plasma treatment of bulk grape tomatoes for microbiological safety and preservation. *Food Research International* 108(1):378-386.

Mior Azmai, WNS, Abdul Latif, NS and Md Zain, N. 2019. Efficiency of edible coating chitosan and cinnamic acid to prolong the shelf life of tomatoes. *Journal of Tropical Resources and Sustainable Sciences* 7(1):47-52.

Murariu, OC, Brezeanu, C, Jităreanu, CD, Robu, T, Irimia, LM, Trofin, AE, Popa, L-D, Stoleru, V, Murariu, F and Brezeanu, PM. 2021. Functional Quality of Improved Tomato Genotypes Grown in Open Field and in Plastic Tunnel under Organic Farming. *Agriculture* 11(7):609-624.

Nasir, MU, Hussain, S and Jabbar, S. 2015. Tomato processing, lycopene and health benefits: A review. *Science Letters* 3(1):1-5.

Oboulbiga, EB, Parkouda, C, Sawadogo-Lingani, H, Compaoré, EW, Sakira, AK and Traoré, AS. 2017. Nutritional composition, physical characteristics and sanitary quality of the tomato variety Mongol F1 from Burkina Faso. *Food and Nutrition Sciences* 8(4):444-455.

Olveira-Bouzas, V, Pita-Calvo, C, Vázquez-Odériz, ML and Romero-Rodríguez, MÁ. 2021. Evaluation of a modified atmosphere packaging system in pallets to extend the shelf-life of the stored tomato at cooling temperature. *Food Chemistry* 364(1):130309.

Oms-Oliu, G, Hertog, M, van de Poel, B, Ampofo-Asiama, J, Geeraerd, A and Nicolai, B. 2011. Metabolic characterization of tomato fruit during pre-harvest development, ripening, and postharvest shelf-life. *Postharvest Biology and Technology* 62(1):7-16.

Osorio, S, Carneiro, RT, Lytovchenko, A, McQuinn, R, Sørensen, I, Vallarino, JG, Giovannoni, JJ, Fernie, AR and Rose, JK. 2020. Genetic and metabolic effects of ripening mutations and vine detachment on tomato fruit quality. *Plant Biotechnology Journal* 18(1):106-118.

Paolo, D, Bianchi, G, Scalzo, RL, Morelli, CF, Rabuffetti, M and Speranza, G. 2018. The Chemistry behind Tomato Quality. *Natural Product and Communications* 13(9):1225-1232.

Parker, R and Maalekuu, B. 2013. The effect of harvesting stage on fruit quality and shelf-life of four tomato cultivars (Lycopersicon esculentum Mill). *Agriculture And Biology Journal of North America* 4(3):252-259.

Pinela, J, Barros, L, Carvalho, AM and Ferreira, ICFR. 2012. Nutritional composition and antioxidant activity of four tomatoes (Lycopersicon esculentum L.) farmer varieties in North-eastern Portugal home gardens. *Food and Chemical Toxicology* 50(3):829-834.

Rababah, T, Feng, H, Yang, W, Eriefej, K and Al-Omoush, M. 2011. Effects of type of packaging material on physicochemical and sensory properties of olive oil. *International Journal of Agricultural and Biological Engineering* 4(4):66-72.

Sammi, S and Masud, T. 2009. Effect of different packaging systems on the quality of tomato (Lycopersicon esculentum var. Rio Grande) fruits during storage. *International Journal of Food Science Technology* 44(5):918-926.

Sattar, MA, Quddus, MA, Rahman, MH, Hossain, MA, Sarker, MH and Islam, MR. 2019. Effect of postharvest temperatures and packaging materials on shelf life and fruit quality of selected hybrid of sweet pepper. *Journal of Energy and Natural Resources* 8(4):137-145.

Sharma, L, Ramesh, K, Paul, V and Pandey, R. 2020. Ripening index: a better parameter for colour based assessment of ripening behaviour of tomato fruits. *Plant Physiology Reports* 25(1):171-177.

Shehata, SA, Abdelrahman, SZ, Megahed, M, Abdeldaym, EA, El-Mogy, MM and Abdelgawad, KF. 2021. Extending Shelf-life and Maintaining Quality of Tomato Fruit by Calcium Chloride, Hydrogen Peroxide, Chitosan, and Ozonated Water. *Horticulturae* 7(9):309-324.

Shezi, S. 2016. Evaluation of the effects of supply chain routes and pre-storage treatments on the postharvest quality of stored 'Nemo-Netta' tomatoes. Unpublished thesis, School of Engineering, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Sibomana, M, Seyoum Workneh, T and Audain, K. 2016a. A review of postharvest handling and losses in the fresh tomato supply chain: a focus on sub-Saharan Africa. *Food Security* 8(2):389-404

Sibomana, M, Workneh, T and Audain, K. 2016b. A review of postharvest handling and losses in the fresh tomato supply chain: a focus on Sub-Saharan Africa. *Journal of Food Security* 8(2):389-404.

Singh, J, Roy, B, Jaldhi, SM and Garg, R. 2020. Postharvest Treatment for Preserving Antioxidant Properties and Total Phenolic Content of Tomatoes and Litchis. *Journal of Thematic Analysis* 1(1):125-135.

Sirisomboon, P, Tanaka, M and Kojima, T. 2012. Evaluation of tomato textural mechanical properties. *Journal of Food Engineering* 111(4):618-624.

Sualeh, A, Daba, A, Kiflu, S and Mohammed, A. 2016. Effect of storage conditions and packing materials on the shelf-life of tomato. *Food Science and Quality Management* 56(1):65-67.

Szabo, K, Teleky, B-E, Mitrea, L, Călinoiu, L-F, Martău, G-A, Simon, E, Varvara, R-A and Vodnar, DC. 2020. Active Packaging—Poly(Vinyl Alcohol) Films Enriched with Tomato By-Products Extract. *Coatings* 10(2):141-159.

Tao, X, Wu, Q, Aalim, H, Li, L, Mao, L, Luo, Z and Ying, T. 2020. Effects of exogenous abscisic acid on bioactive components and antioxidant capacity of postharvest tomato during ripening. *Molecules* 25(6):1346-1364.

Tigist, M, Workneh, TS and Woldetsadik, K. 2013. Effects of variety on the quality of tomato stored under ambient conditions. *Journal of Food Science and Technology* 50(3):477-486.

Tilahun, S, Choi, H-R, Baek, M-W, Cheol, L-H, Kwak, K-W, Park, D-S, Solomon, T and Jeong, C-S. 2021. Antioxidant Properties, γ-Aminobutyric Acid (GABA) Content, and Physicochemical Characteristics of Tomato Cultivars. *Agronomy* 11(6):1204-1217.

Tilahun, S, Taye, AM and Jeong, CS. 2017. Effects of storage duration on physicochemical and antioxidant properties of tomato (Lycopersicon esculentum Mill.). *Journal of Horticultural Science and Technology* 35(1):88-97.

Tolasa, M, Gedamu, F and Woldetsadik, K. 2021. Impacts of harvesting stages and pre-storage treatments on shelf life and quality of tomato (Solanum Lycopersicum L.). *Cogent Food and Agriculture* 7(1):1863620.

Tolesa, GN and Workneh, TS. 2017. Influence of storage environment, maturity stage and pre-storage disinfection treatments on tomato fruit quality during winter in KwaZulu-Natal, South Africa. *Journal of Food Science and Technology* 54(10):3230-3242.

Wang, D, Yeats, TH, Uluisik, S, Rose, JK and Seymour, GB. 2018. Fruit softening: revisiting the role of pectin. *Trends in Plant Science* 23(4):302-310.

Workneh, T and Osthoff, G. 2010. A review on integrated agro-technology of vegetables. *African Journal of Biotechnology* 9(54):9307-9327.

Workneh, TS. 2010. Feasibility and economic evaluation of the low-cost evaporative cooling system in fruit and vegetable storage. *African Journal of Food, Agriculture, Nutrition and Development* 10(8):2984-2997.

Workneh, TS, Osthoff, G and Steyn, M. 2012. Effects of preharvest treatment, disinfections, packaging and storage environment on quality of tomato. *Journal of Food Science and Technology* 49(6):685-694.

4. EVALUATION OF THE EFFECTS OF DIFFERENT PACKAGING MATERIALS ON THE QUALITY ATTRIBUTES OF CHERRY TOMATOES IN SOUTH AFRICA

4.1 Abstract

This study was carried out to evaluate the effects of different packaging materials and storage conditions on the quality attributes of cherry tomatoes in South Africa. The experiment was arranged in a Completely Randomized Block Design consisting of six packaging treatments (the Zibo Punnet PET + Flow wrap, the Old Polypropylene (PP) bag, the Zibo Punnet PET + Zibo PET Lid, the Glued Paper Tray + Flow wrap, the Pulped Paper Tray + Zibo PET Lid and Open storage (the Control)), as well as two storage treatments (Cold and Ambient storage) with data collection points starting from Day 0 and repeated at seven-day intervals over the 28-day storage period (0, 7, 14, 21, 28). The packaging and storage treatments were the main factors. In this experiment, the colour (L*, a* and b*), firmness (Puncture, Kramer Shear and Compression), Physiological Weight Loss (PWL), Total Soluble Solids (TSS), pH, Titratable Acidity (TA), total sugars, Total Phenolic Content (TPC), as well as a microbial analysis, were evaluated. The cold storage conditions were in the range of 8-12°C, 78–80% RH, and the ambient storage conditions were in the range of 22-26°C, 68–72% RH. The results indicated that the packaging and storage conditions had a significant ($P<0.05$) influence on the L* changes, the hue angle, firmness, PWL, TSS, pH value, TA, total sugars, TPC and microbial growth. The packaged cherry tomatoes under cold storage conditions displayed the least significant change in quality. The quality loss was minimal in cherry tomatoes packaged in the Glued Paper Tray + Flow wrap treatment combination resulting in the lowest reduction in L* and hue angle values of 25.8% and 8.3%, firmer fruits, with a Kramer shear and compression of 29.9% and 28.6%, the lowest increase in the TSS and pH value of 22.5% and 3.2%, the lowest decline in the TA, total sugars and TPC of 29.5% , 43.7%, and 27.3%. The Glued Paper Tray + Flow wrap package and cold storage conditions were the most beneficial combination for preserving the quality attributes and preventing excessive microbial growth and deterioration, hence extending the shelf-life of the cherry tomatoes. The experiment revealed that the Paper Trays absorb the moisture inside the packaging, keeping the sample surface dry and shiny, compared to the plastic trays, which condense and produce water droplets, promoting spoilage. This was evident in the spoilage

of tomato samples in the Old PP plastic trays, which deteriorated faster than the other packages, and which were only superseded by the Control samples.

4.2 Introduction

Cherry tomatoes (*Lycopersicon esculentum* var. *cerasifome*) are the most miniature fruit in the tomato family. The fruit is delightful and highly flavoured for eating (Zeng *et al.*, 2020). In South Africa, the production of cherry tomatoes is a small, fast-growing industry, with the relative production increasing by 25% over the space of two years, dating back to 2017. Along with other derivatives, cherry tomatoes are a good source of nutrients in the human diet. Their potent antioxidant properties help to prevent heart and degenerative cancer diseases (Caron *et al.*, 2013; Zeng *et al.*, 2020). They are climacteric and perishable, and they have a brief lifespan that varies between 7 to 12 days, under extreme conditions. Cherry tomato losses are mainly due to poor post-harvesthandling, such as inappropriate packaging materials and storage environments. These factors influence the metabolic and physiological activities that are related to its deterioration (Manasa *et al.*, 2018). Hence, it is essential to control the post-harvest deterioration factors, in order to ensure their quality.

It has been proved that the packaging protects the fruit from injury and contamination. Manasa *et al.* (2018) reported that the packaging and the subsequent cold storage conditions could extend the shelf-life of tomatoes by more than 14 days. The packaging represents a barrier for the exiting gas changes and reduces the respiration rate of tomatoes (Tumwesigye *et al.*, 2017). Its permeable properties allow for an interplay of gases, where the concentration of CO_2 increases, while the O_2 decreases during the process of respiration (Manasa *et al.*, 2018). This interplay alters the biochemical and physiological metabolism of the tomatoes, which extends their shelf-life. However, the atmospheric composition is dependent on the permeable properties of the packaging material, the quantity of the product and the storage environment (Paulsen *et al.*, 2019). Using packaging and cold storage can favour the freshness of the tomatoes, ensuring the conservation of their colour, flavour, aroma and firmness (Thompson *et al.*, 2018).

Temperature and relative humidity are also predominant conditional storage factors that influence the physiological and biochemical quality changes in fruit and vegetables, as they continue their ripening process (Gharezi *et al.,*2012; Al-Dairi and Pathare, 2021). A low temperature and high relative humidity have been commonly found to extend their shelf-life, due to the reduced respiration rate and enzymatic activities (Sualeh *et al.*, 2016). The physiological weight loss tends to intensify under storage conditions with a low relative humidity. This can be attributed to the water vapour deficit between the surrounding environment and the fruit or vegetables, which promotes ranspiration (Razali *et al.*, 2021).

Thus far, research studies on cherry tomatoes have been limited in South Africa; it is still a growing industry and few studies have been carried out on the feasibility of plastic films on cherry tomatoes. Polyethylene and polypropylene have been investigated and reported to maintain the quality of fresh produce. Presently, perforated PET packages dominate the cherry tomato packaging industry (Caron *et al.*, 2013). However, the rising demand for cherry tomatoes, as well as environmental concerns, have resulted in new designs being produced from biodegradable materials, such as paper trays. The aim of this study was to improve the shelf-life of cherry tomatoes through sustainable packaging, and the specific objectives were to evaluate the effects of different packaging materials on their quality attributes.

4.3 Sampling Site and Transportation

Fresh cherry tomatoes, of the "Romanita" type, were harvested at the pink to red maturity stage from ZZ2 farm located in the Matchidi Toscana District, near Johannesburg, South Africa (26.2041° S, 28.0473° E). The tomatoes were harvested on the 23rd January 2020 (summer season) and transported to the Lanseria packhouse in Johannesburg. The fruits were cooled, washed and packaged on the 24th of January 2020, then loaded into pallets and transported to Pietermaritzburg. In the early morning hours of 25th January 2020, the samples arrived at the UKZN laboratories for the Day 0 analysis. The selection of the tomatoes at the pink to red maturity stage coincides with the South African fresh market tomato requirements of consumers. The tomatoes were harvested manually, to avoid mechanical injury, and the size and colour were kept uniform to avoid experimental prejudice.

4.4 Experimental Design

A Randomized Complete Block Design arranged in a three-factorial experiment was selected, the experiment consisted of six different packaging treatments (the Zibo Punnet PET + Flow wrap, the Old PP bag, the Zibo Punnet PET + Zibo PET Lid, the Glued Paper Tray + Flow wrap, the Pulped Paper Tray + Zibo PET Lid, and Open storage), as well as two storage treatments (ambient (24°C) and cold (11°C)) over a 28-day storage period, with five data collection points, starting from the first day of arrival (Day 0) and repeated at seven-day intervals (0, 7, 14, 21 and 28), as shown in Figure 4.1. The packaging treatment and storage conditions were the main factors, whilst the storage period was a sub-factor.

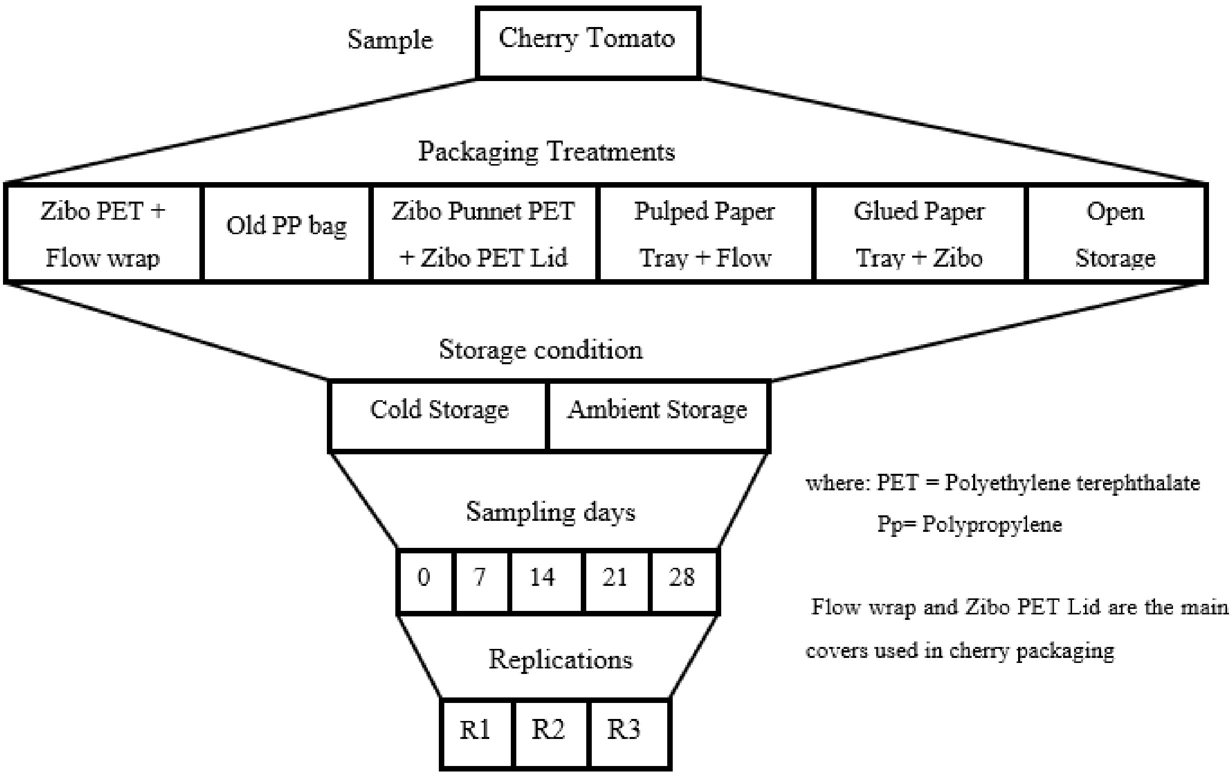

Figure 4.1 Schematic representation of the cherry tomato experimental design

4.5 Packaging Treatments

The tomato samples were packaged using six different packaging materials, as shown in Figure 4.2.

a) Zibo Punnet PET + Flow wrap and Zibo Punnet PET + Zibo PET Lid

PET (Mpact Operation (Pty) Ltd., Johannesburg, South Africa) is non-biodegradable material, which combines terephthalic acid and ethylene glycol to form a polymer chain. The combination results in spaghetti-like strands, which are then extruded, swiftly cooled and cut into smaller resin pellets. The resulting pellets are heated to a molten liquid, which is then easily shaped into practical trays, with unit dimensions of 143 mm × 95 mm × 38 mm. PET is a stable polymer that does not react with food, it is resistant to attacks by micro-organism and it is considered to be biologically inert when ingested. The PETs used in the study had the following properties: water absorption (<0.7%), permeability to CO_2 and O_2, and water vapour transmission at 25°C (0.07-0.11, 0.015-0.04, and 100-115×10^{-13} $cm^3.cm^{-2}.s^{-1}.Pa^{-1}$), thermal conductivity (0.13-0.15 $W.m^{-1}.K^{-1}$) and specific heat (1.3 $KJ.Kg^{-1}.K^{-1}$). The flow wrap used for the cover was a PP film, which was made up of an outer layer, which is a PP core acrylic-coated layer, to prevent friction on the contact surface, and an interior sealant layer. The Flow wrap film had 12 perforated holes with a diameter of 10 mm, which were spaced 30 mm apart. The Zibo PET Lid had ten perforated holes with a diameter of 10 mm, which were spaced 30 mm apart.

b) Old Polypropylene Bag

Polypropylene (PP) (Mpact Operation (Pty) Ltd., Johannesburg, South Africa) is a non-biodegradable addition to the propylene polymer, and the resins that are used are mainly isotactic. PP has the lowest density of 0.89–0.91 $g.cm^{-3}$ amongst all the commodity plastics. It is elastic, more transparent, more effective at bearing water vapour and it has a good chemical resistance. PP has a water vapour transmission rate of 100-300 $g.\mu m.m^{-2}day^{-1}$ at 37.8°C and 90% RH, and a permeability of O_2 and CO_2 of 2083-3916 and 11706-22008 $g.\mu m.m^{-2}h^{-1}.atm^{-1}$ at 25°C. The PP bag with a 500 g capacity had 20 perforated air vents with a diameter of 12 mm, which are spaced 30 mm apart around the PP bag.

c) Glued Paper Tray + Flow wrap

The Glued Paper Tray (Mpact Operation (Pty) Ltd., Johannesburg, South Africa) is made of a biodegradable solid bleached sulphate and a cross-linked coated paperboard. It is formed by turning fibrous materials from wood and recycled paper into pulp, then bleaching it and coating it with Kraft paper. The Glued Paper Tray has three layers: an inside Kraft liner, an outside Kraft liner and a corrugated fluting medium, which give it its strength and rigidity. It is lightweight, yet strong. The paperboard is cut and folded into a rectangular shape and it is then folded by using glue to become a Glued Paper Tray (400g capacity) package with dimensions 150 mm×100 mm×50 mm, and a thickness of 1 mm. The Flow wrap film has 12 perforated holes with a diameter of 10 mm, which are spaced 30 mm apart.

d) Pulped Paper Tray + Zibo PET Lid

The Pulped Paper Tray (Mpact Operation (Pty) Ltd., Johannesburg, South Africa) is a biodegradable pulp that is made from Nano-cellulose fibres obtained from the wood pulp, by using a chemical reaction. The chemical reaction uses citric acid as a cross-linking agent, Dsorbitol (98%) as a plasticizer, sodium hypophosphite monohydrate as a catalyst, as well as a sulphate mixture, to separate the fibres. Its strength against liquid substances is enhanced with cationic starch, which is added to the wet pulp during manufacturing. The resulting pulp is moulded to make the Pulped Paper Tray (300g) packages with dimensions of 120 mm×100 mm×50 mm and a thickness of 3 mm. Zibo PET Lid had rectangular air vents (50 mm×10 mm).

e) Open Storage

The open corrugated cardboard tomato box (Mpact, Johannesburg (Pty) Ltd., South Africa) has a 6 kg capacity, with dimensions of 390 mm×240 mm×20 mm. The corrugated box has four air vents on the side and bottom panels.

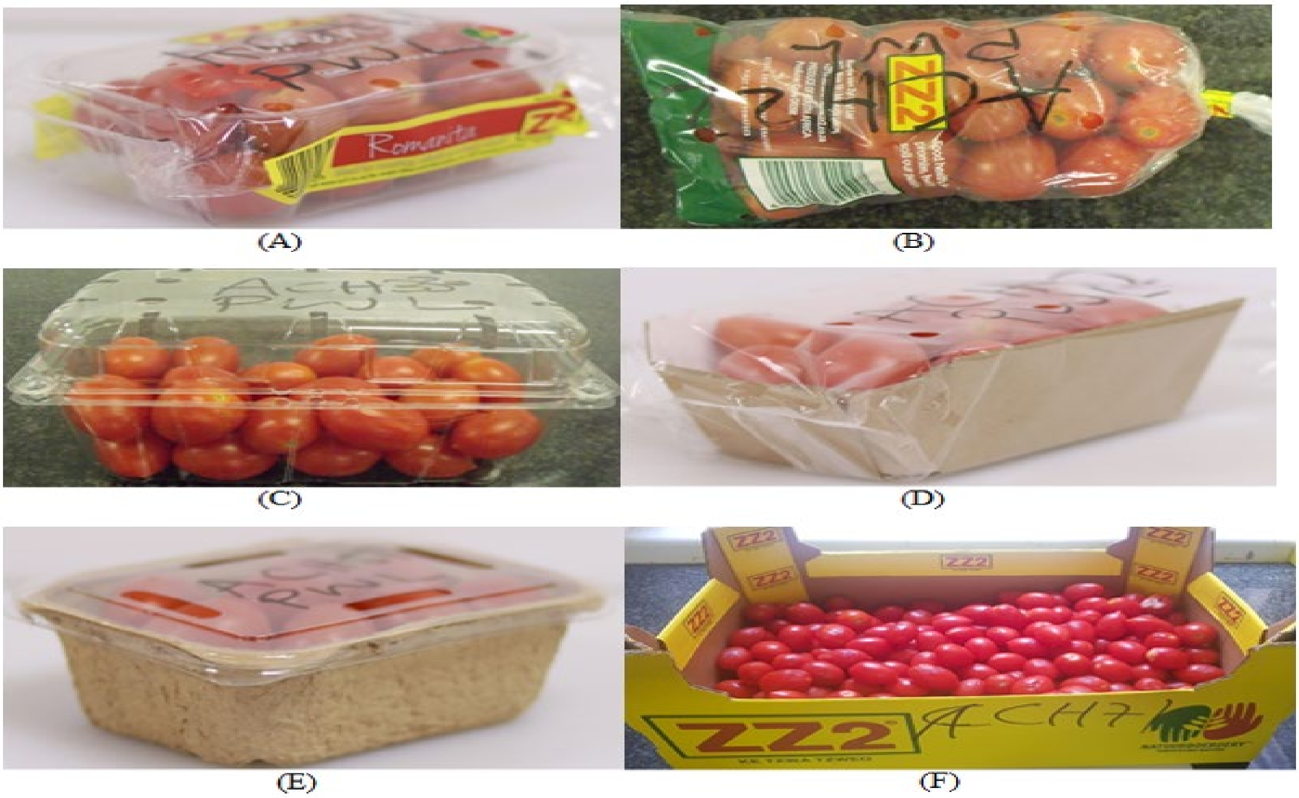

Figure 4.2 Packaging treatments, (A) Zibo PunneP + Flow wrap, (B) Old PP Plastic, (C) Zibo PET Punnet (500g) + Zibo PET Lid, (D) Glued Paper Tray with (400g) + Flow wrap, (E) Pulped Paper Tray + Zibo PET Lid, and (F) Unpackaged

4.6 Storage Temperature and Relative Humidity Measurement

As described in the experimental design in Section 4.4, the tomatoes were divided into those in ambient storage conditions, with an estimated temperature and relative humidity range of

22–24°C, 75–85% RH, and those in a cold storage facility which are set at 11°C, 85% RH. A data logger (HOBO® pro v2, U23-001, USA) was placed inside each storage facility to monitor and record the temperature and relative humidity fluctuations.

4.7 Data Collection

The collected dataset involved the quality assessment of the colour, firmness (Puncture, Kramer and compression), physiological weight loss, total soluble solids, acidity, pH, ascorbic acid and lycopene total sugars, which were measured on Days 0, 7, 14, 21 and 28.

4.7.1 Colour analysis

The colour change was measured for each sample, with three replications. It was measured at different points across the equatorial surface of the fruit, as described by Dominguez *et al.* (2012). The measurements of colour L*, a* and b* were measured by using a Konica Minolta chromameter (Model-CR-300, Ramsey, NJ, USA). The L*, a* and b* were used to calculate the hue angle (h°), based on the individual model formula (h° = tan-1 (b* / a*)).

4.7.2 Firmness analysis

4.7.2.1 Puncture test

As described by Sirisomboon *et al.* (2012), the puncture test was measured by using a Texture Analyser (TA-XT Plus, Texture Technologies Company, USA). The tomato samples were lined horizontally on a flat plate, as shown in Figure 4.3. The analyser was calibrated with a 10 kg (100 N) load cell to transfer the data to the Easy-Match-QC software. It was equipped with a 2 mm diameter probe. The equipment settings were set at a speed of 3 $mm.sec^{-1}$ and a 7.5 mm insertion depth into the tomato. The firmness is defined as the maximum force (N) needed to penetrate the tomato fruit at a constant depth in each sample, with three replications.

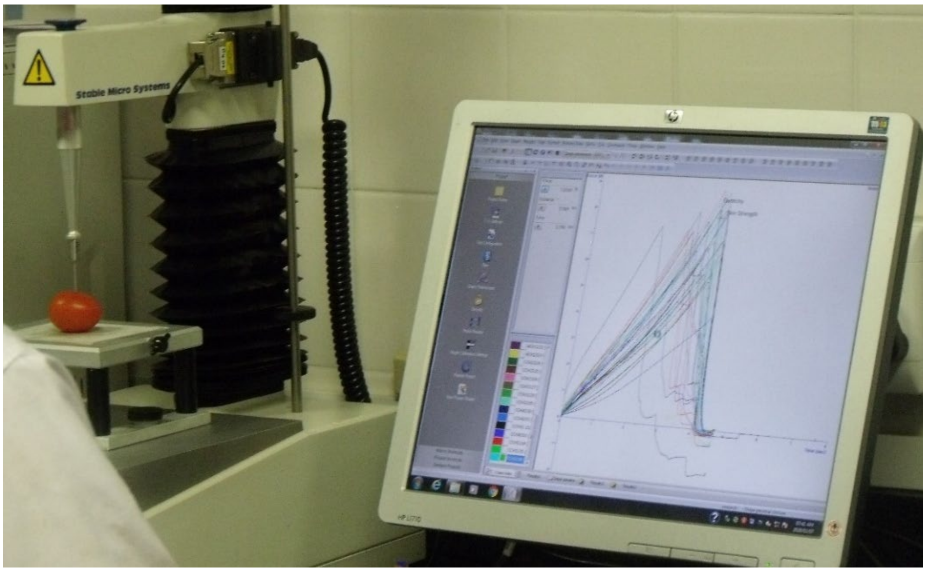

Figure 4.3 Cherry tomato puncture test

4.7.2.2 Kramer shear test

The Kramer shear was determined by using a method adopted from Harker *et al.* (1997) and it was measured by using a Texture Analyzer (TA-XT Plus, Texture Technologies Company, USA), with a load cell probe fitting for a 30 kg load (300 N). Each of three cherry tomato samples were cut, in triplicate, into 10 mm disk slices by using a Vanier Calliper and a knife. The disks were weighed and then positioned in a sample chamber (see Figure 4.4), where the shear press plate pressed the sliced disk at a 10 $mm.min^{-1}$ speed setting. The shear force is a measure of firmness calculated by the peak force, divided by the weight of a sample ($g.g^{-1}$ wt.) disk, to accommodate the difference in the tissue area cut by the plates.

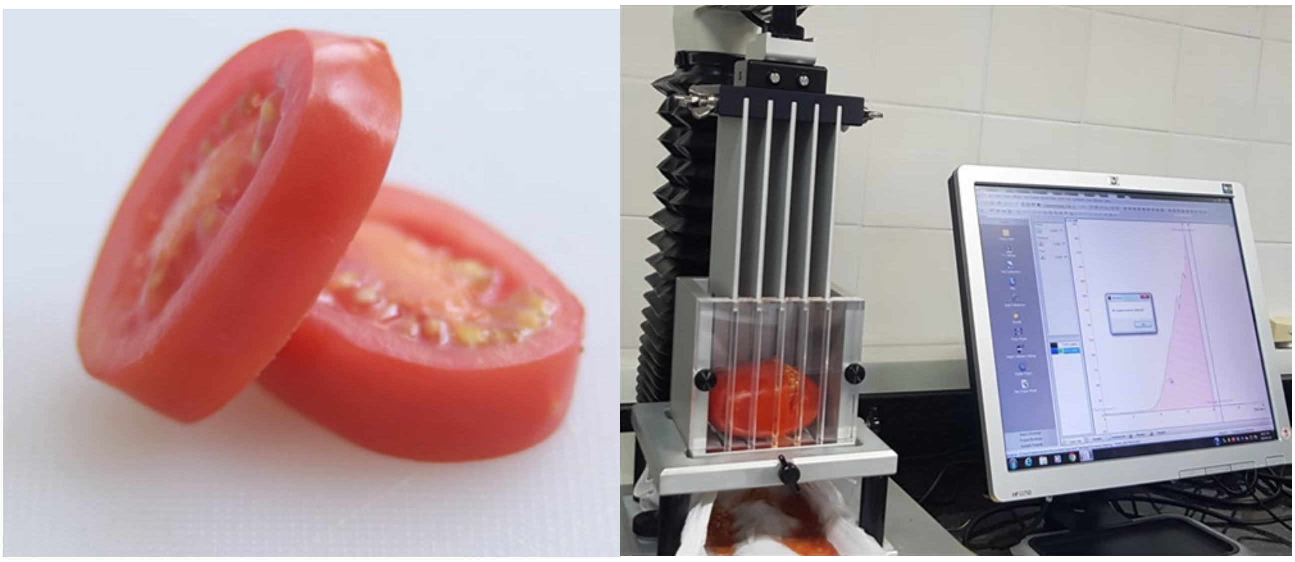

Figure 4.4 Cherry tomato 10 mm sliced disk and Kramer shear test

4.7.2.3 Compression test

As described by Sirisomboon *et al.* (2012), the compression test was measured by using a Texture Analyzer (Instron Universal Testing Machine, Model-3345, Buck, United Kingdom). The analyser was calibrated with a 5 kg weight. It was equipped with a 55 mm diameter plate probe with a 10 $mm.min^{-1}$ speed setting. Each tomato was aligned horizontally on a smooth surface, from the stem end to the top apex, and then pressed by the moving parallel probe until the fruit ruptured, as shown in Figure 4.5. The firmness was defined by the compressive load (N) at the breaking point. The measurements were recorded in triplicate, by using the *Bluehill Instron* data acquisition software.

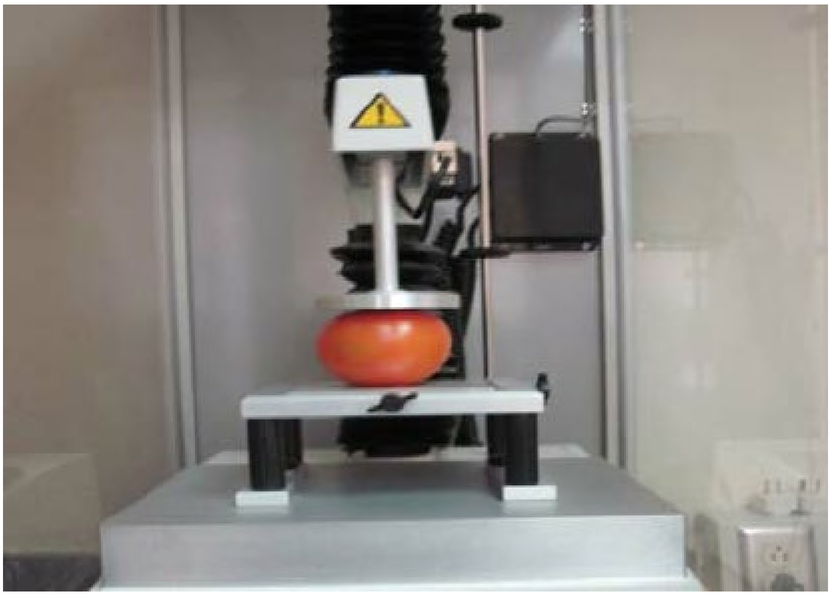

Figure 4.5 Flat-plate compression test of the cherry tomatoes

4.7.3 Physiological weight loss

The physiological weight loss of the tomato samples was measured on Day 0 and they were labelled, to avoid confusion. The total weight loss was the difference between the initial and final weight during each storage interval. The percentage weight method was used, as described by the AOAC (1984). The formula for calculating the percentage weight loss is presented in Equation 4.1. Each measurement was recorded in triplicate, for each sampling day.

$$\%Weight\ loss\ = \frac{W_0 - W_f}{W_o} \times 100 \tag{4.1}$$

where

$W_o =$ the average weight of the tomato sample on Day 0

$W_f =$ the average weight tomato of the tomato sample on the final day

4.7.4 Biochemical analysis

4.7.4.1 Total soluble solids

The Total Soluble Solids (TSS) were measured by using the Jafari *et al*. (2017) method. Three replicates of each treatment were blended and liquified in a blender. The tomato juice was extracted and filtered by using a muslin cloth. A hand-held refractometer (Atago Palette-PR32, Tokyo, Japan) was used to determine the TSS, by placing two to three drops of extracted clear juice on the refractometer prism three times. Between each sampling, the refractometer prism was washed with alcohol and distilled water, and then dried with tissue paper, before being used again. Before the experimentation, the digital refractometer was standardized with distilled water containing 0% TSS and it was adjusted to room temperature.

4.7.4.2 Titratable acidity

The total titratable acidity was determined, as described in Domínguez *et al.* (2012). Three randomly-selected tomatoes from the sample replications were blended by using a fruit blender (Philips Model, HR2103, Makro Pty, PMB, South Africa) for one minute. An aliquot of juice was extracted and filtered by using a muslin cloth and it was then transferred to a sterilized conical flask. The total titratable acidity was determined by titrating 25 ml of the tomato sample juice with 0.1 mol. L^{-1} of sodium hydroxide (NaOH). The titration procedure was repeated three times and the readings were recorded.

4.7.4.3 pH value

As described by Tigist *et al*. (2013), the pH of the tomatoes was measured by using a glass electrode pH meter, which was standardized before use each time with a neutral buffer pH of 7.0 and a pH of 4.0. Three randomly-selected fruits from the sample replications were blended by using a fruit blender (Philips Model, HR2103, Makro Pty, PMB, South Africa) for one minute. The juice was filtered by using a muslin cloth and an aliquot of juice sample was transferred into a sterile beaker, where a pH meter was inserted into the liquid. The procedure was repeated three times and the pH meter readings were recorded.

4.7.4.4 Total sugars

The total sugars were determined by using a method used by Pinela *et al.* (2012), with slight modifications. A tomato fruit sample was blended for two minutes, and 5 mL of the juice was extracted into centrifuge tubes. Then 2 mL of deionized water was added and centrifuged (Avanti J-26S XP; Beckman Coulter, United States of America) at 10,000 rpm for 15 minutes at 4°C. All solutions of the samples were filtered through a 0.45µm nylon syringe filter and 2 mL was injected into High-Performance-Liquid-Chromatography (HPLC) vials. The HPLC system (LC-20AT; Shimadzu, Japan) column was set at 85°C, with ultra-pure water as the mobile phase (RID-10A; Shimadzu, Japan) flowing at 0.6 $ml.min^{-1}$. The chromatographic comparisons identified the sugar compounds with authentic standards of glucose and fructose (the sucrose was negligible). A quantification was performed by using the standard internal method and the sugar content was expressed in mg per 100 g of fresh weight ($mg.100^{-1}g^{-1}$ FW).

4.7.4.5 Total phenolic content

The total phenolic content of tomatoes was determined by using Dufera *et al.*'s (2021) method through the Folin-Ciocaltean (FC) reagent. A 0.1 mL of the fruit sample juice from each of the replications was extracted and mixed with 0.5 mL of the FC reagent, along with 1.5 mL of a 7% sodium carbonate solution. Distilled water was added to make up a final solution volume of 10 mL. The mixture was incubated at 90°C for two hours. The absorbance was measured by using a UV-Vis spectrophotometer at 750 nm against a blank.

4.7.5 Microbiological analysis

The microbial development was determined by using a method adopted by Shezi (2016b). Briefly, a randomly-selected tomato (single) was taken from each treatment for sampling. 30

mL of sterile peptone water (0.85% NaCl and 0.1% peptone, pH 7) was added as an initial solution to the selected sample in a sterile plastic bag containing the sampled tomato. The tomato was gently massaged for five minutes to rinse off and collect the micro-organisms from its surface. The aerobic mesophilic micro-organisms on the tomato surface were determined and enumerated by extracting 0.1 mL of the appropriate serial dilutions, from the first sample to the sixth (10^{-6}) sample. The dilutions were mixed thoroughly for one minute in a Whirlmixer (Model CM-1, Fisher Scientific, Massachusetts, USA) and spread onto the ready-to-use plate count agar plates, followed by an incubation period of 48 hours at 28°C. The counts were given as colony-forming units per tomato (whole surface area). The determination and enumeration of the fungal flora (yeast and mould) present on the tomato surface was done by extracting 0.1 mL of the appropriate decimal solutions, from the first to sixth (10^{-6}) and spread onto ready-to-use Rose-Bengal-chloramphenicol agar plates (RBC-agar), followed by an incubation period of up to seven days at 25°C. The differentiation between the bacterial and fungal colonies was confirmed via microscopy (Kern OBT 102, 4/10/40 Magnification, Germany). The difference were determined by counting the number of Colony Forming Units (CFU's) per cm^{-2} of tomato surface.

4.8 Statistical Data Analysis

All data were reported as the mean± standard deviation for the three replicates. Significance tests were conducted by using the Analysis of Variance (ANOVA) in a completely randomized general design arrangement, using the GenStat® 18th Edition (VSNI, Hempstead, UK). The performance level of the treatment means was done at a statistical significance level of 5% and using Duncan multiple range comparison tests.

4.9 Results and Discussion

This section includes the results and discussion of the effects of the packaging, storage conditions and storage period on the physical, physicochemical changes and microbial development of the cherry tomatoes.

4.9.1 Temperature and relative humidity

The temperature and relative humidity varied significantly ($P<0.05$) during the storage period. The ambient storage temperatures fluctuated between 22℃ at night and 26℃ during the day, while the cold storage. temperatures fluctuated between 8℃ at night and 12℃ during the day

(Figure 3.6, Section 3.8.1). The Relative Humidity (RH) was higher under cold storage conditions, fluctuating at a RH of around 78–80%, while it was low under ambient storage conditions, where it fluctuated between 68–72% RH (Figure 3.6, Section 3.8.1). Tomatoes responded differently to these storage environments. Those under cold storage conditions had a longer storage life than those under ambient conditions. Temperature is a substrate of the metabolic processes, such as transpiration, respiration and ethylene production, that occur in tomatoes. A low temperature slows down these metabolic processes, thereby slowing down the deterioration rate of the fruit (Workneh *et al.*, 2012). Shezi (2016b) also reported similar observations, where tomatoes harvested at different times and stored under cold storage conditions had a better quality after 32 days than those stored under ambient conditions. Workneh and Osthoff (2010) stated that temperature is the most critical post-harvest factor, and if it is not maintained, it can have a significant impact on the quality of fruit and vegetables.

4.9.2 Colour analysis

For consumers, colour is a significant factor in the selection and purchasing process. Consumers shop with their eyes and are drawn to products with vibrant colours. Section 4.9.2 discusses the colour changes of cherry tomatoes, which are affected by different packaging materials and storage conditions for 28 days.

4.9.2.1 Lightness

The rate of colour change (L* value) of cherry tomatoes is presented in Table 4.1. The L* value obtained from this experiment ranged from 37.15 to 17.80, which agrees with the range of values reported by Shehata *et al.* (2021). The packaging had a significant influence ($P<0.001$) on the L* changes in cherry tomatoes. Unpackaged (Control) had the lowest L* value (28.67), which indicated that the decline in the L* values was faster. The Glued Paper Tray (400g) + Flow wrap had the highest L* value (32.28), which indicated that the decline in L* was slower in this packaging. This finding agrees with the findings reported by Meena *et al.* (2020), where the chitosan treatment conserved the L* values and slowed down the colour change (less red colour) during the storage period. The packaging reduces the O_2 levels and enables an increase in CO_2 inside the packaging environment, which retards ripening and colour development (Breda *et al.*, 2017). As a result, the lower rate of respiration helps to retard the deterioration and to preserve the quality of the tomatoes.

The storage environment had a significant (P<0.001) influence on the L* changes of cherry tomatoes. Those stored under cold storage conditions had a higher mean L* value (31.94) than those stored under ambient storage conditions, which had a low mean L* value (30.59). The effects of the storage conditions are similar to those of Khairi *et al*. (2015a), who reported that storing tomatoes at low temperatures slows down the ripening process, compared to storing them at room temperature. The same results were also reported by Buntong *et al.* (2015), namely, that the L* values decreased faster in fruits stored at ambient temperatures, compared to those stored under cold storage conditions.

The L* value of the cherry tomatoes decreased significantly (P<0.001) with an increase in the storage period from 37.15 on Day 0 to 23.85 on Day 28, by showing more red as the ripening stages progressed. Taye *et al.* (2019) also reported that the L* value decreases with the increasing storage time, because of the red colour development, due to the advanced ripening stage in cherry tomatoes.

The interaction of the packaging and storage conditions had no significant (P>0.05) influence on the L* changes in the cherry tomatoes. The interaction between (a) the packaging and the storage period and (b) the storage conditions and storage period was found to significantly (P<0.001) influence their L* value. The results showed that the Zibo Punnet PET + Flow wrap, the Glued Paper Tray + Flow wrap, the Zibo Punnet PET + Zibo PET Lid, the Old PP Bag and the Pulped Paper Tray + Zibo PET Lid packaging treatments displayed higher L* values after Day 28, compared to the Unpackaged (control) samples. This indicates the benefits of the packaging treatments, as opposed to Unpackaged. The results also showed that samples under cold storage conditions had minimal changes in their L* values, compared to those under ambient storage conditions for the 28-day storage period. The three-way interaction between the packaging, storage conditions and storage period proved to have no significant (P>0.05) influence on the L* value of the cherry tomatoes. Cherry tomato samples in Glued Paper Tray + Flow wrap, which were stored under cold storage conditions, had the lowest changes in L* value during the 28-day storage period.

Table 4.1 Effects of the packaging materials and storage conditions on the lightness (L^*) changes in cherry tomatoes over the 28-day storage period (n=3)

Packaging Treatment	Storage Condition	Storage Period (Days)				
		0	7	14	21	28
Zibo Punnet PET + Flow wrap	Cold	37.15^{su}	$35.98 \pm 0.28^{r-u}$	33.33 ± 1.12^{opq}	30.98 ± 0.93^{mn}	27.11 ± 0.92^{hi}
	Ambient	37.15^{su}	34.88 ± 0.31^{qrs}	30.86 ± 2.60^{mn}	$29.26 \pm 1.44^{j-m}$	$24.68 \pm 1.31^{d-g}$
Old PP plastic bag	Cold	37.15^{u}	$35.17 \pm 0.28^{q-u}$	$33.91 \pm 0.34^{o-r}$	30.69 ± 0.19^{lmn}	25.38 ± 0.25^{fgh}
	Ambient	37.15^{su}	34.64 ± 0.22^{pqr}	32.02 ± 1.08^{no}	$29.66 \pm 1.16^{j-m}$	23.14 ± 1.38^{cde}
Zibo PET Punnet + Zibo Lid	Cold	37.15^{su}	$35.85 \pm 0.25^{r-u}$	$33.90 \pm 0.66^{o-r}$	$30.46 \pm 1.02^{k-n}$	26.43 ± 2.57^{ghi}
	Ambient	37.15^{su}	$35.14 \pm 0.04^{q-u}$	32.28 ± 0.60^{no}	26.81 ± 3.84^{ghi}	23.14 ± 0.77^{cde}
Glued Paper Tray + Flow wrap	Cold	37.15^{su}	$35.65 \pm 0.51^{q-u}$	$33.69 \pm 0.07^{o-r}$	31.12 ± 1.40^{mn}	27.59 ± 2.09^{ij}
	Ambient	37.15^{su}	$35.10 \pm 0.13^{q-u}$	32.49 ± 1.31^{nop}	28.33 ± 2.33^{ijk}	$25.00 \pm 0.83^{e-h}$
Pulped Paper Tray + Zibo PET Lid	Cold	37.15^{su}	$34.89 \pm 0.49^{q-t}$	32.38 ± 0.88^{nop}	$28.61 \pm 1.87^{i-l}$	24.10 ± 1.64^{def}
	Ambient	37.15^{su}	$33.82 \pm 0.39^{o-r}$	31.02 ± 0.74^{mn}	26.93 ± 1.69^{hi}	21.42 ± 1.14^{bc}
Unpackaged (Control)	Cold	37.15^{su}	34.63 ± 0.42^{pqr}	$30.35 \pm 0.18^{k-n}$	22.75 ± 0.78^{cd}	20.46 ± 0.25^{b}
	Ambient	37.15^{su}	$33.77 \pm 0.30^{o-r}$	$29.53 \pm 1.71^{j-m}$	23.10 ± 3.33^{cde}	17.80 ± 1.00^{a}

Significance (P) level	
Package (A)	P<.001
Storage condition (B)	P<.001
Storage period (C)	P<.001
A*B	P>0.05
A*C	P<.001
B*C	P<.001
A*B*C	P>0.05

Values are the means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). PET = polyethylene terephthalate; PP = Polypropylene

4.9.2.2 Hue angle

Changes in the hue angle (h°) values of the cherry tomatoes over the 28-day storage period, which were affected by the different packaging materials and storage conditions, are represented in Table 4.2. The h° values range from 54.05 to 44.65, which is in the same range of those reported by Kabir *et al.* (2020a). The packaging significantly (P<0.001) influenced the h° values of the cherry tomatoes. Unpackaged tomato samples (49.10) experienced the highest decline in their *h*° values, compared to those in the packaging treatments. The cherry tomato samples in Glued Paper Tray + Flow wrap (51.32) experienced the lowest decline in h° values. In contrast, the cherry tomato samples in an Old PP plastic bag (49.82) experienced the highest decline in h° values. Olveira-Bouzas *et al.* (2021) reported similar findings, where the h° values in unpackaged tomatoes declined faster and indicated a more intense red colour, compared to the packaged tomatoes.

The results also showed that storage conditions significantly ($P<0.001$) influenced the h° values of the stored cherry tomatoes. Those stored under ambient storage conditions experienced the highest decrease in hue angle (49.59), compared to 51.03 of the those stored under cold storage conditions. Viet and Trang (2015) observed a similar trend in the colour change, where the values of the mini-tomatoes stored at a cold temperature (9℃) were lower than those stored at a high temperature (29℃). Pinheiro *et al.* (2013) also reported a decrease in the hue angle values of tomatoes over a 30-day storage period. The colour changes in the tomatoes are proportionate to their respiration intensity (Ogwu, 2019); hence, the cherry tomato samples stored in a refrigerated environment had a low respiration rate, due to the low temperatures, and thus there were only minor colour changes.

The h° values of the cherry tomatoes varied significantly ($P<0.001$) during the storage period. The results showed that all the tomato samples experienced a decrease in their h° value (54.05 to 46.57). This is attributed to the progress in the ripening stages over the storage period. Similarly, Kabir *et al.* (2020a) reported that the h° values of the tomatoes decrease during storage, when they are packaged using eco-friendly films. The decrease in the h° value of cherry tomatoes is an indication of colour change, due to ripening (Viet and Trang, 2015). Generally, tomatoes become a full red colour as they ripen, and the results showed that their h° values are closer to 0° (Viet and Trang, 2015).

The interaction of (a) the packaging and storage conditions and (b) the packaging and storage period showed no significant ($P>0.05$) influence on the h° values of the cherry tomatoes. However, the storage conditions and storage period had a significant ($P<0.001$) influence on their h° values. Those samples stored under cold storage conditions exhibited slower colour changes, compared to those under ambient storage conditions over the 28-day storage period. According to Kabir *et al.* (2020a), the development of colour results from physiological respiration, which is influenced by the surrounding environment.

Table 4.2 Effects of the packaging materials and storage conditions on the hue angle (h°) in cherry tomatoes during the 28-day storage period (n=3)

Packaging Treatment	Storage conditions	Storage period (Days)				
		0	7	14	21	28
Zibo punnet PET + Flow wrap	Cold	54.05^{r}	53.32±0.30^{pqr}	52.16±1.01$^{n\text{-}r}$	48.92±0.88$^{g\text{-}k}$	47.92±0.55$^{d\text{-}i}$
	Ambient	54.05^{r}	52.61±0.07$^{o\text{-}r}$	49.19±0.45$^{h\text{-}l}$	47.37±0.46$^{b\text{-}h}$	45.97±1.14$^{a\text{-}d}$
Old PP plastic bag	Cold	54.05^{r}	53.50±0.26^{qr}	50.74±2.02$^{j\text{-}o}$	48.82±0.19$^{g\text{-}k}$	46.34±1.92$^{a\text{-}f}$
	Ambient	54.05^{r}	52.73±0.27$^{o\text{-}r}$	48.01±0.09$^{d\text{-}i}$	44.86±3.01^{a}	45.03±2.67^{ab}
Zibo PET Punnet + Zibo lid	Cold	54.05^{r}	52.97±0.46$^{o\text{-}r}$	51.59±1.09$^{m\text{-}r}$	48.70±1.60$^{f\text{-}k}$	47.51±0.16$^{c\text{-}i}$
	Ambient	54.05^{r}	52.04±0.12$^{n\text{-}r}$	48.71±0.36$^{f\text{-}k}$	47.29±0.79$^{b\text{-}h}$	45.21±1.46^{abc}
Glued paper tray + Flow wrap	Cold	54.05^{r}	53.50±0.01^{qr}	52.44±1.80$^{o\text{-}r}$	50.97±2.40$^{k\text{-}p}$	49.58±4.72$^{h\text{-}m}$
	Ambient	54.05^{r}	53.14±0.14$^{o\text{-}r}$	51.73±2.55$^{m\text{-}r}$	47.89±0.26$^{d\text{-}i}$	45.82±0.25$^{a\text{-}d}$
Pulped paper tray + Zibo PET lid	Cold	54.05^{r}	53.83±0.19^{qr}	51.49±0.96$^{l\text{-}q}$	49.96±1.90$^{i\text{-}n}$	47.63±2.84$^{c\text{-}i}$
	Ambient	54.05^{r}	53.02±0.06$^{o\text{-}r}$	49.46±0.68$^{h\text{-}m}$	48.54±0.58$^{e\text{-}j}$	46.57±0.50$^{a\text{-}g}$
Unpackaged (Control)	Cold	54.05^{r}	51.82±0.11$^{m\text{-}r}$	48.97±0.44$^{g\text{-}k}$	47.36±2.01$^{b\text{-}h}$	46.58±0.26$^{a\text{-}g}$
	Ambient	54.05^{r}	49.90±0.85$^{i\text{-}n}$	47.51±0.50$^{c\text{-}i}$	46.11±0.37$^{a\text{-}e}$	44.65±0.95^{a}

Significance (P) level	
Package (A)	P<.001
Storage condition (B)	P<.001
Storage period (C)	P<.001
A*B	P>0.05
A*C	P>0.05
B*C	P<.001
A*B*C	P>0.05

Values are the means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). PET = polyethylene terephthalate; PP = Polypropylene

The interaction of the packaging, storage conditions and storage period had no significant (P>0.05) influence on the h° values of cherry tomatoes. The packaging treatments under cold storage conditions experienced a lower decrease in h° values than those under ambient storage conditions. All the cherry tomato samples experienced a decline in hue angle values during the storage period. The differences in the hue angle can be attributed to the different packaging combinations. The Glued Paper Tray + Flow wrap treatments preserve the colour changes, which indicates a slower respiration rate and ripening process. However, in this experiment there was no clear advantage shown by the non-biodegradable packaging treatments over the biodegradable packaging treatments. Kantola and Helen (2001) found that packaging with plastic films delayed the colouring of the tomatoes, compared to biodegradable packaging, which does not agree with the results of this study. In this study, the structure and size of the perforation was a factor. The Zibo Punnet PET + Flow wrap, Old PP plastic bag, and Zibo PET Punnet + Zibo lid packages have many perforations, which results in the movement of air in and out of the packaging system and therefore supports respiration. The packaging designs are also narrower, which results in the samples being highly compacted and stacked, which causes stress and bruising in tomatoes. They are susceptible to mechanical damage during packaging, and their quality can be substantially decreased by poor post-harvest handling (Pathare and Al-Dairi, 2021).

4.9.3 Firmness

Firmness is an essential factor that is closely associated with the ripeness of the tomatoes. Consumers tend to choose firmer fruit, which do not lose too much juice during slicing and which do not have a tough skin to slice. The firmness of tomatoes is influenced by the toughness of the skin (Puncture test), the flesh firmness (Kramer shear test) and the tissue structure (Compression test), which are discussed in the sections below:

4.9.3.1 Puncture

The puncture test results are presented in Table 4.3 and range from 8.57 to 4.44 N, which is similar to the range reported by Islam *et al.* (2019). The puncture test showed that the packaging treatments had no significant ($P>0.05$) influence on the firmness of cherry tomatoes. Similarly, Sualeh *et al.* (2016) also that the different packaging treatments showed no significant influence on the puncture test of tomatoes. Despite their non-significance, cherry tomatoes in the Pulped Paper Tray + Zibo PET Lid remained firmer and showed a higher puncture force (6.74 N). In contrast, Unpackaged (control) cherry samples were less firm and had the lowest puncture force (6.50 N). Adhikari *et al.* (2020) also observed a higher firmness of tomatoes packaged in ordinary plastic and lower firmness values in unpackaged tomatoes, with no significant ($P>0.05$) differences between them.

The storage conditions significantly ($P<0.001$) influenced the firmness of the cherry tomatoes. Those under cold storage conditions had a higher puncture force (6.88 N) than the puncture force (6.47 N) of those under ambient storage conditions. This result agrees with the results of Pathare and Al-Dairi (2021) and Sualeh *et al.* (2016), who reported that tomatoes stored under cold conditions were firmer than those stored under ambient conditions. Viet and Trang (2015) mentioned that low temperatures slow down the physiological processes that occur in the biochemical tissues of the fruit, which results in a slow ripening process; hence, the quality of the fruit is maintained under cold storage.

The firmness by puncture varied significantly ($P<0.001$) during the storage period. The results showed that there was a decline in the puncture force in all the cherry tomato samples as the storage period progressed. They had a higher average puncture force on Day 0 (8.59 N) and the lowest average on the 28th day (5.07 N). The decline in the puncture force results from a gradual loss in firmness, as the storage time of the cherry tomatoes progresses (Islam *et al.*, 2019). Tolesa *et al.* (2018) reported a similar observation, where there was a decline in the firmness of tomatoes stored inside an evaporative cooler over a storage period of 21 days, which is in agreement with the results obtained in this study. Viet and Trang (2015) reported that the firmness of the tomato fruit declines due to enzyme activity, where the glucose substances inside the fruit are hydrolysed, hemicellulose hydrolises to cellulose, pentose and protopectin soluble pectin, which leads to the gradual softening of the fruit.

The interaction between (a) the packaging and storage conditions and (b) the packaging and storage period had no significant ($P>0.05$) influence on the puncture force of the cherry tomatoes. The three-way interaction of the packaging, storage conditions and storage period also had no significant ($P>0.05$) influence on the puncture force of the cherry tomatoes. Differences are caused by the different packaging combinations; hence, the loss of firmness was not the same in all the treatments. The Pulped Paper Tray + Zibo PET Lid is considered to be better than the other packaging materials. The resolution of enzyme activity is sensitive to the availability of oxygen. The more oxygen that is available, the more the glucose substances are degraded, which results in the softening of the fruit (Adhikari *et al.*, 2020). This finding agrees with the slower softening that is observed in packaged cherry tomatoes, due to low oxygen availability, compared to those in Unpackaged (Control).

Table 4.3 Effects of packaging materials and storage conditions on the puncture (N) changes in cherry tomatoes during the 28-day storage period (n=3)

Packaging Treatment	Storage Condition	Storage period				
		0	7	14	21	28
Zibo Punnet PET + Flow wrap	Cold	8.57 ± 0.44^{q}	8.06 ± 0.06^{pq}	$7.06\pm0.20^{k\text{-}o}$	$6.46\pm0.00^{h\text{-}l}$	$5.51\pm0.40^{b\text{-}g}$
	Ambient	8.57 ± 0.44^{q}	$7.40\pm0.09^{m\text{-}p}$	$6.36\pm0.38^{g\text{-}l}$	$5.52\pm1.04^{b\text{-}g}$	$5.22\pm0.54^{a\text{-}d}$
Old PP Plastic bag	Cold	8.57 ± 0.44^{q}	7.61 ± 0.00^{nop}	$7.07\pm0.31^{k\text{-}o}$	$6.09\pm0.79^{d\text{-}j}$	5.16 ± 0.34^{abc}
	Ambient	8.57 ± 0.44^{q}	$7.27\pm0.00^{l\text{-}p}$	$6.31\pm0.00^{f\text{-}k}$	$5.37\pm0.08^{b\text{-}e}$	4.81 ± 0.07^{ab}
Zibo PET Punnet + Zibo Lid	Cold	8.57 ± 0.44^{q}	7.50 ± 0.00^{nop}	$6.96\pm0.08^{j\text{-}n}$	$5.86\pm1.10^{c\text{-}i}$	$5.45\pm0.61^{b\text{-}g}$
	Ambient	8.57 ± 0.44^{q}	$7.25\pm0.96^{l\text{-}p}$	$6.35\pm0.53^{g\text{-}l}$	$5.40\pm0.06^{b\text{-}f}$	4.87 ± 0.51^{ab}
Glued Paper Tray + Flow wrap	Cold	8.57 ± 0.44^{q}	7.93 ± 0.00^{opq}	$7.14\pm0.74^{k\text{-}p}$	$6.26\pm0.48^{e\text{-}k}$	5.11 ± 1.08^{abc}
	Ambient	8.57 ± 0.44^{q}	7.52 ± 0.06^{nop}	$6.70\pm0.50^{i\text{-}n}$	$6.10\pm0.63^{d\text{-}j}$	4.85 ± 0.56^{ab}
Pulped Paper Tray + Zibo PET Lid	Cold	8.57 ± 0.44^{q}	8.03 ± 0.00^{pq}	7.52 ± 0.27^{nop}	$6.46\pm0.31^{h\text{-}l}$	$5.37\pm0.21^{b\text{-}e}$
	Ambient	8.57 ± 0.44^{q}	$7.26\pm0.43^{l\text{-}p}$	$6.29\pm0.37^{f\text{-}k}$	$5.74\pm0.11^{b\text{-}h}$	4.99 ± 0.07^{abc}
Unpackaged (Control)	Cold	8.57 ± 0.44^{q}	7.91 ± 0.44^{opq}	$6.69\pm0.67^{i\text{-}n}$	$5.63\pm0.36^{b\text{-}h}$	5.10 ± 0.20^{abc}
	Ambient	8.57 ± 0.44^{q}	7.52 ± 0.40^{nop}	$6.51\pm0.27^{h\text{-}m}$	$5.37\pm0.42^{b\text{-}e}$	4.44 ± 0.82^{a}
Significance (P) level						
Package (A)		P>0.05				
Storage condition (B)		P<.001				
Storage period (C)		P<.001				
A*B		P>0.05				
A*C		P>0.05				
B*C		P>0.05				
A*B*C		P>0.05				

Values are the means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). PET = polyethylene terephthalate; PP = Polypropylene

4.9.3.2 Kramer shear

The results on the effects of different packaging treatments and storage conditions on the Kramer shear in cherry tomatoes are presented in Table 4.4. The Kramer shear values ranged from 4.92 to 2.57 $N.g^{-1}$. The results proved that the packaging had a highly-significant influence (P<0.001) on measuring the Shear force of cherry tomatoes. Those stored Unpackaged (control) had lower shear force values, which proves that they lost their structure and firmness faster, compared to those in packaging treatments. Cherry tomatoes in the Glued Paper Tray + Flow wrap cover had higher firmness values, followed by those in the Pulped Paper Tray + Zibo PET Lid, while those in the Zibo PET Punnet + Zibo Lid had the lowest shear force values. Kantola and Helen (2001) observed that the difference between the biodegradable and non-biodegradable packages was not significant. However, the LDPE films were firmer than the biodegradable films, which does not agree with the results in this study. However, the structure and type of packaging used in this study were different from those applied by previous researchers.

The storage conditions were found to have a significant ($P<0.001$) influence on the firmness of cherry tomatoes, which was measured by the Kramer Shear test. Tomatoes stored under cold storage conditions had a higher firmness than those stored under ambient storage conditions. The shear force values between the cold and ambient storage conditions averaged 4.05 $N.g^{-1}$ and 3.71 $N.g^{-1}$ of the fresh weight. The decline in firmness can be attributed to the high biochemical processes associated with ripening, as a result of the higher temperatures during ambient storage. Tolesa and Workneh (2017) reported similar observations, where tomatoes stored in an evaporative cooler had a higher firmness than those stored under ambient conditions. The results showed that cold storage kept the tomato structure intact and firm, which contributes significantly to the maintenance of the quality of cherry tomatoes.

The firmness, as measured by the Kramer shear test, varied significantly ($P<0.001$) over the storage period. The cherry tomatoes had a higher shear force on Day 0 (4.92 $N.\ g^{-1}$) and the lowest shear force (3.02 $N.\ g^{-1}$ FW) on Day 28. This indicated that they lost their firmness as the storage time progressed. The interaction between the packaging and storage conditions did not reveal any significant ($P>0.05$) influence on the shearing force of the cherry samples. However, the interaction between (a) the packaging and the storage period and (b) the storage condition and storage period revealed a highly significant ($P<0.05$) influence on the firmness of the tomatoes. The results proved that the Glued Paper Tray + Flow wrap and the storage conditions are beneficial for preventing the progression of softness in cherry tomatoes, compared to those that had not been subjected to either the packaging or control storage conditions.

Table 4.4 Effects of the packaging materials and storage conditions on Kramer shear ($N.g^{-1}$) changes of cherry tomatoes over the 28-day storage period (n=3)

Packaging Treatments	Storage condition	Storage period (Days)				
		0	7	14	21	28
Zibo Punnet PET + Flow wrap cover	Cold	4.92±0.07^{x}	4.52±0.25^{vw}	4.27±0.04^{q-v}	3.70±0.03^{j-n}	3.22±0.07^{c-g}
	Ambient	4.92±0.07^{x}	4.03±0.14^{n-q}	3.64±0.03^{h-m}	3.32±0.15^{d-i}	2.91±0.15^{bc}
Old PP Plastic bag	Cold	4.92±0.07^{x}	4.08±0.12^{o-t}	4.05±0.15^{n-s}	3.89±0.02^{m-p}	3.20±0.08^{c-f}
	Ambient	4.92±0.07^{x}	3.81±0.03^{l-p}	3.39±0.04^{e-k}	3.18±0.20^{b-f}	2.83±0.27^{ab}
Zibo PET Punnet + Zibo Lid	Cold	4.92±0.07^{x}	4.40±0.45^{r-w}	4.09±0.32^{o-t}	3.72±0.17^{j-n}	2.93±0.31^{bc}
	Ambient	4.92±0.07^{x}	3.87±0.33^{m-p}	3.44±0.46^{e-k}	3.29±0.15^{d-h}	2.58±0.03^{a}
Glued Paper Tray + Flow wrap	Cold	4.92±0.07^{x}	4.68±0.62^{wx}	4.03±0.24^{n-q}	3.75±0.21^{k-o}	3.43±0.17^{e-k}
	Ambient	4.92±0.07^{x}	4.17±0.24^{p-u}	3.69±0.07^{i-n}	3.50±0.03^{f-l}	3.12±0.06^{b-e}
Pulped Paper Tray + Zibo PET LId	Cold	4.92±0.07^{x}	4.49±0.08^{uvw}	4.05±0.09^{n-r}	3.70±0.25^{j-n}	3.38±0.05^{e-k}
	Ambient	4.92±0.07^{x}	4.09±0.20^{o-t}	3.65±0.16^{h-m}	3.48±0.11^{f-l}	3.11±0.25^{b-e}
Unpackaged (Control)	Cold	4.92±0.07^{x}	4.10±0.13^{o-t}	3.70±0.09^{j-n}	3.56±0.20^{g-m}	3.00±0.10^{bcd}
	Ambient	4.92±0.07^{x}	3.74±0.12^{k-o}	3.36±0.09^{d-j}	3.10±0.02^{b-e}	2.57±0.36^{a}

Significance (P) level	
Package (A)	P<.001
Storage condition (B)	P<.001
Storage period (C)	P<.001
A*B	P>0.05
A*C	P<0.05
B*C	P<.001
A*B*C	P>0.05

Values are the means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). PET = polyethylene terephthalate; PP = Polypropylene

4.9.3.3 Compression

The results of this experiment are presented in Table 4.5. The compression values ranged from 72.67 N and 41.15 N. The packaging treatment had a significant (P<0.001) influence on firmness measured by plate compression. Cherry tomatoes packaged in the Pulped Paper Tray + Zibo PET Lid had a slower firmness reduction rate, with 61.37 and 58. 30 N under cold and ambient conditions, respectively. There was a higher firmness loss in tomatoes that were unpackaged, with values of 59.06 and 57.07 N under cold and ambient conditions, respectively. Tomato samples packaged in the Glued Paper Tray + Flow wrap were firmer under cold conditions, with values at 62.18 N, but worse under ambient conditions, with a retained value of 56.14 N. Unpackaged cherry tomatoes, followed by the Old PP plastic bag, lost their turgidity quicker in both cold and ambient conditions. The loss of firmness of those in the Old PP plastic bag package can be attributed to the narrow structure of the packaging material; hence, the tomatoes are packed more compactly inside the package, which causes too much stress and results in bruising and the deformation of the tomato cell walls, and hence, the loss of firmness.

The storage conditions were found to have a significant ($P<0.001$) influence on the firmness of the cherry tomatoes, when measured as a compressive force. Cherry tomatoes stored under cold storage conditions were found to have a higher firmness (60.04 N), compared to those under ambient storage conditions, which had a low firmness (57.10 N). The variation in firmness values between the cold and ambient storage conditions can be attributed to the high temperatures, which influence a number of physiological and biochemical factors that contribute to the resistance of the tomatoes; for example, the break-down of pectin materials in the cell walls, the size of the cells, the specific gravity and the dry matter content (Albaloushi *et al.*, 2012).

The firmness of the cherry tomatoes varied significantly ($P<0.001$) over the 28-day storage period. All the cherry tomatoes softened and progressively lost their rigidity, elasticity and plasticity during storage. However, more losses were observed in the samples subjected to Open Storage, compared to those subjected to packaging treatments. On Day 0, the cherry tomatoes recorded the highest compression load at an average of 72.67 N, and they recorded the lowest on Day 28, with an average value of 44.46 N. According to Albaloushi *et al.* (2012), tissue failure occurs under compression loading as a result of rupturing of the cell walls, which is caused by the extreme stresses during the test performance. As the storage time progresses, the cell wall structure starts to degrade, and hence, there is a decrease in firmness in the tomatoes.

Table 4.5 Effects of the packaging materials and storage conditions on compression force (N) changes in cherry tomatoes over the 28-day storage period (n=3)

Packaging Treatment	Storage Condition	Storage Period (Days)				
		0	7	14	21	28
Zibo Punnet PET + Flow wrap	Cold	72.67±0.00[v]	67.73±0.32[rst]	57.76±1.08[no]	53.56±1.72[h-l]	48.82±7.00[e]
	Ambient	72.67±0.00[v]	67.05±0.05[qrs]	52.98±1.96[g-k]	48.58±2.04[e]	39.09±1.47[a]
Old PP Plastic bag	Cold	72.67±0.00[v]	65.82±0.00[pqr]	56.04±0.00[l-o]	51.85±0.00[f-j]	42.07±0.00[bc]
	Ambient	72.67±0.00[v]	64.84±0.00[pq]	55.89±0.00[l-o]	49.46±0.00[ef]	40.96±0.00[ab]
Zibo PET Punnet + Zibo Lid	Cold	72.67±0.00[v]	67.72±0.32[rst]	58.62±0.00[o]	50.67±0.00[efg]	45.58±0.00[d]
	Ambient	72.67±0.00[v]	65.79±0.00[pqr]	53.93±0.00[i-l]	49.54±2.51[ef]	44.54±0.00[cd]
Glued Paper Tray + Flow wrap	Cold	72.67±0.00[v]	67.75±1.17[rst]	64.07±0.00[p]	54.51±0.00[j-m]	51.89±0.00[f-j]
	Ambient	72.67±0.00[v]	69.57±0.00[st]	52.69±0.00[g-k]	45.72±0.00[d]	40.03±0.00[ab]
Pulped Paper Tray + Zibo PET Lid	Cold	72.67±0.00[v]	69.85±0.10[tu]	57.37±2.46[no]	55.89±1.28[l-o]	51.09±0.00[e-h]
	Ambient	72.67±0.00[v]	67.03±0.00[qrs]	54.47±0.00[j-m]	51.26±0.00[e-i]	46.078±0.00[d]
Unpackaged (Control)	Cold	72.67±0.00[v]	66.73±0.00[pqr]	58.48±4.37[o]	55.23±0.00[k-n]	42.21±1.73[bc]
	Ambient	72.67±0.00[v]	64.71±3.02[pq]	56.88±3.92[m-o]	52.10±1.87[f-j]	41.15±0.84[ab]

Significance (P) level	
Package (A)	P<.001
Storage condition (B)	P<.001
Storage period (C)	P<.001
A*B	P<.001
A*C	P<.001
B*C	P<.001
A*B*C	P<.001

Values are the means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). PET = polyethylene terephthalate; PP = Polypropylene

The interactions of (a) the packaging and storage conditions, (b) the packaging and storage period, and (c) the storage conditions and storage period all had a highly significant (P<0.001) influence on the firmness of cherry tomatoes by compressive force. The tomato samples subjected to Unpackaged (the Control) and under both cold and ambient storage conditions experienced a faster decrease in firmness during the plate compression test, compared to those of the packaging treatments. However, the loss of firmness was more pronounced under ambient storage conditions. Cherry tomato samples packaged in the Glued Paper Tray + Flow wrap and stored under cold storage conditions had the lowest reduction of firmness than samples packaged and subjected to ambient storage conditions. The slowed reduction in firmness can result from the secondary lignification in the tissues of the cell wall that is caused by low temperatures, which results in a firm flesh, in plasticity and elastic tissue walls (Li *et al.*, 2012; An *et al.*, 2020).

The packaging treatment, storage conditions and storage period had a highly significant ($P<0.001$) influence on the firmness of cherry tomatoes in the plate compression test. Tomato samples packaged in the Glued Paper Tray + Flow wrap and subjected to cold storage conditions resulted in a reduced firmness of approximately 29.7% between Day 0 and Day 28. Combining these treatments had a synergistic influence by slowing down the physiological and biochemical activities that promote the degradation of cherry tomatoes, and resulted in a firmer and more elastic fruit. In contrast, cherry tomato samples that were unpackaged and stored under ambient storage conditions had the highest loss of firmness (approximately 43.4%) between Day 0 and Day 28. This firmness test shows that the packaging and cold storage conditions are beneficial for preventing softness in cherry tomatoes, which is one of the primary indicators of the rapid ripening process in this fruit.

4.9.4 Physiological weight loss

The results of the Physiological Weight Loss (PWL%) influenced by the packaging and storage conditions over a 28-day storage period are presented in Table 4.6. The percentage PWL values in this study ranged from 0.47 to 6.44%, which is within the range (0.16-9.58%) reported by Dandago *et al.* (2017). The packaging had a significant influence ($P<0.001$) on the PWL of the cherry tomatoes. Unpackaged cherry tomatoes had the highest percentage weight loss, losing 5.34% of their initial weight under cold storage conditions and 8.85% under ambient storage conditions. The Zibo Punnet PET + Flow wrap had the lowest percentage weight loss of 3.83% and 5.60% under cold and ambient storage conditions, respectively. Caron *et al.* (2013) found that the differences in weight loss of mini-tomatoes in different packaging were due to the ability of the packaging system to accumulate water vapour inside the packaging, which helps to maintain the turgidity of the fruit. This may be attributed to the size and number of perforations within the package. The Zibo Punnet PET + Flow wrap had smaller perforated holes than the other packaging systems. Akbudak *et al.* (2007) also reported that non-perforated

PET packaging presented a more significant mass conservation over time, compared to perforated PET packaging. On the contrary, paper-based packages i.e. the Glued Paper Tray + Flow wrap and the Pulped Paper Tray + Zibo PET Lid, had a high vapour-holding capacity and were hence suitable for the accumulation of water vapour. It is worth noting that Paper Trays absorb the moisture inside the packaging, which keeps the tomato sample dry and shiny, compared to plastic trays. The absorption of moisture makes the paper tray swell and increases its initial weight, which is why the Glued Paper Tray + Flow wrap and the Pulped Paper Tray + Zibo PET Lid treatments appear to have a high PWL in this experiment.

The storage conditions had a significant ($P<0.001$) effect on the PWL of cherry tomatoes. Those stored under ambient conditions had a higher percentage of PWL than those stored under cold conditions in all treatments. On average, cherry tomatoes under ambient storage conditions lost 7.54% of their initial weight. In comparison, cherry tomatoes in cold storage lost 4.13% of their initial weight, which prompted a faster ripening process under ambient storage conditions than under cold storage conditions. This result is similar to that of Gharezi *et al.* (2012), where the PWL was lower under cold storage conditions than under ambient storage conditions in all the tomato treatments. Al-Dairi and Pathare (2021) also reported the increased PWL of tomatoes stored under ambient storage conditions, due to the high respiration rate and dehydration processes, compared to those under cold storage conditions.

There was a significant ($P<0.001$) difference in the PWL over the storage period. It increased progressively with the storage time, from 1.08% after Day 7 to 5.57% after Day 28. The increase in the PWL is primarily due to respiration and transpiration (Pathare and Al-Dairi, 2021). Weight loss through transpiration results from the difference in water vapour pressure in the surrounding atmosphere and on the tomato surface (Razali *et al.*, 2021). Respiration causes weight loss due to the loss of carbon atoms from the tomato when it respires, which produces carbon dioxide molecules from the absorbed oxygen molecule and which is disposed of into the atmosphere (Anyasi *et al.*, 2016).

Table 4.6 Effects of the packaging materials and storage conditions on the physiological weight loss (%) of cherry tomatoes during the 28-day storage period (n=3)

Packaging Treatment	Storage Condition	Storage period (Days)				
		0	7	14	21	28
Zibo Punnet PET + Flow wrap	Cold	0.00^{a}	0.47 ± 0.05^{ab}	$1.59\pm0.08^{b-g}$	$2.70\pm0.08^{g-k}$	$3.35\pm0.17^{h-l}$
	Ambient	0.00^{a}	$0.75\pm0.03^{a-d}$	$2.36\pm0.16^{f-j}$	4.27 ± 0.63^{lm}	6.15 ± 0.30^{pq}
Old PP Plastic bag	Cold	0.00^{a}	0.72 ± 0.09^{abc}	$2.20\pm0.20^{e-j}$	3.66 ± 0.44^{kl}	4.34 ± 0.46^{lm}
	Ambient	0.00^{a}	$0.93\pm0.02^{a-e}$	3.47 ± 1.15^{jkl}	$4.69\pm0.20^{l-o}$	7.78 ± 0.84^{st}
Zibo PET Punnet + Zibo Lid	Cold	0.00^{a}	0.60 ± 0.08^{abc}	$2.10\pm0.22^{e-h}$	$3.37\pm0.16^{h-l}$	$3.37\pm0.16^{h-l}$
	Ambient	0.00^{a}	$1.14\pm0.06^{a-f}$	$3.43\pm0.12^{i-l}$	$5.61\pm0.23^{n-q}$	6.78 ± 1.14^{qrs}
Glued Paper Tray + Flow wrap	Cold	0.00^{a}	0.64 ± 0.09^{abc}	$2.14\pm0.09^{e-i}$	$3.44\pm0.05^{i-l}$	$3.83\pm0.12^{k-l}$
	Ambient	0.00^{a}	$1.20\pm0.03^{a-f}$	4.06 ± 0.36^{l}	5.79 ± 0.26^{opq}	6.11 ± 1.68^{pq}
Pulped Paper Tray + Zibo PET Lid	Cold	0.00^{a}	0.53 ± 0.04^{abc}	$2.02\pm0.13^{d-g}$	$3.35\pm0.17^{h-l}$	4.54 ± 0.55^{lmn}
	Ambient	0.00^{a}	$2.01\pm0.67^{d-g}$	4.29 ± 1.71^{lm}	$5.60\pm1.13^{n-q}$	6.44 ± 0.54^{pqr}
Unpackaged (Control)	Cold	0.00^{a}	$1.81\pm1.66^{c-g}$	4.01 ± 1.46^{l}	$5.82\pm1.32^{n-q}$	$5.33\pm0.51^{m-p}$
	Ambient	0.00^{a}	$2.14\pm0.10^{e-i}$	$5.80\pm0.37^{n-q}$	7.39 ± 0.46^{rs}	8.85 ± 2.75^{t}
Significance (P) level						
Package (A)		P<.001				
Storage condition (B)		P<.001				
Storage period (C)		P<.001				
A*B		P>0.05				
A*C		P<.001				
B*C		P<.001				
A*B*C		P>0.05				

Values are the means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test ($P<0.05$). PET = polyethylene terephthalate; PP = Polypropylene

The interaction between the packaging and storage periods had a significant ($P<0.001$) influence on the PWL of the cherry tomatoes. Compared to other packaging treatments, tomatoes packed in the Zibo Punnet PET + Flow wrap had a minimal weight loss of 3.35% over the 28-day storage period. The interaction between the storage condition and storage period also had a significant ($P<0.001$) influence on the PWL of the tomatoes. Throughout the 28-day storage period, the tomatoes under ambient storage conditions had a significantly higher percentage weight loss than those under cold storage conditions. The interaction of the packaging, storage conditions and storage period had no significant (P>0.05) influence on the PWL of cherry tomatoes. The results obtained for the PWL prove that the packaging of the cherry tomato samples at lower storage temperatures and at a high relative humidity (cold storage conditions) limits the increase in weight loss, which results in a delayed ripening process.

4.9.5 Total soluble solids

The results of the Total Soluble Solids (TSS) changes, as influenced by the packaging and storage conditions over a storage period of 28 days, are presented in Table 4.7. The TSS values obtained in the experiment ranged from 3.84 to 5.64 °Brix, which is within the range of values reported by Kabir *et al.* (2020b). The packaging had a significant influence (P<0.001) on the TSS value of the cherry tomatoes, which all showed an increase in their TSS values over the packaging period, mainly under ambient storage conditions. The unpackaged (control) cherry tomatoes had the highest increase in TSS values, ranging from 3.84°Brix to 5.41°Brix between Day 0 and Day 28. At the same time, the Zibo Punnet PET (400g) + Flow wrap and the Glued Paper Tray (300 g) + Flow wrap both had a minimal increase in TSS values, from 3.84°Brix to 5.12°Brix, respectively. The changes in the TSS are closely related to the sugar-acid metabolism that occurs during the respiration process, and the differences depend on the maturity stage, the storage conditions and the atmospheric combination around the fruit (Islam *et al.*, 2019). Excluding the interplay of gases by restricting the CO_2 and O_2, results in the TSS changes being minimal, which can be explained by a minimal loss of carbohydrates due to the respiration process, which is influenced by the availability of O_2 (Akbudak *et al.*, 2007; Gebeyehu, 2018).

The storage conditions had a significant influence (P<0.001) on the TSS values of the cherry tomatoes. Those stored under cold storage conditions had a lower mean TSS value (4.40 °Brix), compared to the mean TSS value (4.59 °Brix) of those stored under ambient storage conditions. Similar results have been reported by Aragüez *et al.* (2020), where the °Brix of cherry tomatoes at room temperature (22°C) was higher, compared to those stored at a lower temperature (10°C). Gharezi *et al.* (2012) also reported similar observations where cherry tomatoes stored under ambient storage conditions recorded higher TSS values than those stored under cold storage conditions. Sualeh *et al.* (2016) explained that the storage temperature is a substrate for the ripening process in fruits and that the TSS increases with the ripening stages; thus, cherry tomatoes stored under ambient storage conditions ripened faster and had high TSS values, which resulted from the higher temperature and which were supported by faster respiration and ripening rates.

The TSS of the cherry tomatoes varied significantly ($P<0.001$) with the storage period. Their values increased between Day 0 and Day 28 from 3.84 to 5.24 °Brix, respectively. Similar results were reported by Kabir *et al.* (2020a), where the TSS of four cherry tomato cultivars increased with the increase in storage time. Coyago-Cruz *et al.* (2019) and Sammi and Masud (2009) reported that an increase in the TSS in tomatoes during storage can be attributed to their continuous ripening upon senescence, which is caused by the hydrolysis of insoluble polysaccharides into simple sugars.

The interaction of the packaging and storage conditions over the 28-day storage period showed a significant ($P<0.001$) influence on the TSS changes in the cherry tomatoes. The packaging and cold storage conditions helped to delay the biochemical quality changes, which led to a rapid increase in the TSS content. Their interaction between packaging and storage period also had a significant effect ($P<0.001$). Delaying this biochemical process helps to extend the shelf-life of the cherry tomatoes further, since an accumulation of TSS content is related to the fast ripening process that leads to early fruit deterioration. The integration of packaging and cold storage is a more effective post-harvest handling treatment for slowing down the rapid accumulation of TSS, for maintaining the quality and extending the shelf-life of cherry tomatoes. Packaging the tomatoes in the Glued Paper Tray + Flow wrap and storing them in cold storage proved to be ideal for keeping the changes of the TSS content to a minimum (22.4%) between Day 0 and Day 28. This experiment proved that Glued Paper Tray + Flow wrap keeps the TSS changes to a minimum.

Table 4.7 Effects of the packaging materials and storage conditions on the total soluble solid (°Brix) content of cherry tomatoes over the 28-day storage period (n=3)

Packaging Treatment	Storage condition	Storage period (Days)				
		0	7	14	21	28
Zibo Punnet PET + Flow wrap cover	Cold	3.84±0.10^{a}	3.86±0.06^{a}	4.03±0.06^{abc}	4.47±0.15^{e-i}	5.03±0.06^{nop}
	Ambient	3.84±0.10^{a}	3.97±0.06^{ab}	4.27±0.21^{c-f}	4.77±0.23^{j-m}	5.20±0.26^{opq}
Old PP Plastic bag	Cold	3.84±0.10^{a}	3.97±0.15^{ab}	4.37±0.12^{e-h}	4.67±0.06^{i-l}	5.20±0.10^{opq}
	Ambient	3.84±0.10^{a}	4.20±0.17^{b-e}	4.67±0.15^{i-l}	5.03±0.06^{m-p}	5.50±0.00^{rs}
Zibo PET Punnet + Zibo Lid	Cold	3.84±0.10^{a}	3.90±0.00^{a}	4.53±0.12^{f-j}	5.13±0.06^{opq}	5.14±0.04^{opq}
	Ambient	3.84±0.10^{a}	4.03±0.06^{abc}	4.60±0.17^{g-k}	5.30±0.17^{pqr}	5.37±0.51^{qrs}
Glued Paper Tray + Flow wrap	Cold	3.84±0.10^{a}	4.00±0.10^{abc}	4.23±0.42^{b-e}	4.47±0.15^{e-i}	4.70±0.17^{i-l}
	Ambient	3.84±0.10^{a}	4.07±0.06^{a-d}	4.47±0.06^{e-i}	4.63±0.06^{h-k}	5.53±0.12^{rs}
Pulped Paper Pray + Zibo PET lid	Cold	3.84±0.10^{a}	3.99±0.10^{abc}	4.43±0.06^{e-i}	4.83±0.21^{k-n}	5.10±0.17^{n-q}
	Ambient	3.84±0.10^{a}	4.33±0.15^{d-g}	4.63±0.06^{h-k}	4.93±0.06^{l-o}	5.33±0.06^{qrs}
Unpackaged (control)	Cold	3.84±0.10^{a}	4.07±0.06^{a-d}	4.37±0.02^{e-h}	5.10±0.00^{n-q}	5.23±0.04^{pq}
	Ambient	3.84±0.10^{a}	4.27±0.38^{c-f}	4.57±0.12^{g-k}	5.31±0.25^{pqr}	5.60±0.26^{s}

Significance (P) level	
Package (A)	P<.001
Storage condition (B)	P<.001
Storage period (C)	P<.001
A*B	P<.001
A*C	P<.001
B*C	P<.001
A*B*C	P>0.05

Values are the means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). PET = polyethylene terephthalate; PP = Polypropylene

4.9.6 pH value

A complete layout of the pH results influenced by the packaging and storage conditions is presented in Table 4.8. The pH values in this experiment had a range of 4.37 to 4.74, which agrees with the range reported by Aragüez *et al.* (2020). The packaging had a significant effect (P<0.001) on the pH changes in the cherry tomatoes. The unpackaged tomatoes had a higher mean pH value (4.56), compared to the tomatoes in the other packaging treatments. The cherry tomatoes packaged in the Glued Paper Tray + Flow wrap and Pulped Paper Tray + Zibo PET Lid exhibited low mean pH values (4.50), which can be explained by the reduced respiration rate caused by the modified atmosphere inside the packages. The difference in the pH amongst the packages can also be explained by the interplay of the gases (CO2 and O2) in the structure of the packaging. As respiration continues, the packaging creates modified surroundings, with reduced O_2 and increased CO_2, which delays, and therefore reduces, the respiration rate inside the package.

The storage conditions had a significant effect ($P<0.001$) on the pH value of cherry tomatoes. The pH value (4.54) of the fruit stored under ambient storage conditions was higher, compared to the pH value (4.50) of those in cold storage. Similar findings were reported by Gebeyehu (2018), where the pH values of tomatoes under ambient storage conditions were higher than the pH values of those in cold storage. The higher pH value of cherry tomatoes stored under ambient conditions could result from the rapid utilisation of acids for the catabolism of sugar, which is faster than under cold storage conditions. As a result of the higher temperature under ambient storage conditions, the respiration rate is faster, consequently utilizing the organic acids during the process. The cold storage conditions preserved the quality of the cherry tomatoes by slowing down the respiration rate, which resulted in the slower utilization of the organic acids.

The pH of the cherry tomato varied significantly ($P<0.001$) over the storage period. The results showed that it increased as the storage time increased in all the samples, with the mean pH values ranging from 4.37 on Day 0 to 4.65 on Day 28. Gebeyehu (2018) reported that the propensity of an increasing pH is related to the declining acidity (TA), with a longer storage time being observed, since the fruit diminishes its predominant acids with the ripening process. The increase in the pH value during storage can be attributed to the maturity of the fruit and the utilization of organic acids as a substrate for the respiration process (Aragüez *et al.*, 2020).

The interaction of the packaging and storage conditions showed no significant ($P>0.05$) influence on the pH values. The interaction of (a) the packaging and storage period and (b) the storage conditions and storage period proved to have a significant ($P<0.05$) influence on the pH. The highest increase in pH (7.3%) was observed in samples subjected to Open Storage after Day 28. Tomato samples packaged in the Glued Paper Tray + Flow wrap had the lowest increase in pH values (5%), while those in cold storage displayed the slightest increase of 5.3%, compared to those stored under ambient conditions, with the highest increase of 7.3% after 28 days.

Table 4.8 Effects of the packaging materials and storage conditions on the pH values of cherry tomatoes over the 28-day storage period (n=3)

Packaging Treatment	Storage Condition	Storage Period (Days)				
		0	7	14	21	28
Zibo Punnet PET + Flow wrap	Cold	4.37±0.02^{a}	4.43±0.04$^{a\text{-}g}$	4.50±0.03$^{f\text{-}m}$	4.52±0.01$^{i\text{-}p}$	4.60±0.01$^{q\text{-}w}$
	Ambient	4.37±0.02^{a}	4.46±0.02$^{d\text{-}j}$	4.53±0.02$^{k\text{-}q}$	4.60±0.01$^{q\text{-}w}$	4.67±0.02$^{v\text{-}z}$
Old PP Plastic bag	Cold	4.37±0.02^{a}	4.43±0.01$^{a\text{-}f}$	4.51±0.01$^{h\text{-}n}$	4.56±0.01$^{m\text{-}t}$	4.59±0.02$^{o\text{-}v}$
	Ambient	4.37±0.02^{ab}	4.46±0.01$^{d\text{-}k}$	4.56±0.03$^{m\text{-}t}$	4.64±0.05$^{u\text{-}z}$	4.70±0.02^{yzA}
Zibo Punnet PET + Zibo Lid	Cold	4.37±0.02^{ab}	4.42±0.04$^{a\text{-}e}$	4.58±0.19$^{n\text{-}u}$	4.53±0.01$^{j\text{-}q}$	4.61±0.04$^{r\text{-}x}$
	Ambient	4.37±0.02^{ab}	4.51±0.01$^{g\text{-}m}$	4.54±0.02$^{l\text{-}r}$	4.63±0.04$^{t\text{-}y}$	4.71±0.04^{zA}
Glued Paper Tray + Flow wrap	Cold	4.37±0.02^{ab}	4.39±0.02$^{a\text{-}d}$	4.48±0.01$^{e\text{-}l}$	4.52±0.04$^{i\text{-}o}$	4.59±0.01$^{o\text{-}u}$
	Ambient	4.37±0.02^{ab}	4.45±0.01$^{a\text{-}i}$	4.53±0.03$^{j\text{-}q}$	4.62±0.02$^{s\text{-}x}$	4.67±0.02$^{w\text{-}z}$
Pulped Paper Tray + Zibo PET Lid	Cold	4.37±0.02^{ab}	4.38±0.04^{abc}	4.49±0.03$^{e\text{-}m}$	4.55±0.01$^{l\text{-}s}$	4.59±0.03$^{o\text{-}u}$
	Ambient	4.37±0.02^{ab}	4.44±0.01$^{a\text{-}h}$	4.54±0.06$^{k\text{-}q}$	4.60±0.02$^{q\text{-}w}$	4.68±0.01^{xyzA}
Unpackaged (Control)	Cold	4.37±0.02^{ab}	4.62±0.14$^{s\text{-}x}$	4.53±0.01$^{j\text{-}q}$	4.59±0.05$^{p\text{-}v}$	4.63±0.03$^{t\text{-}y}$
	Ambient	4.37±0.02^{ab}	4.50±0.01$^{e\text{-}m}$	4.59±0.01$^{p\text{-}v}$	4.67±0.03$^{y\text{-}z}$	4.74±0.01^{A}

Significance (P) level	
Package (A)	P<.001
Storage condition (B)	P<.001
Storage period (C)	P<.001
A*B	P<0.05
A*C	P<0.05
B*C	P<.001
A*B*C	P<0.05

Values are the means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). PET = polyethylene terephthalate; PP = Polypropylene

The interaction of the packaging, storage conditions and storage period had a significant (P<0.05) influence on the pH values of the cherry tomatoes. The changes in pH result from the respiration, which is retarded by the packaging and cold storage and which enhances the quality of the fruit, giving it a longer storage life. Cherry tomatoes are climacteric, thus their respiration increases with the storage time. The pH could increase as the storage time progresses, due to the depletion of dominant acids as a respiration substrate (Manasa *et al.,* 2018). High temperatures aggravate respiration; hence, all the treatments at ambient temperatures had higher pH values, due to the faster respiration rate, which is aggravated by the high temperatures.

4.9.7 Titratable acidity

Table 4.9 presents the results of Titratable Acidity (TA) that is influenced by the packaging and storage conditions over the 28-day storage period. The TA values range from 0.61 to 0.33, which is similar to the range reported by Tilahun *et al.* (2021b). The packaging had a significant influence ($P<0.05$) on the TA changes of the cherry tomatoes. The unpackaged cherry tomatoes had the highest decrease rate of TA (0.49%), while those packaged in the Pulped Paper Tray + Zibo PET Lid had the lowest decrease rate of TA (0.51%). The Zibo Punnet PET + Flow wrap, the Old PP plastic bag, the Zibo Punnet PET + Zibo Lid and the Glued Paper Tray + Flow wrap recorded similar mean TA values (0.50%). Cocetta *et al.* (2020) observed similar results where unpackaged tomatoes had a higher reduction in TA than those under packaging treatments. Acidity is often used as a sign of maturity as its content decreases; tomatoes with a high TA are deemed less ripe than those with a low TA (Cocetta *et al.*, 2020).

The storage conditions had a significant influence ($P<0.001$) on the TA changes of the cherry tomatoes. Those stored under ambient conditions had a higher reduction rate of TA (0.49%) than those under cold storage conditions (0.51 %). This result agrees with a similar report by Majidi *et al*. (2014), where tomatoes stored under cold storage conditions had a lower TA reduction trend than those stored under ambient temperature conditions. The lower decrease in TA under cold storage conditions, compared to ambient storage conditions, indicates a delay in the ripening of the cherry tomatoes, while it is faster during ambient storage as a result of the high temperatures, which enhance the ripening process.

The TA of the cherry tomatoes varied significantly ($P<0.001$) over the storage period. As the storage time progressed, the results showed a decline in TA values, from 0.61 to 0.37%, of all the cherry tomato samples between Day 0 and Day 28. Anyasi *et al.* (2016) reported a similar observation, with a concomitant decrease in the TA as the storage time increased. According to Tilahun *et al.* (2021b), the declining trend shown by the TA values is a result of the conversion of organic acids and their derivatives into soluble sugars, which cherry tomatoes utilize during respiration.

Table 4.9 Effects of the packaging materials and storage conditions on the titratable acidity (%) of cherry tomatoes over the 28-day storage period (n=3)

Packaging Treatment	Storage Conditions	Storage Period (Days)				
		0	7	14	21	28
Zibo punnet PET + Flow wrap	Cold	0.61 ± 0.02^{s}	$0.55\pm0.01^{n-r}$	0.52 ± 0.05^{mno}	$0.48\pm0.03^{i-l}$	0.38 ± 0.01^{cde}
	Ambient	0.61 ± 0.02^{s}	0.52 ± 0.05^{mno}	0.49 ± 0.01^{jkl}	0.43 ± 0.00^{fgh}	0.38 ± 0.01^{cde}
Old PP Plastic bag	Cold	0.61 ± 0.02^{s}	$0.56\pm0.01^{o-r}$	$0.53\pm0.02^{m-p}$	0.45 ± 0.01^{hij}	0.40 ± 0.06^{def}
	Ambient	0.61 ± 0.02^{s}	$0.54\pm0.00^{n-q}$	0.49 ± 0.01^{klm}	0.41 ± 0.02^{efg}	0.36 ± 0.02^{c}
Zibo punnet PET + Zibo Lid	Cold	0.61 ± 0.02^{s}	0.58 ± 0.00^{rs}	$0.54\pm0.01^{n-q}$	$0.46\pm0.01^{h-k}$	0.37 ± 0.00^{cd}
	Ambient	0.61 ± 0.02^{s}	$0.56\pm0.02^{o-r}$	0.53 ± 0.01^{mno}	0.45 ± 0.01^{ghi}	0.29 ± 0.02^{a}
Glued Paper Tray + Flow wrap	Cold	0.61 ± 0.02^{s}	0.56 ± 0.01^{pqr}	$0.53\pm0.00^{n-q}$	0.45 ± 0.01^{hi}	0.43 ± 0.01^{fgh}
	Ambient	0.61 ± 0.02^{s}	$0.55\pm0.01^{o-r}$	0.51 ± 0.00^{lmn}	0.42 ± 0.01^{fgh}	0.36 ± 0.01^{c}
Pulped Paper Tray + Zibo PET lid	Cold	0.61 ± 0.02^{s}	0.57 ± 0.00^{qr}	$0.54\pm0.02^{n-q}$	0.47 ± 0.02^{ijk}	0.38 ± 0.05^{cde}
	Ambient	0.61 ± 0.02^{s}	$0.55\pm0.03^{o-r}$	0.51 ± 0.01^{lmn}	0.45 ± 0.01^{hi}	0.37 ± 0.02^{cd}
Unpackaged (Control)	Cold	0.61 ± 0.02^{s}	0.57 ± 0.03^{qr}	0.52 ± 0.01^{mno}	$0.48\pm0.01^{i-l}$	0.38 ± 0.02^{cde}
	Ambient	0.61 ± 0.02^{s}	$0.54\pm0.54^{n-q}$	0.47 ± 0.02^{ijk}	0.39 ± 0.01^{cde}	0.33 ± 0.03^{b}

Significance (P) level	
Package (A)	P>0.016
Storage condition (B)	P<.001
Storage period (C)	P<.001
A*B	P<0.05
A*C	P<.001
B*C	P<.001
A*B*C	P>0.05

Values are the means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). PET = polyethylene terephthalate; PP = Polypropylene

The interaction between (a) the packaging and storage conditions, (b) the packaging and storage period, and (c) the storage conditions and storage period proved to have a significant ($P<0.05$) influence on the TA changes in the cherry tomatoes. Those packaged in the Glued Paper Tray + Flow wrap and stored under cold conditions had the smallest decrease in TA of 29.5%, which indicated that the ripening and respiration processes had slowed down, compared to the other packaging treatments. Therefore, the cold storage conditions and packaging treatment can prolong the storability and preserve the quality of cherry tomatoes. The packaging, storage conditions and storage period had no significant ($P>0.05$) influence on the TA of the cherry tomatoes. These findings can be compared to those in Section 4.4.4.2, where an increase in the pH value indicated a loss in acidity for all treatments. Applying the Glued Paper Tray + Flow wrap under cold storage conditions resulted in a slowed conversion rate of acid to sugar and the lowest rise in pH values.

4.9.8 Total sugars

The main sugars found in tomatoes are glucose, fructose and sucrose. The highest concentration was detected in fructose and glucose, while sucrose was negligible. According to Charles *et al.* (2016), fructose and glucose dominate the total sugars in tomatoes, while sucrose depletes up to 90% of its initial concentration. Table 4.10 presents the experimental results of the total sugars (fructose + glucose) that are affected by the packaging and storage conditions. The total sugars range between 6.71 to 3.28 $mg.100g^{-1}$ FW, which are slightly below the total sugars reported by Meena *et al.* (2020). The packaging had a significant ($P<0.0001$) influence on the total sugar concentration of the cherry tomatoes. Unpackaged (Control) cherry tomato samples had a higher decrease of 4.89 $mg.100g^{-1}$ FW. In contrast, cherry tomatoes packaged in the Glued Paper Tray + Flow wrap retained their total sugars (5.19 $mg.100g^{-1}$ FW). The retention of the total sugar concentration in packaged fruits may be attributed to the beneficial effects of the modified atmosphere of the packaging treatment, compared to Open storage (Control). When the tomatoes are packaged, an improved atmosphere is created, where less O_2 is available to promote respiration and more CO_2 is available inside the packaging, as the fruit continues to ripen. Under packaging, respiratory substrates, like sugars, are retarded and the tomatoes can maintain their quality, which explains the faster utilization of sugars in Open storage. The observations of decreasing sugars are similar to those reported for tomatoes by Sammi and Masud (2009) and for the papaya fruit by Azene *et al.* (2014b).

The storage conditions had a significant influence ($P<0.001$) on the concentration of the total sugars. The total sugar content (5.17 mg.100g-1 FW) of cherry tomatoes under cold storage was significantly higher than those under ambient storage conditions (4.85 mg.100g-1 FW). This result indicates that the decreasing rate of the total sugars was faster in cherry tomatoes stored under ambient storage conditions than those stored under cold storage conditions. The metabolic breakdown of organic acids to polysaccharides and carbon dioxide to soluble sugars may have slowed down in cold storage, due to the retarded respiration as a result of the low temperatures. The significant differences between cherry tomatoes under cold and ambient storage conditions agree with the results reported by Gharezi *et al.* (2012).

The total sugars varied significantly ($P<0.001$) over the 28-day storage period. The results showed that the concentration of total sugars decreased from 6.71 mg.100g^{-1} to 3.50 mg.100g^{-1} of fresh weight (FW), on average, between Day 0 and Day 28, respectively. Generally, the total sugars increase as the ripening stage progresses and the tomatoes become completely red, and they decline as the tomatoes degrade with the progressing storage time, due to the over-utilization of its organic compounds (Azene *et al.*, 2014b). This result agrees with a report by Ilić *et al.* (2020), where similar trends in grafted and shaded cherry tomatoes showed a decrease in their total sugars over the storage time.

The interaction of the packaging and storage conditions proved to have no significant ($P>0.05$) influence on the total sugar concentration of the cherry tomatoes. Those packaged and subjected to cold storage conditions had a low reduction rate of the total sugar concentration, compared to those under ambient storage conditions. The interaction between (a) the packaging and storage period and (b) the storage conditions and storage period had a significant ($P<0.05$) influence on the total sugar concentration. Fruits subjected not packaed had the highest decrease in total sugar concentration (47.4%). In comparison, the lowest decrease in the total sugar concentration (45.3%) was found in the Glued Paper Tray + Flow wrap. The three-way interaction of the packaging, storage condition and storage period did not reveal any significant effect ($P>0.05$) on the total sugar concentration of the cherry tomatoes. Those packaged in the Glued Paper Tray + Flow wrap and stored under cold conditions resulted in a slight decrease in the total sugars.

Table 4.10 Effects of the packaging materials and storage conditions on the total sugar ($mg.100g^{-1}$) content of cherry tomatoes during the 28-day storage period (n=3)

Packaging Treatment	Storage Condition	Storage period				
		0	7	14	21	28
Zibo Punnet PET + Flow wrap	Cold	6.71 ± 0.04^{t}	6.23 ± 0.18^{st}	$5.25\pm0.37^{k-q}$	$4.34\pm0.07^{e-i}$	$3.79\pm0.16^{b-e}$
	Ambient	6.71 ± 0.04^{t}	$5.73\pm0.10^{p-s}$	$4.68\pm0.56^{g-k}$	$4.21\pm0.03^{d-h}$	3.44 ± 0.00^{bc}
Old PP Plastic bag	Cold	6.71 ± 0.04^{t}	5.89 ± 0.58^{qrs}	$5.21\pm0.43^{k-p}$	$5.64\pm1.67^{n-s}$	$3.75\pm0.15^{b-e}$
	Ambient	6.71 ± 0.04^{t}	5.88 ± 0.07^{qrs}	$4.84\pm0.21^{h-l}$	$4.12\pm0.05^{d-g}$	3.44 ± 0.09^{bc}
Zibo Punnet PET + Zibo Lid	Cold	6.71 ± 0.04^{t}	$5.68\pm0.36^{o-s}$	$4.51\pm0.51^{f-j}$	3.54 ± 0.42^{bcd}	3.43 ± 0.14^{bc}
	Ambient	6.71 ± 0.04^{t}	$5.43\pm0.33^{l-r}$	$3.92\pm0.36^{b-f}$	3.28 ± 0.27^{ab}	2.73 ± 0.76^{a}
Glued Paper Tray + Flow wrap	Cold	6.71 ± 0.04^{t}	$6.23\pm0.08^{s-t}$	$5.44\pm0.16^{l-r}$	$4.67\pm0.02^{g-k}$	$3.78\pm0.32^{b-e}$
	Ambient	6.71 ± 0.04^{t}	$5.56\pm0.43^{m-r}$	$5.00\pm1.23^{j-n}$	$4.19\pm0.07^{d-h}$	3.57 ± 0.09^{bcd}
Pulped Paper Tray + Zibo PET Lid	Cold	6.71 ± 0.04^{t}	6.02 ± 0.08^{rs}	$5.05\pm0.42^{j-o}$	$4.34\pm0.22^{e-i}$	$3.78\pm0.02^{b-e}$
	Ambient	6.71 ± 0.04^{t}	$5.75\pm0.10^{p-s}$	$4.96\pm0.14^{i-m}$	$4.21\pm0.14^{d-h}$	3.30 ± 0.12^{ab}
Open storage (Control)	Cold	6.71 ± 0.04^{t}	$5.64\pm0.24^{n-s}$	$4.90\pm0.07^{i-m}$	$4.07\pm0.30^{c-g}$	$3.78\pm0.27^{b-e}$
	Ambient	6.71 ± 0.04^{t}	$5.49\pm0.11^{l-r}$	$4.67\pm0.11^{g-k}$	$3.68\pm0.10^{b-e}$	3.28 ± 0.92^{ab}
Significance (P) level						
Package (A)		P<.001				
Storage condition (B)		P<.001				
Storage period (C)		P<.001				
A*B		P>0.05				
A*C		P<.001				
B*C		P<0.05				
A*B*C		P>0.05				

Values are the means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). PET = polyethylene terephthalate; PP = Polypropylene

4.9.9 Total phenolic content

The results of the interaction of the packaging and storage conditions on the Total Phenolic Content (TPC) of cherry tomatoes are presented in Table 4.11. The results of the TPC experiment had a range of 0.66 to 0.34 mg $GAE.g^{-1}$ Fresh Weight (FW), which is above that found by Tilahun *et al.* (2017a). The differences can be attributed to the differences in the geographic location, the cultivar and the growing conditions. The packaging had a significant influence ($P<0.001$) on the total phenolic content. The highest total phenolic content (0.51 mg $GAEg^{-1}$) reduction was recorded in Unpackaged cherry tomatoes. Amongst the packaging treatments, the Glued Paper Tray + Flow wrap had the lowest reduction in the total phenolic content (0.56 mg $GAEg^{-1}$).

In comparison, the Old PP bag (500g) had the highest decrease in TPC (0.52 mg $GAEg^{-1}$), compared to the other packaging combinations. It was observed that the phenolic concentration in tomatoes packaged in the Glued Paper Tray + Flow and Pulped Paper Tray + Zibo PET Lid, decreased less pronouncedly, compared to the other PET packaging treatments. According to Rababah *et al.* (2011), the decrease in the total phenolics results from the oxidation and hydrolytic activities of the phenolic compound enzymes in the presence of more oxygen.

The storage conditions had a significant influence ($P<0.001$) on the total phenolic content of the cherry tomatoes. The results showed that those stored under cold storage conditions had a significantly higher TPC content (0.55 mg $GAEg^{-1}$) than those stored under ambient storage conditions, which had a lower TPC content (0.51 mg $GAEg^{-1}$). These findings mean that the oxidation of polyphenols in cherry tomatoes that were stored under cold storage conditions was slower than in those stored under ambient storage conditions. Viet and Trang (2015) also observed a significant difference in the phenolic content of cherry tomatoes stored at 9°C and 29°C, with those stored at a higher temperature experiencing a significant decrease in the phenolic content, compared to those stored at a lower temperature. According to Viet and Trang (2015) and Deng *et al.* (2018), the higher loss of total phenols under higher storage temperatures can be attributed to high enzyme activity, which promotes the synthesis of polyphenols, hence the high decrease in cherry tomatoes under ambient storage conditions. Similar results have been reported by Piljac-Žegarac and Šamec (2011) for strawberries and raspberries.

The TPC of the cherry tomatoes varied significantly ($P<0.001$) over the 28-day storage period. The results showed a decline in the TPC, from 0.66 mg $GAEg^{-1}$ to 0.41 mg $GAE.g^{-1}$ FW between Day 0 and Day 28, respectively. Viet and Trang (2015) and Tilahun *et al.* (2017a) reported similar observations, where the phenolic content of fully-ripe tomatoes decreased continuously during the storage time. This decline can be attributed to the oxidation of the polyphenols by enzymes (polyphenol oxidase and peroxidase) in the presence of oxygen (Minatel *et al.*, 2017).

Table 4.11 Effects of the packaging materials and storage conditions on the total phenolic (mg GAE.g^{-1}) content of cherry tomatoes during the 28-day storage period (n=3)

Packaging Treatments	Storage Condition	Storage period (Days)				
		0	7	14	21	28
Zibo Punnet PET + Flow wrap	Cold	0.66±0.02^{w}	0.61±0.01^{tu}	0.55±0.01^{qr}	0.49±0.00^{k-n}	0.44±0.00^{e-h}
	Ambient	0.66±0.02^{w}	0.56±0.01^{rs}	0.52±0.01^{op}	0.45±0.01^{g-j}	0.37±0.01^{ab}
Old PP Plastic bag	Cold	0.66±0.02^{w}	0.59±0.02^{t}	0.53±0.02^{pq}	0.48±0.00^{j-m}	0.41±0.00^{de}
	Ambient	0.66±0.02^{w}	0.55±0.01^{qr}	0.49±001^{l-o}	0.44±0.00^{e-h}	0.35±0.02^{a}
Zibo Punnet PET + Zibo Lid	Cold	0.66±0.02^{w}	0.58±0.01st	0.52±0.02^{op}	0.49±0.02^{l-o}	0.42±0.02^{def}
	Ambient	0.66±0.02^{w}	0.56±0.02^{rs}	0.48±0.00^{j-m}	0.45±0.00^{f-i}	0.39±0.01^{bc}
Glued Paper Tray + Flow wrap	Cold	0.66±0.02^{w}	0.64±0.02^{vw}	0.56±0.02^{qr}	0.53±0.03^{pq}	0.48±0.00^{j-m}
	Ambient	0.66±0.02^{w}	0.60±0.00^{t}	0.52±0.00^{op}	0.47±0.01^{i-l}	0.43±0.01^{efg}
Pulped Paper Tray + Zibo PET Lid	Cold	0.66±0.02^{w}	0.63±0.01^{uv}	0.55±0.00^{qr}	0.49±0.02^{l-o}	0.47±0.01^{i-l}
	Ambient	0.66±0.02^{w}	0.60±0.02^{t}	0.51±0.00^{nop}	0.46±0.01^{h-k}	0.42±0.02^{def}
Unpackaged (Control)	Cold	0.66±0.02^{w}	0.59±0.00st	0.51±0.00^{m-p}	0.46±0.01^{g-j}	0.40±0.00^{cd}
	Ambient	0.66±0.02^{w}	0.56±0.01^{rs}	0.48±0.02^{j-m}	0.41±0.01^{de}	0.34±0.00^{a}

Significance (P) level	
Package (A)	P<.001
Storage condition (B)	P<.001
Storage period (C)	P<.001
A*B	P>0.05
A*C	P<.001
B*C	P<.001
A*B*C	P>0.05

Values are the means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). PET = polyethylene terephthalate; PP = Polypropylene

The interaction between the packaging and storage conditions had no significant (P>0.05) influence on the TPC concentration. The cherry tomato samples in the packaging treatments that were subjected to cold storage conditions showed the lowest reduction rate in their TPC concentration. The interaction between (a) the packaging and storage period and (b) the storage conditions and storage period proved to have a highly significant (P<0.001) influence on the TPC of the cherry tomatoes. The Glued Paper Tray + Flow wrap had the lowest reduction rate of 30.7% after Day 28. Tomato samples under cold storage conditions had the lowest reduction rate of 33.8%, compared to the highest TPC reduction rate of 44.6% that was observed in samples under ambient storage conditions after Day 28.

The interaction of the packaging, storage conditions and storage period proved to have no significant (P>0.05) influence on the reduction rate of the TPC of the cherry tomatoes. However, all the cherry tomato samples recorded their lowest phenolic compounds at the end of the 28th day of storage. Piljac-Žegarac and Šamec (2011) added that phenolic compounds quickly oxidize when they come into contact with oxygen or when more oxygen is available in the surroundings. This may affect the sensory properties, such as the flavour, aroma and colour. In this study, the differences in the reduction of phenolics amongst the packaging treatments can be attributed to the difference in the packaging structure and their ability to provide a modified atmosphere, with less oxygen inside the packaging.

4.9.10 Microbiological population

The packaging proved to have a significant influence (P<0.001) on the number of colony-forming units in the APC and FC. Cherry tomatoes packaged in the Zibo Punnet PET + Flow wrap had a significantly high number of CFUs observed during the APC and FC, and they were dominated mostly by moulds and yeasts that were present under the cold and ambient storage conditions. Cherry tomatoes packaged in the Pulped Paper Tray + Zibo PET Lid had an undetectable number of CFUs; although the CFUs were present (positive APC and FC), they were below the detection limit. Similar results were reported by Patrignani *et al.* (2016), where the contamination of peaches packed in plastic packaging materials was higher than in those packed in cardboard boxes. The low microbial growth in Pulped Paper Tray and Glued Paper Tray compared to the PETs and can be attributed to the reduced superficial contamination level used in coating the inner layers of paper trays, compared to PETs (Oloyede and Lignou, 2021).

The results showed that the storage conditions had no significant influence (P>0.05) on the number of CFU's in both the Aerobic Plate Count (APC) and the Fungal Count (FC). The majority of the cherry tomatoes under cold storage conditions had moulds present, while those under ambient storage conditions showed that moulds were dominant and that yeasts were below the Limit of Detection (LOD). Seyoum *et al.* (2011) reported that the storage temperature influences the microbial growth rate in carrots, which does not agree with our results. Their non-significance in this experiment can be attributed to the fact that there might

Table 4.12 Surface burden of the total bacterial development of tomatoes influenced by the packaging and storage conditions and analysed after 14 days of storage (n=3)

Treatment	Storage condition	APC log cfu per tomato	FC log cfu per tomato	Microscopic Observation
Zibo Punnet PET + Flow wrap	Cold	6.38 ± 0.66^{de}	3.81 ± 0.64^{cde}	Both moulds and yeasts
	Ambient	6.79 ± 0.36^{e}	4.45 ± 0.21^{e}	Mainly moulds, yeasts present but below LOD
Old PP bag	Cold	5.57 ± 0.52^{bcd}	$3.73\pm0.45^{b\text{-}e}$	Mainly moulds, yeasts present but below precision LOD
	Ambient	6.04 ± 0.50^{cde}	4.17 ± 0.30^{de}	Moulds and yeasts
Zibo Punnet PET + Zibo PET Lid	Cold	6.30 ± 0.12^{de}	$3.50\pm0.18^{b\text{-}e}$	Moulds dominant, but yeast present
	Ambient	5.11 ± 0.18^{abc}	2.94 ± 0.79^{bcd}	Mainly moulds, yeasts present but below LOD
Glued Paper Tray + Flow wrap	Cold	6.01 ± 0.43^{cde}	$3.46\pm0.85^{b\text{-}e}$	Mainly moulds
	Ambient	6.36 ± 0.87^{de}	4.21 ± 0.79^{de}	Mainly moulds, yeasts present but below precision LOD
Pulped Paper Tray + Zibo PET Lid	Cold	4.96 ± 0.98^{ab}	Below LOD	Moulds and yeasts positive but below precision LOD
	Ambient	4.41 ± 0.26^{a}	0.82 ± 1.61^{a}	Only moulds, Fungi not detected, below LOD of 300 CFU/tomato.
Open Storage (Control)	Cold	5.28 ± 0.47^{abc}	2.75 ± 0.17^{bc}	Mainly yeasts, moulds below precision LOD
	Ambient	4.58 ± 0.21^{a}	2.48 ± 0.00^{b}	Only moulds
Significance (P) level				
Package (A)		<.001	<.001	
Storage condition (B)		0.201	0.965	
A*B		0.067	0.195	

Values are the means of three replications ± standard deviation. Means followed by the same letter(s) within a column are not significant. Duncan's multiple range test (P<0.05). PET = polyethylene terephthalate; PP = Polypropylene. LOD = Limit of detection

not have been any clear microbial development in the experimented data after 14 days of storage. The cherry tomatoes were thoroughly washed and disinfected before packaging, hence the number of colony-forming units was low and could not be detected. Shezi (2016b) reported that the microbial burden is associated with the nature of the crop, the production site and the handling practices. It involves the climatic conditions for growth i.e. the average temperatures and humidity, as well as the soil and rainfall composition. These conditions influence their susceptibility to microbes.

4.10 Conclusion

This study has revealed that the physiological and chemical quality attributes of cherry tomatoes depends on post-harvest handling, including the packaging and storage conditions, and especially by applying these integrated post-harvest treatments. The packaging, storage conditions and storage period were more often found to have the most significant influence on all of the analysed quality parameters of cherry tomatoes. The storage conditions had a more significant influence on the quality changes. The cold storage conditions (8-12°C, 78–80% RH) had a positive effect on the measured quality parameters of the tomato samples, which was to extend their shelf-life, compared to those that are subjected to ambient storage conditions (22-26°C, 68–72% RH). The high temperatures and low relative humidity under ambient storage conditions enhanced the ripening process of the tomatoes, which was evident from the colour changes from a pinkish-yellow to more red and the rapid reduction of firmness, especially in the samples subjected to Open Storage (control) without packaging. Other parameters associated with ripening, as a result of ambient storage conditions, were the increased PWL, TSS and pH values with a synonymous decrease in the TA, Total sugars and TPC. The change in quality of the tomatoes under cold storage conditions was relatively slow and retarded during the 28-day storage period. The storage period of 28 days was sufficient for demonstrating the differences in quality under the different storage conditions, especially under ambient temperature conditions. Lower temperatures are regularly adopted to minimise the enzyme activity; hence, the physiological and biochemical processes contributing to the ripening and senescence of tomatoes are retarded.

A summary of the effects of different packaging materials and storage conditions are presented in Table 6.2, in Appendix A. The packaging preserved the quality of the cherry tomatoes, compared to the control tomato samples. The fruit samples packaged in the Glued Paper Tray + Flow wrap demonstrated restored quality attributes, compared to the other packaging treatments, in terms of slowing down the change in L*, a reduction of the hue angle, firmer fruits (puncture, Kramer, compression), lower PWL, TSS and pH levels, as well as the slow reduction of TA, TS and TPC. The combined effect of the packaging and storage conditions demonstrated a positive influence on the quality changes in the tomatoes. Cherry tomatoes packaged in the Glued Paper Tray + Flow and subjected to cold storage conditions resulted in low colour changes of the L*(25.8%) and hue angle (8.3%), respectively. The most colour changes were found in samples stored under ambient storage conditions, with a reduction in the L* (52.1%) and hue angle (17.4%) over the 28-day storage period. The firmness of the cherry tomatoes was relatively low in packaged tomatoes under cold storage conditions. No relative differences were observed in their firmness throughout the 28-day storage period, when they were measured by using the puncture experiment. The Glued Paper Tray + Flow wrap and cold storage samples, measured with the Kramer shear test and flat-plate compression test, had a higher firmness after 28 days, with a 30.3% and 28.6% reduction rate, compared to a 47.7% and 43.4% reduction rate in the control samples under ambient storage conditions. The PWL was found to be higher in the samples stored under ambient conditions, compared to those stored under cold conditions. The experiment revealed that Paper Trays absorb the moisture inside the packaging, keeping the sample surface dry and shiny, compared to plastic trays, in which condensation occurs and water droplets are produced, which promotes spoilage. This is evident from the spoilage of tomato samples in the Old PP plastic, which deteriorated faster than the other packages and which was only superseded by the control samples. The combination of the Glued Paper Tray + Flow and cold storage resulted in the lowest increase in the TSS (22.5%) and pH value (5.0%), the lowest reduction in the TA (29.5%), as well as the lowest decline in total sugars (43.7%) and TPC (27.3%) over the 28-day storage period.

The results revealed that the integrated application of packaging and cold storage conditions effectively delayed the respiration and ripening processes of cherry tomatoes, hence prolonging their shelf-life. A combination of the Glued Paper Tray + Flow wrap and low cold storage conditions slowed down the quality of the cherry tomatoes, compared to the other packages studied. However, no apparent differences were shown by the Paper Trays to the PET Trays, except for their ability to absorb the moisture inside the packaging, which kept the environment dry and the sample shiny and healthy.

4.11 References

AOAC, 1984. Official Methods of Analysis, 14th ed. Association of Official Analytical Chemists, Virginia, USA, pp. 414-420.

Adhikari, P, Dhakal, A, Pahadi, K, Adhikari, S, Ghimire, P, Subedi, S and Ghimire, D. 2020. Effect of Different Plastic Packaging on Postharvest Quality of Tomato (Lycopersicon Esculentum Mill.). *Tropical Agro-ecosystems* 1(1):15-18.

Akbudak, B, Akbudak, N, Seniz, V and Eris, A. 2007. Sequential treatments of hot water and modified atmosphere packaging in cherry tomatoes. *Journal of Food Quality* 30(6):896-910.

Al-Dairi, M and Pathare, PB. 2021. Kinetic modelling of quality changes of tomato during storage. *Agricultural Engineering International: CIGR Journal* 23(1):183-193.

Albaloushi, N, Azam, M and Amer Eissa, A. 2012. Mechanical Properties of Tomato Fruits Under Storage Conditions 1. *Journal of Applied Sciences Research* 8(1):3053-3064.

An, X, Li, Z, Zude-Sasse, M, Tchuenbou-Magaia, F and Yang, Y. 2020. Characterization of textural failure mechanics of strawberry fruit. *Journal of Food Engineering* 282(1):110016.

Anyasi, TA, Aworh, CO and Jideani, AI. 2016. Effect of packaging and chemical treatment on storage life and physicochemical attributes of tomato (Lycopersicon esculentum Mill cv. Roma). *African Journal of Biotechnology* 15(35):1913-1919.

Aragüez, L, Colombo, A, Borneo, R and Aguirre, A. 2020. Active packaging from triticale flour films for prolonging the storage life of cherry tomatoes. *Food Packaging and Shelf Life* 25:100520.

Azene, M, Workneh, TS and Woldetsadik, K. 2014. Effect of packaging materials and storage environment on postharvest quality of papaya fruit. *Journal of Food Science and Technology* 51(6):1041-1055.

Breda, C, Morgado, D, de Assis, O and Duarte, M. 2017. Effect of chitosan coating enriched with pequi(Caryocar Brasiliense Camb) peel extracts on quality and safety of tomatoes during storage. *Journal of Food Processing and Preservation* 41:e13268.

Buntong, B, Kong, V, Acedo Jr, AL and Kanlayanarat, S.2015. Effects of Different Packaging and Storage Conditions on Postharvest Quality of Tomato. 125-129. International Society for Horticultural Science (ISHS), Leuven, Belgium,

Caron, VC, Tessmer, MA, Mello, SC and Jacomino, AP. 2013. Quality of mini-tomatoes harvested at two maturity stages and kept chilled in three packages. *Horticultura Brasileira* 31(2):279-286.

Charles, MT, Arul, J, Charlebois, D, Yaganza, E-S, Rolland, D, Roussel, D and Merisier, MJ. 2016. Postharvest UV-C treatment of tomato fruits: changes in simple sugars and organic acids contents during storage. *LWT-Food Science and Technology* 65(1):557-564.

Cocetta, G, Riva, M, Castelli, G and Ferrante, A. 2020. New active packaging for improving the shelf life and quality of tomatoes. *Advances in Horticultural Science* 34(1):53-59

Coyago-Cruz, E, Corell, M, Moriana, A, Mapelli-Brahm, P, Hernanz, D, Stinco, CM, Beltrán-Sinchiguano, E and Meléndez-Martínez, AJ. 2019. Study of commercial quality parameters, sugars, phenolics, carotenoids and plastids in different tomato varieties. *Food Chemistry* 277(1):480-489.

Dandago, MA, Ilesanmi, J and Tamme, V. 2017. Effects of packaging and storage conditions on quality and storage life of tomato fruits (Lycopersicon esculentum Mill.) in Kura, Kano State, Nigeria. *Journal of Postharvest Technology* 5(4):71-82.

Deng, M, Deng, Y, Dong, L, Ma, Y, Liu, L, Huang, F, Wei, Z, Zhang, Y, Zhang, M and Zhang, R. 2018. Effect of Storage Conditions on Phenolic Profiles and Antioxidant Activity of Litchi Pericarp. *Molecules (Basel, Switzerland)* 23(9):2276.

Domínguez, I, Ferreres, F, del Riquelme, FP, Font, R and Gil, MI. 2012. Influence of preharvest application of fungicides on the postharvest quality of tomato (Solanum Lycopersicum L.). *Postharvest Biology and Technology* 72(1):1-10.

Gebeyehu, AS. 2018. The Effects Packaging Materials on Post-harvest Quality of Tomato (Solanum Lycopersium). *Journal of Natural Sciences Research* 8(11):97-103.

Gharezi, M, Joshi, N and Sadeghian, E. 2012. Effect of postharvest treatment on stored cherry tomatoes. *Journal of Nutrition and Food Sciences* 2(8):1-10.

Harker, FR, Stec, MG, Hallett, IC and Bennett, CL. 1997. Texture of parenchymatous plant tissue: a comparison between tensile and other instrumental and sensory measurements of tissue strength and juiciness. *Postharvest Biology and Technology* 11(2):63-72.

Ilić, ZS, Koukounaras, A, Milenković, L, Kevrešan, Ž, Bajić, A, Šunić, L, Kovač, R, Fallik, E and Mastilović, J. 2020. Grafting and Shading—The Influence on Postharvest Tomato Quality. *Agriculture and Agricultural Science Procedia* 10(5):181.

Islam, MZ, Lee, Y-T, Mele, MA, Choi, I-L and Kang, H-M. 2019. Effect of fruit size on fruit quality, shelf life and microbial activity in cherry tomatoes. *AIMS Agriculture and Food* 4(2):340-348.

Ivonkovic, A, Zeljko, K, Talic, S and Lasic, M. 2017. Biodegradable packaging in the food industry. *Journal of Food Safety and Food Quality* 68(2):26-38.

Kabir, M, Nur, S, Ali, M, Lee, W-H, Cho, S-I and Chung, S-O. 2020a. Physicochemical quality changes in tomatoes during delayed cooling and storage in a controlled chamber. *Agriculture and Agricultural Science Procedia* 10(6):196-208.

Kabir, MSN, Rasool, K, Lee, W-H, Cho, S-I and Chung, S-O. 2020b. Influence of delayed cooling on the quality of tomatoes (Solanum Lycopersicum L.) stored in a controlled chamber. *AIMS Agriculture and Food* 5(2):272-285.

Kantola, M and Helen, H. 2001. Quality changes in organic tomatoes packaged in biodegradable plastic films. *Journal of Food Quality* 24(2):167-176.

Li, Z, Li, P, Yang, H, Liu, J and Xu, Y. 2012. Mechanical properties of tomato exocarp, mesocarp and locular gel tissues. *Journal of Food Engineering* 111(1):82-91.

Manasa, S, Suresha, G, Vasudeva, K, Krishna, H, Jayappa, J, Ugalat, J and Dayamani, K. 2018. Influence of modified atmosphere package on quality of cherry tomato (Solanum Lycopersicum var. cerasiforme) fruits. *International Journal of Chemical Studies* 6(6):138-143.

Meena, M, Pilania, S, Pal, A, Mandhania, S, Bhushan, B, Kumar, S, Gohari, G and Saharan, V. 2020. Cu-chitosan nano-net improves keeping quality of tomato by modulating physio-biochemical responses. *Scientific Reports* 10(1):1-11.

Minatel, IO, Borges, CV, Ferreira, MI, Gomez, HAG, Chen, C-YO and Lima, GPP. 2017. *Phenolic Compounds: Functional Properties, the Impact of Processing and Bioavailability*. IntechOpen, London, SW7 2QJ, United Kingdom.

Ogwu, MC. 2019. Effects of storage methods and duration on the microbial composition and load of tomato (Solanum Lycopersicum [L.], Solanaceae) fruits. *Bitlis Eren University Journal of Science and Technology* 9(1):1-7.

Oloyede, OO and Lignou, S. 2021. Sustainable paper-based packaging: A consumer's perspective. *Foods* 10(5):1035.

Olveira-Bouzas, V, Pita-Calvo, C, Vázquez-Odériz, ML and Romero-Rodríguez, MÁ. 2021. Evaluation of a modified atmosphere packaging system in pallets to extend the shelf-life of the stored tomato at cooling temperature. *Food Chemistry* 364:130309.

Pathare, PB and Al-Dairi, M. 2021. Bruise Damage and Quality Changes in Impact-Bruised, Stored Tomatoes. *Horticulturae* 7(5):113-133.

Patrignani, F, Siroli, L, Gardini, F and Lanciotti, R. 2016. Contribution of two different packaging materials to microbial contamination of peaches: implications in their microbiological quality. *Frontiers in Microbiology* 7:938.

Paulsen, E, Barrios, S and Lema, P. 2019. Ready-to-eat cherry tomatoes: Passive modified atmosphere packaging conditions for shelf life extension. *Food Packaging and Shelf Life* 22(1):100407.

Piljac-Žegarac, J and Šamec, D. 2011. Antioxidant stability of small fruits in postharvest storage at room and refrigerator temperatures. *Food Research International* 44(1):345-350.

Pinela, J, Barros, L, Carvalho, AM and Ferreira, ICFR. 2012. Nutritional composition and antioxidant activity of four tomatoes (Lycopersicon esculentum L.) farmer' varieties in Northeastern Portugal home gardens. *Food and Chemical Toxicology* 50(3):829-834.

Pinheiro, J, Alegria, C, Abreu, M, Gonçalves, EM and Silva, CL. 2013. Kinetics of changes in the physical quality parameters of fresh tomato fruits (Solanum Lycopersicum, cv.'Zinac') during storage. *Journal of Food Engineering* 114(3):338-345.

Rababah, T, Feng, H, Yang, W, Eriefej, K and Al-Omoush, M. 2011. Effects of type of packaging material on physicochemical and sensory properties of olive oil. *International Journal of Agricultural and Biological Engineering* 4(4):66-72.

Razali, Z, Somasundram, C, Nurulain, SZ, Kunasekaran, W and Alias, MR. 2021. Postharvest Quality of Cherry Tomatoes Coated with Mucilage from Dragon Fruit and Irradiated with UV-C. *Polymers* 13(17):2919.

Sammi, S and Masud, T. 2009. Effect of different packaging systems on the quality of tomato (Lycopersicon esculentum var. Rio Grande) fruits during storage. *International Journal of Food Science and Technology* 44(5):918-926.

Seyoum, T, Osthoff, G, Steyn, M, Engelbrecht, G and Pretorius, J. 2011. The effect of preharvest treatment, disinfection and storage environment on quality of carrots. *Journal of Food Processing and Preservation* 35(3):331-341.

Shehata, SA, Abdelrahman, SZ, Megahed, M, Abdeldaym, EA, El-Mogy, MM and Abdelgawad, KF. 2021. Extending Shelf-life and Maintaining Quality of Tomato Fruit by Calcium Chloride, Hydrogen Peroxide, Chitosan and Ozonated Water. *Horticulturae* 7(9):309-324.

Shezi, S. 2016. Evaluation of the effects of supply chain routes and pre-storage treatments on the postharvest quality of stored 'Nemo-Netta' tomatoes. Unpublished thesis, School of Engineering, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Sirisomboon, P, Tanaka, M and Kojima, T. 2012. Evaluation of tomato textural mechanical properties. *Journal of Food Engineering* 111(4):618-624.

Sualeh, A, Daba, A, Kiflu, S and Mohammed, A. 2016. Effect of storage conditions and packing materials on the shelf life of tomato. *Food Science and Quality Management* 56(1):65-67.

Taye, AM, Tilahun, S, Seo, MH, Park, DS and Jeong, CS. 2019. Effects of 1-MCP on Quality and Storability of Cherry Tomato (Solanum Lycopersicum L.). *Horticulturae* 5(2):29-42.

Thompson, AK, Prange, RK, Bancroft, R and Puttongsiri, T. 2018. *Controlled Atmosphere Storage of Fruit and Vegetables*. CABI, Wallingford, United Kingdom.

Tilahun, S, Lee, YM, Choi, HR, Baek, MW, Lee, J-S, Kang, H-M and Jeong, CS. 2021. Modified atmosphere packaging combined with CO2 and 1-Methyl cyclopropane prolong the storability and maintain antioxidant properties of cherry tomato. *Scientia Horticulturae* 288:e110401.

Tilahun, S, Park, D, Taye, A and Jeong, C. 2017. Effects of Storage Duration on Physicochemical and Antioxidant Properties of Tomato (Lycopersicon esculentum Mill.). *Wonye Kwahak Kisulchi = Korean Journal of Horticultural Science and Technology / Hortic. Sci. Technol.* 35(1) 88-97.

Tolesa, GN and Workneh, TS. 2017. Influence of storage environment, maturity stage and pre-storage disinfection treatments on tomato fruit quality during winter in KwaZulu-Natal, South Africa. *Journal of Food Science and Technology* 54(10):3230-3242.

Tolesa, GN, Workneh, TS and Melesse, SF. 2018. Logistic regression analysis of marketability of tomato fruit harvested at different maturity stages and subjected to disinfection, storage condition and storage period treatments. *Biological Agriculture and Horticulture* 34(1):40-52.

Tumwesigye, K, Sousa, A, Oliveira, J and Sousa-Gallagher, M. 2017. Evaluation of novel bitter cassava film for equilibrium modified atmosphere packaging of cherry tomatoes. *Food Packaging and Shelf-life* 13(1):1-14.

Viet, B and Trang, HT. 2015. Effect of harvesting stages and storage temperature on physicochemical properties and antioxidant activities of yellow cherry tomato (Lycopersicon Esculentum Var. Cerasiforme). *International Journal of Engineering Research and Technology* 4(6):501-506.

Zeng, C, Tan, P and Liu, Z. 2020. Effect of exogenous ARA treatment for improving post-harvest quality in cherry tomato (Solanum Lycopersicum L.) fruits. *Scientia Horticulturae* 261:108959.

5. CONCLUSION AND RECOMMENDATIONS

Tomatoes are one of the most popular agricultural cash crops grown globally because of their dietary benefits for human health. In South Africa, large-scale commercial farmers contribute nearly 95% of the total annual production of tomatoes, while the limited small-scale farmers contribute the remaining 5%. The industry is not, however, without its challenges. High input costs, fluctuating market prices, a shortage of good quality irrigation water, an unreliable electricity supply, poor post-harvest handling, labour issues and a poor road infrastructure are among the top challenges that need to be addressed.

The reviewed literature proved that the packaging and storage of tomatoes, at least for a certain period, is typical for farmers, distributors and industries that process tomato-based products. The quality-defining factors of fresh tomatoes, such as their colour, freshness and firmness, change during storage and display, and are significantly influenced by the post-harvest conditions. The packaging, for example, is not only considered as a container that ensures hygiene and averts mechanical damage to the tomatoes, but it is also is a valuable tool that is used to maintain the bio-active constituents and flavour-related volatiles, and to extend their shelf-life. On the other hand, the storage conditions are also critical for controlling the physicochemical and quality attributes of tomatoes. Several research studies have concentrated on the possible use of tomatoes as processed fruit or fresh produce. However, studies on the effects of the packaging materials during storage are limited. This study evaluated the effects of different packaging materials and storage conditions on the quality attributes of the classic round “Nema-Netta” and “Romanita” cherry tomatoes across the South African supply chain. This study analysed the colour index changes, the physiological weight loss, their firmness (using the puncture test, the Kramer shear test and the compression test), their total soluble solids, pH, titratable acidity, total sugars, total phenolic content, as well as their microbial development.

The packaging and storage conditions influenced the shelf-life of the round “Nema-Netta” and “Romanita” cherry tomatoes, as well as the physiological and biochemical attributes. Cold storage conditions (10-12°C) and a high relative humidity (78-80%) maintained the quality changes in tomatoes better than ambient storage conditions (22-26°C and relative humidity 68-72%). The relative humidity range under cold storage conditions was low, compared to what was reported by Kabir *et al*. (2020) to be an optimum range between 85-95%.

The changes in quality attributes of the round "Nema-Netta" tomatoes were more sustained in the packaged tomatoes than in the unpackaged (control) fruit, under both storage conditions. The measurements of the colour index (L* and h°) showed that all samples were in the range of pinkish-red to red colouration, which indicated full ripeness; hence, all the samples started to lose their quality during the storage period. The tomatoes packaged in the EPS Tray + PVC wrap under cold storage demonstrated the following superior quality attributes:

(a) the lowest colour changes, the lowest reduction in L* of 13.4% and the lowest reduction in hue angle of 14.7%,
(b) the lowest PWL of 1.78%,
(c) firmer fruits, with a puncture, Kramer shear and compression of 30.3%, 41.6% and 28%, respectively,
(d) the lowest increase in TSS of 18.1%,
(e) the lowest increase in pH value of 5.7% and the lowest decline in TA of 25.5%,
(f) the lowest reduction in total sugars of 31.7%, and
(g) the lowest reduction in total phenolic content of 21.2%.

The SP Tray + PVC wrap followed closely behind, showing close-matching quality changes in the tomatoes, with a difference of less than 5%, compared to those in the EPS Tray + PVC wrap. The results showed no clear advantage of the EPS Trays (non-biodegradable) over the SP Tray (biodegradable) on most of the evaluated quality attributes, which indicates that biodegradable packaging can be used for tomatoes. However, some of the tomatoes in the SP Trays experienced a Blossom end-rot, which was observed mainly on the SP Tray + PVC wrap under ambient storage conditions towards the end of the storage period. In general, all the round tomato samples showed a decline in quality over the 28-day storage period, depending on the packaging and storage conditions.

The "Romanita" cherry tomatoes were influenced by the packaging and storage conditions. Those stored under cold storage conditions had minimal changes in quality, compared to those stored under ambient storage conditions. The cherry tomatoes in Open storage experience the highest quality decline, compared to those in the packaging treatments. The quality loss was minimal in cherry tomatoes packaged in the Glued Paper Tray + Flow wrap treatment combination. Their better-retained quality was based on the following:

(a) the colour changes, the lowest reduction in L* values of 25.8% and the lowest hue angle of 8.3%,
(b) firmer fruits, with a Kramer shear and compression of 29.9% and 28.6%, respectively,
(c) the lowest increase in the TSS of 22.5%,
(d) the lowest increase in pH value of 3.2%,
(e) the lowest decline in the TA of 29.5%,
(f) the lowest decline in total sugars of 43.7%, and
(g) the lowest decline in the TPC of 27.3%.

The Pulped Paper Tray + Zibo PET Lid was the second-best and showed an undetectable number of colony-forming units. The results revealed that the integrated application of packaging and cold storage conditions effectively delayed the respiration and ripening processes of cherry tomatoes, hence prolonging their shelf-life. A combination of the Glued Paper Tray + Flow wrap and low cold storage conditions slowed down the deterioration of the quality of the cherry tomatoes, compared to the other packages studied. However, there were no apparent differences between the Paper Trays and the PET trays, except for their ability to absorb the moisture inside the packaging, thus keeping the environment dry and the samples shiny and healthy.

Future Research

This study generated extensive quantitative data. However, the focus was mainly on the effects of the different packaging treatments and storage conditions on the quality of the tomato samples. These collected data can be used to model the ripening process of fruit and vegetables that are influenced by different packaging materials and storage conditions and to determine a correlation of the quality attributes influenced by the different post-harvest combinations. The collected data on water vapour and gas permeability have not been presented in this study, but can be used to develop a model and to correlate it with the quality attributes over time.

The use of biodegradable packaging materials and storage techniques in post-harvest handling in the food industry could be of great value for providing a holistic approach to environmentally-friendly materials and minimising post-harvest losses. Fruit and vegetables are subject to chilling injuries in the supply chain, and is a significant contributor to the post-harvest losses. Hence, more practical investigations and comparisons of the varying temperatures and relative humidity are required. The study of more environmentally-friendly packaging techniques can be beneficial for the South African supply chain.

6. APPENDICES

6.1 Appendix A

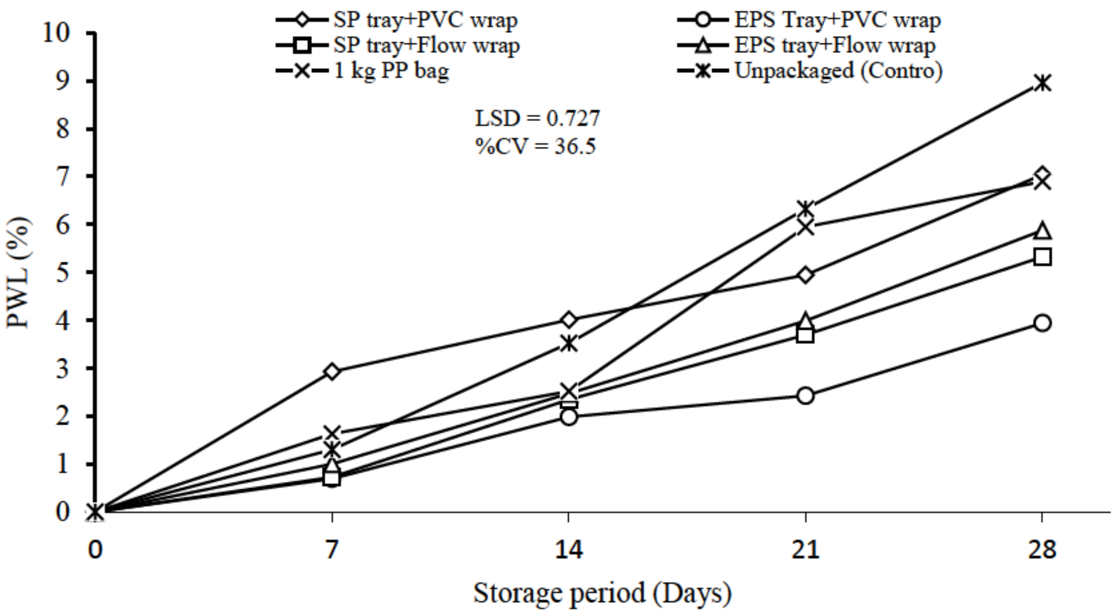

Figure 6.1 Effect of different packaging on the physiological weight loss of tomatoes

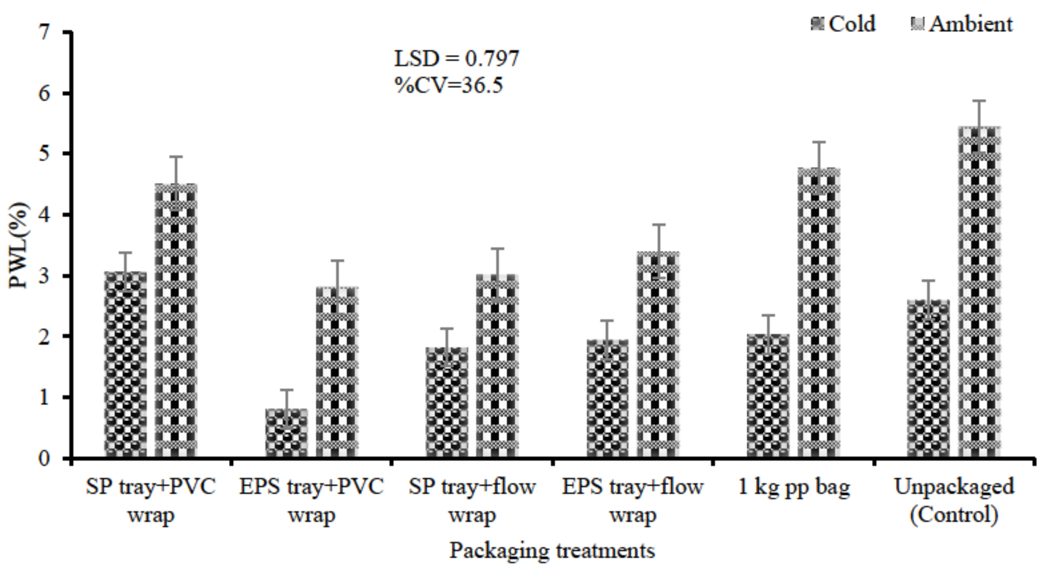

Figure 6.2 Comparison effect of storage conditions on the physiological weight loss of tomatoes

Day 0 Day 28

Figure 6.3 Condition of tomatoes packaged in the SP Tray + PVC wrap on Day 0 and Blossom end-rot on Day 28

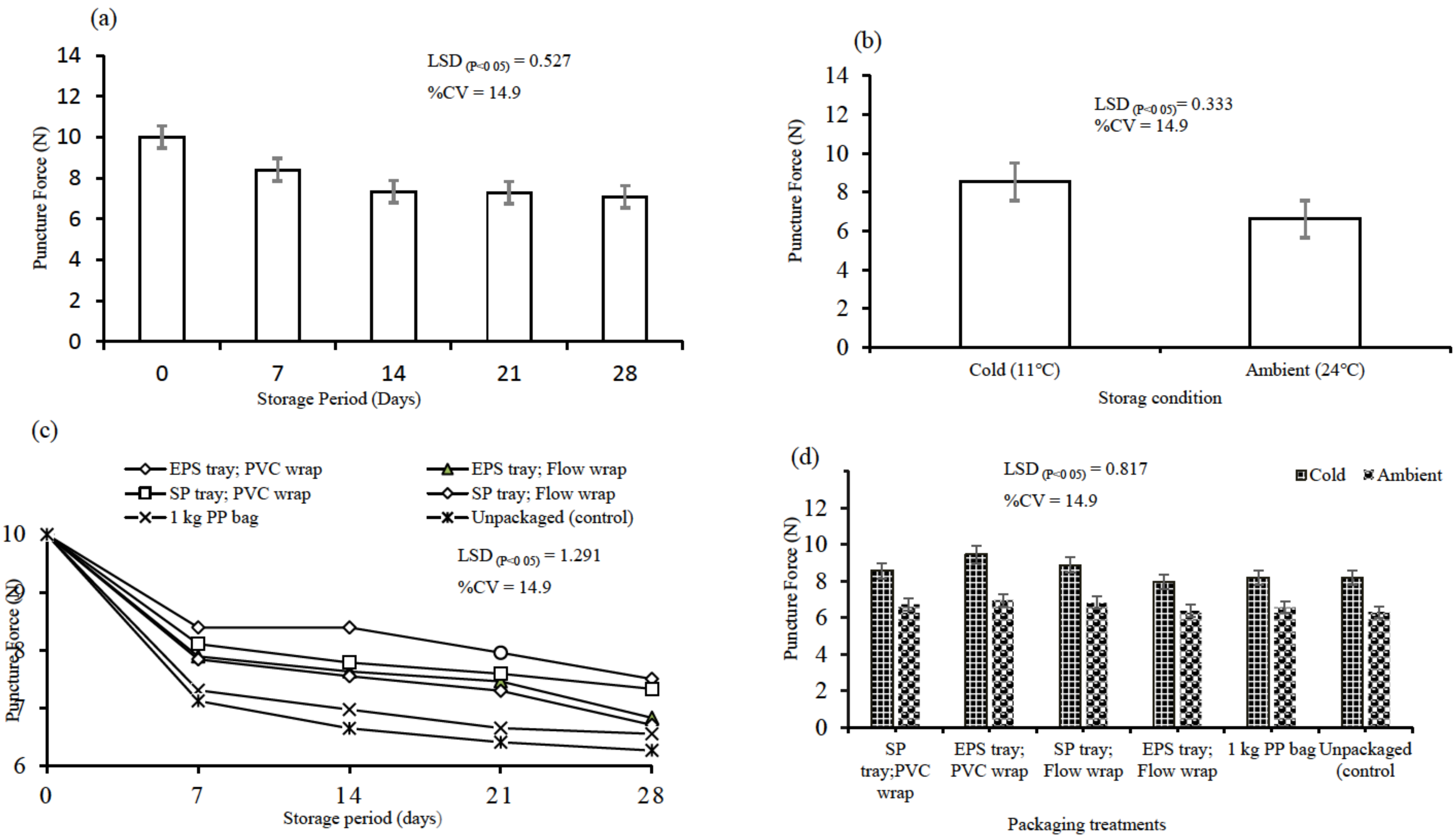

Figure 6.4 Storage period (a), Storage conditions (b), Packaging and storage period (c), Packaging and storage conditions (d) on puncture

Table 6.1 Summary of the effects of different packaging materials and storage conditions on the quality of round tomatoes

Packaging treatments	Storage conditions	L*	Hue Angle (h°)	PWL	Puncture	Kramer shear	Compre-ssion	TSS	pH value	TA	Total sugars	TPC
SP Tray + PVC Wrap	Cold	13.1	18.2	5.45	39.5	45.9	31.0	19.7	6.4	49.0	43.5	40.5
	Ambient	15.0	21.5	8.64	44.7	56.1	35.0	27.0	9.0	52.9	44.1	47.7
EPS Tray + PVC Wrap	Cold	12.3	14.7	1.78	30.3	41.6	28.0	18.1	5.7	25.5	31.7	21.2
	Ambient	16.3	18.8	6.11	39.0	53.9	33.5	30.5	8.1	51.0	35.6	35.6
SP Tray + Flow Wrap	Cold	16.5	20.7	3.92	38.3	45.8	31.4	18.9	7.1	31.4	37.0	21.2
	Ambient	19.0	21.9	6.74	38.6	56.0	40.3	21.6	6.7	52.9	50.5	34.4
EPS Tray + Flow Wrap	Cold	13.1	20.2	4.29	39.1	49.0	35.8	19.7	6.9	35.3	41.7	21.2
	Ambient	17.7	23.3	7.48	43.5	49.4	33.5	22.4	7.6	47.1	52.4	36.0
PP bag	Cold	16.0	20.8	4.46	40.6	49.8	30.2	21.1	6.9	35.3	55.8	46.3
	Ambient	20.0	21.9	9.34	41.3	56.5	39.7	27.8	8.3	45.1	56.8	51.5
Unpackaged [control]	Cold	15.2	21.5	6.00	43.6	61.6	32.2	25.1	9.0	33.3	49.1	45.8
	Ambient	23.0	24.3	11.93	44.8	63.3	53.2	31.6	9.5	51.0	61.7	63.0

Table 6.2 Summary of the effects of different packaging materials and storage conditions on the quality of cherry tomatoes

Packaging treatments	Storage conditions	L*	Hue Angle (h°)	PWL	Puncture	Kramer shear	Compre-ssion	TSS	pH value	TA	Total sugars	TPC
Zibo Punnet PET + Flow wrap	Cold	27.1	11.3	3.35	35.7	34.6	32.8	31.0	5.3	37.7	43.5	33.3
	Ambient	33.6	14.9	6.15	39.1	40.9	45.1	35.4	6.9	37.7	48.7	43.9
PP Bag	Cold	31.7	14.3	4.34	39.8	35.0	42.1	35.4	5.0	34.4	44.1	37.9
	Ambient	37.8	16.7	7.78	43.9	42.5	43.7	43.2	7.6	41	48.7	47.0
Zibo Punnet PET + Zibo PET Lid	Cold	28.9	12.1	3.37	36.4	40.4	37.3	33.9	5.5	39.3	48.9	36.4
	Ambient	37.8	16.4	6.78	43.2	47.6	38.7	39.8	7.8	52.5	59.3	40.9
Glued Paper Tray + Flow wrap	Cold	25.8	8.3	3.83	40.4	30.3	28.6	22.4	5.0	29.5	43.7	27.3
	Ambient	32.7	15.2	6.11	43.4	36.6	44.9	44.0	6.9	41.0	46.8	34.8
Pulped Paper Tray + Zibo PET Lid	Cold	35.2	11.9	4.54	37.3	31.3	29.7	32.8	5.0	37.7	43.7	28.8
	Ambient	42.4	13.8	6.44	41.8	36.8	36.6	38.8	7.1	39.3	50.8	36.4
Open Storage [control]	Cold	45.0	13.8	5.33	40.5	39.0	41.9	36.2	5.9	37.7	43.7	39.4
	Ambient	52.1	17.4	8.85	48.2	47.8	43.4	45.8	8.5	45.9	51.1	48.5