DEVELOPMENT AND OPTIMIZATION OF AN INTEGRATED POST-HARVEST MANAGEMENT SYSTEM FOR THE HANDLING AND STORAGE OF FRESH TOMATOES IN SOUTH AFRICAN SUPPLY CHAINS

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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Agricultural Engineering, School of Engineering of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by the Post-Harvest Innovation Programme (PHI) and the Tomato Producer Organization (TPO).

The contents of this work have not been submitted in any form to another University. Except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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I, Kipchumba Cherono declare that:

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List of publications:

1. Cherono K and Workneh TS. 2017. A review of the role of transportation on the quality changes of fresh tomatoes and their management in South Africa and other emerging markets. International Food Research Journal (IFRJ). In Press, with a manuscript ID, IFRJ17247.R1.
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ABSTRACT

In South African tomato fruit supply chains, transportation activities dominate the supply operations, with 60 % of total fruit produced in the country being grown in the Limpopo Province and supplied countrywide to markets as far as Cape Town. Although it has been established that poor transportation conditions lead to the loss of quality and mechanical damage in fresh tomatoes, the role of road quality and various tomato postharvest treatment conditions in contributing to quality losses of tomatoes during long distance transportation is not well known. This study investigates the effects of long distance transportation and in-field handling practices on the quality of tomatoes in South African tomato supply chains, with the aim of developing an integrated post-harvest management system for transporting fruit from farms to domestic markets. Tomatoes were harvested from two farms in Limpopo in the morning and afternoon. They were transported, using large bins and smaller lugs, pre-cooled within two and six hours and stored under ambient and cold storage conditions. Transportation experiments were also conducted in the summer and winter, where tomatoes of red, green and pink maturity stages were harvested and transported from three farms in Limpopo to Pietermaritzburg. They were then subjected to seven integrated disinfection treatments and stored under ambient and cold storage conditions. Route distances and road quality were measured during transportation. Fruit colour, firmness, marketability, pH, weight-loss, lycopene, sugars and ascorbic acid (AA) contents were also analysed over a 30-day storage period. The data was used to develop logistic and kinetic models for the supply of tomatoes. A transportation planning model was also developed using data from all the experiments that minimised logistical costs, while meeting consumer quality requirements for a given demand. The study showed that up to 17 % of tomato post-harvest losses in emerging economies occur during transportation. Harvesting in the morning and pre-cooling within two hours improved fruit marketability and weight-loss by up to 20 % and 75 kg ton^{-1}, respectively, compared to harvesting in the afternoon and pre-cooling after six hours. The Esmefour-Pietermaritzburg route (ZZ) was longer than the Point Drift-Pietermaritzburg (PD) and Steve Mohale's Farm-Pietermaritzburg route (EM) by 263.44 and 223.81 km, respectively. Seventy percent (70 %) of the EM road length had International Roughness Index (IRI) values less than 2.5 m km^{-1}, while the ZZ and PD routes had 63 and 58 % of their road length recording IRI values less than 2.5 m km^{-1}, respectively. Combining biocontrol treatment with chlorinated water (Chl+Bio) or anolyte water (Ano+Bio) effectively controlled the fruits' weight-loss. Ano+Bio gave tomatoes

with comparable visual appearance to fruit treated with chlorinated water, but with better visual appearance and marketability, compared to fruit treated with biocontrol, hot water, HWT+Bio or tap water (control). Fruit transported along the EM route had a 5 and 10 % higher mean marketability, compared to fruit transported along the PD and ZZ routes, respectively. The developed logistic model showed that the probability of fruit marketability was comparatively lower for fruit transported over rough roads, compared to the probability of marketability of fruit transported over smoother roads. Fruit transported over moderately rough roads, that were furthest from the market, had the lowest probability of marketability. Fruit harvested at the green maturity stage, transported through the shortest, smoothest roads, stored under refrigerated environment and treated with Ano+Bio, resulted in fruit with the highest probability of marketability. The chemical and nutritional analyses of samples of selected treatments showed that fruit dipped in Ano+Bio had the least AA loss, compared to fruit subjected to other treatments. Fruit transported over moderately rough surface road surface profile and the longest distance (ZZ) lost the highest AA of all the routes. Fruit harvested and transported in the winter had a 14 % and 9 % decrease in AA content during the 30-day storage period for samples stored in ambient and cold storage conditions, respectively. On the other hand, fruit harvested and transported in the summer showed an 85 % and 35 % decrease in AA concentration over the 30-day storage period, for ambient and cold stored fruit, respectively. Fruit transported through the shortest, smoothest road (EM), had a mean lycopene content of 40.9 mg kg^{-1}. In contrast, fruit transported over the longest distance, with roads that had moderately rough surface profile (ZZ), had a mean lycopene content of 37.6 mg kg^{-1}. The disinfection treatments and harvesting season significantly ($p \leq 0.05$) influenced the sugar content of stored tomatoes. The study showed that tomato postharvest nutrient losses in commercial supply chains are not only affected by environmental and post-harvest practices, but also by road quality. In a typical scenario, the transportation planning model was shown to improve the profits of the growers by over 8000 ZAR per truckload of fruit compared to cases where the model was not used, while ensuring that consumers' fruit quality requirements are met. The novel aspects of the research lie in the establishment of the effects of long-distance transportation on the quality and shelf-life of tomatoes under practical supply conditions. Guidelines for in-field handling and the long-distance transportation of fresh tomatoes have been developed, as well as environmentally-friendly disinfection treatments for commercial and emerging farmers. The developed transportation planning model that integrates key tomato quality attributes and other supply chain parameters is another novel output of the study.

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LIST OF ABBREVIATIONS AND SYMBOLS

The following is a list of abbreviations, acronyms and symbols that are used throughout this thesis. It gives the acronym, abbreviation or symbol, its meaning and the page where it is used for the first time.

Abbreviation or symbol	meaning	Page
FFV	Fresh fruits and vegetables	1
MAP	Modified atmospheric packaging	3
GDP	Gross domestic product	11
FPM	Fresh produce market	13
L*	Lightness colour parameter	16
a*	Redness colour parameter	16
b*	Yellowness colour parameter	16
AA	Ascorbic acid	18
IP	Intellectual property	26
B-13	Yeast isolate B13	26
CFU	Colony forming unit	27
RMAP	Required modified atmospheric packaging	29
LDPE	Low density polyethylene	29
PVC	Polyvinyl chloride	29
CA	Controlled atmosphere	29
RH	Relative humidity	29
1-MCP	1 methylcyclopropene	30
MIP	Mixed integer programming	31
CPLEX®	CPLEX solver optimization studio	31
K	Reaction rate constant	33
E_a	Activation energy	33
PH1	Rietpol packhouse	45
PH2	Dikgale packhouse	45
Fff	Fruit flesh firmness	47
h	Hue angle	48
CFD	Computational fluid dynamics	53
SEM	Standard error of the mean	56
PD	Point drift to Pietermaritzburg transportation route	62
EM	Steve Mohale's farm to Pietermaritzburg transportation route	62
ZZ	Esme four to Pietermaritzburg transportation route	62
IRI	International roughness index	62
C	Chroma	67
Chl	Chlorinated water at 100 ppm	66
Bio	Biocontrol treatment using B-13	66
HWT	Hot water treatment	66
Chl+Bio	Integrated treatment of chlorinated water and biocontrol	66
HWT+Bio	Integrated treatment of hot water and biocontrol	66
Ano+Bio	Integrated treatment of anolyte water and biocontrol	66
LSD	Least significant difference	124
y_i	Binary variable that returns marketable or unmarketable	137

Abbreviation or symbol	meaning	Page
y*	Probability of marketability	137
τ	Fruit marketability threshold	137
x	Quality attribute	138
P_i	Logistic probability of a binary variable	138
dos	Days of storage	140
p□	Estimated probability of marketability of tomato fruit	140
GAP	Good agricultural practice	152
DCIP	2, 6 Dichlorophenolindophenol	154
PCA	Principal components analysis	186
EPCA	Exploratory principal components analysis	189
KMO	Kaiser -Meyer-Olkin Measure of Sampling Adequacy	190
C_i	Compositional factors affecting food quality	206
E_j	Environmental factors that drive food quality deterioration	206
RMSE	Root mean square error	207
R^2	Coefficient of determination	208
TA	Titratable acidity	212
T_P	Transportation activities of tomatoes from farm to Packhouse	227
RQ_1	Road quality and distance to emerging farmer's Packhouse	227
RQ_2	Road quality and distance to commercial farmer's Packhouse	227
RQ_3	Road quality and distance to commercial farmer's Packhouse	227
T_L	Transportation from Pack houses to distribution centres	227
T_M	Transportation from distribution centres to markets	227

1. INTRODUCTION

1.1 Rationale for the Study

The world's population has been shifting from rural areas to cities globally over the last few decades, with estimates showing that urban areas held more than half of the world's population by 2014 (Seto *et al.*, 2011). The United Nations (UN) projected that the growth of global rural population plateaued by the dawn of the new millennium (UN, 2017). On the contrary, the global urban population has been growing and is projected to reach 66 % of the world's total by 2050 (Montgomery, 2008). The growth of urban populations in Africa and Asia is projected to grow faster than other cities in the world, with nearly an additional 2.5 billion people living in urban cities by 2050 (UN, 2017). Sustainable development challenges will, therefore, be one of the most pressing issues globally in the next few decades as the world continues to urbanise (Brenner and Schmid, 2014).

There is evidence to show that food systems, which are one of the most important components that sustain urban populations globally, are gradually evolving, and efficiency has become one of the focal points (Louw *et al.*, 2007). In the African continent for instance, food supply chains in some of the emerging markets are rapidly starting to exhibit attributes similar to those of food supply chains in developed markets (Greenberg, 2013). Large supermarket outlets are beginning to dominate these markets, necessitating changes in organization, coordination and management of these supply chains (Louw *et al.*, 2007). The fresh fruit and vegetable (FFV) segment globally has also been showing growth due to changes in consumer patterns (Jedermann *et al.*, 2014). Similarly, increasing urbanisation has compelled foods to be produced in remote areas that are far from the markets, necessitating long distance transportation (van der Vorst *et al.*, 2007; Macheka *et al.*, 2017). The increase in global income levels has also caused a shift of eating habits from dry foods to fresh foods, including FFV, that are healthier and have a high water content (Jedermann *et al.*, 2014). Coupled with heightened consumer awareness and a health-conscious global population, there is pressure on FFV systems to continually deliver high quality products efficiently and sustainably, at competitive prices.

Tomato fruit is one of the most widely produced FFV globally whose importance is only second to potatoes (Jones *et al.*, 2017). The global tomato production stood at 164 million tons in 2014, with China being the leading producer (FAOSTAT, 2015). In 2014, tomato production in South

Africa was estimated at 580851 metric tons (FAOSTAT, 2016) and contributed 24 % of the total vegetable production, from an area of 6000 hectares (NDA, 2015). The major tomato-producing areas in South Africa are Limpopo, Mpumalanga, Lowveld and Middleveld areas of the KwaZulu-Natal Province, as well as the southern parts of the Eastern and Western Cape (Pillay and Rogerson, 2013).

When ripe, the tomato fruit is high in nutritional and health-promoting compounds that include reducing sugars (mainly glucose and fructose), Vitamin E, A and C, polyphenols, organic acids, and lycopene, an important bioactive compound which imparts red colour (Canene-Adams *et al.*, 2005; Helyes and Lugasi, 2006). Lycopene and other antioxidants in tomatoes are thought to be responsible for reducing the risk of occurrence of degenerative health conditions through several mechanisms (Canene-Adams *et al.*, 2005). These important phytochemicals in tomato fruit can be maximized through cultivar selection, control of environmental factors, appropriate agronomic practices, selection of the right stage of harvest and suitable postharvest management and handling practices from the field to the consumer (Dorais *et al.*, 2008).

The quality of tomato for fresh produce market in terms of its freshness and general quality attributes is affected by pre-harvest factors, as well as the handling and storage conditions after harvesting. It is estimated that 30-40 % of tomato fruit in emerging markets is lost due to postharvest spoilage (Moneruzzaman *et al.*, 2009). These losses may constitute a loss in physical quality or losses in essential nutrients, including vitamins and minerals (Nasrin *et al.*, 2008). Recent studies have reported 20-50 % of postharvest losses of fresh tomatoes in tropical countries occurring during handling and transportation (Mujtaba and Masud, 2014). Although the exact level of postharvest losses in tomatoes during their transportation under South African conditions is not known, estimates by Sibomana *et al.* (2016) for the overall supply chain peg it at 10.1 %. These estimates are at best conservative, and in many instances, do not account for practicalities in the supply of tomato fruit under commercial conditions. This is especially critical since commercial farmers contribute 95 % of the total tomato fruit supplied to South African markets (DAFF, 2015).

The perishable nature of tomatoes necessitates quality management practices to be put in place. Research on the technologies and approaches for maintaining tomato fruits' quality have been increasingly explored in recent times in a bid to improve the prospects of lengthening their shelf-life, improving their market value and keeping quality.

Storage and packaging conditions are important factors that determine the quality and shelf-life of tomatoes. For instance, changes in the phytochemical and nutrient attributes of tomato fruit can occur at different rates depending on the storage conditions. Environmental control strategies where both temperature and humidity are controlled have also been widely studied and reported (Shewfelt and Prussia, 2009; Kubo, 2015). Controlled atmospheric storage and Modified Atmospheric Packaging (MAP) are some of the strategies that have been implemented in industrial and commercial applications to improve the quality and shelf-life of harvested tomatoes by regulating metabolic processes that lead to deterioration in quality (Ali et al., 2004; Sandhya, 2010). There is still need to further understand how in-field environmental conditions contribute to changes in the quality of tomato fruits downstream the supply chain.

Surface treatments are important in managing microbial contamination of tomato fruit and thereby protecting them against spoilage, hence ensuring that these products meet the legal microbial quality standards. The use of surface disinfectants such as chlorine (Wei *et al.*, 1995; Guo *et al.*, 2014) and electrolysed water (Deza *et al.*, 2003) have been investigated in an attempt to optimize their efficacy in inactivating a host of different microbial pathogens on tomatoes. The use of edible coatings such as chitosan, bee waxes, gum Arabic and mineral oil have recently gained interest due to the dual effects of exerting antimicrobial properties and having barrier properties that extend tomato shelf-life, as well as having compounds that confer health benefits to consumers (Mahfoudhi *et al.*, 2013; Guerreiro *et al.*, 2015). The increased need for environmentally-friendly processing technologies on fresh foods has also made surface disinfection of tomatoes using chlorine unpopular (Pinheiro *et al.*, 2014), hence the need for alternative technologies and techniques. The use of biocontrol agents in extending the shelf-life of tomatoes has also not been assessed yet it has shown promising results in other fruit.

The nutritional quality and shelf-life of harvested tomato depend, partly, on proper handling and harvesting practices (Arah *et al.*, 2015). Moneruzzaman *et al.* (2009) reported that all tomato cultivars have the longest shelf-life when harvested at the mature green stage. Different post-harvest handling practices also affect quality attributes, such as firmness during storage, colour development, the product's weight-loss and shelf-life. The maturity stage at harvest, as well as chemical and physiological treatments, coupled with the storage and handling conditions, can be managed, to maximize the shelf-life of tomatoes, with a minimal loss of physical and nutritive quality (Moneruzzaman *et al.*, 2009).

Integrated agro-technologies have also been studied to evaluate the beneficial synergies of various treatments in maintaining the post-harvest quality and extending the shelf-life of harvested tomatoes. Multilayer edible coatings have been used by Dávila-Aviña *et al.* (2014) to preserve the quality of tomatoes, without negatively affecting their bioactive compounds. Workneh *et al.* (2009) also used MAP, evaporative cooling and ComCat® treatments to maintain the keeping quality and marketability of tomato fruit stored in an evaporative cooler for 24 days. Although integrated agro-technologies have shown good results in maintaining the quality of tomato, the potential of some of the integrated agro-technologies have not been assessed under commercial conditions.

Transportation activities play a critical role during the supply of tomatoes to the markets, yet no studies have been carried out to gain insight into the effects of long distance transportation on the quality and shelf-life of tomatoes under practical conditions. Simulations have been carried out that, at best give estimates of these effects, but do not account for practicalities during the supply of tomato fruit, especially in commercial conditions (Linke and Geyer, 2002; Aba *et al.*, 2012).

1.2 Justification

Tomatoes in South Africa are produced in regions far north of the country and transported over large distances to their markets. The growing areas are concentrated in the Limpopo Province in South Africa, and the province hosts some of the largest commercial fresh tomato growers in the southern hemisphere (Munyeka, 2014). The province supplies over 60 % of the total fresh tomatoes sold in various markets, nationwide (DAFF, 2013). This spoke-and-wheel supply configuration makes transportation one of the most important operations that needs careful planning in order to minimise postharvest losses, enhance profitability of the growers and ensure the overall sustainability of the enterprises involved. The physiological nature of tomatoes makes them some of the most perishable FFVs. Their short shelf-life and climacteric nature makes the supply of tomatoes to distant markets without appreciable losses in quality a challenge. The effect of long distance transportation of tomato in commercial South African set-ups has not been investigated, particularly from a quality perspective.

The careful application of various post-harvest management strategies to fresh tomato fruit throughout its supply chain will ensure that products supplied meet the quality requirements of consumers. The understanding of the changes in tomato quality during their supply through different supply chain routes, from field-to-market, is necessary for the development of an integrated post-harvest management system. This in-depth understanding of quality losses, and effective approaches to minimize them have to be studied to establish the optimum supply conditions that maximize quality and minimize the overall postharvest handling and storage costs. With a broad range of tools that can be used to model and optimize production processes, process optimization of the post-harvest management of tomatoes can help reduce post-harvest losses and yield products that meet a complex mix of quality and supply chain criteria.

1.3 Aim of Study

The aim of this study is to investigate the effects of different handling and transportation conditions on the quality and shelf-life of fresh tomato using empirical and modelling approaches.

1.4 Objectives

The specific objectives of this study are:

(a) to quantify *in situ* post-harvest losses of fresh tomato due to different handling practices in South African commercial production set up,

(b) to investigate the effect of various handling, storage and transportation practices, on the physicochemical quality of tomato fruit of different maturity stages supplied along three South African supply chain routes,

(c) to assess the effect of different transportation and storage conditions on the chemical and nutritional quality of fresh tomatoes supplied along three South African supply chain routes,

(d) to develop integrated post-harvest treatments for maintaining the quality of fresh tomato fruit in south African supply conditions, and

(e) to model and optimize firmness, colour and ascorbic acid content as predictors of the quality of fresh tomato along three supply chain routes, while taking into account logistical costs, demand and quality constraints.

1.5 Roadmap of Study

This study is centred on establishing the effect of long distance transportation on the quality and shelf-life of fresh tomatoes under commercial supply conditions in South Africa. An in-depth analysis of fruit quality losses from the field to the market is carried out under practical commercial supply chain conditions. Quality preservation technologies, handling and storage practices are developed and tested, with the aim of developing fruit handling and transportation guidelines for the South African tomato industry. The study culminates in the development of a transportation planning model targeting commercial growers in the South African tomato industry.

Chapter two is a review of literature related to transportation of fresh tomatoes in South Africa and other emergent markets. It highlights gaps in knowledge and suggests new frontiers of research. Chapter three presents a detailed analysis of the effect of in-field handling, transportation and storage conditions on the quality and shelf-life of tomato fruit supplied under South African commercial conditions. This chapter addresses objective (a) of the study. Chapter four is an in-depth study of the effect of different storage conditions, disinfection treatments and transportation conditions on the physicochemical quality attributes of tomato fruit of different maturity stages. Chapter five is an analysis of the effect of different packaging units during long distance transportation on the physicochemical quality attributes of tomatoes supplied through different supply routes. Chapter six presents a detailed analysis of the suitable storage, handling and surface disinfection treatments for the supply of fruit through different supply routes in South African supply chains, based on their physicochemical quality attributes. A logistic model is developed to assess and select these conditions. Chapter seven presents the effects of different handling, storage and route conditions on the chemical and nutritive quality of tomato fruit. Chapter eight is a multivariate approach that assesses the overall impact of different supply chain parameters on the quality of tomato fruit of different maturity stages. These five chapters address objective (b), (c) and (d). Chapter nine tackles the development of kinetic and shelf-life models during the transportation and storage of tomatoes of different maturity stages under four transportation and storage temperature regimes. Chapter ten borrows from the kinetic and shelf-life models, in the development of the transportation planning model. Chapter nine and ten addresses objective (e). Chapter 11 gives conclusions of the study and suggests new paths for future investigations based on the reported findings.

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2. A REVIEW OF THE ROLE OF TRANSPORTATION ON THE QUALITY CHANGES OF FRESH TOMATOES AND THEIR MANAGEMENT IN SOUTH AFRICA AND OTHER EMERGING MARKETS

2.1 Abstract

This review is a summary of emerging approaches in the maintenance of tomato quality, from a supply chain planning perspective, in South Africa and other emerging markets. The review systematically covered as much literature as was available, which is related to postharvest management of fresh tomato fruit quality in South Africa and selected African nations. It focuses on the increasingly important role that transportation conditions play in the postharvest quality management of fresh tomato fruit in the current global environment, where fresh food supply chains are ever more vertically integrated and coordinated. The review established transportation being one of the important operations that accounts for up to 20 % of the postharvest quality loss in fresh tomato supply chains in Africa and other emerging economies. There is also limited literature on the mechanics and the driving factors of postharvest quality losses during long distance transportation of tomato fruits. The use of old approaches in logistical and supply chain planning, where the experience of managers is relied upon increases uncertainty in the performance of these supply chains. The study recommends further research on the impact of transportation conditions on the loss of nutritive elements from fresh tomatoes. The multiple nutrient deterioration kinetics of tomato fruit can be integrated into robust planning models that can aid the supply of quality fresh tomatoes at competitive prices.

Keywords: *agro-technologies; mechanical damage; planning models; postharvest quality losses; road quality*

2.2 Introduction

Tomato (*Solanum Lycopersicum*) is the second most important vegetable globally, after potatoes, that is produced for its edible fruit (Mujtaba and Masud, 2014). In its fresh form, it is eaten in fruit salads, on sandwiches and in salsa, or it is processed into pastes, preserves, juices and soups (Mujtaba and Masud, 2014; Pinheiro *et al.*, 2014). Many dishes incorporate tomatoes and their consumption in this way is interwoven into the cultures of different communities, hence explaining its global appeal in meal preparation (Beckles, 2012). When ripe, tomatoes are rich in health-promoting compounds that are thought to reduce the risk of occurrence of degenerative health conditions (Canene-Adams *et al.*, 2005).

In south Africa, the tomato industry is one of the important components of the agricultural sector and a valuable contributor to the growth of the national Gross Domestic Product (GDP). In 2014, it contributed 24 % of the national gross vegetable production and has experienced steady growth in terms of production throughout the last decade (NDA, 2015). It was projected that by the end of 2015, the industry would be valued to be in excess of 160 million USD (NDA, 2015).

Globally, the growing urban population has necessitated the restructuring of food systems, with the localization of agricultural zones in areas that are far from markets (Louw *et al.*, 2008). By the year 2050, it is projected that most of the world’s population will reside in urban areas (Madlener and Sunak, 2011). Coupled with the underlying economies of scale in agricultural production, these factors have necessitated the transportation of fresh produce over long distances to their markets (Ellis and Sumberg, 1998). This phenomenon will continue to put pressure on existing food systems, including supply chains, and it will necessitate the efficient management of supply chains, especially those of fresh foods such as tomatoes.

The physiological nature of tomato fruit lends itself susceptible to a myriad of factors that could lead to an appreciable loss in market value and quality during freight (Mujtaba and Masud, 2014). The level of postharvest losses of tomato in sub-Saharan Africa has been reported to be relatively higher than those recorded in developed economies (Sibomana *et al.*, 2016). Although concrete data are unavailable, estimates peg postharvest tomato losses to be 10.1 and 10.2 % in Kenya and South Africa, respectively, and as high as 13.4 % in Nigeria (Sibomana *et al.*, 2016). In contrast, these losses have been reported by FAOSTAT (2015) to be 5, 4 and 5.5 %, in Spain, Italy and USA, respectively. Poor infrastructure and inadequate investment in research has contributed to these losses. It has been particularly reported that much of tomato fruit losses occur during storage and transportation (Idah *et al.*, 2007b). Environmental control during transport has been the key approach for maintaining the quality of fresh fruits and vegetables (FFVs) during their supply (Shewfelt and Prussia, 2009; Kubo, 2015). Temperature and humidity control, for instance, have been used to develop the necessary standards for tomatoes and other FFV for certain markets (Kader and Rolle, 2004). In this way, the product storage and transportation time and temperature history is a prerequisite for FFV products to be sold in certain markets. Handling conditions during the transport of FFV, including product packaging are critical in management of their quality (Kader, 1984). The condition of the roads during inland transport is also an important factor that can be targeted as a loss mitigating avenue for tomato fruit (Idah *et al.*, 2007a).

The need to ensure sustainable food production necessitates the evaluation and implementation of possible strategies that can eliminate or minimize postharvest losses of tomato (Kader, 2004). This review is motivated by the increasingly interconnected agri-food supply networks within the commercial global environment of FFVs, with transportation playing a dominant role in the movement of tomato products and other fresh foods. Unlike other postharvest operations, such as precooling or storage, transportation is one of the delicate operations in the tomato supply chain. Post-harvest losses contribute to relatively higher economic losses, as this is the last mile to the market. A multi-pronged understanding of tomato fruit transportation as a critical operation from a fruit physiology, rheological, logistical and supply chain planning perspective, will give insight into new areas of research that need to be explored, to further improve the efficiency of the tomato supply chain networks in South Africa and other emerging markets. The study systematically reviewed comprehensively, the literature related to postharvest management of tomato quality in South Africa and selected African countries, with an emphasis on how transportation conditions lead to losses in quality. Logistical planning and distribution approaches were also reviewed, and the knowledge gained from the review used to suggest how quality changes of tomatoes and logistical planning, can be integrated to develop supply chain planning models.

2.3 The Structure of Tomato Supply Chains in South Africa

2.3.1 Production

Tomato is cultivated in South Africa by both commercial and emerging farmers and is the second most important vegetable in terms of economic importance (Louw *et al.*, 2007; Munyeka, 2014). The South African tomato industry has shown steady growth over the last two decades, and by the end of 2014, the gross production stood at 566,180 million tons (DAFF, 2015).

Tomatoes are produced in almost all the provinces in South Africa, but the Limpopo Province (3,590 ha) is the major producer, contributing approximately 75 % of the country's total area covered by the crop (DAFF, 2013). Due to its relatively warm climate, it is estimated that Limpopo Province contributes 60 % of the total fresh tomato fruit grown in South Africa and about 45 % of the annual turnover of Johannesburg's fresh produce market (FPM) (Munyeka, 2014). Table 2.1 shows a summary of the contribution of each province to the national tomato production as a percentage of the total cultivated area.

Table 2.1 The contribution of South African provinces to national tomato production (Michael and Gundidza, 2012)

Province	Area planted as a percentage of the national total
Limpopo	55
Mpumalanga	14
Eastern Cape	12
KwaZulu-Natal	10
North West	5
Western Cape	3
North West/Free state	1

Commercial tomato production is carried out in all provinces, except in Gauteng (Michael and Gundidza, 2012), with the commercial sector contributing 95 % of the total production and emerging growers contributing the remaining 5 % (DAFF, 2013). The tomato industry in South Africa is characterized by concentrated supply chains that are dominated by large companies that organize and coordinate the marketing and support services of the industry (Swinnen *et al.*, 2013).

2.3.2 Market size

South Africa is not a major tomato exporter; and therefore, almost all of the national production goes to the domestic market while a small percentage goes to processing and export (DAFF, 2013). The South African national fresh produce market is the dominant sales outlet, and is generally considered the preferred marketing avenue for fresh tomatoes and other FFVs (DAFF, 2015). In South Africa, the main players in the supply and distribution of tomatoes are; producers, wholesalers, wholesale-retail, retailers and consumers (DAFF, 2015). In general, the distribution network flows from the producers to the consumers via a range of intermediaries. A detailed description of the South African tomato supply and distribution channels is given by Sibomana *et al.* (2016) and DAFF (2013).

The Limpopo Province is clearly the most important producer of fresh tomato in South Africa. It also has the latent capacity for production to regional and international markets. The exploration of these markets would effectively expand the market size of the South African tomato industry, bringing with it the benefits of increased jobs and improved rural incomes (Swinnen *et al.*, 2013). Exporting to regional and international markets would have transportation as the dominant activity. An in-depth understanding of the effect of long distance transportation on the quality and shelf-life of tomatoes in South African conditions is therefore required, to effectively export to these markets without incurring an appreciable loss in quality, since quality problems cumulate in tomatoes from the first mile. There is an emerging trend for exported fresh tomato products to be more profitable than products sold on the domestic market (DAFF, 2015), which further makes this market more appealing to commercial producers.

2.3.3 Marketing and procurement structure

The South African tomato industry has a well-structured marketing system, the national fresh produce markets (FPMs) being the dominant marketing outlet that producers and individual farmers use to sell their produce (DAFF, 2013). The FPMs have brokers who sell volumes on a commission basis (DAFF, 2015). Sales also occur through retail chains such as supermarkets as well as informal markets (Sibomana *et al.*, 2016). Unlike other markets in the region such as Mozambique and Malawi, the South African fresh tomato marketing structure allows for shorter marketing linkages, with no middlemen, or a minimal number of them, in the value chain (Mango *et al.*, 2015). This helps to deliver value to producers and consumers and to avoid excessive price distortions. Although the average tomato prices per ton have been reported to be generally stable in South African domestic market (DAFF, 2015), price fluctuations have also been reported at various sales outlets over time (Munyeka, 2014), due to variation in the marketing margins by various players in the value chain. Farm gate prices have been shown to influence the retail prices far more than wholesale prices, hence their predictive power on retail prices (Munyeka, 2014). Although retailers have diverse fresh tomato procurement structures (Louw *et al.*, 2007), supermarkets and other large retail outlets mainly source their tomatoes from a small number of approved suppliers, who have the required capital and procurement capacity that are necessary to supply their products all-year-round and adhere to the stringent quality requirements (Louw *et al.*, 2008). These suppliers enter into sourcing contracts with the big retailers (Louw *et al.*, 2008).

2.4 Logistical Planning

Growers typically transport their tomatoes to pack-houses owned by the growers by road, using trucks. After processing and packaging, the fruit is transported using high capacity trucks to local retail outlets, processing plants or export points (DAFF, 2015). Fresh tomatoes have a short shelf-life and their quality starts to decline naturally immediately after harvest (Moneruzzaman *et al.*, 2009). It has been suggested that the perishability of fresh produce, including tomatoes, are the risk-loading factors that render these supply chains sensitive to logistical delays and general supply chain disruptions (Zuurbier, 1999). This therefore implies tight margins during their transportation and distribution, which necessitates good planning and coordination (Zuurbier, 1999). Postharvest practices including handling, pre-cooling procedures and harvesting protocols have to be well integrated into logistical planning operations. Their importance cannot be understated due to their key role in influencing the quality of fresh tomatoes and other FFV as they move down the supply chain. Market information, as well as production and logistical activities, have to be well-planned and coordinated. Although limited studies have been carried out on how tomato supply chains in South Africa are managed from a planning and logistical perspective, it has been, however, reported that the tomato industry in South Africa is highly integrated, comparable to the emerging markets in central Europe and Latin America (Louw *et al.*, 2007). There is a high degree of concentration in processing, distribution and retailing activities compared to other markets in the region and the African continent (Greenberg, 2013). The supply chain activities are also vertically coordinated and integrated due to the increased presence of dominant growers and large retail and supermarket brands (Louw *et al.*, 2008). Vertical coordination is defined as the process of organizing a subsequent set of activities between one or more suppliers and one or more consumers, while vertical integration is the organization of one or more stages of the value chain under the management of a single company (Zuurbier, 1999). Vertical integration and coordination enables information relating to product quality, market dynamics and consumer feedback to flow seamlessly from one end of the supply chain to the other. This reduces risks and improves efficiency of the tomato supply chains. There are efforts by commercial growers to integrate emerging farmers into their supply chains by providing technical support systems and information sharing. Although product traceability is not well-developed, after harvest, commercial growers are able to track products from the pack-house to the market. The modes of transport by different actors have been discussed in detail by

Sibomana *et al.* (2016). Commercial growers, marketing agents and big retailers have information-sharing tools that enable product tracking and traceability, availability of pricing and inventory information. Generic fresh fruit and vegetable supply chain models have also been developed by Ortmann (2005) that identify and optimize the utilization of fresh fruit export transport, storage and cooling capacities in South Africa.

2.5 Important Quality Changes during the Handling and Transportation of Tomatoes

Tomato is a climacteric fruit that gradually ripens even after harvest, when it has reached a certain maturity point (Rančić *et al.*, 2010). Ripening, therefore, is the primary physiological process of importance during the handling and transportation of the tomato fruit. A ripe tomato fruit contains 93-95 % water and 5-7.5 % dry matter (Pangaribuan, 2005). Fructose and glucose are the main reducing sugars in tomatoes, with concentrations ranging from 1.0-1.4 %, and 0.93-1.2 % of its fresh weight, respectively (Suárez *et al.*, 2008). The compositional nature of tomato makes it susceptible to water loss, decay, microbial attack and damage during transportation and storage. At the end of ripening, tomatoes reach their end of their physiological life and undergo senescence, after which the product becomes unmarketable. Because tomatoes are highly perishable, they have a short post-harvest life, necessitating proper handling, coordination and the scheduling of transport activities.

The quality of fresh market tomato encompasses physical, nutritive, chemical and safety attributes (Tigist *et al.*, 2013). Some of the attributes that are related to consumer acceptance include texture, flavour, taste (sourness, sweetness) and juiciness, all of which are sensory aspects (Kader, 2002). The physical quality attributes of fresh tomato include firmness, colour, size, shape, and the fresh weight (Gierson and Kader, 1986). Some of the chemical characteristics include the sugar and acid content, while the nutritive parameters that are of importance in fresh tomato include vitamin and mineral content (Nasrin *et al.*, 2008). Bioactive compounds comprise of antioxidants (lycopene, β- and α-carotene and phenolic compounds) and oxidized metabolites (Gil *et al.*, 2002; Moneruzzaman *et al.*, 2009). These attributes holistically influence the postharvest quality attributes and shelf-life of fresh tomato.

2.5.1 Physical quality changes

Colour is an important quality attribute that is used to assess the ripeness of tomato fruit and is an important parameter that influences the buying decisions of consumers (Francis, 1995).

There are six maturity indices related to the external colour and the ripening stage of fresh tomatoes, according to the USDA classification (Choi *et al.*, 1995). These are the green, breaker, turning, pink, light-red and red maturity stages. In general, as the ripening process in tomato progresses, the colour changes from green to red. In the L*a*b* colour space, a* values gradually increase from negative values with time when tomato reaches the breaker stage and gradually increases to positive values (turning stage) and stabilizes when they reach the light red stage, signifying a change in colour from green to red (López Camelo and Gómez, 2004). The L* (indicative of lightness) and b* values decrease slightly, as ripening approaches the terminal stages (Shewfelt *et al.*, 1988). The $(a^*/b^*)^2$ of tomato is used as an objective index of assessing its ripeness (Pathare *et al.*, 2013).

Light and temperature may influence the ripening index of tomato (Dumas *et al.*, 2003), whereby, screening light inhibits β-carotene synthesis while increased exposure to light increases β-carotene synthesis. Temperature influences colour development by stimulating plastid development at temperatures above 12 ^{o}C and below 30 ^{o}C (López Camelo and Gómez, 2004).

The size, shape and weight of tomato at harvest are attributes that are primarily related to the genetic traits of a particular cultivar and, in some instances, pre-harvest conditions (Díez and Nuez, 2008). For instance, there are the cherry-type, round-shaped, pear-shaped, plump-type, pear-oval, pear-elongated, small- or large-sized tomato cultivars.

During ripening and maturation, fresh tomatoes are characterized by, albeit modest, changes in their shape and size. Shrivelling of tomato fruit occurs as it approaches senescence, and is accompanied by loss of weight due to respiration and water loss through transpiration (Guo *et al.*, 2014). Changes in shape and size are also accompanied by loss of fruit firmness due to the breakdown of cellulose, pectin and lignin by pectinesterases (PE), polygalacturonase (PG) and β-galacturose (β-gal) in the cell wall (Tigist *et al.*, 2013).

The action of these enzymes has significant ramifications on the product's texture, and generally results in mealiness, an attribute that is undesirable to consumers (Tigist *et al.*, 2013). Shrivelled and mealy products lose their market value and consumer appeal. Excessive water loss, respiration and loss of firmness should be managed using appropriate postharvest handling practices to maintain the quality of tomatoes during their transportation, distribution and storage.

2.5.2 Chemical quality changes

Organic acids and soluble sugars are the major components of soluble solids in fresh tomato, and their relative amounts vary, depending on the tomato cultivar (Tigist *et al.*, 2013). The balance of sugars and acids influences the flavour of fresh tomato. In general, the acid content of tomato under normal storage conditions decreases with storage time. Tigist *et al.* (2013) reported the average acid content of eight tomato varieties during storage to range from 0.25 % at the end of storage, to 0.89 % at harvest. Sugars have been reported by Betancourt *et al.* (1977) to initially increase under normal storage conditions and are later used up for growth and terminal metabolic processes (Beckles, 2012). The storage temperature is a significant factor affecting the accumulation of sugars in tomato, with low temperature favouring the accumulation of soluble sugars, rather than higher temperatures (Beckles, 2012). Maul *et al.* (2000) reported glucose levels to be significantly higher in tomato samples stored at 5 ^{o}C compared to those stored at 12 ^{o}C and 20 ^{o}C, while fructose levels and sucrose equivalents were considerably higher in tomato samples stored at 5 ^{o}C and 10 ^{o}C compared to those stored at higher temperatures (Beckles, 2012).

2.5.3 Nutritive quality changes

Ascorbic acid (AA) is one of the most important quality attributes in fresh fruits and vegetables. The AA content of fresh tomato has been reported to range from 14.6 to 21.7 mg 100 g^{-1} (Tigist *et al.*, 2013). Toor and Savage (2006) also reported an AA content of 9.29 to 15.08 mg 100 g^{-1}, and observed a slight increase in AA mid-storage time, followed by a decrease as the fruit approached senescence. In general, minerals and vitamins (apart from vitamin C) are relatively trace and are not aspects that are often assessed as significant contributors to the nutritional quality of fresh market tomatoes (Heuvelink, 2005). Logistical planning operations can have ramifications on the nutritive quality changes of fresh tomatoes and other FFVs. This information is limited in the literature especially for tomatoes in South African supply chains.

2.5.4 Changes in bioactive compounds

Tomatoes are rich in lycopene, a bioactive compound that is known to have numerous disease-mitigation and immune-boosting benefits on human health (Brandt *et al.*, 2006). Lycopene biosynthesis and accumulation is a genetically-controlled process that causes its accumulation to increase under normal storage conditions with storage time, and peaks before senescence. Lycopene is produced through genetically-controlled biosynthetic pathways and accumulates following increased expression of *hp* and *og*^{c} genes (Brandt *et al.*, 2006). It is synthesized from phytoene, and through the central isoprenoid pathway, four desaturation steps generate lycopene (Liu *et al.*, 2012). Lycopene accumulation in tomato fruit is primarily dependent on prevailing light intensity and temperature conditions (Toor and Savage, 2006), with higher temperatures favouring its accumulation than lower temperatures. Heat treatments on tomato also affect lycopene accumulation. Soto-Zamora *et al.* (2005) and Tucker *et al.* (2007) discussed some of the approaches through which lycopene can be enhanced in fresh tomato. Phenolic content of tomatoes, just like lycopene, has important antioxidant properties. The accumulation of phenolics in tomato is commonly induced as a response to wounding and serves as a defence mechanism that brings about the accumulation of secondary metabolites (Antunes *et al.*, 2013). Phenolics also have a protective effect on AA content of tomato during storage. Flavonoids are some of the important phenolics in tomato and are also affected by storage temperature. The factors that control the accumulation of phenolics and other antioxidants in fresh tomato have been discussed in detail by Antunes *et al.* (2013).

2.5.5 Changes in sensory quality

The flavour and aroma of tomato are important customer acceptability traits (Shewfelt, 1999). Amino acids, soluble sugars, pigments and over 400 aroma compounds produce the characteristic tomato flavour and aroma (Yilmaz, 2001; Díaz de León-Sánchez *et al.*, 2009). Commercial harvesting conditions, as well as postharvest handling practices, have a significant effect on the flavour and aroma of fresh market tomatoes (Maul *et al.*, 2000), since these conditions often cause injuries that induce early ripening resulting in qualitative and quantitative changes that alter the product's flavour and aroma (Moretti *et al.*, 2002). Maul *et al.* (2000) reported that tomato aroma and flavour is significantly affected by low temperatures and long storage durations, with such products exhibiting low tomato flavour and ripe aroma. A poor tomato flavour has been one of the most prevalent consumer complaints, especially in tomatoes that are sourced through commercial supply chains (Díaz de León-Sánchez *et al.*, 2009).

The postharvest quality of fresh produce is essential to both distributors and consumers as it determines its freshness, shelf-life and the keeping quality. The postharvest quality indicators of fresh tomato are strongly linked to its ripening, a dominant process that occurs during transportation and storage. Due to the perishable nature of tomato fruit, postharvest handling practices and transportation conditions have to be cognizant of these changes to ensure that products are transported to distant market without appreciable loss in quality.

2.6 Contribution of Transportation to Post-Harvest Quality Losses of Tomatoes

The composition and structural configuration of tomatoes make them susceptible to mechanical damage and injuries that trigger physiological, chemical and microbial changes that, in turn, lead to a loss in quality. Although it is difficult to quantify the magnitude of losses during transportation of tomatoes, developing countries have generally recorded higher transportation losses than developed countries (Arah *et al.*, 2015). Some countries in Africa have reported tomato transportation losses that are as high as 20 % (Aba *et al.*, 2012).

The primary factors that contribute to changes in tomato fruit quality during transportation relate to the environmental conditions surrounding the product during transport, the physiological and mechanical properties of the fruit, the degree of roughness of the road surface, the vehicle's characteristics, the characteristics of the packaging units, the transit time and the distance (Vursavuş and Ozgüven, 2004; Aba *et al.*, 2012).

During transportation, tomatoes are often subjected to rough handling and rough roads, which leads to mechanical damage, and hence a loss of value, as the products move through the supply chain (Idah *et al.*, 2007b; Mutari and Debbie, 2011). Transport delays occasioned by poor road quality, bad weather and poor coordination of transport operations can cause further losses, especially if the products are held in collection points that do not have cooling facilities (Njenga, 2015). The tomato fruit continues to function physiologically while it is in transit and these physiological functions lead to a deterioration in its quality during transport, especially in high temperatures and relative humidity (Mashau *et al.*, 2012). Long transit times and poor temperature management during transportation of tomatoes are also important factors that can cause accelerated metabolic and enzymatic processes leading to loss in market value and increased risk of mechanical damage (Vursavuş and Ozgüven, 2004). Bruised tomatoes provide entry wounds for spoilage and for pathogenic microorganisms to infect these sites, or to internalize in the intact tissues (Çakmak *et al.*, 2010; Mutari and Debbie, 2011). This can lead, not only economic losses, but also risks to health associated with the consumption of contaminated tomato products. Microbial contamination of fresh tomatoes in South Africa and other emerging economies are known trigger economic losses in the tomato supply chain, as a result of product quarantine, recall or disposal and in some cases, the loss of human life (Yun *et al.*, 2015). The upward trend in frequency and magnitude of these occurrences has been associated with the changes in processing operations, where bulk handling and centralization of packing operations is the common practice for a majority of the global supply chains (Hedberg *et al.*, 1999).

Some of the commonly isolated bacterial pathogens reported in tomato include: *Salmonella (Lynch et al., 2009), Shigella* (Dugassa *et al.*, 2015) and E. *coli* 0157:H7 (Mukherjee *et al.*, 2004), just to name a few. Viral contaminants in tomato have also been speculated in the literature (Bartz *et al.*, 2015). Fungal contamination in tomato has been reported by Seo *et al.* (2010). *Rhizopius Nigricans, Botyrytis Cinerea and Penicillium Expansum* are some of the yeasts that cause serious post-harvest spoilage problems in tomato (Liu *et al.*, 2007; Zhao *et al.*, 2008; Wang *et al.*, 2010).

The mechanical damage and bruising that tomatoes are subjected to during transportation is caused by a variety of forces, including vibrational, abrasive, impact, compressional and cutting forces (Çakmak *et al.*, 2010; Aba *et al.*, 2012). During transportation, vibrational forces from the vehicle, due to abrupt changes in the road profile, cause the fruit to move randomly within the packaging units and depending on the intensity, direction and duration of the displacement, these forces may reach thresholds that cause damage, and hence, a loss of quality (Çakmak *et al.*, 2010). Vibration also causes tomato fruit to rotate and rub against the surfaces of other fruit and the packaging units, causing abrasion, bruising and softening (Çakmak *et al.*, 2010; Aba *et al.*, 2012). Cuts can occur when the fruit is pushed or rotated onto sharp edges of packaging units (Çakmak *et al.*, 2010). The level of damage caused by vibration on tomato fruit is linked to the frequency, amplitude and the duration of vibrational force (Vursavuş and Ozgüven, 2004) as these parameters influence the amount of energy available to cause damage (Idah *et al.*, 2007a).

Vibration bruising and abrasion damage causes increased fruit moisture loss, discolouration and wounding (Mutari and Debbie, 2011). Fruit injuries have been known to trigger heightened metabolic processes that accelerate deterioration in quality and reduction in shelf-life (Mutari and Debbie, 2011; Mashau *et al.*, 2012). Bruised tissues suffer from enzymatic breakdown of affected areas including cell walls leading to rapid degradation of cell wall polysaccharides (Li *et al.*, 2010). The result of this breakdown is notably softened spots on the fruit surface (Li *et al.*, 2010). Overloading fruit in wooden crates causes excessive compressive stress to the fruit at the bottom, which leads to deformation and an accumulation of field and respiration heat, resulting in significant losses (Arah *et al.*, 2015). Studies by Çakmak *et al.* (2010) have reported high degree of mechanical damage in products that were transported through highways than rough roads due to high acceleration and long transportation time. It has also been shown that an increase in the transportation distance increases the proportion of fruit damaged during freight (Vursavuş and Ozgüven, 2004). A study by Mutari and Debbie (2011) simulated the damage on tomato fruit due to different transportation conditions. It was observed that damaged fruit produced a higher ethylene content, higher respiration and weight loss, compared to undamaged fruit. Damaged fruit also recorded significantly lower firmness values compared to undamaged fruit. They attributed this observation to the increased metabolic processes in damaged fruit leading to water loss and hence the loss of turgidity by the cells resulting in their collapse when pressure is applied. They recommended maintenance of cold chain during transportation and cushioning of packaging units. The varietal response and effect of fruit maturity at harvest on damage response was also recommended as aspects of the experiment that needed further research. There is also need for further research on the effect of fruit shape on the bruise susceptibility of tomato (Li *et al.*, 2010).

The internal structure of the tomato fruit has also been shown by Li *et al.* (2010) to be a factor influencing the mechanical damage susceptibility of the fruit. Although the mechanism through which the internal locular structure effects the bruise susceptibility was not established, it was observed that four locular tomato fruits had a significant effect on the degree of mechanical damage, while three locular fruit had no significant effect (Li *et al.*, 2010). Other studies have also shown that the level of mechanical damage depends on the maturity at harvest with red-ripe tomatoes being more susceptible to damage than green fruit (Arah *et al.*, 2015).

It has been shown that bruised tomatoes have lower AA content than undamaged tomatoes (Moretti *et al.*, 1998; Aba *et al.*, 2012). However, a similar study by Sablani *et al.* (2006) reported inconclusive observations. There is therefore the need for further research on the effect of various transportation conditions, on the chemical and nutritional quality of tomato fruit.

2.7 Impact of Packaging Materials and Handling during Transportation of Tomatoes

During transportation of tomatoes, good packaging units should cushion the products against deformation and bruising, offer protection against moisture loss, pathogens, predators and insulation from extreme temperatures (Arah *et al.*, 2015). Packaging units are also important for containment of tomato fruit, they offer structural support, hence are important agents through which product damage can be mitigated during transportation. Unsuitable packaging materials have been identified as one of the key contributors to the mechanical damage of tomatoes during transportation (Idah *et al.*, 2007b; Li *et al.*, 2010).

The configuration and properties of the material surfaces that are used to package tomatoes are particularly important, since they transmit the forces from the road-vehicle system to the fruit. Baskets woven from palm and jute bags have been reported to be the common packaging units used for long distance transportation of tomatoes to markets in Nigeria, where they also double-up as a pricing units (Idah *et al.*, 2007b; Çakmak *et al.*, 2010). Some studies have also reported that wooden crates and woven baskets are the commonly-used packaging materials used to transport tomatoes in Africa (Arah *et al.*, 2015). It has been, however, reported that they have poor ventilation and this has been reckoned to be the cause of decay and other forms of tomato spoilage (Idah *et al.*, 2007b; Çakmak *et al.*, 2010). It has also been reported that the cushioning of fruit from vibrations using these packaging units is poor and leads to high incidences of mechanical damage. It has been shown that the position of tomatoes in the packaging unit also affects the degree of mechanical damage on the fruit (Çakmak *et al.*, 2010; Aba *et al.*, 2012). Fruit positioned at the top layer in bulk bins suffered more damage due to relatively higher vibrational energy they receive causing them to rotate and impact on each other (Vursavuş and Ozgüven, 2004). A study by Aba *et al.* (2012) that simulated the intensity of vibration and degree of damage on tomato fruits in a plastic container and traditional woven basket, showed severe damage on fruit located at the bottom and the sides of the traditional basket. On the other hand, damage on the fruits was localized near the upper surface of plastic basket. Studies that compared the degree of protection offered by different packaging units to various fresh fruits such as apples and figs have shown the importance of vibration transmissivity by these units (Vursavuş and Ozgüven, 2004; Çakmak *et al.*, 2010). In a study by Aba *et al.* (2012), traditional woven palm basket showed a higher vibration transmissivity of 0.22 g compared to plastic basket that recorded 0.20 g. The fruit in traditional basket had significantly higher bruise dimensions than those in the plastic basket (Aba *et al.*, 2012). In addition to damage, packaging materials made from woven palm material and lined with grass can potentially cause transmission of microbial contaminants to the fruit (Ofor *et al.*, 2009). Hard and rigid materials, such as wooden crates, have been reported to have a high vibrational transmissivity, hence causing more damage than other materials (Vursavuş and Ozgüven, 2004). A study by Idah *et al.* (2007a), where damage to tomatoes was simulated by dropping fruit onto wooden, metal, foam, plastic and cardboard surfaces, it was shown that fruit dropped on wooden, metal and plastic surfaces suffered severe damage, while foam inflicted the least damage. The information from the study is particularly useful for designers of packaging units of tomatoes and other fresh fruits.

Rough handling during transportation of tomatoes, including subjecting fruit to drop heights exceeding 1.4 m when transferring produce from containers have been shown to be a one of the causes of mechanical damage to tomato fruit (Idah *et al.*, 2007a; Mutari and Debbie, 2011). Processes in pack-houses and other bulk handling units should therefore be cognisant of this. Analysis of the movement of fruit during pack-house operations using TuberLogs® could provide valuable information on the areas where excessive dropping of tomatoes may be occurring.

In south African tomato supply chains, fruit is commonly transported using plastic bulk bins, plastic crates and recyclable carton boxes. Some of these packaging units used are shown in Figure 2.1. Some emerging farmers still use wooden crates to transport tomatoes.

Figure 2.1 A Pictorial view of various packaging materials used in South African tomato industry. Cardboard boxes (A) are commonly-used transport fruit to the retail markets. Plastic bulk bins (B) are used by large growers to transport fruit from the field to pack houses. Plastic crates (C) are used during harvesting by commercial growers (see B) and transportation of fruit from the farm to pack houses by emerging farmers. Wooden crates (D) were previously used by emerging farmers to transport tomato fruit to the market

Tomatoes in South African supply chains are typically transported to pack-houses in bulk bins by tractors and trucks, where they are pre-cooled prior to processing. After processing, the graded and packed tomatoes, typically in boxes, are transported in non-refrigerated trucks to marketing points (commonly fresh produce markets) or supermarkets and other retail outlets. The road networks are typically rough roads in and around the farms.

Major roads commonly termed as national roads, connect the pack-houses to their markets. Commercial growers typically use larger trucks, while emerging farmers commonly use hired trucks. The south African tomato transportation practices and infrastructure compares well with the systems used in many developed countries, except for the transportation in non-refrigerated conditions. Other African countries, however, use poor packaging materials and have poor road infrastructure leading to considerably high postharvest losses. A comparison of some of the transportation infrastructure and packaging materials used in South Africa and other African nations is shown in Figure 2.2. Under South African conditions, transportation is done over long distances due to centralization of production zones in the northern parts of the country. This makes transportation a critical operation in the South African tomato supply chains.

Figure 2.2 Transportation of tomatoes by a commercial producer in South Africa through a farm road (A), with (B) depicting hired trucks used by emerging farmers. (C) shows a wooden crate and grass used as cushioning material during transportation of tomato fruit in Tanzania (Njenga, 2015), while (D) shows the poor road infrastructure and some of the transport systems used by farmers in Kenya to transport produce (Njenga, 2015)

2.8 Emerging Trends in Post-Harvest Quality Management of Fresh Tomato in South African Supply Chains

Packaging of tomatoes prior to transportation as previously discussed, not only facilitates handling but also protects them from physical, mechanical as well as other agents of damage. Other processing operations prior to freight also play a critical role in ensuring quality standards are met and go a long way in improving the shelf-life of tomatoes delivered to different markets. Pre-cooling, for instance, ensures that field heat and heat due to fruit respiration is removed from tomatoes after harvesting, before they are packaged and transported. Pre-cooling of tomatoes and other FFV is a discipline of study on its own and cannot be exhaustively discussed in the present review but its importance is worth mentioning nonetheless. Disinfection of tomatoes is also important in reduction of microbial population on fruit surfaces to levels that are safe for human consumption. Storage practices that maintain the cold chain, scrub excessive accumulation of ethylene and control gaseous composition are some of the other important practices prior to transportation that determine the quality of tomatoes received downstream the supply chain. These handling and processing operations prior to tomato transportation are in no way exhaustive and will vary depending on the supply chain in question. It is however, important to note that regardless of the careful planning and excellent execution transportation operations in tomato supply chains, these pre-transportation operations also contribute to the overall quality of fresh tomatoes when they reach the market.

The extension of the shelf-life of fresh tomato has been intensively researched in a bid to enable transportation of high quality fresh tomato fruit to distant markets. Advances in understanding of the physiology of tomato ripening and the underlying biochemical, chemical and genetic signals that control this process have yielded various approaches that enable the maintenance of tomato quality over reasonably long periods of time. The following sections present a summary of the some of the recent technologies that are currently in use.

2.8.1 Biotechnological and biocontrol approaches

The commercial control of tomato ripening has been realized through the careful selection of slow or early ripening varieties (Matas *et al.*, 2009). Targeting of some of the complex network of transcriptional factors that control ripening due to new insights in genetic engineering, has proven to be a promising approach towards addressing issues associated with the quality and shelf-life of tomato fruit (Matas *et al.*, 2009). However, some of the commercial transgenic tomato varieties have altered nutrient composition, flavour, genetic instability and undesirable texture as a result of incomplete ripening (Matas *et al.*, 2009). Intellectual property (IP) restrictions, negative consumer attitudes, health and environmental concerns have limited the commercial application of these technologies (Falk *et al.*, 2002; Matas *et al.*, 2009; Siddiqui *et al.*, 2014). The long-term safety of genetically-engineered tomatoes and a myriad of regulatory hurdles (Redenbaugh *et al.*, 1993; Falk *et al.*, 2002) further complicates the adoption of this technology. For instance, the direct methods used for managing the effect of exogenous ethylene during the transport of tomatoes, for example, using ethylene scrubbers, or ozone lamps in cold storage units, may be a more practical approach for commercial entities.

Research in the use of biocontrol agents as microbial antagonists that competitively control yeasts and bacterial contamination in tomato fruit is still in its infancy in South Africa, and its application in commercial set-ups is yet to be tested. However, biocontrol agents such as B-13 have been commercially successful in controlling a broad range of microbial pathogens in citrus (Liu *et al.*, 2010). Some of these biocontrol products have been registered for use in controlling a range of postharvest spoilage agents in South African citrus industry.

2.8.2 Surface disinfection

Surface decontamination using different sanitizing agents, thermal and radiation sources not only reduces the microbial burden that often cause spoilage, but also removes pests and insects from the fruits, and, in turn improves the postharvest shelf-life of fresh tomato fruit (Venta *et al.*, 2010). Hot water, chlorine and trisodium phosphate, are some of the oldest sanitizing agents that have shown varied success in the control of microbial contamination and decay of fresh tomatoes (Sapers and Jones, 2006; Chaidez *et al.*, 2007). Surface sanitizers are generally regarded as effective if they can reduce the microbial load on tomato fruit surface by at least 2 log CFU g^{-1} (Chaidez *et al.*, 2007).

Ozonated water has been tested as an alternative to chlorine that is perceived to have environmental and health concerns (Chaidez *et al.*, 2007; Venta *et al.*, 2010). The study by Chaidez *et al.* (2007) compared the efficacy of using chlorinated and ozonated water, using two application methods to decontaminate inoculated Salmonella on tomato fruit surface. Spraying achieved comparable results of a 2.5-3.0 log CFU g^{-1} reduction for both methods, while immersion of tomato in ozonated water achieved lower reductions compared to immersion in chlorinated water. Venta *et al.* (2010) reported that ozone-treated tomatoes were firmer and had less weight-loss compared to the control group after 16 days of storage. Tzortzakis *et al.* (2007) also demonstrated that low-level ozone atmospheric environment in cold storage of tomato is capable of not only preventing disease onset and proliferation, but also maintaining fruit quality especially in terms of firmness and taste. The use of electrolyzed water has been reported by Islam *et al.* (2015) and Deza *et al.* (2003) to be useful in decontamination of *E. coli* on tomato fruit to levels <1 log CFU g^{-1}. Other recently-assessed chemical sanitizers include chlorine dioxide, bromine, iodine, acids and quaternary ammonium compounds (Goodburn and Wallace, 2013). Although research has shown that ozone treatment is an effective surface disinfectant, scrubs ethylene and induces fruit defences, its use has been limited to a few large tomato producers in South Africa.

The use of pulsed light (Aguiló-Aguayo *et al.*, 2013), ultrasound (Aguiló-Aguayo *et al.*, 2013) sonic treatment (Gündüz *et al.*, 2010), UV and gamma radiation (Mukhopadhyay *et al.*, 2013; Mukhopadhyay *et al.*, 2015) are some of the emerging surface disinfection methods attempted on fresh tomato that have achieved varied levels of success. Most of these treatments are yet to be adopted in South African tomato industry.

Anolyte water has been established by Workneh *et al.* (2012) as a novel disinfectant on tomato, but there is a need to integrate it further with other pre-storage treatments, to improve its efficacy. There is need to also develop and test suitable application technologies that can enable it to be adopted by the tomato industry.

2.8.3 Edible coatings

Edible coatings play the dual role of improving the shelf-life of tomatoes and other fruits, by modifying the atmosphere around the products hence reducing respiration, water loss, as well as preserving their texture (Dávila-Aviña *et al.*, 2014). In some cases, edible coatings exert antimicrobial effects (Dávila-Aviña *et al.*, 2014). This technology has recently received considerable attention, because it is environmentally friendly, and it passes on its accrued health benefits to consumers. Some of the edible coatings that have been investigated on tomato include mineral and carnauba oil (Dávila-Aviña *et al.*, 2014), chitosan (Ramos-García *et al.*, 2012), essential oils (Sivakumar and Bautista-Banos, 2014), bee wax (Fagundes *et al.*, 2014) and gum Arabic (Ali *et al.*, 2013). These publications depict surface coats as a viable alternative to some of the chemical treatments that present environmental and health concerns. In South Africa, edible coatings have been extensively investigated by Bill *et al.* (2014) and have shown potential in controlling postharvest diseases in avocado. However, the use of edible coatings is yet to be adopted by the South African tomato industry.

2.8.4 Packaging

Tomato packaging is one of the principal means of extending its shelf-life. Packaging materials have barrier properties on foods that control the rate at which low molecular compounds enter and leave the package (Muratore *et al.*, 2005). The extension of tomato shelf-life can be achieved through ripening retardation, by sealing the produce in packaging films that alter the gas composition around them with time, and this is termed as Modified Atmosphere Packaging (MAP) (Ali and Thompson, 1998). MAP results in an increase in CO_2 concentration and the reduction in O_2 inside the fruit packaging, hence reducing respiration, resulting in a reduction in the rate of fruit softening (Ali and Thompson, 1998; Workneh *et al.*, 2009). Ali and Thompson (1998) showed that tomatoes packaged in plastic films softened at a lower rate, had lower weight loss and decay, compared to the control. The treated samples, however, had comparable colour to the control group and did not exhibit negative physiological attributes during storage. Similar observations have also been reported by Workneh *et al.* (2012).

The use of biodegradable biofilms has recently generated interest due to their sustainability, suitability and the accrued antimicrobial properties, as opposed to synthetic materials (Muratore *et al.*, 2005). Active biofilm packaging has also been reported by García-García *et al.* (2013) to actively absorb ethylene and reduce tomato ripening. MAP, together with cold storage, can significantly increase the shelf-life of tomato fruit, making its transport to distant markets possible (García-García *et al.*, 2013). MAP packaging, however, has to be designed to achieve Required Modified Atmospheric (RMA) gas composition to meet these objectives, often a difficult target to achieve. Low Density Polyethylene (LDPE), Polyvinyl Chloride (PVC) and Polypropylene are some of the MAP packaging materials commonly used (Kantola and Helén, 2001).

Controlled Atmosphere (CA) can also be used to extend the shelf-life of tomato, whereby, systems continually monitor and adjust the gas composition surrounding the products to optimal levels (Gorris and Peppelenbos, 1992). This system is, however, used in bulk storage of valuable fresh fruits as it is expensive to set up, run and maintain. The use of vacuum packaging with refrigeration has also been suggested by Gorris and Peppelenbos (1992).

2.8.5 Temperature and humidity control

Humidity and temperature control are the most common approaches used to extend the shelf-life of fresh tomatoes in South African supply chains. Low-temperature storage is widely-used since higher temperatures increase fruit respiration and shortens their shelf-life (Pinheiro *et al.*, 2014). Storage temperature of fresh tomato depends on the maturity stage and cultivar (Medeiros *et al.*, 2012; Pinheiro *et al.*, 2013; Pinheiro *et al.*, 2014). It has been generally known that temperatures lower than 13 ^{o}C induce chilling injury in tomato (McDonald *et al.*, 1999).

Pinheiro *et al.* (2013) showed that the kinetics of tomato quality degradation greatly depended on storage temperature and duration. High temperature, low RH and extended storage conditions lead to the loss of valuable nutrients in tomatoes, especially vitamins (Sablani *et al.*, 2006). It is widely accepted that vitamin C is the most thermo-sensitive nutrient compound in tomato fruit and shows a gradual decrease with increase in storage temperature (Sablani *et al.*, 2006).

Alternative cooling systems in South Africa are being developed such as evaporative cooling systems for use off the grid. The combination of these cooling systems with other postharvest preservation technologies has proved successful. Such studies have been reported by Workneh *et al.* (2009).

2.8.6 Integrated postharvest management approaches

Integrated postharvest technologies harness the synergy from a series of treatments that are beneficial to the postharvest shelf-life of a product. Treatment combinations of packaging (e.g. MAP, CA etc.), temperature and humidity control, surface decontamination, application of genetic and hormonal control technologies and surface coats with edible coatings may be used as a set of integrated post-harvest treatments (Workneh *et al.*, 2012; Mukhopadhyay *et al.*, 2015).

The application of integrated post-harvest treatments has shown remarkable success in retarding quality loss in tomatoes (Ali *et al.*, 2004). For instance, 1-Methylcyclopropene (1-MCP) together with MAP, compared to either treatment separately, was reported by Sabir and Agar (2011) to significantly reduce weight-loss, maintain colour, firmness and lycopene content of pink and red tomato for up to 21 days. Workneh *et al.* (2009) also reported that MAP and storage temperature control using evaporative cooling, reduced weight loss and the rate of ripening of stored tomatoes, resulting in significant improvement in their marketability. This emerging research niche still has potential, especially in cases where integrated, novel treatments are used to improve the post-harvest quality and shelf-life of fresh tomatoes (Stevens *et al.*, 1997).

2.9 Modelling Approaches in Tomato Supply Chain Planning

Tomato supply chains have become increasingly complex due to integration of fresh fruit and vegetables (FFV) value chains into national, regional and international sourcing networks. The perishable nature of tomato fruit that makes its shelf-life short, constraints in the utilization of available resources and uncertainties associated with the management and supply of fruit to distant market makes conventional planning methods that rely on past experiences unreliable (Ahumada and Villalobos, 2011). For this reason, it has been reported that the transportation phase in the supply of fresh foods, generates the highest amount of waste, due to sub-optimal handling and storage, which leads to an appreciable deterioration in quality (Shukla and Jharkharia, 2013). The need for quality fresh tomatoes to reach distant markets further makes planning models important tools in fresh food supply chains.

Models in supply chain planning can be used to aid strategic, tactical or operational decisions. A review by Ahumada and Villalobos (2009) gives a detailed classification of models used for planning agri-food supply chains. Similar work has been also done more recently by Shukla and Jharkharia (2013). Some of the key objectives of supply chain planning are: to reduce production and operational costs, achieve improved food quality, reduce food waste and increase sustainability of fresh food supply chains (Soysal *et al.*, 2012).

2.9.1 An overview of the use of planning models in tomato supply chains

The use of planning models in tactical operations including harvesting, transportation and distribution of fresh produce has received considerable attention recently. The main goal of a majority of these models is to maximize profits through the efficient use of resources, to reduce operating costs and to maximize the utilization of existing capacity (Ahumada and Villalobos, 2011). For instance, Osvald and Stirn (2008) employed a model for the distribution of vegetables that reduced the associated costs by 27 %, by minimizing the distribution costs of vehicles used, the distances travelled while minimizing quality loss. The loss in quality was represented by a linear function that was related to the time the products spent on the road during transportation, where product colour was used as a surrogate to assess the overall quality of tomato fruit. The constraints of acceptable quality by consumers were imposed, based on the fruit colour. The model enabled selection of the best means of transport with the least loss in quality, minimum costs and the least delivery time. This model was formulated as a mixed integer program (MIP) and implemented in CPLEX® solver. Most of the planning models are also aimed at ensuring timely delivery of fresh produce based on deterministic assumptions and demand that does not incorporate uncertainty (Ahumada *et al.*, 2012; Soysal *et al.*, 2012). There has been increased interest in planning models that incorporate uncertainty in some of its variables since a majority of the real-life scenarios involve uncertain weather conditions, yield, demand and product prices (Soysal *et al.*, 2012). Some of the planning models have incorporated uncertainty in crop yields and market prices (Soysal *et al.*, 2012), uncertain juice acidity parameters in blending of fruit juices from different sources (Munhoz and Morabito, 2014) and more recently a planning model that considered uncertain demand from consumers in selecting the best growers to supply tomatoes to different grocery shops (Mateo *et al.*, 2016).

With respect to transportation, the major parameters that are commonly determined by planning models are the routes to take, quantities of products to be supplied through each route and selection of transportation mode from a range of options depending on the attributes of each (Tsolakis *et al.*, 2014). Models that have transportation components are often geared towards supply of goods of superior value to consumers at competitive prices while complying with a host of pre-set regulations and performance criteria (Tsolakis *et al.*, 2014). A study by Rong *et al.* (2011) developed a supply planning model that minimized the total costs, including the production and transportation costs, the cooling costs for transportation and storage facilities, as well as storage and waste management costs. The problem was formulated using a mixed-integer linear model and implemented in CPLEX® solver. Its objective was to choose the best distribution network that met consumer quality constraints based on distribution and storage temperature profile of the products while minimizing the overall supply costs. The study however took a deterministic approach and did not factor aspects of temperature abuse.

2.9.2 Modelling tomato quality changes during transportation and storage

In general, two broad approaches have been used to model food quality attributes. The systems approach focuses on the totality of food quality attributes in a broad sense and enables prediction of a wide scope of food quality changes during their movement in the supply chain

(Vorst, 2000). On the other hand, process-oriented approaches usually break down the problem (decomposition) in order to capture biological, chemical, physical and biochemical processes occurring in fresh foods (Tijskens and Schouten, 2014). Fundamental knowledge is used to predict the future behaviour of the product, under any circumstances (Tijskens and Schouten, 2014). Sloof *et al.* (1996) presented a procedure for conceptualizing a quality change model that involved three systems, namely, product behaviour (the dynamic model), coupled with the quality assignment model and an environmental model. This approach presents distinct advantages as opposed to methods where block systems are used. For instance, such procedures yield models that can be used in other applications with appropriate adjustments.

Some researchers have considered fresh tomatoes as a system having a fixed shelf-life while others have modelled with the notion of variable perishability as a function of the prevailing environmental conditions (Rong *et al.*, 2011). The firmness and colour of tomato are the most important quality attributes to consumers (Schouten *et al.*, 2007a). These parameters have been widely modelled as quality indicators of tomato stored under different environmental conditions (Schouten *et al.*, 2007a; 2007b). Equations 2.1 and 2.2 are tomato quality deterioration models developed by Schouten et al. (2007a). Equation 2.1 and 2.2 gives the colour and firmness changes, respectively, as function of time.

$$Red(t) = Red_{max} + k_{pre}.\Delta t_C \frac{factor\ 1.\ factor\ 2}{factor\ 2 + (Red_{ref} - Red_{min})e^{factor\ 1(k_{Rpre}.\Delta t_C - k_{Rpost}.t)}} \tag{2.1}$$

$$F(t) = (F_{ref} - F_{fix})e^{-k_{Fpost}.t - k_{Fpre}\Delta t_F} + F_{fix} \tag{2.2}$$

Where Red(t) is the development of red pigment at a given time t after harvest, Red_{max} ln 1000/G is the asymptotic colour value at $+\infty$, Red_{min} ln1000/G is the asymptotic colour value at $-\infty$, G is the green colour intensity, k_{Rpre} the reaction rate constant during pre-harvest, Red_{ref} arbitrarily chosen reference colour during post-harvest, Δt_C is the colour biological age in days needed to change the colour from Red_{ref} to Red_0 and k_{prec} is the rate of formation of red colour precursor compounds. Factor 1= Red_{max}+k_{Prec}.Δt_c-Red_{min}, Factor 2 = Red_{max}+k_{Prec}.Δt_c-Red_{ref}, R_0 is the colour at harvest, k_{Rpre} is assumed to be equal to k_{Rpost} at the mean growth temperature over the last six weeks prior to harvest, k_{Fpre} and k_{Fpost} is the reaction rate constant for the firmness breakdown before harvest and after harvest, respectively. F_{fix} invariable part of firmness at infinite time, F(t) the firmness decay during post-harvest with respect to time t, F_{ref} an arbitrary reference firmness and Δt_F the firmness biological age in days needed to change the firmness from F_{ref} to F_0. F_0 is the firmness at harvest.

All the rate constants are temperature dependent and follow the Arrhenius Law given by Equation 2.3.

$$K = K_{ref}.e^{\frac{E_a}{R}.(\frac{1}{T_{ref}}-\frac{1}{T})} \qquad (2.3)$$

Where T, Tref, Ea and R are the absolute temperature (K), arbitrarily chosen reference temperature, activation energy (J mol^{-1}) and universal gas constant (8.314 J mol^{-1} K^{-1}), respectively.

Other quality models for tomato and other FFV products have been developed by Schouten *et al.* (2002), Munhoz and Morabito (2014), and applied in predicting their shelf-life and keeping quality of various FFV.

The work by Giannakourou and Taoukis (2003) represented the vitamin C loss in frozen vegetables using first order reaction kinetics using Equation 2.4.

$$C = C_0.e^{-kt} \qquad (2.4)$$

Where C_0 and C are the initial concentrations of vitamin C and concentration of vitamin C at time t, respectively. k is the reaction rate constant of vitamin C loss.

Their kinetic model allowed the predication of the remaining shelf-life of frozen vegetables under non-isothermal conditions, mimicking the realities of fluctuating temperature during distribution of fresh fruits and vegetables. This model, however, considered only the thermal effect that can occasion vitamin C losses and used room temperature to model the kinetics of vitamin C. A similar study by Amodio *et al.* (2015) developed shelf-life models of fresh rocket based on the degradation kinetics of vitamin C under isothermal and non-isothermal conditions at various storage temperatures. The study showed that vitamin C degradation kinetics closely followed the trends in the overall quality score. These models are potentially useful for planning the distribution and storage of FFV, especially tomato fruit that has vitamin C as one of its important nutrients. The good correlation of internal quality and the overall appearance make these models important tools for predicting the overall quality of FFV since they give an indication of the nutritional and physical quality.

Batch models describe the changes in quality attributes of products or an individual product using probability theory as a function of time by combining quality models (Tijskens and Schouten, 2014). This approach allows the estimation of the biological age of each product in a batch along the supply chain. Biological age, in this case, is the time necessary for a property (e.g. colour or firmness) to change from an initial condition to an arbitrarily-selected reference (Schouten *et al.*, 2007a; 2007b). Batch models that combine firmness and colour with consumer limits in fresh tomato supply chains have been used by Schouten *et al.* (2007b) to provide purchase periods, between which batches change from being acceptable (unripe-ripe) and end with a batch becoming unacceptable (ripe-overripe).

2.10 Conclusion

This review has shown the critical role transportation plays on the postharvest quality changes of tomato fruit. The importance of transportation systems and conditions during supply of tomatoes will become even more critical as supply chains in emerging markets become more integrated and coordinated. The mechanics of tomato fruit damage under an array of transportation conditions (road quality, transit time, vehicle-systems used, packaging materials etc.) are important in implementing sustainable tomato supply chains. The literature shows that there is need to use analytical tools to plan distribution of tomato fruit in South Africa and other emerging economies in such a manner that these supply chains operate efficiently and deliver quality fresh tomatoes at competitive prices, in a sustainable way. Thus, supply chain planning models are critical for ensuring the efficient performance of fresh tomato value chains.

The development of nutrient loss kinetics under various storage and transportation conditions is one of the important ingredients missing in supply chain planning models. For instance, the degradation kinetics of vitamin C has been well-researched and reported for various fruits and vegetables and used to predict their shelf-life, but its use in modelling fresh tomato nutrient changes in supply chain planning models has been limiting. Integrating multiple nutrient degradation kinetics in tomato supply chain planning models could improve the usefulness of such models.

The inclusion of road quality as a contributing factor to fruit damage in tomato supply chain models has not been considered as an addition to environmental factors. The varietal effects and maturity at harvest are some of the other parameters that can be included in tomato supply chain planning models to advance their practicality and usefulness.

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3. EFFECT OF INFIELD HANDLING CONDITIONS AND TIME TO PRE-COOLING ON THE SHELF-LIFE AND QUALITY OF TOMATOES

3.1 Abstract

This study investigated the effects of post-harvest handling practices prior to storage on the quality of tomato fruit in South African supply chains. Pink mature tomatoes were harvested in the morning and afternoon, transported from two farms located 40 km apart to two central pack-houses located within the proximity of each farm in Limpopo, South Africa. The samples were transported using bins (468 kg capacity) and lugs (20 kg capacity). After harvesting, the samples were either immediately transported to the pack-house and precooled within two hours, or left in the field and transported to the Pack-house to be pre-cooled after six hours, to simulate delays during transportation. On arrival at the pack-houses, tomatoes were sampled from the bottom 0.15 m of each lug and bin, forced-air precooled, and washed. After precooling, the samples were stored under ambient and refrigerated storage (15±2 ^{o}C). Tomato colour, firmness, weight loss, marketability and pH were monitored over a 24-day storage period. The rate of change of fruit hue angle was significantly ($p \leq 0.05$) higher for samples handled using bins compared to those handled using lugs. Handling conditions had no significant ($p > 0.05$) effect on the rate of loss in tomato flesh firmness. The bottom layer of the tomatoes handled using bins had 30 % mechanical damage compared to 2 % in lugs. Harvesting in the morning and pre-cooling within two hours improved tomatoes' marketability and reduced weight-loss by up to 200 and 75 kg ton^{-1}, respectively, compared to harvesting in the afternoon and pre-cooling after six hours. The study recommends minimizing the time to pre-cooling, harvesting in the morning and using lugs as fresh tomato industry best practices.

***Keywords**: transportation effect; bin; lug; postharvest quality losses; postharvest practices*

3.2 Introduction

Tomato fruit in its fresh form is an important consumer product and a valuable industrial commodity (Beckles, 2012). It is consumed in virtually all cultures and countries in the world, and enjoys global appeal in meal preparation (Beckles, 2012; Arah *et al.*, 2015). In South Africa, tomato production contributes 24 % of the total gross fresh fruit and vegetable (FFV) production (DAFF, 2015). The Limpopo Province is the major growing area, accounting for over 75 % of the total planted area, with the large-scale commercial growers producing 95 % of the total tomato output (DAFF, 2015).

Tomato fruit, due to its climacteric nature, is highly perishable and its quality starts to deteriorate immediately after harvest. The rate of quality degradation is influenced by both pre- and post-harvest factors (Arah *et al.*, 2015). Some of the pre-harvest factors include plant stresses, crop production practices and pre-harvest practices. Post-harvest factors include handling and storage conditions during and after harvest, and are important agents that can be used to manage post-harvest quality deterioration in FFV supply chains.

In the last 30 years, extensive research in improving the pre-harvest factors affecting tomato fruit production has resulted in a 37 % increase in the global yield (FAOSTAT, 2015). There is, however, a need for investment in post-harvest quality management, as it has been shown that postharvest losses of tomato in some regions in Africa are as high as 40 % (Macheka *et al.*, 2017). There is a scarcity of information quantifying the level of post-harvest losses in the South African tomato supply chains, although recent estimates by Sibomana *et al.* (2016) estimate it to be 10.2 % of the total production. Transportation and post-harvest infield handling practices have been cited as some of the drivers of post-harvest loss downstream in commercial supply chains (Etebu *et al.*, 2013). Storage conditions of FFV particularly in African tropical climate lead to high deterioration rates in quality when not well managed. Studies by Workneh *et al.* (2012) have tested low cost evaporative coolers for long term storage of tomatoes. However, such studies give did not consider practicalities such as temperature fluctuations during supply and distribution of tomatoes, as well as interaction with other postharvest factors such as harvesting and handling practices as critical operations that can affect the physical and nutritional quality of tomatoes.

The quality deterioration of FFV is time and temperature dependent (Jedermann *et al.*, 2014) and deterioration processes continually occur during harvest, and postharvest. It is, therefore, important for the time to precooling of harvested produce to be minimized, coupled with other appropriate measures to minimize the damaging effect of accumulation of field heat in order to maximize the shelf-life of such products (Rab *et al.*, 2013). It has been generally established that a loss of a day of shelf-life in harvested tomatoes occurs for every delay of one-hour in precooling after harvesting (Arah *et al.*, 2015). Similarly, the accumulation of field heat in harvested fruit can be minimized by scheduling harvesting periods to cooler times of the day (Arah *et al.*, 2015).

There are numerous studies that have investigated the effect of pre-cooling on the shelf-life and quality of tomato (Acedo Jr *et al.*, 2009; de Castro *et al.*, 2005; Rab *et al.*, 2013). However, none of these studies has accounted for practicalities in the commercial supply chains, particularly the logistical backlogs that hinder efficient and quick transportation of harvested produce from the field to the cooling units. This study aimed at establishing the effect of time to pre-cooling, harvesting time, as well as the handling and storage conditions, on the quality and shelf-life of commercially-produced fresh tomatoes in South Africa.

3.3 Materials and Methods

3.3.1 Tomato fruit samples

Tomatoes (*Solanum lycopersicum* cv. Nemo-Netta*)* were harvested at the pink maturity stage on two farms located in the Limpopo Province, South Africa. The farms were situated in Rietpol (23°47’2.335” S 29°29’59.189” E) and Dikgale (23°39’22.903” S 29°45’16.117” E) during the summer season (harvested on 25th March 2016). The tomatoes from Rietpol and Dikale farms were then transported to their respective pack-houses situated at 23°44’0.103” S 29°35’5.362” E (PH1) and 23°39’53.294” S 29°45’1.151” E (PH2), respectively. These farms and pack-houses typified operations of some of the largest commercial tomato growers in South Africa. During transportation, the sample tomatoes were packed in either a large plastic crate, referred to as a bin (2 m x1 m x 0.4 m), or smaller plastic crate, referred to as a lug (0.5 m x 0.4 m x 0.3 m). A pictorial presentation of the bin and the lug is shown in Figure 3.1.

Figure 3.1 A photographic presentation of a large plastic bins (A) and smaller lugs (B) used to transport tomato fruits to the pack houses under commercial conditions

In each farm, two bins and lugs were harvested in the morning (07:00) and another set harvested in the afternoon (13:00). One bin and a lug were immediately transported to the pack-house after harvesting, and pre-cooled within two hours of harvesting, while the other set was left outside and pre-cooled six hours later to simulate logistical delays. The pack-houses in Rietpol and Dikgale were 20 km and 5 km respectively, from the field where the fruit was harvested.

3.3.2 Sample preparation

Upon receiving the samples at the pack-house, the samples were pre-cooled in a forced-air mechanical cooler (Carrier, USA) until the samples reached 13 ºC, which typically took 1±0.25 hours. A total of 120 tomatoes were then sampled from the bottom 0.15 m of each bin or lug, and dipped in 0.1 % v/v Sporekill® (ICA International Chemicals Pty, Stellenbosch, South Africa), a fresh fruit disinfectant containing 120 g L^{-1} didecyldimethyl ammonium chloride for three minutes. The excess Sporekill® solution was thereafter blotted off from the fruit surfaces using a paper towel, then put in a carton (0.40 m by 0.30 m by 0.25 m), with each carton having 30 tomatoes. The samples were thereafter stored in ambient conditions typically ranging from 19-30 °C or cold storage units set to operate at 13-17 °C.

3.3.3 Experimental design

The experiment was set up in a Randomized Complete Block Design, with the two handling conditions (bins and lugs), two harvesting times (morning and afternoon), two storage temperatures (ambient and cold storage) and two times to pre-cooling (2 and 6 hours) as the factors. The two pack-houses were used as the blocks. The experiment was dulicated, and the four boxes of fruit from each lug and bin randomly assigned to the two storage environments.

3.3.4 Data collection

Tomato fruit colour, firmness, product temperature, marketability, weight loss and pH were measured over a 24-day storage period, with sampling on Day 1, and after 4, 8, 16 and 24 days of storage. On-site assessment of these quality parameters was carried out, briefly as follows:

3.3.4.1 Fruit temperature

The surface temperature of six tomatoes from each replicate was measured using an infrared thermometer (ST677, AssTech Instrumentation, Randburg, South Africa).

3.3.4.2 Colour

The colour of the six fruits from each replicate was measured using a Konica Minolta Chroma meter (Model CR-400, Narachi Pty, South Africa). Readings were taken at an observer angle of 2^{o}, after standardizing with a white tile (Y = 93.8, X = 0.3030, y = 0.3191). L* a* b* and *h* values were reported for each reading (Caron *et al.*, 2013).

3.3.4.3 Firmness

Firmness was measured according to the procedure by described by Polenta *et al.* (2015). In brief, the fruit fresh firmness (FFf) of six tomatoes from each replicate was assessed using a durometer (Analog HP fruit firmness tester, Lauderdale, Florida, USA), a hand-held device that measures the firmness of fruit by the force required to indent the fruit skin. Each fruit was tested at three adjacent sites of its equatorial axis and the average reading was recorded.

3.3.4.4 pH

Fruit pH was measured using the procedure described by Tigist *et al.* (2013), briefly as follows: Three fruits from each replicate were each macerated in a fruit blender (Phillips model HR2103, Makro Pty, Pietermaritzburg South Africa) for one minute and the juice was extracted into a beaker, using a muslin cloth. The pH of the juice was then measured using a pH meter (HI98118, Hanna instruments Pty, South Africa). The data were recorded in triplicate.

3.3.4.5 Weight-loss

The weight-loss of the tomato fruit was measured by labelling and weighing two batches of three fruit from each replicate on each sampling day. This procedure followed the method described by Caron *et al.* (2013). The fruits' weight-loss was calculated relative to Day 1 by quantifying the reduction in weight at each storage period as a percentage of the initial weight.

3.3.4.6 Subjective quality analysis

The subjective quality assessment of stored products was carried out briefly as follows: Visual assessment of incidences of decay, shrinkage and emergence of post-harvest disorders was made on fruit in each box. Marketability was estimated according to Workneh *et al.* (2012), where, fruit that would ordinarily be sellable was quantified as a percentage of the initial quantity of stored fruit, on each sampling day. Damaged, decayed, or overripe fruit was considered unmarketable, and was removed from the stored samples.

3.3.5 Data Analysis

All the data collected was analysed using SPSS version 24 (IBM, USA). General analysis of variance was used to assess the effect of handling conditions, harvesting time, time to pre-cooling and storage conditions on the shelf-life, quality and marketability of the stored tomatoes stored under in-field storage conditions. The rate of change in colour and firmness was calculated over each storage interval.

3.4 Results and Discussion

3.4.1 Storage temperature conditions

The variation in ambient and fruit surface temperature of fruit stored in Rietpol Packhouse (PH) and Dikgale Packhouse (PH2) are shown in Figure 3.2 (A) and Figure 3.2 (B), respectively. The ambient and surface temperature of sample fruit stored in PH2 was higher than that of fruit stored in PH1. Higher ambient temperature conditions resulted in higher fruit surface temperature in the fruit stored in PH2 compared to that of fruit stored in PH1.

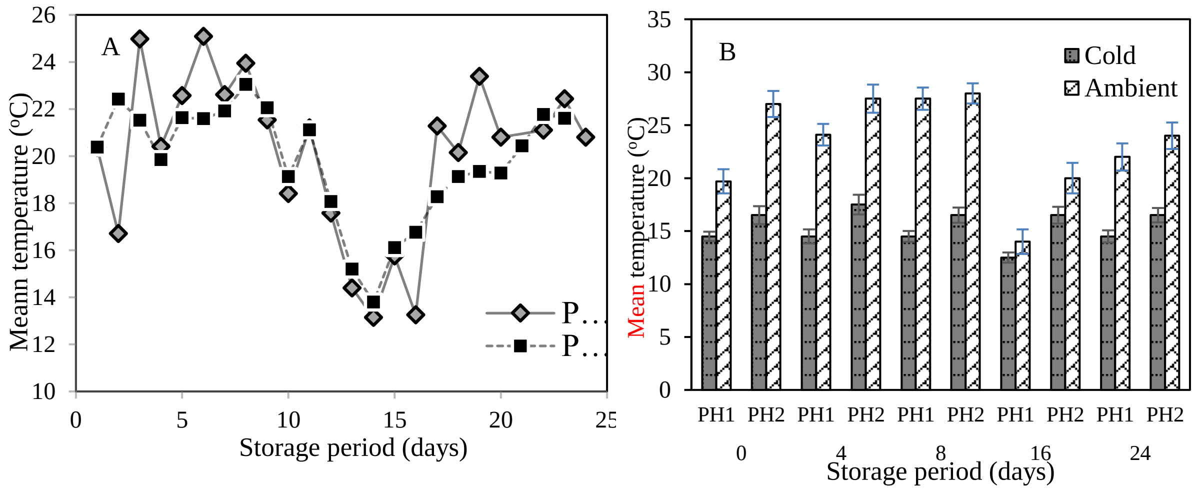

Figure 3.2 Surface temperature of tomato fruit stored in ambient and cold storage conditions (A), and ambient temperature conditions at Rietpol (PH1) and Digale (PH2) pack-houses (B)

3.4.2 Fruit quality changes

3.4.2.1 Colour

The hue angle *(h)* measures the colour of food products on a 360° colour space (Pinheiro *et al.*, 2015). Angles of 90^{o} are assigned to a yellow hue, 180^{o} green hue, 270^{o} blue hue and 0^{o} red hue (Pinheiro *et al.*, 2015). The fruit *h* gradually reduced over the storage period for all treatment conditions, typifying the progression of ripening as colour changed from green to red. There was a significant ($p \leq 0.05$) reduction in the fruit *h* between successive sampling days over the storage period. Handling conditions and harvesting time had a significant ($p \leq 0.05$) effect on the *h* of samples stored in PH1. Time to pre-cooling had no significant ($p > 0.05$) effect on the *h* of tomato fruit handled and stored in PH1.

Similarly, the *h* reduced gradually over the storage period for samples stored in PH2 with significant changes ($p \leq 0.05$) between sampling Days 0, 4, 8 and 16. The difference in *h* between sampling Days 16 and 24 was, however, not significant ($p > 0.05$). This may be attributed to a higher rate of deterioration of these samples due to the relatively higher temperature conditions in PH2 compared to PH1 (Figure 3.2A). Handling conditions in sample fruit stored in PH2 was the only significant ($p \leq 0.05$) factor affecting the reduction in *h*. As expected, the reduction in *h* of tomatoes stored in ambient conditions was higher than that of fruit stored in cold storage, based primarily on the natural relationship of temperature and the rate of biochemical reactions. The samples handled using bins also showed a higher rate of colour change compared to those handled using lugs across the two pack-houses (Figure 3.3). In PH1, best treatment for fruit stored under cold storage was those precooled within 2 hours (2 hour-precooled) and morning harvested tomato (Bins) and 2 hour-precooled and afternoon harvested samples (Lugs), while ambient stored samples showed the best treatment to be 2 hour-precooled and morning harvested samples (Bins and Lugs). In PH2, samples stored in cold storage (Bins), 2 hour-precooled samples harvested in the afternoon appeared to be the best in retaining its colour, and those handled using lugs clearly showed that samples harvested in the morning and precooled within 2 hours to have the least rate of change in colour. In ambient stored samples, both the lugs and bins showed that morning harvested and 2-hour precooled samples were the best samples, in terms of the retention of colour. The rate of colour change indicated by *h* peaked between Day 1-4 of storage, and decreased in subsequent storage periods (Figure 3.3) an observation that can be corroborated by Hurr *et al.* (2005). Studies reported in the literature show that changes in the colour of tomato fruit of other maturity stages behaved differently (Hurr *et al.*, 2005). For instance, the study by Tadesse and Abtew (2015) showed that the rate of degradation in colour of green mature tomato peaked between day 4-8.

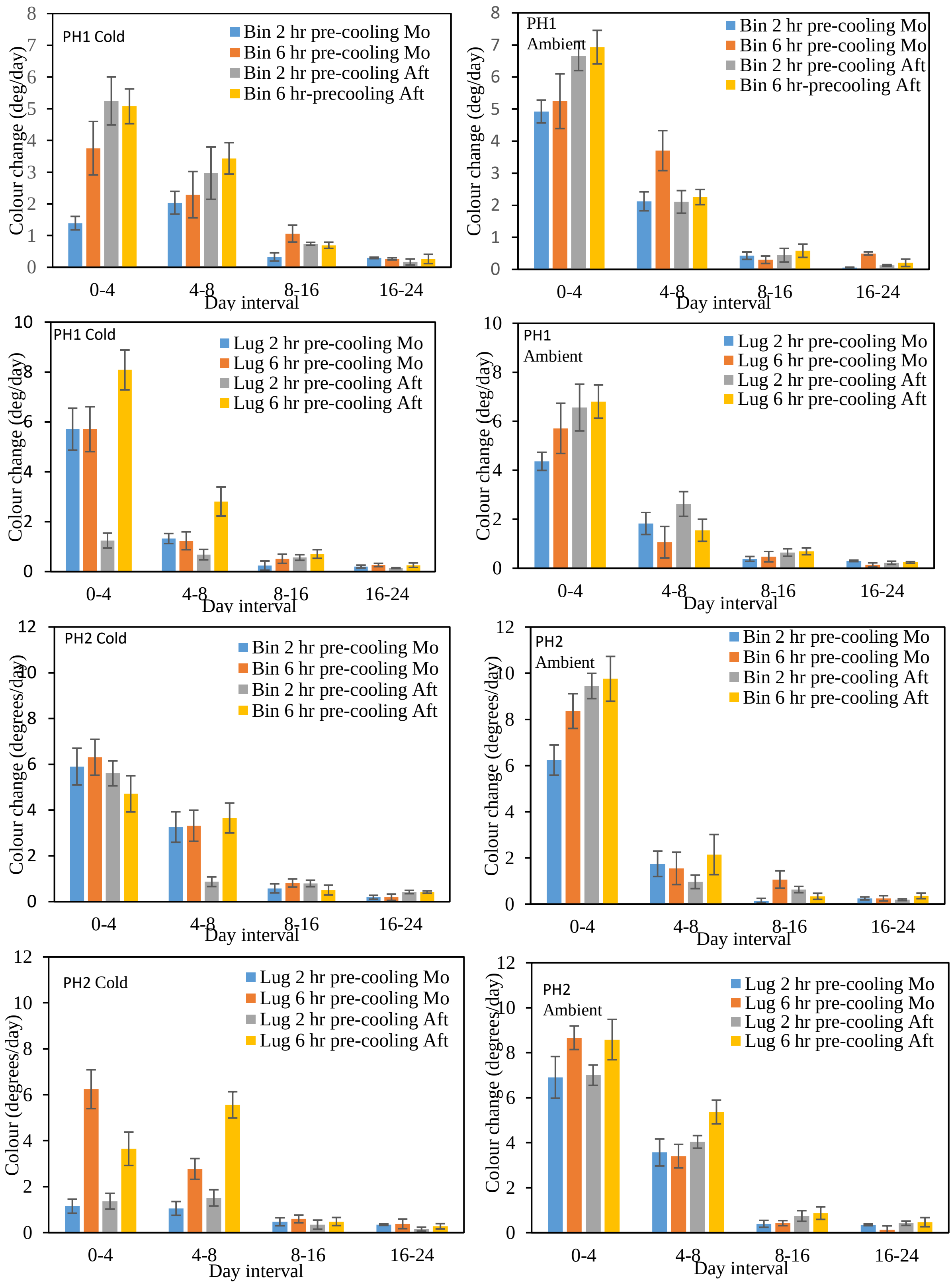

Figure 3.3 Effect of handling using lugs or bins on the rate of fruit colour change of tomatoes subjected to different times to precooling and harvesting times of the day

This observation underscores the importance of handling practices that reduce the rate of deteriorative processes immediately after harvest such as minimisation of the time to precooling and subsequent maintenance of the cold chain of pink harvested tomato. It has been well established that the degradation of colour components of fresh fruits follow first order reaction kinetics that render them possible to obtain the temperature-dependent kinetic constants (Moura *et al.*, 2011). These constants increase concomitant with storage temperature following the Arrhenius law (Pinheiro *et al.*, 2015). This may explain the higher rate of colour change in ambient stored tomato compared to cold stored tomato.

Degradation of tomato fruit colour is related to handling conditions, cooling practices and harvesting practices. As demonstrated in this study, the reduction of time to precooling and scheduling harvest to cooler times of the day had a beneficial effect on the colour of harvested tomato and are important contributors in maintaining its quality. In the context of this study, even though the time to precooling showed a minor positive effect on tomato fruit colour, Acedo Jr *et al.* (2009) recommended hydro-cooling as an effective alternative to room and forced air cooling. However, strategies to manage fruit decay should be put in place as hydro-cooling may promote fruit decay. Combining hydro-cooling with disinfectant solutions during wet dumping may be suggested to the industry as the first step of efficiently removing field heat.

South African consumers prefer fruit at the pink to light-red tomatoes, due to their perceived freshness, and consider red tomatoes to have a shorter shelf-life, which results in their association with a lower market value (Vermeulen and Bienabe, 2010). The maintenance of colour by improving handling and harvesting conditions is one of the avenues of improving the quality and market value of tomato fruit produced and supplied through commercial set-ups in South Africa.

3.4.2.2 Changes in fruit flesh firmness (FFf)

Fruit flesh firmness gradually decreased over the storage period and was significantly ($p \leq 0.05$) lower for each successive sampling day, for samples stored in both PH1 and PH2. Time to pre-cooling and storage conditions had a significant ($p \leq 0.05$) effect on the product firmness in PH1, while time to precooling, harvesting time and storage conditions significantly ($p \leq 0.05$) influenced the product firmness in PH2. The rate of reduction in firmness was comparatively higher for ambient stored samples compared to those stored in cold storage, a phenomenon expected from a physiological perspective due to the temperature difference between the two storage conditions (Figure 3.2A). It was somewhat surprising that handling conditions appeared to have no significant ($p>0.05$) effect on the rate of reduction in firmness of samples stored in PH1 and PH2. Shorter time to pre-cooling and cooler harvesting periods had a positive effect in retarding the rate of loss of firmness in cold-stored samples in PH2 (Figure 3.4). However, samples in ambient storage in PH2 showed a minimal improvement in the loss of firmness, even with shorter times to pre-cooling and cooler harvesting periods. A similar observation was also made for cold-stored samples in PH1. In contrast, shorter times to pre-cooling and harvesting at the cooler times of the day were important factors in slowing firmness loss for ambient stored samples in PH1. The rate of firmness reduction peaked between day 4 and 8 (Figure 3.4), and declined over the subsequent storage period. This is consistent with observations by Tijskens *et al.* (1998) that showed that polygalacturonase (PG) activity in stored tomato fruit peaked during day 4-7 depending on the storage temperature. Another study by Hurr *et al.* (2005) observed an increased rate of reduction in firmness of pink mature tomato over a 2-4 day interval, while in storage at 20 ^{o}C. In the same study, fruit of other maturity stages behaved differently.

This suggests that the kinetics of firmness degradation in tomato is dependent on the storage temperature and maturity stage. It appeared that the reduction in firmness of fruit stored in lower temperature conditions depict exponential, first order kinetics (Figure 3.4). It has been suggested by Pinheiro *et al.* (2013) that kinetics of tomato firmness follow Arrhenius fractional conversion kinetic model.

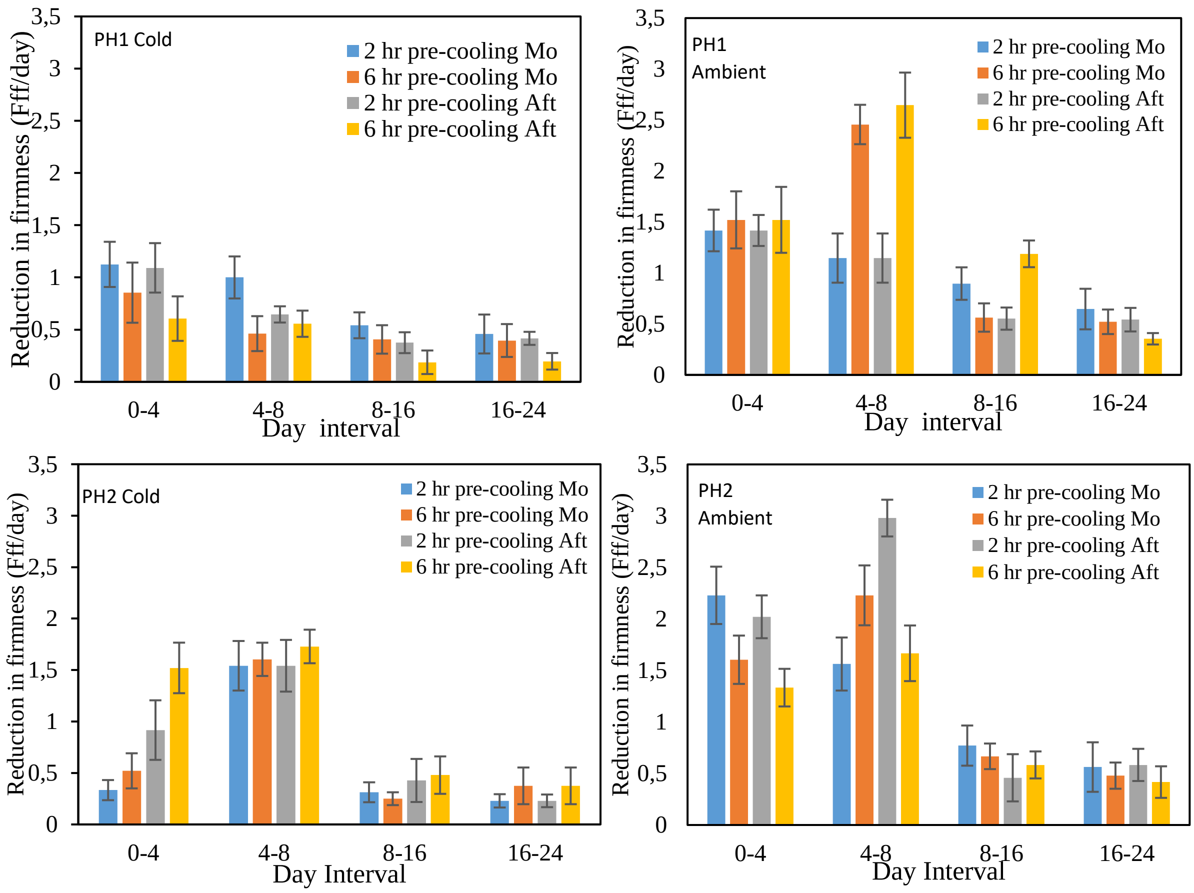

Figure 3.4 Effect of various postharvest practices on the rate change of tomato fruit firmness. PH1 and PH2 are 40 and 5 km from their respective Pack houses, with a majority of road length connecting the farm to PH1 being of smoother road length than PH2. PH1 mainly comprised of dirt road.

Loss of firmness in tomato is an enzymatically-controlled process that results in its reduction due to the breakdown of cellulose, pectin and lignin by pectinesterase (PE), polygalacturonase (PG) and β-galactosidase (β-gal) in the cell wall (Tigist *et al.*, 2013). Enzyme-controlled processes are temperature-dependent. The factors that significantly affected product firmness in the two pack-houses differed. Temperature control may be the underlying factor for this difference where time to pre-cooling or cold storage were important in maintaining the cold chain in PH1 pack-house, while all the other factors except the handling condition were important in PH2 pack-house.

The shorter transport distance may be the underlying factor explaining the non-significance of handling condition as an important factor in controlling the firmness of samples stored in PH2 pack-house, while better road conditions (95 % Class A road) for transport route to PH1 explained the non-significance of this factor on the firmness of the samples. The cooler temperatures during harvest at the farm supplying tomato to PH1 (Figure 3.2A) and subsequent storage in cold room meant that the cold chain was generally maintained, explaining the minimal effect time-to precooling, and time of harvest had on the product firmness. In PH2, which had relatively higher ambient temperatures during harvest, shorter time to pre-cooling and harvesting in the morning were important factors to cold-stored samples, and is suggestive that they may have retarded enzymatic activities by continuous maintenance of the cold chain over the storage period. Shorter time to pre-cooling and storage in ambient conditions in PH2 may have also resulted in tomatoes experiencing cold chain breaks or temperature abuse described by Sibomana *et al.* (2017). Further research should be carried out on the heat flow around the products in lugs or bins, using tools such as computational fluid dynamics (CFD), to establish the temporal and spatial distribution of heat around the products under various stacking patterns, storage and handling conditions.

3.4.2.3 Weight loss

Fruit weight loss significantly ($p \leq 0.05$) increased between successive sampling days, and was significantly ($p \leq 0.05$) higher for samples transported using bins than lugs for both pack-houses. Similarly, the fruit weight loss of samples stored in ambient storage was significantly ($p \leq 0.05$) higher compared to that of fruit stored in cold storage. Harvesting time significantly ($p \leq 0.05$) influenced the weight loss of samples stored in PH1 pack-house, while the time to precooling was also a significant factor, affecting the weight-loss of fruit stored in PH2. Reduction of the time to pre-cooling, harvesting in cooler times of the day and storage in ambient or cold temperature conditions in PH1 had varied effects on the weight loss of the samples handled in bins and lugs. In PH2 the reduction in time to precooling and harvesting in the morning had a positive reduction in the weight loss of both ambient and cold-stored samples handled using bins or lugs, with morning harvested samples precooled after 2 hours showing the least weight loss for both handling and storage conditions (Figure 3.5). The differences in weight loss between samples of PH1 that had been 6hr precooled mo and 6hr precooled aft, had the morning samples record higher weight loss. The effect of harvesting in the morning was in this case negated due to afternoon rain during harvesting

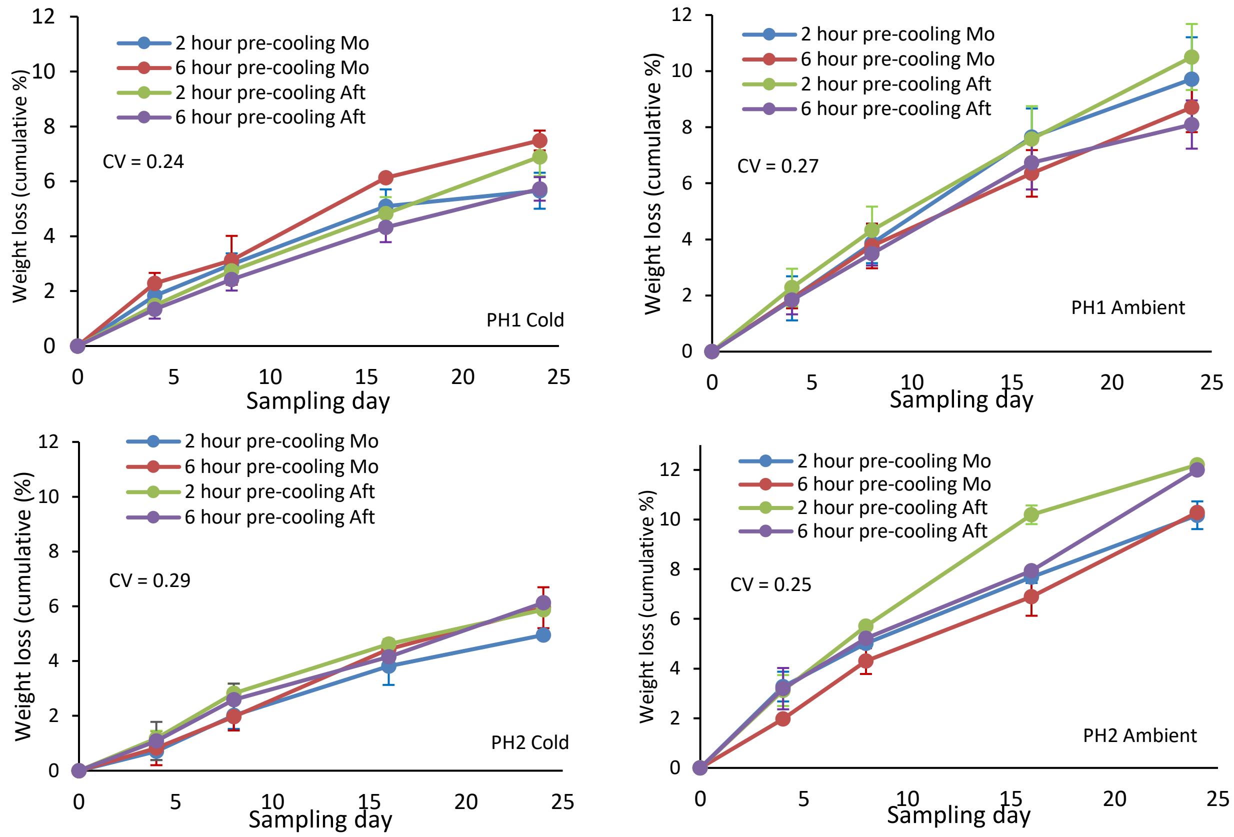

Figure 3.5 Cumulative weight loss of ambient and cold-stored sample tomato fruit as influenced by various postharvest practices with storage period. PH1 and PH2 are 40 and 5 km from their respective Pack houses, with a majority of road length connecting the farm to PH1 being of smoother road length than PH2. PH1 mainly comprised of dirt road.

Fruit weight loss is primarily driven by evapotranspiration (Arah *et al.*, 2015) and the rate of respiration (Rab *et al.*, 2013). These processes are both RH and temperature-dependent. Water loss and respiration in stored tomato are primarily influenced by storage temperatures, where higher storage temperatures trigger higher weight loss. As observed in this study, ambient stored samples showed higher weight loss than those stored in cold storage. This observation is consistent with findings reported by Islam and Morimoto (2016).

Higher storage temperatures in PH2 amplified the effects of both time to pre-cooling and the harvesting time on fruit weight loss, the effects of which, in some cases, were not clearly apparent in PH1, due to the lower storage temperatures. Respiration is also driven by mechanical injuries that may trigger undesirable metabolic processes that accelerate ripening, hence weight loss (Opara and Pathare, 2014). Products handled using bins exhibited a higher percentage of mechanical injuries (Figure 3.6). In addition to loss in quality, relatively higher rate of respiration may have occurred in tomato handled in bins explaining the higher weight loss observed. Water loss in tomatoes lead to significant economic losses. Even small quantities of water loss in FFV lead to excessive shrivelling and wilting leading to not only loss of consumer appeal but also significant reduction of their economic value.

3.4.2.4 pH changes

Product pH gradually increased over the storage duration with significant ($P \leq 0.05$) differences being observed between successive sampling days. Storage and handling conditions, significantly ($P \leq 0.05$) influenced the pH of products stored in both pack-houses, while the time of harvest was not a significant ($p > 0.05$) contributor of differences in pH for samples of all treatments.

Fruit pH increased with storage period in all treatment conditions (Table 3.1), an observation that is in agreement with findings by Anthon *et al.* (2011). It is also notable that the pH values of samples stored in PH2 were higher than those in PH1, and this is suggestive that pH can be used as an indicator of the rate of deterioration, where samples with higher pH can be deductively inferred to be nearing their senescence. The increase in pH over the storage period is partially attributed to the progression in fruit ripening, which causes the loss of acid content, due to its conversion to sugars through gluconeogenesis (Anthon *et al.*, 2011).

The pH of tomato is an important quality parameter that is influenced by the acid content of the fruit (Arah *et al.*, 2015). Tomato is considered to be a low pH fruit and this has a bearing on both its resistance against microbial attack and the sensory characteristics (Etebu *et al.*, 2013). It is generally desirable to maintain the pH of tomato fruit during storage at optimum levels (pH of 4.25), as higher pH values result in tomato fruit with altered flavour (Anthon *et al.*, 2011). The use of cold storage, the minimization of multiple handling processes and prevention of fruit overloading by process re-design (e.g. the use of modular bins, instead of the standard bins in bulk handling system) could reduce fruit damage as demonstrated in Table 3.1, that depicts a lower rate of increase in pH for tomato products handled using lugs.

Table 3.1 Variation of the mean pH of tomato fruit transported using lugs and bins with storage. Harvesting was done in the morning and afternoon, and the fruit precooled within 6 and 2 hours after harvesting. PH1 and PH2 designates samples stored in Rietpol and Digale pack-house, respectively

		Treatments							
Day	**Pack-house**	Handling		Time to precooling		Time of harvest		Storage	
		Bins	Lugs	2 hours	6 hours	Morning	Afternoon	Cold	Ambient
0	PH1	3.97 ± 0.08^{a}	3.94 ± 0.07^{a}	3.98 ± 0.06^{a}	3.93 ± 0.08^{a}	3.90 ± 0.08^{a}	4.01 ± 0.05^{b}	3.90 ± 0.08^{a}	3.97 ± 0.07^{a}
	PH2	3.99 ± 0.05^{a}	3.90 ± 0.08^{b}	3.94 ± 0.05^{a}	3.82 ± 0.09^{a}	3.96 ± 0.07^{a}	3.93 ± 0.07^{a}	3.92 ± 0.08^{a}	3.95 ± 0.07^{a}
4	PH1	4.19 ± 0.10^{a}	4.14 ± 0.06^{a}	4.18 ± 0.07^{a}	3.99 ± 0.10^{b}	4.21 ± 0.10^{a}	4.12 ± 0.06^{b}	4.14 ± 0.11^{a}	4.16 ± 0.06^{a}
	PH2	4.10 ± 0.05^{a}	4.06 ± 0.05^{a}	4.09 ± 0.05^{a}	4.07 ± 0.05^{a}	4.07 ± 0.06^{a}	4.10 ± 0.05^{a}	4.07 ± 0.05^{a}	4.07 ± 0.06^{a}
8	PH1	4.27 ± 0.09^{a}	4.28 ± 0.09^{a}	4.32 ± 0.10^{a}	4.23 ± 0.07^{a}	4.34 ± 0.10^{a}	4.21 ± 0.06^{a}	4.22 ± 0.10^{a}	4.27 ± 0.09^{a}
	PH2	4.23 ± 0.09^{a}	4.21 ± 0.06^{b}	4.21 ± 0.07^{a}	4.23 ± 0.07^{a}	4.21 ± 0.08^{a}	4.23 ± 0.07^{a}	4.14 ± 0.08^{a}	4.26 ± 0.07^{a}
16	PH1	4.45 ± 0.07^{a}	4.34 ± 0.09^{b}	4.45 ± 0.08^{a}	4.48 ± 0.08^{a}	4.40 ± 0.11^{a}	4.40 ± 0.05^{a}	4.35 ± 0.08^{a}	4.42 ± 0.09^{a}
	PH2	4.42 ± 1.00^{a}	4.37 ± 0.06^{b}	4.35 ± 0.07^{a}	4.44 ± 0.08^{a}	4.37 ± 0.08^{a}	4.42 ± 0.08^{a}	4.35 ± 0.06^{a}	4.42 ± 0.10^{a}
24	PH1	4.56 ± 0.09^{a}	4.52 ± 0.10^{a}	4.56 ± 0.09^{a}	4.52 ± 0.11^{a}	4.56 ± 0.10^{a}	4.52 ± 0.09^{a}	4.42 ± 0.07^{a}	4.63 ± 0.07^{b}
	PH2	4.64 ± 0.09^{a}	4.57 ± 0.09^{a}	4.60 ± 0.07^{a}	4.61 ± 0.11^{a}	4.59 ± 0.09^{a}	4.62 ± 0.10^{a}	4.49 ± 0.05^{a}	4.68 ± 0.09^{b}

Rows with different letters pairwise designates significant difference ($p<0.05$) All values are mean±SEM

3.4.2.5 Subjective quality analysis

During sampling, approximately 30 % of samples at the bottom of the bins showed cracks and flattening (Figure 3.6) while <2 % of fruit transported using lugs depicted minor side cuts. Fruit transported in lugs also appeared to have less bruising injuries compared to those transported using bins and this became more apparent over a longer storage duration (Figure 3.6). Differences in samples due to the time to pre-cooling and harvesting time could not be visually discerned.

Figure 3.6 Typical images of tomato products depicting damage at the bottom of bins (A), flattening (C) and cracking (D) of samples transported in bins, as well as side cuts of samples transported in lugs (B). Images on the right depict the long-term effect of bruising on tomato fruit that became pronounced in samples handled in bins (F) compared to lugs (E)

The Sporekill® solution appeared to be effective in managing microbial contamination in the fruit since mould growth was not observed over the entire storage period. However, physiological disorders (cracking, sour rot) were observed towards fruit senescence. These disorders were more prevalent in ambient stored samples after 16 days of storage. Cold-stored samples showed only a minimal number of fruit affected by these disorders, compared to the ambient samples after 16 days of storage, hence the significant ($p \leq 0.05$) differences in marketability between cold and ambient stored samples as depicted in Figure 3.7. At the end of the storage period, fruit stored in cold storage that was harvested in afternoon and the morning had an average marketability of 40 and 45 %, respectively. Similarly, 20 and 25 % of fruit stored under ambient conditions was marketable at the end of the storage period for the afternoon and morning harvest, respectively.

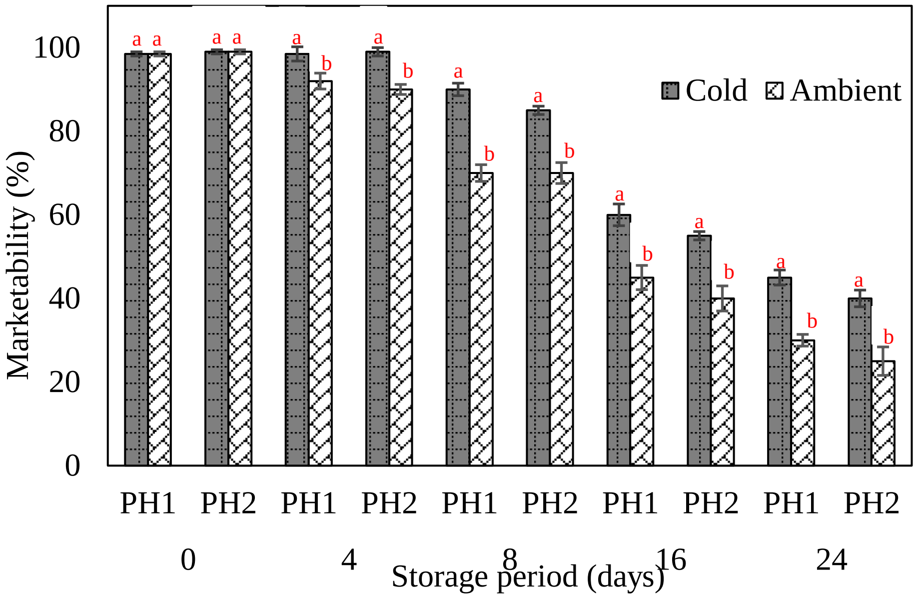

Figure 3.7 Variation of marketability with storage duration for tomato samples stored in Rietpol (PH1) and Digale (PH2) pack houses. The farm supplying fruit to PH1 was approximately 40 km from the pack house and comprised mainly of smoother roads, while the farm suppling fruit to PH2 was approximately 5 km from the pack house and comprised mainly of dirt roads. Bars marked with different letters pairwise are significantly ($p \leq 0.05$) different.

The visual cues of fresh fruits are the first quality attributes that consumers base their buying decisions upon (Siddiqui *et al.*, 2015). Handling conditions and storage temperature appeared to be the major factors that determine the degree of visual damage and the onset of visible physiological disorders. The depth of product-stacking in bins meant that samples at the bottom layer were loaded beyond their bio-yield point, explaining the numerous cracks and flattening depicted by these products. This contrasted with samples transported using lugs that showed minimal bruising. Multiple handling also explained the numerous bruises on fruit transported in bins due to transfer by pouring from the smaller lugs into the larger bins for transport to the pack-houses.

Cold storage is important in maintaining the quality and shelf-life of fresh fruits as lower temperatures slow down deteriorative metabolic processes such as respiration and transpiration based on the Q10 concept (Siddiqui *et al.*, 2015). Cold and ambient stored samples in PH2 had a significantly ($p<0.05$) higher surface temperatures compared to those stored in PH1 (Figure 2b). This may have been due to differences in the cold room temperatures, attributed to maintenance issues in the cold room at PH2, as well as the geographical differences in the location of PH2 and PH1 (about 40 km apart). Their geographical locations may have caused the differences in the prevailing ambient temperature conditions (Figure 3.2A).

3.5 Conclusion

In this study, in-field transportation, handling conditions and harvesting practices in commercial tomato supply chains were investigated with the aim of developing guidelines that improve the fruit quality and shelf-life downstream the supply chain. The results showed that at the end of the storage period, 45 % and 25 % of morning harvested, cold stored tomato and afternoon harvested, ambient stored fruit was marketable, respectively. This translates to a difference of 200 kg ton^{-1} of stored produce. Weight loss mitigation of up to 75 kg ton^{-1} of stored fruit can be achieved by harvesting in the morning, precooling within 2 hours and storing in cold storage, when compared to harvesting in the afternoon, precooling after six hours and storage in ambient conditions, similar to those of PH2. Reducing the time to pre-cooling and harvesting at the cooler times of the day, especially in regions of warm to high ambient temperature conditions is recommended as one of the industry's best practices. It was also noted that, in some instances under industry practices, the delay between harvesting and washing the fruit may be more than 6 hours, therefore the results presented in this study would be conservative in terms of quality deterioration and this further motivates for delay reduction as a recommendation to improve shelf-life. The findings of this study are that sub-optimal storage temperature conditions, cold chain management and handling during transport are the major contributors of post-harvest losses in tomato supply chains. In commercial conditions, multiple handling often increases fruit injuries and exacerbates deterioration in tomato quality by triggering an increase in ethylene production resulting in increased respiration. Process re-design of handling operations to minimize handling steps, and use of modular bins that have dual layers to reduce the depth of tomato fruit during transportation should be assessed by the industry. Further studies should be carried out to establish the spatial and temporal distribution of heat through and around the stacked units and patterns used to handle tomato during pre-cooling, in order to maximize pre-cooling air circulation and heat loss.

3.6 Acknowledgements

The researchers thank the Post-Harvest Innovation Programme (PHI) for funding this research under Grant Number 7/2014, and Tomato Producer Organization (TPO) for the PhD scholarship to the first author. We also thank ZZ2 and Steve Mohale's farm for the provision of sample tomatoes and permitting their facilities and resources to be used in the course of this study.

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4. EFFECT OF TRANSPORTATION CONDITIONS AND PRE-STORAGE TREATMENTS ON THE QUALITY AND SHELF-LIFE OF FRESH TOMATOES IN SELECTED SOUTH AFRICAN SUPPLY CHAINS

4.1 Abstract

This study investigated the effect of various pre-storage treatments and transportation conditions on the quality of fresh tomatoes along three supply chains in South Africa. The experimental design consisted of tomatoes of three maturity stages (red, pink and green), two harvesting seasons (summer and winter), three transportation routes with varying road quality conditions, seven disinfection treatments and two storage environments (ambient or cold storage 11 ^{o}C). Samples were drawn at suitable intervals over a 30-day storage period and fruit colour, firmness, weight-loss, pH and marketability assessed. The Esmefour-Pietermaritzburg route (ZZ) was longer than the Point Drift-Pietermaritzburg (PD) and Steve Mohale's farm-Pietermaritzburg route (EM) by 263.4 and 223.8 km, respectively. Seventy percent of the EM road length had International roughness index (IRI) values less than 2.5 m km^{-1}, while the ZZ and PD routes had 63.0 and 58.0 % of their road length recording IRI values of less than 2.5 m km^{-1}, respectively. The mean hue angle and firmness of fruit stored under cold storage environment was 16.3 and 19.2 % higher than that of fruit stored under ambient conditions, respectively. Samples transported through EM had the highest mean firmness (19.41 N) and marketability (74.5 %), least cumulative mean weight-loss across the two seasons (4.9 %), while samples transported through PD had the best colour retention with an average hue angle of 52.6. Hot water treatment in combination with biocontrol (B-13 yeast isolate) was effective in retarding colour changes in the fruit, while biocontrol treatment in combination with chlorinated water or anolyte water was effective in minimizing fruit weight-loss. Anolyte water and chlorinated water in combination with biocontrol gave tomatoes with better visual appearance and marketability compared to fruit treated with hot water, hot water in combination with biocontrol or tap water (control). This study recommends the timely maintenance of roads in and around farms through which the fruit is transported to the markets, transportation planning that minimizes the overall time that the fruit takes to reach the markets, as well as the maintenance of the cold chain during distribution and storage of fresh tomatoes.

Anolyte water in combination with biocontrol is recommended to the tomato industry as an integrated pre-storage treatment that gives fruit of the highest quality and longest shelf-life.

Keywords: *anolyte water; IRI; road quality; surface disinfection; post-harvest fruit losses*

4.2 Introduction

Fresh tomatoes are affected by numerous postharvest factors that influence their quality and shelf-life after harvest. For this reason, tomatoes are regarded as some of the most perishable fresh foods (Antonious and Snyder, 1994). The nutritional composition of fresh tomatoes makes them an attractive host for spoilage and pathogenic microorganisms (Yoo *et al.*, 2015). Transportation and distribution of fresh tomatoes, as well as the accompanied handling conditions can potentially lead to fruit injury and mechanical damage (Scheerlinck *et al.*, 2006; Verheul *et al.*, 2015). The potential for microbial contamination during processing, storage and distribution is an important factor that can lead to spoilage of tomatoes (Ofor *et al.*, 2009; Shenge *et al.*, 2015). Environmental conditions, including the gas composition of air around the fruit during storage, transportation and distribution of fresh tomatoes are some of the most important factors that influence their postharvest quality (Paull, 1999; Dumas *et al.*, 2003) .

Air temperature and RH influence the rate of metabolic activities in fruits, since these metabolic processes proceed even after harvest (Paull, 1999). The air temperature affects the rate of enzymatic activity and other biochemical reactions based on the Q_{10} concept (Taoukis and Labuza, 2003; Lana *et al.*, 2005). Similarly, air RH influences the moisture loss from fruit through transpiration, by modifying the partial vapour pressure difference between the surrounding air and the fruit (Paull, 1999). The RH of the air can also cause moisture condensation when cold fruits are put in a relatively warm room (Tano *et al.*, 2007). Condensation on the surface of tomatoes is one of the causes of fruit decay and other post-harvest disorders (Peet, 2008). Tomato bruising and impact damage has also been shown to trigger a surge in ethylene production in tomatoes that results in early ripening and a decrease in shelf-life (Scheerlinck *et al.*, 2006; Mutari and Debbie, 2011). Although there are studies reporting the effect of transportation on the propagation of tomato fruit bruising, there are knowledge-gaps regarding the effect of transportation over roads of varying surface profiles, on the quality of tomato fruit under defined commercial conditions.

Temperature and RH control have traditionally been the primary means of extending the shelf-life of fresh tomatoes. However, practicalities during transportation and distribution expose the products to fluctuating temperature, as most commercial value chains, especially in emerging markets, do not utilize refrigerated trucks (de Castro *et al.*, 2005). Alternative novel technologies tailored to mitigate tomato quality losses under commercial supply conditions, should therefore, be developed. Integrated postharvest technologies combine the synergistic effects of individual treatments to maintain the quality of tomatoes (McDonald *et al.*, 1999; Soto-Zamora *et al.*, 2005; Mukhopadhyay *et al.*, 2013). For instance, optimum storage temperature conditions can be combined with a range of pre-storage treatments that modify the microclimate around the fruit (Getinet *et al.*, 2008; Moneruzzaman *et al.*, 2008). Such pre-storage treatments may include the use of various edible coatings, that have been shown to have a significant improvement on the vitamin C content of fresh tomatoes (Dávila-Aviña *et al.*, 2014). Other studies have reported chitosan integrated with other natural compounds to have adequate control over *Rhizopus stolonifer* and *Escherichia coli* in tomato fruit (Ramos-García *et al.*, 2012). Because of the nature of the harvested tomato fruit and the commercial processing conditions, the fruit is exposed to a range of spoilage and pathogenic microorganisms. An adequate disinfection regime is, therefore, necessary to guarantee the safety and shelf-life of such products. Chlorinated water has been the global standard disinfectant for fruits and vegetables. However, its use has also had its share of challenges due to the perceived environmental and health concerns from an increasingly health conscious global consumer population (Boyette *et al.*, 1993). For this reason, some regions have banned the use of chlorinated water for treatment of fruit going to their markets (Gil *et al.*, 2009). There is therefore, the need for alternative disinfectant treatments for tomato fruits and other fresh fruits and vegetables (FFV). These novel disinfectants can then be integrated with other treatments such as edible coatings or cold storage to further improve their effectiveness.

Tomato supply chains in South Africa have become increasingly integrated and vertically coordinated due to the changing structure of global FFV value chains (Louw *et al.*, 2007; Greenberg, 2013). In South Africa, the Limpopo Province contributes approximately 75 % of the total fresh tomato fruit supplied to various markets (DAFF, 2015). The province is ideal for tomato production due to its warm climate and domiciles some of the largest commercial fresh tomato growers in the Southern hemisphere (Louw *et al.*, 2007; Munyeka, 2014). The South African tomato industry is dominated by commercial growers who account for 95 % of the total tomato fruit supplied (DAFF, 2013). The localization of production zones in northern parts of the country necessitates transportation and distribution of fresh tomatoes to areas that are as far as Cape Town. Transportation has been reported to be responsible for up to 20 % of the total postharvest losses of fresh tomatoes in Africa and other emerging economies (Aba *et al.*, 2012). Transportation conditions, including road quality, transportation distances and transit times affect the rate of quality deterioration in fresh tomatoes. The effect of long distance transportation conditions on the postharvest quality of fresh tomatoes has not been studied, especially in commercial value chains in South Africa. In addition, an understanding of how tomato fruit of different maturity stages at harvest respond to different transportation and handling conditions, as well as a host of other integrated treatment technologies in South African supply chains has not been established. The aim of this study was to investigate the effect of various transportation conditions on the postharvest quality of fresh tomatoes harvested at red, pink and green maturity stages in South African supply chains. The study also sought to develop novel integrated pre-storage treatments that would improve postharvest quality and shelf-life of fresh tomatoes under typical commercial conditions.

4.3 Materials and Methods

4.3.1 Tomato fruit samples

Tomato fruit (*Solanum lycopersicum*) of Nemo-Netta variety was obtained from three farms in Limpopo Province located in Esmefour (22°19’48.7” S 30°28’21.3” E), Pont drift (22°11’52.7” S 29°11’30.7” E) and Mooketsi (23°26’05.2” S 30°26’47.5” E). The fruit was harvested at three maturity stages (red, pink and green). The harvested tomatoes were graded, and non-defective fruit packed in plastic bins 2 m in length, 1 m wide and 0.4 m deep.

4.3.2 Transportation conditions

The fruit was transported to the fresh produce market in non-refrigerated trucks along three supply routes, namely, Point Drift to Pietermaritzburg (PD), Mooketsi to Pietermaritzburg (EM) and Esmefour to Pietermaritzburg (ZZ), which had varying road surface profiles. On arrival in Pietermaritzburg, the tomatoes were taken to the Bioresources Engineering laboratory of the University of KwaZulu-Natal for application of pre-storage treatments, storage and analysis. The trucks were driven at 80 km h^{-1} on highways and 60 km h^{-1} on rough roads.

4.3.3 Experimental design

The experimental design consisted of three transportation conditions (varying distances and road quality), three maturity stages at harvest, two storage conditions and seven pre-storage treatments, arranged in full factorial design. A schematic of the experimental design is shown in Figure 4.1.

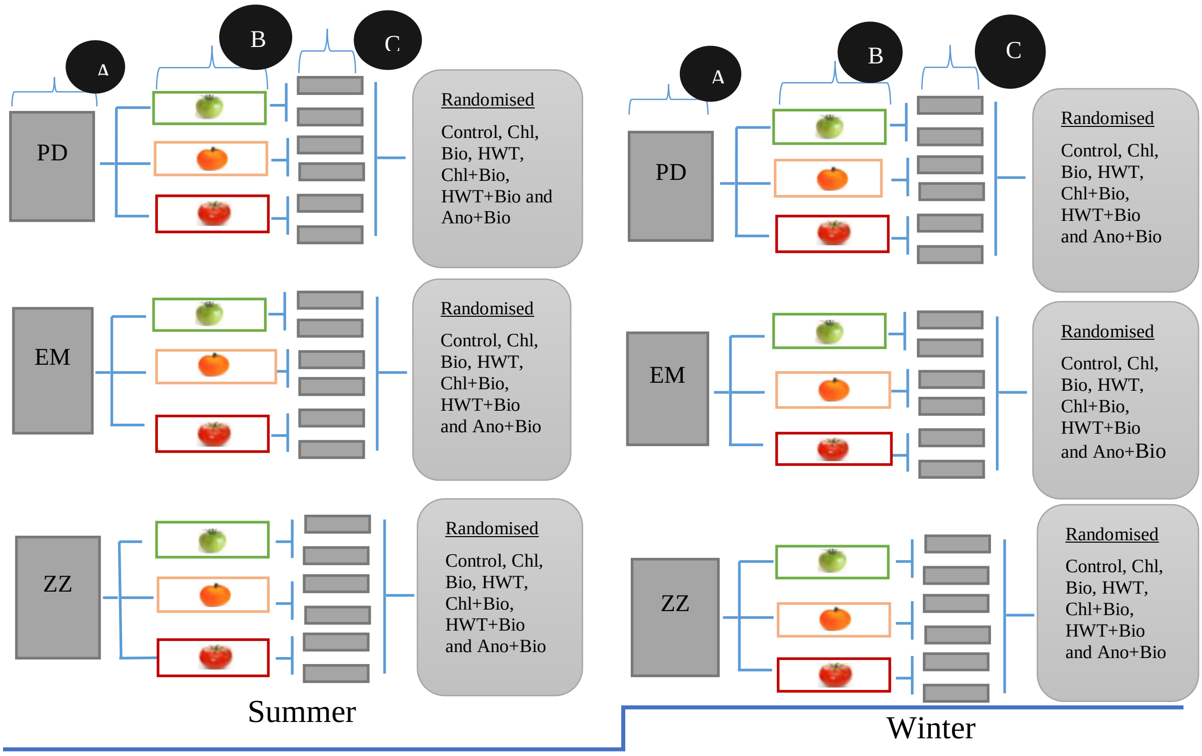

Figure 4.1 Experimental design with (A) as transportation conditions, (B) the fruit maturities at harvest and (C) ambient and cold storage conditions (11 ^{o}C). The experiment was carried out in summer and winter. The seven pre-storage treatments were triplicated in a full factorial experiment

4.3.4 Data collection

4.3.4.1 Measurement of temperature conditions and road quality

While transporting the products, the time, temperature and RH conditions in the trucks was measured at suitable intervals using iButton loggers (Maxim Integrated, California, USA) placed in three locations (top, middle and bottom) inside the truck. Each route had varying distances of both rough and asphalt roads. The road quality, which signified the quality of ride induced on the tomatoes was measured using a road surface laser profilometer (PaveProf V2.0, Pavetesting, UK).

4.3.4.2 Colour

Fruit colour was measured using a Minolta Chroma meter (Model CR-400, Narachi Pty, South Africa). Readings were made at an observer angle of 2^o after standardizing the instrument with a white tile (Y = 93.8, X = 0.3030, y = 0.3191). Illuminant C was used to measure the L*a*b*c and h values, where two readings were taken from three fruits, for each replication (Kerkhofs *et al.*, 2005; Pinheiro *et al.*, 2015). The fruit colour was assessed before storage (Day 1) and after 8, 16, 24 and 30 days of storage.

4.3.4.3 Fruit firmness

Tomato fruit firmness was tested using Instron universal testing machine (model 3345, Advanced Laboratory Solutions, South Africa) attached to a 6.1 mm flat end stainless steel probe at a cross-head speed of 20 mm min^{-1}. The force-deformation curves were automatically recorded by the Bluhill® software (Batu, 2004), which also reported the maximum force required to puncture the tomato skin. Three fruits was tested per replication, and results reported as the maximum puncture force in N for each sampling day (Batu, 2004).

4.3.4.4 pH

Product pH was measured using a pH meter (Orion Star A210, Thermo Scientific, South Africa) with a probe designed to measure solids (Favati *et al.*, 2009). The instrument was first standardized using 4.01, 10.00 and 7.00 pH buffers. Two tomato fruits were macerated using a food processor (Philips Model HR2106/01, Makro, Pietermaritzburg, South Africa) for 1 minute and the juice extracted through a cheesecloth into a 50 mL beaker. The pH of the extracted aliquot was then determined using the pH meter. Readings were repeated thrice per replication, for the selected sampling days.

4.3.4.5 Physiological weight-loss

Weight-loss was determined at selected intervals of storage using the method proposed by Pinheiro *et al.* (2013). Three batches of 3 tomatoes per treatment were marked and weighed at Day 1 and the percentage weight-loss reported on day 8, 16, 24 and 30, relative to Day 1.

4.3.4.6 Subjective quality evaluation

This procedure followed the method used by Tadesse *et al.* (2012). Subjective tests were performed to ascertain the proportion of the sample that was marketable under shelf-life studies. The overall visual appearance was the primary criterion used to judge if samples were still marketable during sampling. Fruit that was perceived to have shrivelled excessively, to have decayed or to have been physiologically damaged in any way, and that could not be sold at the local markets, was considered unmarketable and was therefore removed from the test sample during sampling.

4.3.5 Data analysis

Data analysis was carried out using Genstat 18 (VSI international, UK). Multivariate analysis of variance (MANOVA) was used to analyse the effect of transportation conditions, pre-storage treatments, storage and handling conditions on the quality of tomato fruit of various maturities at harvest. Seasonal comparisons were also carried out with pooled data.

4.4 Results and Discussion

4.4.1 Road conditions

The ZZ route was 263.44 and 223.81 km further than the PD and EM route, respectively. Table 4.1 presents a summary of the observed road quality conditions and transportation distances.

Table 4.1 A summary of road conditions during transportation of tomatoes from three commercial farms in Limpopo to Pietermaritzburg

Route	Distance (km)	Drive time (h)	IRI values (m km^{-1})	
			% less than 2.5	% less than 5
EM (Steve Mohale's farm to Pietermaritzburg)	934.12	10.43	70	91
PD (Point drift to Pietermaritzburg)	894.49	9.33	58	90
ZZ (Esme four to Pietermaritzburg)	1157.93	12.76	63	95

The PD route had a larger proportion of its road length comprising rough roads (Table 4.1). Similarly, the EM route had a higher proportion of its road length comprising smoother road surface compared to both the PD and ZZ routes. Based on international road classification using IRI values, thresholds of 2.7 m km^{-1} and 1.5 m km^{-1} have been set for acceptable and good quality roads, respectively (Arhin *et al.*, 2015). These values, however, relate to road comfort and are not related to damage to produce during transport. Although the IRI values in this study will give an indication of the relationship between road roughness and effect on tomato quality, classification and guidance threshold values should be developed for fragile agricultural commodities.

4.4.2 Air temperature and relative humidity during transportation

The air temperature and RH varied inside the truck depending on the season of each transportation trial. Figures 4.2 and 4.3 depict the variations in temperature and RH conditions in the trucks with time during the summer and winter transportation runs.

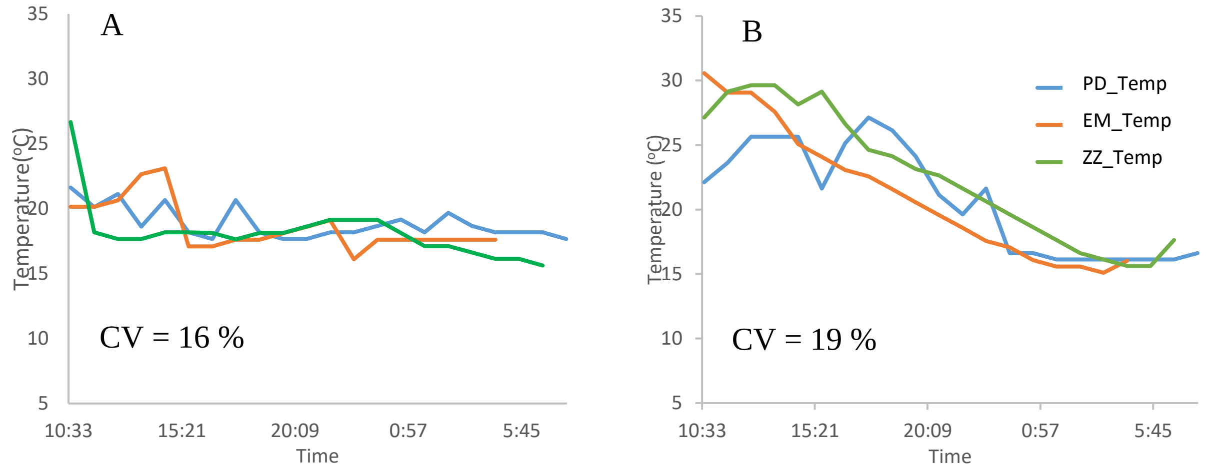

Figure 4.2 Average temperature conditions in the trucks during transportation of tomatoes. Winter conditions are depicted in (A) and summer conditions in (B) (n = 3)

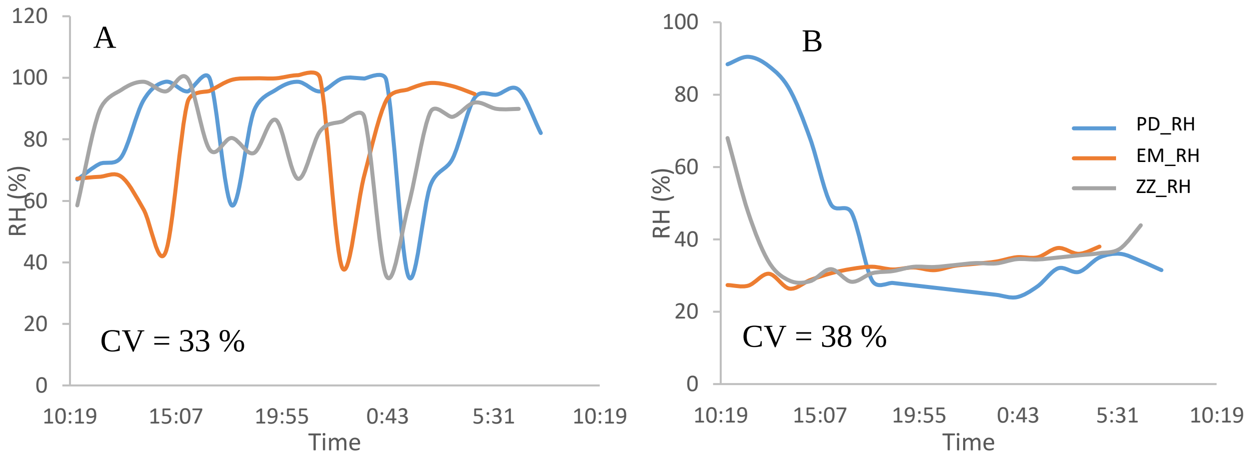

Figure 4.3 Relative humidity conditions in the trucks during transportation of tomatoes. Winter conditions are depicted in (A) and summer conditions in (B) (n = 3)

Temperature levels during the summer trial were higher than those of the winter trial, and that the RH conditions fluctuated more rapidly and in magnitude compared to the temperature conditions (Figure 4.2 and 4.3). Relatively higher RH conditions also prevailed during the winter trial compared to the summer trial (Figure 4.3). These conditions can be generally explained by the higher ambient temperature conditions in the summer compared to winter, and the observed trends were, therefore, expected.

4.4.3 Colour

Fruit colour expressed as hue angle (h) generally decreased progressively over the storage period across all fruit maturities, storage or transportation conditions. This decrease signifies the advancement of fruit ripening that causes fruits' colour to turn from green (h of 180^{o}) to red (h of 0^{o}). The h of fruit harvested at the green maturity stage was also higher than those of red and pink maturity stages, with the fruit harvested at the red maturity stage having the lowest hue angles. Similarly, the h of fruit stored under cold storage (11 ^{o}C) conditions was also higher than those stored under ambient temperature conditions. These trends in h were observed in both the summer and winter harvests (Table 4.2 and Table 4.3). Samples harvested and transported during the summer and winter depicted differences in h on their arrival to Pietermaritzburg, but these differences were not apparent as the storage period progressed (Table 4.2 and Table 4.3). These trends in h were expected, from a physiological and biochemical perspective. The reduction in h with the storage duration can be attributed to the normal ripening process that causes chemical and biochemical changes in fruit, including accumulation and synthesis of pigments such as lycopene in tomatoes (Javanmardi and Kubota, 2006; Nasir *et al.*, 2015). Seasonal and environmental conditions also affect the rate of enzymatic and metabolic reactions, that are mostly temperature-dependent (Liu *et al.*, 2015). This explains the lower hue angles in fruit stored under ambient conditions, as well as those harvested during the summer season, since high temperature conditions lead to higher deterioration rates in tomatoes. Table 4.2 is a summary the effect of the pre-storage treatments, transportation conditions and tomato fruit maturity stages on the changes in tomato fruit h with storage.

Fruit harvested at the green maturity stage had a higher average hue angle reduction compared to those harvested at red and pink red maturity stages, with fruit harvested at red maturity stage having the lowest average percentage hue angle reduction. On average, there was a 51-58 % reduction in hue angle for fruit harvested at the green maturity stage, depending on the transportation route, 25-31 % reduction for fruit harvested at pink maturity stage and 10-18 % reduction in hue angle for fruit harvested at the red maturity stage. The percentage reduction in h with storage for fruit stored under ambient conditions was 2-7 % higher than that of fruit stored in the cold storage environment.

Table 4.2 A summary of changes in hue angle with storage period for tomato fruit harvested and transported during the summer season

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient*	Cold (11^{o}C)
PD+Green	Control	104.63^{d}	104.63^{d}	81.26^{l}	56.70^{cde}	53.61^{i}	57.52^{ghij}	45.50^{abcde}	47.83^{abcde}	-	45.48^{abcde}
	Chlorine	104.63^{d}	104.63^{d}	77.41^{kl}	66.15^{hijk}	48.53^{efgh}	71.29^{kl}	45.64^{bcdef}	51.26^{abcde}	-	50.52^{lmnop}
	Biocontrol	104.63^{d}	104.63^{d}	76.15^{kl}	82.73^{pq}	52.81^{hi}	57.21^{fghi}	45.36^{abcde}	57.17^{hijk}	-	49.53^{ijklm}
	HWT	104.63^{d}	104.63^{d}	48.91^{abcd}	92^{ijklm}	49.50^{fghi}	69.66^{kl}	46.42^{efghi}	58.18^{ijk}	-	47.23^{abcde}
	HWT+BIO	104.63^{d}	104.63^{d}	58.96^{ij}	74.40^{klmn}	51.71^{ghi}	63.50^{jk}	46.15^{cdefg}	62.38^{k}	-	47.72^{bcdef}
	CHL+BIO	104.63^{d}	104.63^{d}	62.71^{j}	72.37^{jklm}	45.58^{abcde}	76.03^{l}	50.09^{j}	54.84^{fghij}	-	47.72^{bcdef}
	ANO+BIO	104.63^{d}	104.63^{d}	63.5^{j}	80.78^{opq}	52.62^{hi}	73.21^{l}	44.72^{abcde}	62.67^{k}	-	47.90^{cdefg}
PD+Pink	Control	61.07^{bc}	61.07^{bc}	45.36^{abcd}	50.34^{abc}	45.81^{abcde}	49.89^{abcd}	42.75^{abcde}	46.13^{abcde}	-	45.26^{abcde}
	Chlorine	59.63^{abc}	59.63^{abc}	46.36^{abcd}	50.00^{abcd}	46.2^{abcdef}	50.69^{abcd}	44.59^{abcde}	46.99^{abcde}	-	44.73^{abcde}
	Biocontrol	59.63^{abc}	59.63^{abc}	46.39^{abcd}	48.10^{ab}	45.38^{abcde}	50.38^{abcd}	43.67^{abcde}	47.97^{abcde}	-	43.73^{abcd}
	HWT	59.63^{abc}	59.63^{abc}	46.35^{abcd}	51.42^{abc}	44.81^{abcde}	50.81^{abcd}	43.49^{abcde}	45.75^{abcde}	-	43.95^{abcde}
	HWT+BIO	59.63^{abc}	59.63^{abc}	47.14^{abcd}	51.97^{abcd}	44.41^{abcde}	49.89^{abcd}	44.26^{abcde}	48.09^{abcde}	-	46.37a^{bcde}
	CHL+BIO	59.63^{abc}	59.63^{abc}	45.13^{abcd}	52.98^{abc}	44.92^{abcde}	51.79^{abcd}	46.59^{efghi}	46.20^{abcde}	-	44.04^{abcde}
	ANO+BIO	59.63^{abc}	59.63^{abc}	47.39^{abcd}	49.63^{abcd}	45.26^{abcde}	47.97^{abcd}	44.10^{abcde}	45.71^{abcde}	-	44.04^{abcde}
PD+Red	Control	52.59^{ab}	52.59^{ab}	47.13^{abcd}	48.64^{abc}	47.95^{cdefg}	49.34^{abcd}	42.99^{abcde}	46.13^{abcde}	-	42.79^{a}
	Chlorine	52.59^{ab}	52.59^{ab}	44.14^{abc}	49.38^{abcd}	44.30^{abcde}	50.29^{abcde}	43.01^{abcde}	44.27^{ab}	-	43.58^{abc}
	Biocontrol	52.59^{ab}	52.59^{ab}	44.63^{abcd}	46.85^{ab}	43.91^{abcde}	47.31^{abcd}	42.76^{abcde}	45.85^{abcde}	-	42.58^{a}
	HWT	52.59^{ab}	52.59^{ab}	43.81^{a}	50.40^{abc}	44.68^{abcde}	48.60^{abcd}	43.16^{abcde}	44.56^{abc}	-	44.49^{abcde}
	HWT+BIO	52.59^{ab}	52.59^{ab}	45.41^{abcd}	49.77^{abc}	43.87^{abcde}	46.05^{abc}	43.51^{abcde}	46.26^{abcde}	-	45.70^{abcde}
	CHL+BIO	52.59^{ab}	52.59^{ab}	44.75^{abcd}	47.46^{ab}	42.77^{ab}	46.88^{abcde}	41.53^{a}	42.78^{a}	-	43.14^{ab}
	ANO+BIO	52.59^{ab}	52.59^{ab}	44.04^{abc}	50.07^{abc}	44.00^{abcde}	48.18^{abcd}	41.76^{ab}	43.25^{a}	-	45.26^{abcde}
EM+Green	Control	105.40^{d}	105.40^{d}	49.53^{abc}	57.05^{defg}	45.35^{abcde}	51.36^{abcd}	44.76^{abcde}	49.01^{abcde}	-	48.06^{cdefg}
	Chlorine	105.40^{d}	105.40^{d}	50.37^{abcd}	59.04^{efgh}	47.67^{bcdef}	56.06^{efgh}	45.90^{cdefg}	48.68^{abcde}	-	47.03^{abcde}
	Biocontrol	105.40^{d}	105.40^{d}	51.49^{abcd}	61.97^{fghi}	45.40^{abcde}	49.39^{abcd}	44.28^{abcde}	51.63^{abcde}	-	49.02^{ghijk}
	HWT	105.40^{d}	105.40^{d}	52.78^{abcd}	65.09^{ghij}	44.40^{abcde}	53.49^{bcde}	47.86^{hij}	51.13^{abcde}	-	50.10^{jklmn}
	HWT+BIO	105.40^{d}	105.40^{d}	49.97^{abcd}	68.15^{ijkl}	46.35^{abcde}	52.45^{bcde}	45.51^{abcde}	53.34^{cdefg}	-	50.29^{klmno}
	CHL+BIO	105.40^{d}	105.40^{d}	53.14^{cdef}	72.32^{jklm}	47.53^{bcdef}	51.08^{abcd}	44.63^{abcde}	50.68^{abcde}	-	47.56^{bcdef}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient*	Cold (11^{o}C)
	ANO+BIO	105.40^{d}	105.40^{d}	55.71^{efgh}	79.54^{nopq}	47.14^{bcdef}	55.37^{cdef}	45.74^{bcdef}	51.15^{abcde}	-	50.77^{mnopq}
EM+Pink	Control	65.63^{c}	65.63^{c}	50.99^{abcd}	50.38^{abc}	46.18^{abcde}	49.76^{abcd}	45.53^{bcdef}	47.49^{abcde}	-	50.32^{klmno}
	Chlorine	65.63^{c}	65.63^{c}	47.37^{abcd}	48.84^{abcd}	48.16^{defg}	50.25^{abcd}	44.80^{abcde}	51.01^{abcde}	-	48.59^{efghi}
	Biocontrol	65.63^{c}	65.63^{c}	49.80^{abcd}	48.91^{abc}	46.85^{abcde}	50.34^{abcd}	46.07^{cdefg}	45.61^{abcde}	-	47.04^{abcde}
	HWT	65.63^{c}	65.63^{c}	52.78^{abcd}	50.27^{abcd}	43.50^{abcd}	50.54a^{bcd}	46.26^{defgh}	50.74^{abcde}	-	46.56^{abcde}
	HWT+BIO	65.63^{c}	65.63^{c}	49.97^{abcd}	50.70^{abc}	45.11^{abcde}	50.22^{abcd}	49.57^{ij}	46.93^{abcde}	-	48.80^{fghij}
	CHL+BIO	65.63^{c}	65.63^{c}	48.45^{abcd}	51.54^{abcd}	46.41^{abcde}	48.73^{abcd}	43.70^{abcde}	48.01^{abcde}	-	48.80^{fghij}
	ANO+BIO	65.63^{c}	65.63^{c}	48.87^{abcd}	48.89^{abcd}	44.37^{abcde}	47.76^{abcd}	43.95^{abcde}	45.75^{abcde}	-	47.01^{abcde}
EM+Red	Control	50.98^{a}	50.98^{a}	45.44^{abcd}	48.66^{abc}	44.83^{abcde}	44.99^{ab}	42.41^{abcd}	45.86^{abcde}	-	45.50^{abcde}
	Chlorine	50.98^{a}	50.98^{a}	48.38^{abcd}	47.59^{ab}	44.31^{abcde}	47.61^{abcd}	42.22^{abc}	45.20^{abcd}	-	43.09^{ab}
	Biocontrol	50.98^{a}	50.98^{a}	48.50^{abcd}	47.97^{ab}	44.44^{abcde}	48.09^{abcd}	44.25^{abcde}	49.20^{abcde}	-	47.46^{bcdef}
	HWT	50.98^{a}	50.98^{a}	48.97^{abcd}	47.30^{ab}	44.13^{abcde}	46.81^{abcd}	44.45^{abcde}	44.76^{abc}	-	46.31^{abcde}
	HWT+BIO	50.98^{a}	50.98^{a}	47.98^{abcd}	48.28^{abc}	43.09^{abc}	48.21^{abcd}	42.68^{abcde}	46.48^{abcde}	-	45.80^{abcde}
	CHL+BIO	50.98^{a}	50.98^{a}	46.62^{abcd}	46.79^{ab}	44.97^{abcde}	46.69^{abcd}	44.83^{abcde}	45.40^{abcde}	-	45.12^{abcde}
	ANO+BIO	50.98^{a}	50.98^{a}	43.87^{ab}	44.53^{a}	42.06^{a}	42.19^{a}	43.60^{abcde}	45.28^{abcd}	-	44.93^{abcde}
ZZ+Green	Control	108.77^{d}	108.77^{d}	52.56^{abcd}	64.26^{ghij}	45.35^{abcde}	51.92^{bcde}	44.77^{abcde}	52.85^{bcdef}	-	52.16^{opqr}
	Chlorine	108.77^{d}	108.77^{d}	57.54^{ghij}	65.98^{hijk}	45.33^{abcde}	55.86^{defg}	43.23^{abcde}	61.32^{jk}	-	54.36^{pqr}
	Biocontrol	108.77^{d}	108.77^{d}	62.78^{j}	66.37^{hij}	46.17^{abcde}	53.27^{bcde}	45.07^{abcde}	50.44^{abcde}	-	55.44^{r}
	HWT	108.77^{d}	108.77^{d}	71.15^{k}	70.13^{ijk}	46.06^{abcde}	54.42^{bcde}	45.93^{cdefg}	56.80^{ghijk}	-	54.09^{pqr}
	HWT+BIO	108.77^{d}	108.77^{d}	53.78^{defg}	75.93^{lmno}	45.78^{abcde}	59.78^{ij}	45.36^{abcde}	54.29^{efghi}	-	47.66^{bcdef}
	CHL+BIO	108.77^{d}	108.77^{d}	57.78^{hij}	77.24^{mnop}	47.52^{bcdef}	56.30^{efgh}	45.88^{cdefg}	52.53^{bcdef}	-	54.85^{qr}
	ANO+BIO	108.77^{d}	108.77^{d}	57.51^{ghij}	85.03^{q}	46.22^{abcde}	59.26^{hij}	45.45^{abcde}	53.86^{defgh}	-	51.10^{nopq}
ZZ+Pink	Control	66.34^{c}	66.34^{c}	50.16^{abcd}	53.62^{abcd}	46.27^{abcde}	45.94^{abc}	46.20^{cdefg}	47.53^{abcde}	-	50.57^{mnop}
	Chlorine	66.34^{c}	66.34^{c}	55.90^{fghi}	53.17^{abcd}	46.93^{abcde}	47.27^{abcde}	44.21^{abcde}	47.58^{abcde}	-	47.16^{abcde}
	Biocontrol	66.34^{c}	66.34^{c}	53.00^{bcde}	47.94^{ab}	44.49^{abcde}	48.09^{abcd}	44.89^{abcde}	48.34^{abcde}	-	47.46^{bcdef}
	HWT	66.34^{c}	66.34^{c}	50.15^{abcd}	54.98^{bcde}	46.96^{abcde}	46.65^{abcd}	45.00^{abcde}	47.81^{abcde}	-	48.04^{cdefg}
	HWT+BIO	66.34^{c}	66.34^{c}	52.59^{abcd}	49.27^{abcd}	46.15^{abcde}	45.74^{abc}	47.15^{fghij}	47.37^{abcde}	-	44.33^{abcd}
	CHL+BIO	66.34^{c}	66.34^{c}	53.52^{defg}	51.24^{abcd}	45.51^{abcde}	46.36^{abcd}	44.71^{abcde}	49.21^{abcde}	-	49.01^{fghij}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient*	Cold (11°C)
	ANO+BIO	66.34^{c}	66.34^{c}	51.83^{abcd}	50.56^{abcd}	46.75^{abcde}	46.92^{abcde}	44.03^{abcde}	47.39^{abcde}	-	49.24^{hijkl}
ZZ+Red	Control	54.89^{ab}	54.89^{ab}	49.81^{abcd}	48.42^{abc}	44.18^{abcde}	47.84^{abcd}	42.81^{abcde}	48.11^{abcde}	-	46.49^{abcde}
	Chlorine	54.89^{ab}	54.89^{ab}	48.66^{abcd}	51.53^{abcd}	44.78^{abcde}	45.72^{abc}	44.39^{abcde}	48.62^{abcde}	-	46.51^{abcde}
	Biocontrol	54.89^{ab}	54.89^{ab}	47.94^{abcd}	46.95^{ab}	44.06^{abcde}	46.93^{abcde}	45.82^{cdefg}	45.63^{abcde}	-	46.87^{abcde}
	HWT	54.89^{ab}	54.89^{ab}	52.55^{abcd}	48.76^{abcd}	43.35^{abcd}	46.62^{abcd}	44.82^{abcde}	46.48^{abcde}	-	48.30^{defgh}
	HWT+BIO	54.89^{ab}	54.89^{ab}	51.93^{abcd}	48.18^{ab}	44.28^{abcde}	45.43^{ab}	47.24^{ghij}	46.25^{abcde}	-	45.89^{abcde}
	CHL+BIO	54.89^{ab}	54.89^{ab}	49.49^{abcd}	45.43^{a}	43.73^{abcde}	45.21^{ab}	45.47^{abcde}	47.35^{abcde}	-	46.25^{abcde}
	ANO+BIO	54.89^{ab}	54.89^{ab}	49.07^{abcd}	46.51^{a}	44.98^{abcde}	45.80^{abc}	44.75^{abcde}	48.22^{abcde}	-	47.12^{abcde}

Significance level (p)	
Treatments (A)	0.298
Storage (B)	<.001
Route (C)	0.019
Maturity stage (D)	<.001
AXB	0.209
AXC	0.999
BXC	0.203
AXD	0.988
BXD	0.628
CXD	0.046
AXBXC	0.996
AXBXD	0.792
AXCXD	0.998
BXCXD	0.907
AXBXCXD	1.000
CV (%)	31.6
SE	5.421
LSD	10.631

Means within the same column followed by the same letter are not significantly different (p>0.05). HWT signifies hot water treatment, BIO designates biocontrol treatment using B-13 yeast isolate, ANO anolyte water and CHL chlorinated water. PD signifies tomatoes transported through Point Drift-Pietermaritzburg route, EM through Mooketsi-Pietermaritzburg and ZZ through Esmefour-Pietermaritzburg. The transportation routes had varying road quality conditions and distances.* indicates that missing data. No samples were available on day 30 under ambient storage.

A comparison of the h of fruit transported through the three road conditions showed that EM (55 %) route had a higher degree of reduction in fruit h compared to the ZZ (54.9 %) and the PD (54.8 %) routes for fruit harvested at the green maturity stages. Similarly, the ZZ (29 %) route also had a higher degree of reduction in h compared to the EM (28 %) and PD (25 %) routes for fruit harvested at the pink. For fruit harvested at the red maturity stage the PD route (17 %) had the highest reduction in fruit hue angle compared to the EM (12 %) and ZZ (16 %) route.

The differences in reduction in hue angle with fruit maturity at harvest reflect the biological age of the fruit and shows that fruit harvested much later will have a reduced shelf-life, and hence margins in time lag during transportation between the farm and the market have to be planned accordingly. Storage under cold conditions have been identified as the single, most effective avenue of maintaining the quality of fresh produce due to the link between high temperature conditions with increased metabolic processes (Jedermann *et al.*, 2014). Storage in ambient conditions resulted in significantly ($p \leq 0.05$) higher reductions in fruit hue angle. Transportation on poor quality roads appeared to have a minimal effect on fruit harvested at the green maturity stage, with fruit transported through the three conditions showing minor differences in the degree of hue angle reduction. Fruit harvested at red and pink maturity stages however, were affected by road conditions. Tomatoes harvested at red and pink maturity stages are known to be susceptible to mechanical damage and this could have been exacerbated by the roads of poor quality that are far from the markets (PD and ZZ). This is in agreement with studies that have been reported in the literature (Mohammadi-Aylar *et al.*, 2010).

Pre-storage treatments had a negligible effect on the changes in fruit hue angle depending on the with the transportation and storage conditions, the season of harvest and fruit maturity at harvest. The effect of pre-storage treatments on the fruit h was also not significant ($p > 0.05$) for fruit harvested and transported in the winter and summer (Table 4.2 and 4.3)

Table 4.3 shows a summary of changes in h with storage for samples harvested and transported during the winter season. Fruit harvested and transported during the winter showed a higher rate of reduction in h for fruit transported through the EM route compared to both the PD and ZZ routes. Similarly, fruit transported through the ZZ route appeared to have the least reduction in h compared to the EM and PD routes across all maturity stages.

Table 4.3 The effect of various experimental factors on changes in hue angle with storage period for tomato fruit harvested and transported during the winter season

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)
PD+Green	Control	108.41^{e}	108.41^{e}	53.72^{nopqr}	56.43^{ghijk}	48.38^{mnopq}	45.87^{abcde}	44.86^{hijkl}	46.33^{abcde}	45.03^{ijklm}	44.52^{abcde}
	Chlorine	108.41^{e}	108.41^{e}	55.90^{qrst}	66.65^{vwx}	47.34^{ijklm}	56.63^{nopqr}	45.21^{ijklm}	54.66^{o}	43.58^{efghi}	52.13^{lmn}
	Biocontrol	108.41^{e}	108.41^{e}	51.42^{jklmn}	65.56^{uvw}	47.40^{ijklm}	55.25^{jklmn}	47.01^{pqr}	51.11^{efghi}	46.05^{nop}	51.87^{klmn}
	HWT	108.41^{e}	108.41^{e}	53.03^{lmnop}	66.65^{vwx}	49.24^{pqr}	51.13^{efghi}	46.64^{opqr}	46.51^{abcde}	44.23^{ghijk}	48.42^{efghi}
	HWT+BIO	108.41^{e}	108.41^{e}	51.71^{klmno}	72.32^{xy}	46.26^{defgh}	53.69^{hijkl}	45.43^{jklmn}	53.22^{lmno}	44.82^{hijkl}	49.18^{ghijk}
	CHL+BIO	108.41^{e}	108.41^{e}	56.65^{rst}	63.37^{rtuvw}	48.71^{nopqr}	51.34^{efghi}	46.51^{nopqr}	48.58^{bcdef}	45.42^{klmno}	49.93^{hijkl}
	ANO+BIO	108.41^{e}	108.41^{e}	56.66^{rst}	61.70^{pqrst}	46.28^{defgh}	51.37^{efghi}	42.46^{bcdef}	50.33^{cdefg}	42.95^{bcdef}	49.57^{hijkl}
PD+Pink	Control	74.25^{c}	74.25^{c}	50.70^{ghijk}	56.46^{ghijk}	44.81^{abcde}	52.23^{efghi}	45.42^{jklmn}	48.38^{bcdef}	44.22^{ghijk}	49.19^{ghijk}
	Chlorine	74.25^{c}	74.25^{c}	50.8^{ghijkl}	59.30^{lmnop}	49.52^{qr}	50.04^{efghi}	42.93^{cdefg}	48.73^{bcdef}	46.10^{nop}	49.21^{ghijk}
	Biocontrol	74.25^{c}	74.25^{c}	49.05^{cdefg}	52.69^{bcdef}	46.93^{hijkl}	52.21^{efghi}	44.66^{ghijk}	51.46^{ghijk}	47.50^{opq}	48.08^{efghi}
	HWT	74.25^{c}	74.25^{c}	50.48^{fghij}	55.92^{fghij}	48.96^{opqr}	49.89^{defgh}	42.99^{cdefg}	49.72^{cdefg}	45.95^{mnop}	52.23^{lmn}
	HWT+BIO	74.25^{c}	74.25^{c}	48.97^{cdefg}	57.92^{jklmn}	46.38^{fghij}	50.81^{efghi}	45.15^{ijklm}	50.40^{defgh}	43.21^{defgh}	47.78^{defgh}
	CHL+BIO	74.25^{c}	74.25^{c}	53.16^{mnopq}	56.77^{ijklm}	48.30^{jlmno}	51.49^{efghi}	48.23^{r}	52.51^{ijklm}	45.60^{lmnop}	48.08^{efghi}
	ANO+BIO	74.25^{c}	74.25^{c}	50.82^{ghijk}	59.13^{klmno}	47.69^{ijklm}	54.68^{hijkl}	45.78^{lmnop}	50.06^{cdefg}	45.23^{jklmn}	50.33^{ijklm}
PD+Red	Control	63.68^{b}	63.68^{b}	46.49^{abcde}	52.89^{bcdef}	44.64^{abcde}	48.04^{bcdef}	43.17^{defgh}	49.87^{cdefg}	41.78^{abcde}	46.37^{bcdef}
	Chlorine	63.68^{b}	63.68^{b}	49.27^{cdefg}	56.49^{hijkl}	46.66^{ghijk}	48.81^{cdefg}	44.80^{hijkl}	50.09^{cdefg}	44.71^{ghijk}	50.75^{jklmn}
	Biocontrol	63.68^{b}	63.68^{b}	49.48^{defgh}	53.47^{cdefg}	45.02^{abcde}	52.15ef^{ghi}	45.48^{jklmn}	49.15^{bcdef}	47.81^{pq}	47.93^{defgh}
	HWT	63.68^{b}	63.68^{b}	49.08^{cdefg}	56.49^{ghijk}	46.30^{efghi}	41.00^{a}	42.32^{bcdef}	49.78^{cdefg}	44.10^{fghij}	49.42^{hijkl}
	HWT+BIO	63.68^{b}	63.68^{b}	48.18^{cdefg}	51.79^{bcdef}	46.06^{cdefg}	51.37^{efghi}	45.17^{ijklm}	51.96^{hijkl}	43.61^{efghi}	47.69^{defgh}
	CHL+BIO	63.68^{b}	63.68^{b}	48.32^{cdefg}	54.57^{efghi}	45.98^{cdefg}	51.93^{efghi}	44.89h^{ijkl}	46.49^{abcde}	43.54^{efghi}	44.59^{abcde}
	ANO+BIO	63.68^{b}	63.68^{b}	49.37^{cdefg}	53.57^{defgh}	46.38^{fghij}	49.20^{cdefg}	47.52^{qr}	51.24^{fghij}	44.36^{ghijk}	46.76^{bcdef}
EM+Green	Control	109.71^{e}	109.71^{e}	56.51^{rst}	56.21^{fghij}	46.42^{fghij}	49.32^{cdefg}	40.30^{abcde}	48.95^{bcdef}	42.83^{abcde}	47.03^{bcdef}
	Chlorine	109.71^{e}	109.71^{e}	51.04^{hijkl}	65.11^{uvw}	45.08^{abcde}	58.54^{rtu}	43.42^{defgh}	51.84^{hijkl}	44.37^{ghijk}	49.84^{hijkl}
	Biocontrol	109.71^{e}	109.71^{e}	50.82^{ghijk}	60.84^{opqrs}	45.37^{bcdef}	58.54^{rstu}	44.02^{fghij}	48.82^{bcdef}	44.54^{ghijk}	47.09^{cdefg}
	HWT	109.71^{e}	109.71^{e}	49.52^{efghi}	57.99^{jklmn}	40.57^{ab}	55.20^{jklmn}	41.42^{bcdef}	50.41^{defgh}	40.20^{abcde}	46.77^{bcdef}
	HWT+BIO	109.71^{e}	109.71^{e}	48.14^{cdefg}	53.88^{defgh}	41.95^{abcde}	49.57^{cdefg}	41.32^{bcdef}	46.77^{abcde}	39.69^{abc}	45.41^{abcde}
	CHL+BIO	109.71^{e}	109.71^{e}	48.35^{cdefg}	67.09^{vwx}	44.49^{abcde}	59.36^{u}	43.44^{defgh}	54.19^{no}	42.41^{abcde}	50.80^{jklmn}
	ANO+BIO	109.71^{e}	109.71^{e}	48.4^{cdefgh}	60.64^{mnopq}	44.12^{abcde}	55.71^{klmno}	39.87^{abcd}	52.79^{klmno}	41.38^{abcde}	47.84^{defgh}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold	Ambient	Cold (11ºC)	Ambient	Cold (11ºC)	Ambient	Cold (11ºC)	Ambient	Cold (11ºC)
EM+Pink	Control	86.09^{d}	86.09^{d}	44.71^{abcde}	54.59^{efghi}	44.85^{abcde}	52.99^{ghijk}	43.54^{efghi}	51.03^{efghi}	40.54^{abcde}	47.17^{cdefg}
	Chlorine	86.09^{d}	86.09^{d}	47.73^{bcdef}	49.94^{abcde}	41.11^{abcd}	54.95^{ijklm}	39.47^{abc}	49.08^{bcdef}	40.51^{abcde}	47.34^{cdefg}
	Biocontrol	86.09^{d}	86.09^{d}	46.28^{abcde}	49.23^{abcde}	44.70^{abcde}	50.42^{efghi}	42.08^{bcdef}	45.71^{abcde}	43.23^{defgh}	46.76^{bcdef}
	HWT	86.09^{d}	86.09^{d}	44.00^{abcde}	51.38^{bcdef}	43.38^{abcde}	50.16^{efghi}	41.87^{bcdef}	51.73^{hijkl}	41.81^{abcde}	53.39^{mn}
	HWT+BIO	86.09^{d}	86.09^{d}	48.28^{cdefg}	50.20^{abcde}	43.12^{abcde}	50.08^{efghi}	42.99^{cdefg}	45.45^{abcde}	41.28^{abcde}	45.13^{abcde}
	CHL+BIO	86.09^{d}	86.09^{d}	43.49^{abcde}	53.82^{defgh}	40.96^{abc}	51.01^{efghi}	39.78^{abcd}	44.95^{abcde}	40.32^{abcde}	44.06^{abcde}
	ANO+BIO	86.09^{d}	86.09^{d}	47.38^{bcdef}	49.18^{abcde}	41.35^{abcde}	49.41^{cdefg}	40.75^{abcde}	49.69^{cdefg}	40.04^{abcd}	46.36^{bcdef}
EM+Red	Control	61.80^{b}	61.80^{b}	44.30^{abcde}	44.21^{a}	41.40^{abcde}	41.58^{ab}	45.91^{mnopq}	41.20^{a}	39.46^{a}	42.17^{abcd}
	Chlorine	61.80^{b}	61.80^{b}	41.23^{ab}	46.38^{abc}	41.69^{abcde}	47.45^{abcde}	40.69^{abcde}	44.99^{abcde}	40.48^{abcde}	42.98^{abcde}
	Biocontrol	61.80^{b}	61.80^{b}	42.86^{abcd}	49.68^{abcde}	39.95^{a}	45.07^{abcde}	42.86^{cdefg}	44.12^{abc}	42.90^{abcde}	41.33^{ab}
	HWT	61.80^{b}	61.80^{b}	45.29^{abcde}	49.42^{abcde}	41.94^{abcde}	49.25^{cdefg}	41.29^{bcdef}	46.79^{abcde}	40.02^{abcd}	40.23^{a}
	HWT+BIO	61.80^{b}	61.80^{b}	43.38^{abcde}	45.98^{ab}	43.12^{abcde}	42.65^{abc}	42.65^{bcdef}	44.64^{abcd}	41.29^{abcde}	43.45^{abcde}
	CHL+BIO	61.80^{b}	61.80^{b}	42.73^{abc}	48.62^{abcde}	41.17^{abcde}	45.24^{abcde}	41.11^{abcde}	43.27^{ab}	39.93^{abcd}	43.18^{abcde}
	ANO+BIO	61.80^{b}	61.80^{b}	40.00^{a}	48.53^{abcde}	40.68^{ab}	42.91^{abcd}	37.78^{a}	44.63^{abcd}	40.73^{abcde}	41.81^{abc}
ZZ+Green	Control	106.90^{e}	106.90^{e}	61.25^{t}	56.21^{fghij}	51.74^{r}	58.66^{tu}	43.00^{cdefg}	50.09^{cdefg}	39.50^{ab}	50.69^{jklmn}
	Chlorine	106.90^{e}	106.90^{e}	49.19^{cdefg}	77.58^{y}	48.90^{opqr}	58.13^{pqrst}	43.93^{efghi}	47.53^{bcdef}	44.35^{ghijk}	48.92^{fghij}
	Biocontrol	106.90^{e}	106.90^{e}	49.13^{cdefg}	89.51^{z}	45.90^{cdefg}	56.16^{mnopq}	43.37^{defgh}	54.59^{no}	42.92^{abcde}	50.74^{jklmn}
	HWT	106.90^{e}	106.90^{e}	50.84^{ghijk}	56.21^{fghij}	45.04^{abcde}	58.60^{tu}	42.62^{bcdef}	53.74^{mno}	42.38^{abcde}	50.66^{jklmn}
	HWT+BIO	106.90^{e}	106.90^{e}	57.10^{st}	56.21^{fghij}	46.38^{fghij}	56.00^{lmnop}	41.98^{bcdef}	52.81^{klmno}	43.20^{defgh}	49.10^{ghijk}
	CHL+BIO	106.90^{e}	106.90^{e}	54.93^{pqrs}	68.80^{wx}	44.12^{abcde}	58.37^{qrstu}	42.23^{bcdef}	52.76^{jklmn}	42.48^{abcde}	50.92^{jklmn}
	ANO+BIO	106.90^{e}	106.90^{e}	54.13^{opqrs}	72.64^{xy}	45.04^{abcde}	58.45^{qrstu}	43.00^{cdefg}	51.19^{efghi}	43.10^{cdefg}	50.90^{jklmn}
ZZ+Pink	Control	67.42^{b}	67.42^{b}	46.15^{abcde}	56.21^{fghij}	43.59^{abcde}	52.56^{fghij}	41.98^{bcdef}	50.03^{cdefg}	50.09^{q}	48.42^{efghi}
	Chlorine	67.42^{b}	67.42^{b}	48.46^{cdefg}	60.72^{nopqr}	43.57^{abcde}	51.94^{efghi}	42.23^{bcdef}	48.71^{bcdef}	42.01^{abcde}	46.16^{bcdef}
	Biocontrol	67.42^{b}	67.42^{b}	46.36^{abcde}	53.32^{cdefg}	44.95^{abcde}	51.88^{efghi}	42.62^{bcdef}	47.41^{bcdef}	43.18^{defgh}	48.53^{efghi}
	HWT	67.42^{b}	67.42^{b}	46.82^{abcde}	56.21^{fghij}	43.36^{abcde}	53.51^{hijkl}	43.00^{cdefg}	48.85^{bcdef}	44.63^{ghijk}	49.92^{hijkl}
	HWT+BIO	67.42^{b}	67.42^{b}	56.16^{rst}	62.90^{qrstu}	47.43^{ijklm}	57.36^{opqrs}	43.00^{cdefg}	48.96^{bcdef}	42.05^{abcde}	55.00^{n}
	CHL+BIO	67.42^{b}	67.42^{b}	45.57^{abcde}	53.31^{cdefg}	44.66^{abcde}	47.81^{abcde}	43.37^{defgh}	46.26^{abcde}	41.33^{abcde}	50.5^{1jklmn}
	ANO+BIO	67.42^{b}	67.42^{b}	47.37^{bcdef}	53.42^{cdefg}	44.23^{abcde}	52.07^{efghi}	43.93^{efghi}	49.36^{bcdef}	42.93^{abcde}	48.53^{efghi}
ZZ+Red	Control	53.86^{a}	53.86^{a}	44.61^{abcde}	56.21^{fghij}	43.20^{abcde}	45.93^{abcde}	41.61^{bcdef}	45.82^{abcde}	42.83^{abcde}	46.53^{bcdef}
	Chlorine	53.86^{a}	53.86^{a}	45.00^{abcde}	51.96^{bcdef}	43.29^{abcde}	48.57^{cdefg}	41.70^{bcdef}	45.87^{abcde}	41.74^{abcde}	48.87^{fghij}
	Biocontrol	53.86^{a}	53.86^{a}	46.66^{abcde}	48.01^{abcde}	44.08^{abcde}	45.73^{abcde}	45.58^{klmno}	46.80^{abcde}	42.16^{abcde}	47.15^{cdefg}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)
	HWT	53.86^{a}	53.86^{a}	45.95^{abcde}	56.21^{fghij}	41.98^{abcde}	50.05^{efghi}	41.97^{bcdef}	47.04^{abcde}	42.33^{abcde}	48.63^{efghi}
	HWT+BIO	53.86^{a}	53.86^{a}	51.35^{ijklm}	47.37^{abcd}	46.17^{defgh}	54.21^{hijkl}	42.87^{cdefg}	47.24^{abcde}	42.76^{abcde}	49.75^{hijkl}
	CHL+BIO	53.86^{a}	53.86^{a}	44.48^{abcde}	47.74^{abcde}	43.51^{abcde}	45.35^{abcde}	42.63^{bcdef}	50.73^{defgh}	42.19^{abcde}	46.14^{bcdef}
	ANO+BIO	53.86^{a}	53.86^{a}	45.06^{abcde}	47.02^{abcd}	42.86^{abcde}	48.61^{cdefg}	$42.80c^{defg}$	49.64^{cdefg}	41.58^{abcde}	48.53^{efghi}

Significance level (p)	
Treatments (A)	0.942
Storage (B)	<.001
Route (C)	0.044
Maturity stage (D)	<.001
AXB	0.852
AXC	0.852
BXC	0.492
AXD	0.997
BXD	0.109
CXD	0.135
AXBXC	1.000
AXBXD	0.994
AXCXD	1.000
BXCXD	0.672
AXBXCXD	1.000
CV (%)	30.7
SE	16.774
LSD	10.402

Means within the same column followed by the same letter are not significantly different (p>0.05). HWT signifies hot water treatment, BIO designates biocontrol treatment using B-13 yeast isolate, ANO anolyte water and CHL chlorinated water. PD signifies tomatoes transported through Point Drift-Pietermaritzburg route, EM through Mooketsi-Pietermaritzburg and ZZ through Esmefour-Pietermaritzburg. The transportation routes had varying road quality conditions and distances.

Comparison of the summer and winter seasons also showed higher deterioration of fruit in summer season hence the lack of samples after 24 days of storage for fruit stored under ambient conditions during the summer trial. The mean hue angle of fruit transported through PD, EM and ZZ routes during the winter were 55.62, 53.93 and 53.36, respectively. This depicts a time dependence of colour changes for fruit transported in the winter season. Fruit transported through moderately rough road profile, over a longer period (ZZ) had the highest deterioration in quality. This is in agreement with observations made by Aba *et al.* (2012).

A MANOVA of the data showed that fruit maturity at harvest, transportation and storage conditions were significant ($p \leq 0.05$) factors affecting the changes in h for fruit harvested and transported in the summer and winter seasons, while pre-storage treatments was not a significant ($p>0.05$) factor. An analysis of the pooled data from the summer and winter showed that fruit harvested in the winter had a significantly ($p \leq 0.05$) higher hue angle than those harvested in the summer.

The colour of tomatoes is the first quality attribute perceived visually by consumers and is an important visual cue that customers base their buying decisions upon (López Camelo and Gómez, 2004). Tomato fruit colour change from green to red results from simultaneous degradation of chlorophyll and synthesis of lycopene and other carotenoids (López Camelo and Gómez, 2004). The fruit hue angle is one of the most widely-used colour attributes for describing the colour changes of fresh tomatoes (Dillon *et al.*, 2014). The synthesis of some of these carotenoids have been shown to be light and temperature-dependent, and huge changes in hue angle occur due to high ripening rates at typically temperatures exceeding 30 ^{o}C (López Camelo and Gómez, 2004). Colour development also depends on fruit maturity at harvest since the carotenoid content of tomatoes vary widely depending on the cultivar and fruit maturity at harvest (Tadesse and Abtew, 2015). Ripening generally causes the increased accumulation of lycopene and β-carotene in tomatoes. In a study by Tadesse and Abtew (2015) where tomatoes were harvested at green maturity stage and stored at 4, 20 and 30 ^{o}C, it was observed that the rate of h change increased with increasing storage temperature. They attributed this effect to the fact that tomatoes stored at higher temperatures accumulated lycopene and β-carotene at a higher rate that those stored at colder temperatures. This explains the differences in h among fruit of different maturity stages, storage conditions and harvesting seasons.

The transportation conditions exerted environmental effects due to differences in temperature and RH and also caused high ripening rates in cases where damage to fruit due to bruising and other mechanical injuries occurred. It has been-well established that damage to tomatoes induces ethylene production that can trigger higher ripening rates in damaged fruit compared to intact tomatoes (Mutari and Debbie, 2011). This was especially the case for fruit transported through the PD route during the summer season. However, during the winter season, higher deterioration rates of fruit transported through the EM may be attributed to the relatively higher temperatures on the day of transport (Figure 4.2).

4.4.4 Fruit firmness

Table 4.2 shows a summary of changes in firmness of sample tomato fruit harvested in the summer at different maturity stages, transported over varying road conditions, and stored in cold and ambient conditions. Slight hardening of the fruit was also observed towards the end of the storage period. The fruit firmness was also higher for fruit harvested at the green maturity stage compared to the pink and red maturity stages, with fruit harvested at the red maturity stage having the lowest firmness values. Similarly, tomatoes stored under ambient conditions generally had lower firmness values compared to those stored under cold storage conditions. These trends were observed for fruit harvested and transported in the winter and summer (Table 4.4 and 4.5). The firmness of samples harvested and transported during the summer season depicted higher firmness values on arrival in Pietermaritzburg across all routes, although the reduction in firmness during subsequent sampling days was higher for fruit harvested during the summer season. The fruit harvested and stored under ambient conditions in the summer lost their firmness much faster than the winter harvest and no samples were available beyond 24 days of storage.

Fruit firmness reduction in tomatoes is an enzymatically-controlled process that proceeds even after harvest and is generally higher in fruit harvested at a later maturity stage since ripening and other enzymatic processes have proceeded for a longer time (Hertog *et al.*, 2007). Enzymatic and other physiological processes in biological materials are also temperature-dependent, with higher temperatures causing higher enzymatic activities and higher metabolic reactions. These processes lead to water loss and loss of turgidity of cells that constitute structural elements of tomato fruit (Tigist *et al.*, 2013). Higher temperatures therefore, result in a higher degree of reduction in firmness, due to increased weight-loss driven by respiration, as well as activities of pectolytic enzymes (van Dijk *et al.*, 2006).

Table 4.4 A summary of changes in tomato fruit firmness with storage for tomato fruit harvested and transported in the summer

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient*	Cold (11°C)
PD+Green	Control	32.36^{gh}	32.36^{gh}	24.31^{f}	21.12^{efgl}	27.78^{r}	$20.51^{fghijkl}$	$15.46^{bcdefgh}$	21.06^{hijkl}	-	16.25^{bcdef}
	Chlorine	32.36^{gh}	32.3^{6gh}	21.53^{cdef}	26.75^{defg}	20.22^{mnopq}	$22.40^{mnopqrs}$	$15.24^{bcdefghi}$	22.63^{mnopq}	-	19.44^{ghijk}
	Biocontrol	32.36^{gh}	32.36^{gh}	23.23^{efgh}	$20.28^{efghijk}$	17.22^{ghijk}	$17.27^{bcdefgh}$	$15.77^{cdefghijk}$	20.82^{hijkl}	-	20.84^{ijklm}
	HWT	32.36^{gh}	32.36^{gh}	19.01^{abcdef}	$20.88^{efghijk}$	20.89^{opq}	$15.86^{abcdefgh}$	$17.01^{ghijklmn}$	22.50^{mnopq}	-	19.29^{ghijk}
	HWT+BIO	32.36^{gh}	32.36^{gh}	19.03^{abcdef}	26.27^{defg}	20.17^{mnopq}	$20.08^{efghijk}$	$15.17^{bcdefghij}$	23.48^{opqrs}	-	19.07f^{ghij}
	CHL+BIO	32.36^{gh}	32.36^{gh}	22.71^{def}	$22.01^{efghijk}$	$15.54^{abfghijklm}$	21.80^{klmnop}	$17.80^{ijklmno}$	19.34^{fghij}	-	21.95^{jklmn}
	ANO+BIO	32.36^{gh}	32.36^{gh}	20.44^{abcdef}	23.01^{efg}	20.85^{nopq}	$18.40^{bcdefghi}$	$16.99^{ghijklmn}$	27.46^{s}	-	17.24^{bcdef}
PD+Pink	Control	17.41^{abcd}	17.41^{abcd}	15.01^{abcdef}	17.20^{efghi}	$14.52^{afghijk}$	$16.18^{abcdefg}$	12.24^{bcde}	16.62^{abcde}	-	16.25^{bcdef}
	Chlorine	17.41^{abcde}	17.41^{abcde}	13.27^{abcd}	$21.75^{efghijk}$	$16.58^{efghijk}$	$17.24^{bcdefghij}$	$14.86^{bcdefghi}$	20.91^{hijkl}	-	19.44^{ghijk}
	Biocontrol	17.41^{ab}	17.41^{ab}	16.75^{abcdef}	18.34^{efghi}	13.96^{afghij}	$21.61^{jklmnop}$	$16.07^{defghijkl}$	18.24^{defgh}	-	20.84^{ijklm}
	HWT	17.41^{ab}	17.41^{ab}	15.01^{abcdef}	18.11^{efghi}	13.56^{afghi}	$18.57^{cdefghijk}$	11.58^{b}	17.82^{cdefg}	-	19.29^{ghijk}
	HWT+BIO	17.41^{ab}	17.41^{ab}	17.41^{abcdef}	24.22^{aefg}	12.47^{bcdefg}	$18.24^{bcdefgh}$	$14.07^{bcdefgh}$	17.87^{cdefg}	-	19.07^{fghij}
	CHL+BIO	17.41^{ab}	17.41^{ab}	14.20^{abcde}	$20.91^{efghijk}$	17.61^{hijk}	$17.82^{bcdefgh}$	11.66^{bc}	19.64f^{ghij}	-	21.95^{jklmn}
	ANO+BIO	17.41^{abc}	17.41^{abc}	17.49^{abcdef}	16.86^{efgh}	14.21^{afghij}	$16.90^{bcdefgh}$	$13.92^{bcdefghij}$	16.24^{abcde}	-	17.24^{bcdef}
PD+Red	Control	15.83^{a}	15.83^{a}	17.20^{abcdef}	$22.61^{efghijk}$	13.45^{afghi}	13.86^{abcd}	13.10^{bcdefg}	18.10d^{efgh}	-	14.60^{abcde}
	Chlorine	15.83^{a}	15.83^{a}	21.75^{cdef}	14.47^{abcd}	12.96^{afgh}	14.74^{abcde}	11.97^{bcd}	16.01^{abcde}	-	17.05^{bcdef}
	Biocontrol	15.83^{a}	15.83^{a}	18.34^{abcdef}	13.55^{abc}	11.94^{bcdef}	14.02^{abcd}	14.96^{bcdefg}	16.27^{abcde}	-	17.02^{bcdef}
	HWT	15.83^{a}	15.83^{a}	18.11^{abcdef}	14.67^{abcd}	$14.56^{afghijk}$	13.93^{abcd}	12.07^{bcde}	16.44^{abcde}	-	16.87^{bcdef}
	HWT+BIO	15.83^{a}	15.83^{a}	24.22^{f}	$21.24^{efghijk}$	$16.30^{defghijkp}$	13.57^{abc}	$13.65^{bcdefghi}$	16.29^{abcde}	-	15.58^{bcdef}
	CHL+BIO	15.83^{a}	15.83^{a}	20.91^{bcdef}	16.46^{efg}	$14.07^{bcdefghij}$	$16.63^{abcdefg}$	$15.30^{bcdefgh}$	14.42^{abcde}	-	13.57^{abcde}
	ANO+BIO	15.83^{a}	15.83^{a}	16.86^{abcdef}	18.11^{efghi}	$13.56^{bcdefghi}$	$17.62^{bcdefghi}$	13.00^{bcdefg}	17.48^{cdefg}	-	10.21^{a}
EM+Green	Control	35.93^{h}	35.93^{h}	23.72^{ef}	29.70^{ijkl}	$15.51^{afghijklm}$	23.95^{pqrs}	19.90^{opqr}	24.88^{qrs}	-	22.44^{lmnop}
	Chlorine	35.93^{h}	35.93^{h}	19.16^{abcdef}	23.46^{aefg}	20.05^{lmnopq}	$18.33^{bcdefghi}$	$16.07^{defghijk}$	22.72^{nopqr}	-	23.09^{nopqr}
	Biocontrol	35.94^{h}	35.94^{h}	24.87^{gh}	27.26^{efg}	18.59^{jkq}	25.62^{rs}	$18.54^{lmnopqr}$	25.98^{rs}	-	24.13^{pqr}
	HWT	35.94^{h}	35.94^{h}	19.54^{abcdef}	27.82^{efg}	17.42^{hijk}	24.82^{qrs}	21.03^{qr}	23.95^{pqrs}	-	27.49^{r}
	HWT+BIO	35.94^{h}	35.94^{h}	23.68^{ef}	25.42^{cdefg}	$16.35^{defghijk}$	$21.48^{ijklmnop}$	19.90^{opqr}	20.89^{hijkl}	-	18.79^{efghi}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient*	Cold (11^{o}C)
	CHL+BIO	35.94^{h}	35.94^{h}	24.32^{f}	27.72^{efg}	22.40^{q}	$22.00^{lmnopqr}$	19.90^{opqr}	25.68^{rs}	-	24.66^{qr}
	ANO+BIO	35.94^{h}	35.94^{h}	24.58^{f}	29.17^{hijkl}	20.77^{nopq}	25.08^{qrs}	19.13^{mnopqr}	22.18^{lmnop}	-	16.86^{bcdef}
EM+Pink	Control	31.41^{gh}	31.41^{gh}	21.84^{cdef}	23.18^{efg}	19.18^{kq}	15.16^{abcdef}	$17.42^{hijklmn}$	19.02^{efghi}	-	17.12^{bcdef}
	Chlorine	31.41^{gh}	31.41^{gh}	16.56^{abcdef}	28.89^{g}	21.16^{pq}	22.64^{nopqrs}	19.65^{nopqr}	17.78^{cdefg}	-	18.00^{defgh}
	Biocontrol	31.41^{gh}	31.41^{gh}	21.88^{cdef}	28.35^{fg}	21.09^{opq}	$20.76^{ghijklm}$	18.01^{jklmno}	12.69^{abc}	-	21.70^{jklmn}
	HWT	31.41^{gh}	31.41^{gh}	19.39^{abcdef}	$19.57^{efghijk}$	$16.29^{defghijkp}$	15.91^{abcdef}	$17.79^{ijklmnop}$	13.50^{abcd}	-	22.21^{klmno}
	HWT+BIO	31.41^{gh}	31.41^{gh}	17.98^{abcdef}	28.06^{efg}	20.89^{opq}	15.44^{abcde}	21.57^{r}	21.61^{jklmn}	-	20.31^{ijklm}
	CHL+BIO	31.41^{gh}	31.41^{gh}	23.96^{f}	26.76^{defg}	20.80^{nopq}	19.93^{efghij}	21.09^{qr}	17.74^{cdefg}	-	17.71^{defgh}
	ANO+BIO	31.41^{gh}	31.41^{gh}	21.34^{cdef}	28.96^{hijkl}	16.00^{a}	21.04^{hijklm}	20.70^{pqr}	19.04^{efghi}	-	18.64^{efghi}
EM+Red	Control	15.44^{a}	15.44^{a}	19.38^{abcdef}	18.78^{efghij}	12.27^{bcdef}	16.59^{abcde}	12.12^{bcde}	16.50^{abcde}	-	14.49^{abcde}
	Chlorine	15.44^{a}	15.44^{a}	20.31^{abcdef}	22.85^{efg}	10.95^{bc}	14.93^{abcde}	$16.82^{fghijklm}$	19.15^{efghi}	-	18.46^{efghi}
	Biocontrol	15.44^{a}	15.44^{a}	$15.16^{abcdefg}$	$21.59^{efghijk}$	$13.20^{bcdefgh}$	14.87^{abcde}	12.06^{bcde}	12.17^{ab}	-	11.94^{ab}
	HWT	15.44^{a}	15.44^{a}	17.95^{abcdef}	$21.16^{efghijk}$	$14.04^{bcdefghij}$	13.6^{1abcd}	$16.09^{defghij}$	14.81^{abcde}	-	15.51^{bcdef}
	HWT+BIO	15.44^{a}	15.44^{a}	17.59^{abcdef}	15.70^{e}	17.80^{hijkq}	$16.81^{bcdefgh}$	$13.75^{bcdefgh}$	16.38^{abcde}	-	14.63^{abcde}
	CHL+BIO	15.44^{a}	15.44^{a}	17.01^{abcdef}	19.21^{efghij}	$14.38^{afghijk}$	$20.24^{efghijkl}$	12.34^{bcde}	13.57^{abcd}	-	17.39^{cdefg}
	ANO+BIO	15.44^{a}	15.44^{a}	17.00^{abcdef}	$20.94^{efghijk}$	12.00^{a}	13.33^{abc}	$14.95^{bcdefgh}$	22.46^{mnopq}	-	19.75^{hijkl}
ZZ+Green	Control	29.98^{g}	29.98^{g}	18.91^{abcdef}	27.75^{efg}	17.72^{hijkq}	26.20^{s}	$14.47^{bcdefghi}$	19.40^{fghij}	-	20.87^{ijklm}
	Chlorine	29.98^{g}	29.98^{g}	19.56^{abcdef}	32.03^{kl}	17.18^{ghijk}	24.71^{qrs}	$18.44^{lmnopqr}$	21.54^{ijklm}	-	18.50^{efghi}
	Biocontrol	29.98^{g}	29.98^{g}	21.91^{cdef}	35.26^{l}	$15.93^{defghijklm}$	$20.93^{ghijklm}$	$15.55^{bcdefgh}$	19.13^{efghi}	-	18.55^{efghi}
	HWT	29.98^{g}	29.98^{g}	20.96^{bcdef}	23.71^{aefg}	$16.46^{efghijk}$	23.37^{opqrs}	$16.17^{efghijkl}$	17.07^{bcdef}	-	20.37^{ijklm}
	HWT+BIO	29.98^{g}	29.98^{g}	20.29^{abcdef}	23.08^{efg}	19.22^{kq}	19.18^{defghi}	$15.85^{defghij}$	17.36^{bcdef}	-	14.07^{abcde}
	CHL+BIO	29.98^{g}	29.98^{g}	25.71^{h}	30.86^{jkl}	17.39^{hijk}	21.06^{hijklm}	$16.01^{defghij}$	21.45^{ijklm}	-	22.57^{mnopq}
	ANO+BIO	29.98^{g}	29.98^{g}	21.23^{cdef}	24.27^{aefg}	17.23^{ghijk}	21.63^{jklmn}	$14.55^{bcdefgh}$	21.91^{klmno}	-	16.80^{bcdef}
ZZ+Pink	Control	20.21^{abcde}	20.21^{abcdef}	16.68^{abcdef}	$22.68^{efghijk}$	17.17^{ghijk}	16.58^{abcdef}	$15.05^{bcdefgh}$	19.82^{ghijk}	-	17.74^{defgh}
	Chlorine	20.21^{abcde}	20.21^{abcdef}	$15.30^{abcdefg}$	$21.52^{efghijk}$	16.78^{fghijk}	18.43^{bcdefg}	18.20^{klmno}	16.95^{abcde}	-	17.92^{defgh}
	Biocontrol	20.21^{abcde}	20.21^{abcdef}	16.24^{abcdef}	18.24^{efghi}	$16.03^{defghijklm}$	$20.32^{efghijk}$	$13.53^{bcdefgh}$	19.90^{ghijk}	-	16.77^{bcdef}
	HWT	20.21^{abcde}	20.21^{abcdef}	11.35^{ab}	18.43^{efghij}	$14.75^{afghijk}$	17.52^{bcdefg}	12.68^{bcdef}	18.56^{defgh}	-	15.86^{bcdef}
	HWT+BIO	20.21^{abcde}	20.21^{abcdef}	17.66^{abcdef}	$21.67^{efghijk}$	17.28^{ghijk}	16.28^{abcde}	$17.02^{ghijklm}$	19.71^{fghij}	-	17.04^{bcdef}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient*	Cold (11°C)
	CHL+BIO	20.21^{abcde}	20.21^{abcdef}	12.84^{abc}	24.61^{cdefg}	14.72^{afghijk}	18.15^{bcdef}	13.61^{bcdefgh}	15.42^{abcde}	-	16.99^{bcdef}
	ANO+BIO	20.21^{abcde}	20.21^{abcdef}	15.09^{abcdef}	20.91^{efghijk}	17.15^{ghijk}	22.51^{nopqr}s	14.39^{bcdefg}	17.96^{cdefg}	-	23.85^{opqr}
ZZ+Red	Control	22.71^{bf}	22.71^{bf}	15.02^{abcdef}	16.21^{ef}	15.29^{afghijkl}	14.79^{abcde}	13.87^{bcdef}	15.19^{abcde}	-	16.19^{bcdef}
	Chlorine	22.71^{bcf}	22.71^{bcf}	12.51^{abc}	16.33^{ef}	12.30^{bcdef}	17.26^{bcdefg}	14.85^{bcdef}	15.78^{abcde}	-	14.71^{abcde}
	Biocontrol	22.71^{bcdf}	22.71^{bcdf}	12.19^{abc}	16.96^{efgh}	18.21^{ijkq}	12.93^{ab}	11.30^{a}	13.88^{abcde}	-	13.84^{abcde}
	HWT	22.71^{bcdef}	22.71^{bcdef}	12.63^{abc}	18.60^{efghij}	15.22^{afghijk}	14.97^{abcdef}	16.12^{defgh}	13.65^{abcd}	-	12.08^{abc}
	HWT+BIO	22.71^{bcdef}	22.71^{bcdef}	10.79^{a}	10.70^{a}	11.81^{bcde}	11.16^{a}	12.37^{bcde}	11.76^{a}	-	16.57^{bcdef}
	CHL+BIO	22.71^{bcdef}	22.71^{bcdef}	16.44^{abcdef}	11.89^{ab}	11.57^{bcd}	13.10^{abc}	14.21^{bcde}	17.82^{cdefg}	-	16.61^{bcdef}
	ANO+BIO	22.71^{bcdef}	22.71^{bcdef}	16.87^{abcdef}	18.16^{efghi}	10.7^{2b}	13.95^{abcd}	11.56^{b}	16.01^{abcde}	-	15.64^{bcdef}

Significance level (p)	
Treatments (A)	0.796
Storage (B)	<.001
Route (C)	<.001
Maturity stage (D)	<.001
AXB	0.850
AXC	0.666
BXC	0.950
AXD	0.006
BXD	0.002
CXD	0.022
AXBXC	0.978
AXBXD	0.117
AXCXD	0.845
BXCXD	0.563
AXBXCXD	0.915
CV (%)	27.3
SE	5.225
LSD	3.240

Means within the same column followed by the same letter are not significantly different ($p>0.05$). HWT signifies hot water treatment, BIO designates biocontrol treatment using B-13 yeast isolate, ANO anolyte water and CHL chlorinated water. PD signifies tomatoes transported through Point Drift-Pietermaritzburg route, EM through Mooketsi-Pietermaritzburg and ZZ through Esmefour-Pietermaritzburg. The transportation routes had varying road quality conditions and distances. .* indicates that missing data. No samples were available on day 30 under ambient storage.

These factors explain the higher degradation of firmness in fruit stored under ambient conditions or harvested in the summer season, compared to those stored under cold storage conditions or harvested in the winter season.

Comparison of the effect of various transportation conditions on the sample fruits' loss of firmness in the summer showed fruit transported on the EM route to have lower loss in firmness compared to that of fruit transported over the PD and the ZZ routes. The percentage reduction in firmness for fruit harvested at the green maturity stage was the highest for fruit transported through PD (45 %) compared to that transported using the EM (41 %) and ZZ (42 %) route. The percentage reduction in fruit firmness for fruit harvested at pink maturity stage was higher for fruit transported using the PD route (38 %) compared to EM (6.2 %) and ZZ (18.4 %) route. Similarly, fruit transported through the ZZ (40 %) route had the highest reduction in firmness for fruit harvested at the red maturity stage compared to the PD (10 %) and EM (3 %) routes. Fruit harvested at the green (43 %) maturity stage had a higher percentage reduction in fruit firmness compared to those harvested at the Pink (20 %) and red (17 %) maturity stages. Fruit stored under ambient conditions had significantly ($p \leq 0.05$) lower firmness values compared to those stored under cold storage environment.

Road quality during transportation of fragile agricultural commodities is known to affect their quality and shelf-life downstream the supply chain (Miranda *et al.*, 2015; Moggia *et al.*, 2017). Bruising and mechanical injuries on tomatoes during handling and transportation is known to induce early ripening by the triggering a surge in ethylene production (Mutari and Debbie, 2011). This explains the relatively higher loss in firmness in fruit transported over the longer (ZZ) and relatively rough (PD) road conditions. The lower percentage loss in fruit firmness for fruit harvested at the red maturity stages compared to the green maturity stage is primarily attributed to the biological age of the fruit, suggesting that fruit harvested earlier have a longer shelf-life, and that fruit firmness is more sensitive to rough handling than fruit colour, since transportation over rougher road conditions (PD) did not result in higher reduction in hue angle.

Table 4.5 presents a summary of changes in fruit firmness with storage period for tomato fruit harvested and transported during the winter season. Fruit harvested and transported through the EM route appeared to have lower loss in firmness compared to fruit transported through the PD and ZZ routes. Similarly, Fruit transported using the PD route appeared to have higher reduction in their firmness compared to that of fruit transported through the ZZ and EM routes.

Table 4.5 A summary of changes in firmness of tomato fruit harvested and transported in the winter season

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)
PD+Green	Control	29.02^{e}	29.02^{e}	21.14^{ijklm}	22.37^{hijkl}	18.37^{e}	24.26^{j}	15.58^{bcdef}	17.38^{abcde}	15.14^{bcd}	23.58^{j}
	Chlorine	29.02^{e}	29.02^{e}	20.52^{ghijk}	23.17^{ijklm}	15.31^{abcde}	22.29^{fghij}	16.75^{bcdef}	19.99^{cdefg}	14.38^{abcd}	14.42^{abcde}
	Biocontrol	29.02^{e}	29.02^{e}	15.59^{abcde}	24.08^{lmnop}	13.54^{abc}	23.52^{ghij}	16.01^{bcdef}	18.15^{abcde}	13.38^{abcd}	16.81^{defgh}
	HWT	29.02^{e}	29.02^{e}	19.67^{defgh}	20.97^{fghij}	18.40^{e}	16.13^{abcde}	14.41^{bcdef}	19.75b^{cdef}	12.46^{abc}	15.58^{cdefg}
	HWT+BIO	29.02^{e}	29.02^{e}	19.65^{defgh}	21.51^{ghijk}	12.16^{a}	18.22^{abcde}	18.13^{efghi}	20.20^{defgh}	12.92^{abc}	18.48^{hi}
	CHL+BIO	29.02^{e}	29.02^{e}	21.81^{klmno}	24.71^{nopqr}	13.28^{abc}	19.99^{cdefg}	16.75^{bcdef}	18.84^{abcde}	14.05^{abcd}	19.25^{i}
	ANO+BIO	29.02^{ce}	29.02^{ce}	18.18^{bcdef}	20.06^{defgh}	14.99^{abcd}	21.66f^{ghij}	14.05^{bcdef}	19.06^{abcde}	24.76^{e}	16.26^{cdefg}
PD+Pink	Control	24.32^{b}	24.32^{b}	20.07^{fghij}	23.67^{jklmn}	15.91^{bcde}	15.78^{abcd}	18.77^{hijkl}	16.49^{abcde}	13.45^{abcd}	14.41^{abcde}
	Chlorine	24.32^{b}	24.32^{b}	18.30^{bcdef}	20.53^{efghi}	14.91^{abcd}	16.91^{abcde}	12.98^{b}	20.10^{cdefg}	12.05^{abc}	15.64^{cdefg}
	Biocontrol	24.32^{b}	24.32^{b}	18.59^{cdefg}	22.44^{hijkl}	17.81^{de}	20.85^{defgh}	20.66^{jklmn}	15.89^{abcde}	14.62^{abcd}	16.34^{cdefg}
	HWT	24.32^{b}	24.32^{b}	20.01^{fghij}	17.97^{bcdef}	14.44^{abc}	20.20^{cdefg}	15.16^{bcdef}	17.38^{abcde}	10.87^{a}	18.14^{ghi}
	HWT+BIO	24.32^{b}	24.32^{b}	14.65^{abcde}	18.25^{bcdef}	17.94^{de}	20.65^{cdefg}	13.09^{bc}	18.38^{abcde}	13.20^{abcd}	14.39^{abcde}
	CHL+BIO	24.32^{b}	24.32^{b}	20.64^{hijkl}	22.24^{hijkl}	14.33^{abc}	20.62^{cdefg}	12.98^{b}	19.02^{abcde}	13.80^{abcd}	17.63^{fghi}
	ANO+BIO	24.32^{b}	24.32^{b}	19.02^{cdefg}	21.22^{fghij}	15.37^{abcde}	20.49^{cdefg}	14.26^{bcdef}	17.19^{abcde}	15.33^{cd}	16.68^{defgh}
PD+Red	Control	20.28^{ab}	20.28^{ab}	17.48^{abcde}	20.86^{fghij}	13.41^{abc}	15.40^{abc}	16.34^{bcdef}	20.28^{defgh}	14.32^{abcd}	15.94^{cdefg}
	Chlorine	20.28^{ab}	20.28^{ab}	17.75^{abcde}	19.22^{cdefg}	14.26^{abc}	18.51^{abcde}	17.56^{defgh}	18.07^{abcde}	16.77^{d}	17.23^{efghi}
	Biocontrol	20.28^{ab}	20.28^{ab}	14.45^{abcd}	15.46^{abcde}	13.47^{abc}	18.16^{abcde}	16.32^{bcdef}	15.59^{abcde}	13.42^{abcd}	14.73^{abcde}
	HWT	20.28^{ab}	20.28^{ab}	14.05^{abc}	19.68^{defgh}	16.52^{cde}	17.94^{abcde}	15.98^{bcdef}	16.00^{abcde}	11.50^{ab}	11.06^{ab}
	HWT+BIO	20.28^{ab}	20.28^{ab}	14.12^{abc}	13.93^{ab}	15.00^{abcd}	21.26^{efghi}	14.43^{bcdef}	14.55^{abc}	14.23^{abcd}	16.23^{cdefg}
	CHL+BIO	20.28^{ab}	20.28^{ab}	19.88^{efghi}	17.65^{bcdef}	13.04^{ab}	14.61^{a}	17.56^{defgh}	15.94^{abcde}	14.33^{abcd}	15.98^{cdefg}
	ANO+BIO	20.28^{ab}	20.28^{ab}	15.07^{abcde}	14.99^{abcd}	15.19^{abcde}	17.88^{abcde}	13.23^{bcd}	13.79^{a}	12.77^{abc}	13.47^{abcde}
EM+Gree	Control	31.55^{ef}	31.55^{ef}	26.28^{s}	28.47^{tuvw}	18.37^{e}	16.13^{abcde}	18.08^{efghi}	20.49^{efghi}	15.14^{bcd}	23.58^{j}
	Chlorine	31.55^{ef}	31.55^{ef}	25.34^{rs}	29.76^{w}	15.31^{abcde}	24.26^{j}	17.58^{efghi}	20.64^{fghij}	14.38^{abcd}	14.42^{abcde}
	Biocontrol	31.55^{ef}	31.55^{ef}	20.26^{fghij}	28.87^{vw}	13.54^{abc}	22.29^{fghij}	15.83^{bcdef}	24.21^{rs}	13.38^{abcd}	16.81^{defgh}
	HWT	31.55^{ef}	31.55^{ef}	23.63^{nopqr}	24.17^{lmnop}	18.40^{e}	23.52^{gij}	19.24^{ijklm}	23.30^{opqrs}	12.46^{abc}	15.58^{cdefg}
	HWT+BIO	31.55^{ef}	31.55^{ef}	22.16^{klmno}	26.08^{pqrst}	12.16^{a}	18.22^{abcde}	20.61^{jklmn}	21.01^{hijkl}	12.92^{abc}	18.48^{hi}
	CHL+BIO	31.55^{ef}	31.55^{ef}	22.27^{klmno}	28.71^{uvw}	13.28^{abc}	19.99^{cdefg}	18.27^{fghij}	22.96^{nopqr}	14.05^{abcd}	19.25^{i}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)
	ANO+BIO	31.55^{ef}	31.55^{ef}	23.80^{opqrs}	30.18^{w}	14.99^{abcd}	21.66^{fghij}	20.90^{klmn}	23.80^{qrs}	24.76^{e}	16.26^{cdefg}
EM+Pink	Control	24.54^{bc}	24.54^{bc}	21.74^{klmno}	22.45^{hijkl}	15.91^{bcde}	15.40^{abc}	18.59^{ghijk}	23.89^{qrs}	13.45^{abcd}	14.41^{abcde}
	Chlorine	24.54^{bcd}	24.54^{bcd}	18.73^{cdefg}	27.65^{rstuv}	14.91^{abcd}	18.51^{abcde}	18.01^{efghi}	15.32^{abcde}	12.05^{abc}	15.64^{cdefg}
	Biocontrol	24.54^{bcd}	24.54^{bcd}	18.53^{cdefg}	20.30^{efghi}	17.81^{de}	18.16^{abcde}	21.70^{lmn}	16.78^{abcde}	14.62^{abcd}	16.34^{cdefg}
	HWT	24.54^{bcd}	24.54^{bcd}	23.30^{mnopq}	16.50^{bcdef}	14.44^{abc}	17.94^{abcde}	16.70^{bcdef}	21.46^{ijklm}	10.87^{a}	18.14^{ghi}
	HWT+BIO	24.54^{bcd}	24.54^{bcd}	21.31^{jklmn}	19.72^{defgh}	17.94^{de}	21.26^{efghi}	22.42^{n}	18.42^{abcde}	13.20^{abcd}	14.39^{abcde}
	CHL+BIO	24.54^{bcd}	24.54^{bcd}	18.55^{cdefg}	22.60^{hijkl}	14.33^{abc}	14.61^{ab}	22.11^{mn}	19.57^{bcdef}	13.80^{abcd}	17.63^{fghi}
	ANO+BIO	24.54^{bcd}	24.54^{bcd}	21.27^{jklmn}	24.36^{mnopq}	15.37^{abcde}	17.88^{abcde}	16.57^{bcdef}	21.05^{hijkl}	15.33^{cd}	16.68^{defgh}
EM+Red	Control	22.01^{ab}	22.01^{ab}	15.87^{abcde}	22.37^{hijkl}	13.41^{abc}	15.40^{abc}	15.86^{bcdef}	14.82^{abcd}	14.32^{abcd}	15.94^{cdefg}
	Chlorine	22.01^{ab}	22.01^{ab}	15.92^{abcde}	18.56^{bcdef}	14.26^{abc}	18.51^{abcde}	20.68^{jklmn}	21.82^{lmnop}	16.77^{d}	17.23^{efghi}
	Biocontrol	22.01^{ab}	22.01^{ab}	19.58^{defgh}	20.79^{efghi}	13.47^{abc}	18.16^{abcde}	17.36^{cdefg}	18.37^{abcde}	13.42^{abcd}	14.73^{abcde}
	HWT	22.01^{ab}	22.01^{ab}	23.02^{lmnop}	19.41^{defgh}	16.52^{cde}	17.94^{abcde}	16.56^{bcdef}	21.56^{jklmn}	11.50^{ab}	11.06^{ab}
	HWT+BIO	22.01^{ab}	22.01^{ab}	20.17^{fghij}	20.53^{efghi}	15.00^{abcd}	21.26^{efghi}	14.00^{a}	19.27^{abcde}	14.23^{abcd}	16.23^{cdefg}
	CHL+BIO	22.01^{ab}	22.01^{ab}	20.29^{fghij}	18.82^{bcdef}	13.04^{ab}	14.61^{ab}	17.31^{bcdef}	17.27^{abcde}	14.33^{abcd}	15.98^{cdefg}
	ANO+BIO	22.01^{ab}	22.01^{ab}	15.09^{abcde}	18.07^{bcdef}	15.19^{abcde}	17.88^{abcde}	13.56^{a}	16.51^{abcde}	12.77^{abc}	13.47^{abcde}
ZZ+Green	Control	34.09^{f}	34.09^{f}	23.99^{qrs}	22.60^{hijkl}	18.37^{e}	24.26^{j}	15.78^{bcdef}	23.09^{opqrs}	15.14^{bcd}	15.14^{bcdef}
	Chlorine	34.09^{f}	34.09^{f}	20.20^{fghij}	20.61^{efghi}	15.31^{abcde}	22.29^{fghij}	15.57^{bcdef}	24.17^{rs}	14.38^{abcd}	14.38^{abcde}
	Biocontrol	34.09^{f}	34.09^{f}	20.22^{fghij}	25.56^{opqrs}	13.54^{abc}	23.52^{ghij}	14.78^{bcdef}	26.31^{s}	13.38^{abcd}	13.38^{abcde}
	HWT	34.09^{f}	34.09^{f}	19.38^{cdefg}	23.84^{klmno}	18.40^{e}	16.13^{abcde}	18.21^{fghij}	21.63^{klmno}	12.46^{abc}	12.46^{abcd}
	HWT+BIO	34.09^{f}	34.09^{f}	24.04^{qrs}	23.67^{jklmn}	12.16^{a}	18.22^{abcde}	18.08^{efghi}	23.98^{qrs}	12.92^{abc}	12.92^{abcde}
	CHL+BIO	34.09^{f}	34.09^{f}	18.95^{cdefg}	28.28^{stuvw}	13.28^{abc}	19.99^{acdef}	14.52^{bcdef}	21.59^{klmno}	14.05^{abcd}	14.05^{abcde}
	ANO+BIO	34.09^{f}	34.09^{f}	18.61^{cdefg}	20.89^{fghij}	14.99^{abcd}	21.66^{fghij}	17.87^{efghi}	22.76^{mnopq}	24.76^{e}	24.76^{j}
ZZ+Pink	Control	24.26^{b}	24.26^{b}	15.29^{abcde}	23.38^{ijklm}	14.33^{abc}	15.78^{abcd}	12.99^{b}	18.35^{abcde}	13.45^{abcd}	13.45^{abcde}
	Chlorine	24.26^{b}	24.26^{b}	23.96^{pqrs}	20.74^{efghi}	14.44^{abc}	16.91^{abcde}	14.73^{bcdef}	20.49^{efghi}	12.05^{abc}	12.05^{abc}
	Biocontrol	24.26^{b}	24.26^{b}	16.29^{abcde}	27.28^{qrstu}	14.91^{abcd}	20.85^{defgh}	15.82^{bcdef}	20.84^{ghijk}	14.62^{abcd}	14.62^{abcde}
	HWT	24.26^{b}	24.26^{b}	12.84^{a}	16.71^{bcdef}	15.37^{abcde}	20.20^{cdefg}	13.80^{bcde}	21.91^{lmnop}	10.87^{a}	16.71^{defgh}
	HWT+BIO	24.26^{b}	24.26^{b}	15.21^{abcde}	21.41^{ghijk}	15.91^{bcde}	20.65^{cdefg}	18.16^{efghi}	23.73^{pqrs}	13.20^{abcd}	13.20^{abcde}
	CHL+BIO	24.26^{b}	24.26^{b}	15.36^{abcde}	21.76^{ghijk}	17.81^{de}	20.62^{cdefg}	15.51^{bcdef}	17.82^{abcde}	13.80^{abcd}	13.80^{abcde}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)
	ANO+BIO	24.26^{b}	24.26^{b}	18.64^{cdefg}	20.40^{efghi}	17.94^{de}	20.49^{cdefg}	18.04^{efghi}	20.48^{efghi}	15.33^{cd}	15.33^{bcdef}
ZZ+Red	Control	19.55^{a}	19.55^{a}	18.19^{bcdef}	11.45^{a}	13.41^{abc}	15.40^{abc}	14.25^{bcdef}	14.91^{abcde}	14.32^{abcd}	14.32^{abcde}
	Chlorine	19.55^{a}	19.55^{a}	15.44^{abcde}	17.71^{bcdef}	14.26^{abc}	18.51^{abcde}	16.65^{bcdef}	14.19^{ab}	16.77^{d}	16.77^{defgh}
	Biocontrol	19.55^{a}	19.55^{a}	13.06^{ab}	15.00^{abcd}	13.47^{abc}	18.16^{abcde}	13.82^{bcde}	18.86^{abcde}	13.42^{abcd}	13.42^{abcde}
	HWT	19.55^{a}	19.55^{a}	19.02^{cdefg}	15.93^{abcde}	16.52c^{de}	17.94^{abcde}	15.65^{bcdef}	15.24^{abcde}	11.50^{ab}	10.50^{a}
	HWT+BIO	19.55^{a}	19.55^{a}	14.22^{abc}	18.87^{bcdef}	15.00^{abcd}	21.26^{efghi}	13.00^{a}	17.28^{abcde}	14.23^{abcd}	14.23^{abcde}
	CHL+BIO	19.55^{a}	19.55^{a}	18.19^{bcdef}	14.06^{abc}	13.04^{ab}	14.61^{ab}	15.21^{bcdef}	15.10^{abcde}	14.33^{abcd}	14.33^{abcde}
	ANO+BIO	19.55^{a}	19.55^{a}	14.50^{abcd}	19.01^{bcdef}	15.19^{abcde}	17.88^{abcde}	15.54^{bcdef}	19.99^{cdefg}	12.77^{abc}	12.77^{abcde}

Significance level (p)	
Treatments (A)	0.318
Storage (B)	<.001
Route (C)	<.001
Maturity stage (D)	<.001
AXB	0.344
AXC	0.698
BXC	0.204
AXD	0.211
BXD	0.153
CXD	<.001
AXBXC	0.487
AXBXD	0.771
AXCXD	0.567
BXCXD	0.009
AXBXCXD	0.322
CV (%)	27.6
SE	5.370
LSD	3.335

Means within the same column followed by the same letter are not significantly different ($p>0.05$). HWT signifies hot water treatment, BIO designates biocontrol treatment using B-13 yeast isolate, ANO analyte water and CHL chlorinated water. PD signifies tomatoes transported through Point Drift-Pietermaritzburg route, EM through Mooketsi-Pietermaritzburg and ZZ through Esmefour-Pietermaritzburg. The transportation routes had varying road quality conditions and distances.

A MANOVA of the fruit firmness data showed the fruit maturity at harvest, storage and the transportation conditions as significant ($p \leq 0.05$) factors that influenced the changes in firmness, while pre-storage treatments was not a significant ($p > 0.05$) factor. Analysis of pooled data showed that fruit harvested and transported in the winter season had significantly ($p \leq 0.05$) higher firmness than fruit harvested and transported in the summer. The average firmness of fruit transported through PD, EM and ZZ was 18.48, 19.65 and 18.6 N, respectively, for fruit transported in the winter. Conversely, the mean firmness of fruit transported in the summer was 16.66, 19.11 and 17.01N for fruit transported through PD, EM and ZZ, respectively.

Testing the firmness of tomato fruit by puncture measures the integrity of the fruit pericarp where softening enzymes are localized (Jackman *et al.*, 1990). Maintenance of tomato fruit firmness is important from a growers' and consumers' standpoints. Tomato fruit firmness plays an important role in exerting desirable textural properties when the fruit is used as salads, and other culinary purposes. Fruits that have softened excessively are often mealy and less desirable to consumers and often lead to challenges in handling such products due to their increased susceptibility to mechanical damage (Miranda *et al.*, 2015; Moggia *et al.*, 2017). The maturity stage at harvest has been also shown to be a significant factor influencing the susceptibility of tomato fruit to mechanical damage (Mohammadi-Aylar *et al.*, 2010). Fruit transported through the EM route had relatively higher firmness values due to the relatively shorter distance of transportation and smoother road surface profile. This translated to less mechanical damage on the fruit compared to the other routes.

4.4.5 Physiological weight-loss

The cumulative weight-loss of fruit increased with storage period for tomato fruit harvested and transported in the summer and winter. Table 4.6 shows a summary of changes in weight-loss with storage period for fruit harvested and transported through PD, EM and ZZ route in the summer. The weight loss of fruit stored under ambient conditions was higher than that of fruit stored under cold storage. Similarly, the weight-loss of fruit transported during the summer was generally higher compared to that of fruit transported during the winter. The effect of fruit maturity at harvest on changes in fruit weight-loss with storage appeared to be variable, although fruit of the pink maturity stage appeared to have the highest weight-loss. These trends were observed across both harvesting and transportation seasons.

Table 4.6 A summary of changes in tomato fruit physiological weight-loss during storage for fruit harvested and transported in the summer

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient*	Cold (11^{o}C)
PD+Green	Control	0^{a}	0^{a}	7.19^{wxyz}	1.58^{cdefg}	12.17^{lmnop}	3.79^{ab}	14.46^{efghi}	8.83^{opqr}	-	10.51^{lmno}
	Chlorine	0^{a}	0^{a}	8.19^{zA}	2.09^{mnopq}	14.61^{stuvw}	4.95^{bcdef}	20.82^{tuvw}	8.84^{opqr}	-	10.67^{mnop}
	Biocontrol	0^{a}	0^{a}	6.30^{rstuv}	2.19^{npqrs}	11.68^{klmno}	5.45^{fghij}	17.48^{klmno}	7.59^{fghij}	-	10.08^{hijk}
	HWT	0^{a}	0^{a}	6.23^{rstuv}	1.90^{jklmn}	11.42^{hijkl}	4.31^{abcde}	17.66^{klmno}	6.02^{abcde}	-	7.23^{abcde}
	HWT+BIO	0^{a}	0^{a}	7.66^{xyzA}	1.83^{ijklm}	14.98^{tuvwx}	4.13^{abcde}	22.01^{vwx}	5.79^{abcd}	-	7.16^{abcde}
	CHL+BIO	0^{a}	0^{a}	8.69^{A}	1.91^{jklmn}	16.24^{x}	4.16^{abcde}	22.84^{wx}	6.08^{abcde}	-	8.41^{bcdef}
	ANO+BIO	0^{a}	0^{a}	6.21^{rstuv}	2.29^{rstuv}	13.87^{rstuv}	5.08^{bcdef}	20.58^{stuvw}	7.07^{bcdef}	-	9.14^{efghi}
PD+Pink	Control	0^{a}	0^{a}	5.64^{opqrs}	1.85^{jklmn}	10.51^{cdefg}	5.18^{cdefg}	13.92^{cdefg}	9.56^{r}	-	13.10st
	Chlorine	0^{a}	0^{a}	6.37^{stuvw}	2.23^{pqrst}	12.79^{mnopq}	4.92^{bcdef}	17.03^{ijklm}	6.94^{bcdef}	-	10.01^{hijk}
	Biocontrol	0^{a}	0^{a}	6.48^{stuvw}	2.96^{y}	10.22^{bcdef}	5.24^{defgh}	13.89^{cdefg}	7.99^{jklmn}	-	10.36^{jklm}
	HWT	0^{a}	0^{a}	6.69^{tuvwx}	2.10^{mnopq}	13.05^{nopqr}	4.82^{abcde}	19.66^{rstuv}	7.29^{bcdef}	-	9.64^{ghijk}
	HWT+BIO	0^{a}	0^{a}	5.49^{nopqr}	1.75^{hijkl}	11.12^{efghi}	3.89^{abc}	18.17^{mnopq}	6.12^{abcde}	-	7.66^{abcde}
	CHL+BIO	0^{a}	0^{a}	6.25^{rstuv}	2.04^{lmnop}	12.24^{lmnop}	4.40^{abcde}	16.58^{ijklm}	8.09^{lmnop}	-	10.43^{klmn}
	ANO+BIO	0^{a}	0^{a}	6.24^{rstuv}	2.46^{tuvwx}	11.61^{jklmn}	4.94^{bcdef}	15.53^{ghijk}	7.38^{defgh}	-	9.64^{ghijk}
PD+Red	Control	0^{a}	0^{a}	7.90^{yzA}	2.91^{xy}	14.40^{stuvw}	5.07^{bcdef}	17.99^{lmnop}	11.33^{s}	-	14.61^{t}
	Chlorine	0^{a}	0^{a}	6.69^{tuvwx}	2.03^{lmnop}	13.03^{nopqr}	4.08^{abcde}	15.78^{ghijk}	5.93^{abcde}	-	7.86^{abcde}
	Biocontrol	0^{a}	0^{a}	7.72^{yzA}	2.97^{y}	15.23^{uvwx}	6.01^{klmno}	22.93^{wx}	9.46^{qr}	-	12.34^{qrs}
	HWT	0^{a}	0^{a}	7.03^{vwxyz}	2.57^{uvwxy}	14.02^{rstuv}	4.61^{abcde}	20.74^{tuvw}	7.64^{ghijk}	-	10.42^{klmn}
	HWT+BIO	0^{a}	0^{a}	8.26^{zA}	2.84^{wxy}	16.32^{x}	5.29^{efghi}	22.56^{wx}	7.86^{ijklm}	-	10.46^{klmn}
	CHL+BIO	0^{a}	0^{a}	8.19^{zA}	2.60^{vwxy}	16.13^{wx}	5.08^{bcdef}	23.93^{x}	8.38^{nopqr}	-	10.83^{mnop}
	ANO+BIO	0^{a}	0^{a}	7.16^{wxyz}	2.81^{wxy}	14.80^{tuvwx}	5.71^{hijkl}	21.62^{uvwx}	9.13^{pqr}	-	11.49^{pqrs}
EM+Green	Control	0^{a}	0^{a}	7.23^{wxyz}	2.40^{stuvw}	11.58^{jklmn}	4.17^{abcde}	14.47^{defgh}	5.84^{abcde}	-	7.59^{abcde}
	Chlorine	0^{a}	0^{a}	5.81^{pqrst}	2.04^{lmnop}	9.32^{abcdef}	4.81^{abcde}	12.30^{abcde}	6.19^{abcde}	-	7.11^{abcd}
	Biocontrol	0^{a}	0^{a}	3.29^{abcde}	1.86^{jklmn}	7.60^{a}	4.96^{bcdef}	10.75^{a}	6.31^{abcde}	-	7.29^{abcde}
	HWT	0^{a}	0^{a}	2.14^{a}	1.71^{fghij}	8.83^{abcd}	4.78^{abcde}	12.50^{abcde}	6.43^{abcde}	-	7.44^{abcde}
	HWT+BIO	0^{a}	0^{a}	2.75^{ab}	2.18^{npqrs}	7.84^{a}	6.76^{qr}	11.10^{ab}	7.94^{jklmn}	-	8.88^{defgh}
	CHL+BIO	0^{a}	0^{a}	2.80^{abc}	1.91^{jklmn}	8.21^{ab}	5.05^{bcdef}	11.51^{abc}	6.32^{abcde}	-	7.82^{abcde}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient*	Cold (11^{o}C)
	ANO+BIO	0^{a}	0^{a}	3.05^{abcd}	2.933^{xy}	8.66^{abcd}	6.68^{pqr}	11.68a^{bc}	8.02^{klmno}	-	9.12^{efghi}
EM+Pink	Control	0^{a}	0^{a}	7.73^{yzA}	1.957^{klmno}	15.80^{vwx}	4.97^{bcdef}	19.61^{rstu}	6.06^{abcde}	-	7.11^{abcd}
	Chlorine	0^{a}	0^{a}	5.43^{mnopq}	1.775^{hijkl}	11.24^{ghijk}	4.82^{abcde}	14.67^{efghi}	6.23^{abcde}	-	8.43^{bcdef}
	Biocontrol	0^{a}	0^{a}	2.97^{abcd}	2.265^{qrstu}	10.45^{cdefg}	4.70^{abcde}	13.80^{cdefg}	6.69^{abcde}	-	8.30^{abcde}
	HWT	0^{a}	0^{a}	6.02qrs^{tu}	2.525^{tuvwx}	12.20^{lmnop}	6.87^{qr}	15.28^{ghijk}	8.74^{opqr}	-	12.74^{rs}
	HWT+BIO	0^{a}	0^{a}	4.84^{hijkl}	1.597^{cdefg}	10.62^{defgh}	4.63^{abcde}	13.51^{bcdef}	5.73^{abc}	-	6.60^{ab}
	CHL+BIO	0^{a}	0^{a}	4.57^{fghij}	1.897^{jklmn}	9.89^{bcdefg}	6.16^{lmnop}	13.40^{bcdef}	8.47^{nopqr}	-	10.10^{ijkl}
	ANO+BIO	0^{a}	0^{a}	3.33^{bcdef}	1.833^{ijklm}	8.86^{abcd}	5.85^{jklmn}	11.92^{abc}	7.05^{bcdef}	-	8.56^{bcdef}
EM+Red	Control	0^{a}	0^{a}	6.28^{rstuv}	1.761^{hijkl}	13.11^{opqrs}	5.77^{ijklm}	17.09^{jklmn}	8.34^{nopqr}	-	10.15^{ijkl}
	Chlorine	0^{a}	0^{a}	5.81^{pqrst}	1.528^{bcdef}	11.73^{klmno}	5.60^{ghijk}	15.22^{fghij}	7.67^{hijkl}	-	11.00^{nopq}
	Biocontrol	0^{a}	0^{a}	5.22^{klmno}	1.947^{klmno}	9.50^{abcdef}	7.16^{r}	13.94^{cdefg}	8.84^{opqr}	-	13.14st
	HWT	0^{a}	0^{a}	6.83^{uvwxy}	1.559^{bcdef}	14.21^{stuvw}	6.18^{lmnop}	16.76^{ijklm}	8.23^{mnopq}	-	10.71^{mnop}
	HWT+BIO	0^{a}	0^{a}	4.62^{ghijk}	1.643^{defgh}	11.19^{fghij}	6.83^{qr}	13.54^{bcdef}	8.10^{lmnop}	-	9.16^{efghi}
	CHL+BIO	0^{a}	0^{a}	4.60^{fghij}	1.616^{cdefg}	9.15^{abcdef}	5.99^{klmno}	11.94^{abcd}	8.52^{nopqr}	-	10.25i^{jkl}
	ANO+BIO	0^{a}	0^{a}	5.39^{lmnop}	1.732^{efghi}	13.34^{qrstu}	5.97^{klmno}	17.56^{klmno}	7.44^{efghi}	-	8.36^{bcdef}
ZZ+Green	Control	0^{a}	0^{a}	4.05^{cdefg}	1.579^{cdefg}	9.37^{abcdef}	5.19^{cdefg}	15.21^{fghij}	7.27^{bcdef}	-	8.63^{cdefg}
	Chlorine	0^{a}	0^{a}	3.80^{bcdef}	1.285^{abcde}	9.09^{abcde}	3.92^{abcd}	14.55^{efghi}	5.67^{ab}	-	6.80^{abc}
	Biocontrol	0^{a}	0^{a}	3.88^{bcdef}	1.358^{abcde}	9.60^{abcdef}	4.12^{abcde}	14.68^{efghi}	6.04^{abcde}	-	7.82^{abcde}
	HWT	0^{a}	0^{a}	4.17^{defgh}	1.005^{a}	8.59^{abcd}	3.53^{a}	15.52^{ghijk}	5.09^{a}	-	6.33^{a}
	HWT+BIO	0^{a}	0^{a}	3.39^{bcdef}	1.134^{abc}	8.48^{abc}	3.57^{a}	12.70^{abcde}	5.21^{a}	-	6.70^{abc}
	CHL+BIO	0^{a}	0^{a}	3.74^{bcdef}	1.229^{abcde}	9.42^{abcdef}	3.75^{ab}	12.45^{abcde}	5.16^{a}	-	7.71^{abcde}
	ANO+BIO	0^{a}	0^{a}	3.34^{abcde}	1.488^{abcde}	10.32^{cdefg}	6.18^{lmnop}	13.59^{bcdef}	7.95^{jklmn}	-	9.04^{defgh}
ZZ+Pink	Control	0^{a}	0^{a}	5.80^{pqrst}	1.202^{abcde}	13.29^{pqrst}	4.45^{abcde}	19.50^{qrstu}	7.36^{cdefg}	-	9.05^{defgh}
	Chlorine	0^{a}	0^{a}	4.71^{hijkl}	1.581^{cdefg}	9.99^{bcdefg}	4.30^{abcde}	14.50^{efghi}	5.97^{abcde}	-	7.51^{abcde}
	Biocontrol	0^{a}	0^{a}	4.94^{ijklm}	1.853^{jklmn}	10.95^{efghi}	4.32^{abcde}	18.19^{mnopq}	6.30^{abcde}	-	9.45^{fghij}
	HWT	0^{a}	0^{a}	3.73^{bcdef}	1.503^{bcdef}	10.25^{bcdef}	4.91^{bcdef}	16.79^{ijklm}	6.54^{abcde}	-	8.02^{abcde}
	HWT+BIO	0^{a}	0^{a}	4.47^{efghi}	1.186^{abcd}	11.07^{efghi}	4.18^{abcde}	17.69^{klmno}	6.27^{abcde}	-	7.54^{abcde}
	CHL+BIO	0^{a}	0^{a}	4.12^{efgh}	1.085^{ab}	9.41^{abcdef}	4.33^{abcde}	15.13^{fghij}	5.99^{abcde}	-	8.07^{abcde}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient*	Cold (11^{o}C)
	ANO+BIO	0^{a}	0^{a}	3.63^{bcdef}	1.435^{abcde}	12.19^{lmnop}	5.71^{hijkl}	18.52^{opqrs}	7.99^{klmno}	-	10.07^{ijkl}
ZZ+Red	Control	0^{a}	0^{a}	3.57^{bcdef}	1.57^{cdefg}	10.10^{bcdef}	6.37^{mopqr}	16.75^{ijklm}	9.49^{qr}	-	11.22^{opqr}
	Chlorine	0^{a}	0^{a}	3.57^{bcdef}	1.35^{abcde}	10.65^{defgh}	4.60^{abcde}	16.77^{ijklm}	6.10^{abcde}	-	8.51^{bcdef}
	Biocontrol	0^{a}	0^{a}	4.35^{efghi}	1.30^{abcde}	10.47^{cdefg}	4.27^{abcde}	15.35^{ghijk}	6.39^{abcde}	-	7.74^{abcde}
	HWT	0^{a}	0^{a}	$4.54^{efghijkl}$	1.16^{abcd}	8.70^{abcd}	3.76^{ab}	$15.68^{ghijklm}$	$6.10^{abcdefg}$h	-	7.56^{abcdef}
	HWT+BIO	0^{a}	0^{a}	$4.73^{hijklmn}$	$1.26^{abcdefg}$	9.15^{abcdef}	4.07^{abcde}	$16.42^{hijklmno}$	5.76^{abcd}	-	$8.07^{abcdefg}$h
	CHL+BIO	0^{a}	0^{a}	$4.93^{ijklmno}$	1.19^{abcd}	$11.44^{ijklmnop}$	3.95^{abcd}	19.03^{pqrst}	5.77^{abcd}	-	7.28^{abcde}
	ANO+BIO	0^{a}	0^{a}	5.08^{jklmno}	$1.72^{ghijklmno}$	$11.29^{ghijklmn}$	$4.52^{abcdefg}$hi	18.28^{nopqrs}	$6.64^{abcdefg}$hij	-	$9.04^{defghijkl}$

Significance level (p)	
Treatments (A)	0.532
Storage (B)	<.001
Route (C)	<.001
Maturity stage (D)	<.001
AXB	0.886
AXC	0.723
BXC	<.001
AXD	0.940
BXD	0.540
CXD	0.037
AXBXC	0.886
AXBXD	0.967
AXCXD	0.992
BXCXD	0.074
AXBXCXD	0.999
CV (%)	79.4
SE	5.1111
LSD	3.1736

Means within the same column followed by the same letter are not significantly different ($p>0.05$). HWT signifies hot water treatment, BIO designates biocontrol treatment using B-13 yeast isolate, ANO anolyte water and CHL chlorinated water. PD signifies tomatoes transported through Point Drift-Pietermaritzburg route, EM through Mooketsi-Pietermaritzburg and ZZ through Esmefour-Pietermaritzburg. The transportation routes had varying road quality conditions and distances.* indicates that missing data. No samples were available on day 30 under ambient storage.

Variation in transportation conditions showed that fruit transported through the EM route had the least weight-loss, while those transported through the PD route had the highest weight-loss compared to the other routes during the summer (Table 4.6). The average cumulative weight-loss for fruit transported through PD, EM and ZZ was 7.1, 5.9 and 5.6 %, respectively. In comparison to the summer season (Table 4.7), the cumulative weight-loss for fruit harvested transported in the winter was 5.9, 3.9 and 7.5 % for fruit transported through PD, EM and ZZ routes, respectively. Similarly, the cumulative weight-loss for fruit stored in the cold storage environment was 3.42 % and 4.62 % for fruit transported in the winter and summer, respectively. The weight-loss was comparatively higher for sample fruit stored in ambient conditions, with these samples recording a weight-loss of 8.07 and 8.25 % for fruit transported in the winter and summer, respectively.

The analysis on fruits' weight-loss data showed the maturity at harvest, transportation and storage conditions as significant ($p \leq 0.05$) factors influencing the fruits' weight-loss for tomatoes harvested and transported during the summer season. The pre-storage treatments however, had no significant ($p > 0.05$) effect on the fruits' weight-loss. There was significant ($p \leq 0.05$) two-way interactions of route and storage, as well as the route and maturity stage. This implies that a change in the storage condition from cold storage to ambient storage causes an increase in weight loss, although not to the same extent across fruit of different transportation conditions. Similarly, a change from green to pink maturity stage causes an increase in fruit weight-loss, but at varying degrees across the three transportation conditions.

Table 4.7 depicts changes in the tomato fruit weight-loss for fruit harvested and transported during the winter season across various storage conditions and fruit maturities at harvest. The effect of transportation conditions on the fruit weight-loss for fruit harvested and transported during the winter showed that fruit from the EM route had the least weight-loss compared to the PD and ZZ routes, while fruit transported through the ZZ route had the highest weight-loss. The fruit weight-loss data for fruit harvested and transported in the winter had the storage and transportation conditions as the significant ($p \leq 0.05$) factors affecting fruit weight-loss while the maturity stage and pre-storage treatments had no significant ($p > 0.05$) effect on fruit weight-loss. Similarly, a two-way interaction of route and storage conditions was present.

Physiological weight-loss in tomatoes is a consequence of the transpiration and other metabolic processes in the fruit (Javanmardi and Kubota, 2006).

Table 4.7 Changes in fruit weight-loss during storage of tomatoes harvested and transported in the winter season across various storage and transportation conditions

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)
PD+Green	Control	0^{a}	0^{a}	2.34^{ab}	1.16^{abcde}	9.86^{lmnop}	2.82^{abcde}	16.75^{pqrst}	4.19^{bcdef}	16.75^{lmnop}	4.19^{bcdef}
	Chlorine	0^{a}	0^{a}	2.34^{ab}	1.43^{abcde}	9.46^{jklmn}	3.82^{defgh}	14.61^{mnopq}	5.73^{klmno}	17.29^{mnopq}	5.73^{klmno}
	Biocontrol	0^{a}	0^{a}	1.46^{ab}	0.62^{a}	8.62^{ghijk}	2.76^{abcde}	13.04^{hijkl}	4.71^{defgh}	17.90^{nopqr}	4.71^{defgh}
	HWT	0^{a}	0^{a}	2.16^{ab}	1.11^{abcde}	7.94^{defgh}	3.72^{defgh}	11.39^{efghi}	5.83^{lmnop}	15.28^{jklmn}	5.83^{lmnop}
	HWT+BIO	0^{a}	0^{a}	2.20^{ab}	1.01^{abcde}	10.10^{lmno}	2.97^{abcde}	15.95^{opqrs}	4.65^{cdefg}	19.45^{pqrst}	4.65^{cdefg}
	CHL+BIO	0^{a}	0^{a}	1.86^{ab}	1.26^{abcde}	8.26^{efghi}	3.74^{defgh}	13.41^{jklmn}	5.46^{ijklm}	16.96^{lmnop}	5.46^{ijklm}
	ANO+BIO	0^{a}	0^{a}	1.58^{ab}	1.40^{abcde}	8.83^{ijklm}	3.80^{defgh}	15.46^{opqrs}	5.89^{mnopq}	20.03^{qrst}	5.89^{mnopq}
PD+Pink	Control	0^{a}	0^{a}	2.63^{abc}	1.19^{abcde}	8.74^{hijkl}	3.68^{defgh}	18.11^{stuv}	5.31^{hijkl}	23.96^{uvw}	5.31^{hijkl}
	Chlorine	0^{a}	0^{a}	1.73^{ab}	1.28^{abcde}	6.57^{bcdef}	3.68^{defgh}	10.22^{bcdef}	5.37^{ijklm}	15.24^{jklmn}	5.37^{ijklm}
	Biocontrol	0^{a}	0^{a}	2.41^{ab}	1.10^{abcde}	9.98^{lmnop}	3.83^{defgh}	15.95^{opqrs}	5.16^{ghijk}	20.22^{rst}	5.16^{ghijk}
	HWT	0^{a}	0^{a}	2.21^{ab}	0.80^{ab}	9.60^{klmno}	3.23^{abcde}	15.74^{opqrs}	5.09^{fghij}	15.74^{jklmn}	5.09^{fghij}
	HWT+BIO	0^{a}	0^{a}	1.71^{ab}	0.79^{ab}	8.05^{defgh}	3.33^{abcde}	11.45^{efghi}	5.12^{fghij}	15.58^{jklmn}	5.12^{fghij}
	CHL+BIO	0^{a}	0^{a}	2.39^{ab}	1.79^{defgh}	9.40^{jklmn}	4.18^{fghij}	14.30^{lmnop}	6.51^{pqrst}	14.30^{ijklm}	6.51^{pqrst}
	ANO+BIO	0^{a}	0^{a}	1.84^{ab}	1.28^{abcde}	8.93^{ijklm}	3.60^{cdefg}	14.25^{lmnop}	5.40^{ijklm}	19.08^{opqrs}	5.40^{ijklm}
PD+Red	Control	0^{a}	0^{a}	1.91^{ab}	1.35^{abcde}	7.05^{bcdef}	4.32^{ghijk}	11.50^{efghi}	5.94^{mnopq}	11.50^{cdefg}	5.94^{mnopq}
	Chlorine	0^{a}	0^{a}	1.86^{ab}	0.95^{abcd}	8.52^{fghij}	3.49^{cdefg}	13.21^{ijklm}	5.06^{fghij}	16.61^{lmnop}	5.06^{fghij}
	Biocontrol	0^{a}	0^{a}	1.90^{ab}	1.35^{abcde}	7.85^{cdefg}	3.71^{defgh}	11.82^{fghij}	5.18^{ghijk}	15.13^{jklmn}	5.18^{ghijk}
	HWT	0^{a}	0^{a}	1.68^{ab}	0.99^{abcd}	10.45^{mnop}	3.43^{bcdef}	13.86^{klmno}	5.84^{lmnop}	13.86^{hijkl}	5.84^{lmnop}
	HWT+BIO	0^{a}	0^{a}	2.09^{ab}	0.85^{ab}	10.25^{lmno}	3.50^{cdefg}	15.35^{opqrs}	5.28^{hijkl}	15.35^{jklmn}	5.28^{hijkl}
	CHL+BIO	0^{a}	0^{a}	1.58^{ab}	1.30^{abcde}	7.75^{cdefg}	3.51^{cdefg}	13.02^{hijkl}	5.86^{lmnop}	16.11^{klmno}	5.86^{lmnop}
	ANO+BIO	0^{a}	0^{a}	1.57^{ab}	1.08^{abcde}	6.24^{abcde}	3.80^{defgh}	9.74^{bcdefg}	5.87^{lmnop}	13.72^{ghijk}	5.87^{lmnop}
EM+Green	Control	0^{a}	0^{a}	2.26^{ab}	1.51^{abcde}	3.71^{a}	2.73^{abcde}	9.25^{bcdefg}	3.77^{abcde}	12.54^{efghi}	3.77^{abcde}
	Chlorine	0^{a}	0^{a}	2.58^{abc}	1.28^{abcde}	4.83^{ab}	2.67^{abcde}	10.02^{bcdef}	3.84^{abcde}	12.89^{fghij}	3.84^{abcde}
	Biocontrol	0^{a}	0^{a}	2.16^{ab}	1.41^{abcde}	4.94^{ab}	2.41^{abcd}	7.23^{abc}	3.19^{abcd}	9.14^{bcd}	3.19^{abcd}
	HWT	0^{a}	0^{a}	1.38^{a}	1.08^{abcde}	5.33^{abc}	3.21^{abcde}	5.77^{a}	4.19^{bcdef}	5.77^{a}	4.19^{bcdef}
	HWT+BIO	0^{a}	0^{a}	2.13^{ab}	1.88^{fghij}	6.06^{abcde}	3.20^{abcde}	7.21^{ab}	4.31^{bcdef}	7.21^{ab}	4.31^{bcdef}
	CHL+BIO	0^{a}	0^{a}	2.14^{ab}	1.53^{abcde}	6.71^{bcdef}	3.27^{abcde}	8.38^{abcde}	5.00^{efghi}	10.78^{cdefg}	5.00^{efghi}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)
	ANO+BIO	0^{a}	0^{a}	2.69^{abc}	1.38^{abcde}	6.97^{bcdef}	2.56^{abcde}	9.75^{bcdefg}	3.60^{abcde}	12.48e^{fghi}	3.60^{abcde}
EM+Pink	Control	0^{a}	0^{a}	2.08^{ab}	1.27^{abcde}	5.96^{abcde}	2.76^{abcde}	8.81^{abcdef}	4.45^{bcdef}	11.81^{defgh}	4.45^{bcdef}
	Chlorine	0^{a}	0^{a}	2.24^{ab}	1.53^{abcde}	6.22^{abcde}	2.58^{abcde}	9.27^{bcdefg}	3.39^{abcde}	11.38^{cdefg}	3.39^{abcde}
	Biocontrol	0^{a}	0^{a}	2.76^{abc}	1.29^{abcde}	7.14^{bcdef}	2.33^{abcd}	10.75^{defgh}	3.56^{abcde}	13.06^{fghij}	3.56^{abcde}
	HWT	0^{a}	0^{a}	2.11^{ab}	1.17^{abcde}	6.46^{bcdef}	2.54^{abcde}	8.39^{abcde}	3.44^{abcde}	8.39^{abc}	3.44^{abcde}
	HWT+BIO	0^{a}	0^{a}	2.44^{abc}	1.01^{abcde}	5.52^{abcd}	2.12^{abc}	8.72^{abcdef}	3.17^{abcd}	10.59^{cdefg}	3.17^{abcd}
	CHL+BIO	0^{a}	0^{a}	2.39^{ab}	0.97^{abcd}	5.95^{abcde}	2.13^{abc}	8.57^{abcde}	3.24^{abcd}	8.57^{abcd}	3.24^{abcd}
	ANO+BIO	0^{a}	0^{a}	2.51^{abc}	0.94^{abcd}	7.03^{bcdef}	1.91^{ab}	10.39^{cdefg}	2.84^{ab}	10.39^{bcdef}	2.84^{ab}
EM+Red	Control	0^{a}	0^{a}	1.93^{ab}	1.30^{abcde}	5.75^{abcde}	2.86^{abcde}	8.52^{abcde}	4.10^{abcde}	11.13^{cdefg}	4.10^{abcde}
	Chlorine	0^{a}	0^{a}	2.25^{ab}	1.23^{abcde}	5.69^{abcde}	2.40^{abcd}	8.18^{abcd}	3.30^{abcde}	10.08^{bcdef}	3.30^{abcde}
	Biocontrol	0^{a}	0^{a}	2.49^{abc}	1.32^{abcde}	5.72^{abcde}	2.67^{abcde}	8.56^{abcde}	3.99^{abcde}	8.56^{abcd}	3.99^{abcde}
	HWT	0^{a}	0^{a}	2.33^{ab}	1.11^{abcde}	6.60^{bcdef}	2.59^{abcde}	10.84^{defgh}	3.94^{abcde}	10.84^{cdefg}	3.94^{abcde}
	HWT+BIO	0^{a}	0^{a}	2.27^{ab}	1.23^{abcde}	5.87^{abcde}	2.10^{abc}	8.78^{abcdef}	2.79^{ab}	8.78^{abcd}	2.79^{ab}
	CHL+BIO	0^{a}	0^{a}	1.88^{ab}	0.90^{abc}	6.14^{abcde}	1.81^{a}	9.11^{bcdefg}	2.40^{a}	9.11^{bcd}	2.40^{a}
	ANO+BIO	0^{a}	0^{a}	2.45^{abc}	1.27^{abcde}	6.41^{bcdef}	2.15^{abc}	9.56^{bcdefg}	2.92^{abc}	9.56^{bcde}	2.92^{abc}
ZZ+Green	Control	0^{a}	0^{a}	6.17^{ghi}	1.06^{abcde}	13.68^{v}	4.12^{fghij}	21.02^{w}	6.28^{opqrs}	26.36^{w}	5.56^{jklmn}
	Chlorine	0^{a}	0^{a}	4.77^{defg}	1.06^{abcde}	10.02^{lmno}	4.38^{hijkl}	14.73^{mnopq}	6.38^{opqrs}	19.86^{pqrst}	5.79^{lmnop}
	Biocontrol	0^{a}	0^{a}	5.27^{efgh}	1.23^{abcde}	10.48^{mnop}	4.04^{efghi}	15.09^{nopqr}	5.79^{lmnop}	20.06^{qrst}	6.28^{opqrs}
	HWT	0^{a}	0^{a}	4.78^{defg}	1.05^{abcde}	12.09^{qrst}	5.23^{qrstu}	17.23^{qrstu}	8.08^{vw}	23.64^{uvw}	6.38^{opqrs}
	HWT+BIO	0^{a}	0^{a}	5.96^{fghi}	1.09^{abcde}	11.71^{pqrs}	4.99^{nopqr}	14.81^{mnopq}	7.34^{tuvw}	19.07^{opqrs}	6.88^{rstuv}
	CHL+BIO	0^{a}	0^{a}	6.78^{i}	1.02^{abcde}	13.36^{uv}	4.72^{jklmn}	18.43^{uvwx}	6.88^{stuv}	22.09^{tuv}	7.30^{tuvw}
	ANO+BIO	0^{a}	0^{a}	4.93^{defgh}	0.79^{ab}	9.92^{lmnop}	3.60^{cdefg}	13.97^{lmnop}	5.56^{jklmn}	16.92^{lmnop}	8.08^{vw}
ZZ+Pink	Control	0^{a}	0^{a}	3.81^{cd}	2.38^{k}	12.81^{stuv}	4.75^{klmno}	18.18^{tuvw}	7.06^{stuvw}	23.26^{uv}	7.06^{stuvw}
	Chlorine	0^{a}	0^{a}	4.59^{def}	1.86^{efghi}	11.00^{opqr}	4.92^{mnopq}	15.04^{nopqr}	6.88^{rstuv}	17.65^{nopqr}	6.88^{rstuv}
	Biocontrol	0^{a}	0^{a}	4.48^{de}	2.01^{hijk}	9.83^{lmnop}	4.32^{ghijk}	13.21^{ijklm}	5.85^{lmnop}	17.32^{mnopq}	5.85^{lmnop}
	HWT	0^{a}	0^{a}	5.93^{fghi}	1.61^{bcdef}	11.92^{pqrs}	6.48^{uv}	15.31^{opqrs}	9.86^{x}	19.51^{pqrst}	9.86^{x}
	HWT+BIO	0^{a}	0^{a}	5.58^{efghi}	1.64^{bcdef}	11.82^{pqrs}	6.17^{stuv}	16.94^{pqrst}	8.65^{wx}	16.94^{lmnop}	8.65^{wx}
	CHL+BIO	0^{a}	0^{a}	4.99^{defgh}	2.15^{jk}	13.96^{v}	6.40^{tuv}	18.85^{vwx}	8.65^{wx}	24.55^{vw}	8.65^{wx}
	ANO+BIO	0^{a}	0^{a}	5.30^{efgh}	1.98^{ghijk}	11.63^{pqrs}	5.06^{opqrs}	16.61^{pqrst}	6.86^{qrstu}	16.61^{lmnop}	6.86^{qrstu}
ZZ+Red	Control	0^{a}	0^{a}	5.03^{defgh}	1.37^{abcde}	10.80^{nopq}	4.45^{ijklm}	14.99^{nopqr}	6.55^{pqrst}	19.79^{pqrst}	6.59^{pqrst}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)
	Chlorine	0^{a}	0^{a}	5.02^{defgh}	1.74^{cdefg}	11.87^{pqrs}	4.78^{lmnop}	15.56^{opqrs}	6.86^{qrstu}	15.56^{jklmn}	6.86^{qrstu}
	Biocontrol	0^{a}	0^{a}	5.28^{efgh}	1.78^{defgh}	11.87^{pqrs}	4.31^{ghijk}	16.96^{pqrst}	6.14^{nopqr}	19.74^{pqrst}	6.14^{nopqr}
	HWT	0^{a}	0^{a}	6.21^{hi}	1.78^{defgh}	11.86^{pqrs}	6.7^{v}	15.41^{opqrs}	8.70^{wx}	15.41^{jklmn}	8.70^{wx}
	HWT+BIO	0^{a}	0^{a}	5.83^{efghi}	1.07^{abcde}	12.65^{rstu}	5.14^{pqrst}	17.91^{rstuv}	7.97^{uvw}	17.91^{nopqr}	7.97^{uvw}
	CHL+BIO	0^{a}	0^{a}	6.12^{ghi}	2.02^{hijk}	13.22^{tuv}	5.43^{rstuv}	20.98^{x}	7.43^{tuvw}	20.98^{stu}	7.43^{tuvw}
	ANO+BIO	0^{a}	0^{a}	2.90^{bc}	2.05^{ijk}	8.52^{fg}hij	4.34^{ghijk}	12.07^{ghijk}	6.21^{nopqr}	15.30^{jklmn}	6.21^{nopqr}

Significance level (p)	
Treatments (A)	0.528
Storage (B)	<.001
Route (C)	<.001
Maturity stage (D)	0.277
AXB	0.688
AXC	0.370
BXC	<.001
AXD	0.957
BXD	0.408
CXD	0.967
AXBXC	0.765
AXBXD	0.813
AXCXD	0.993
BXCXD	0.261
AXBXCXD	0.999
CV (%)	85.5
SE	4.9131
LSD	3.0467

Means within the same column followed by the same letter are not significantly different ($p>0.05$). HWT signifies hot water treatment, BIO designates biocontrol treatment using B-13 yeast isolate, ANO anolyte water and CHL chlorinated water. PD signifies tomatoes transported through Point Drift-Pietermaritzburg route, EM through Mooketsi-Pietermaritzburg and ZZ through Esmefour-Pietermaritzburg. The transportation routes had varying road quality conditions and distances.

However, excessive weight-loss in tomatoes results in fruit that have shrivelled excessively leading to the loss of market value and consumer appeal (Žnidarčič and Požrl, 2006). These processes are predominantly temperature related (Žnidarčič and Požrl, 2006). Fruit weight-loss was higher in fruit stored under ambient storage and those harvested during the summer. Although it has been reported that tomato fruit weight-loss decreases with the ripening processes (Shahnawaz *et al.*, 2012), fruit harvested at the pink maturity stage depicted higher weight-loss than tomatoes harvested at red and pink maturity stages. Biocontrol treatment in combination with Anolyte water, HWT or chlorine was effectively reduced weight-loss in the fruit due to the effect of the yeast in creating a micro-coat around the fruit, that created a partial water vapour barrier (Dávila-Aviña *et al.*, 2014). Fruit from the EM route had the lowest weight-loss due to the relatively smooth road conditions compared to the PD and EM routes. This implies less damage to fruit during transportation which is known to trigger an upsurge of ethylene production that increases ripening and water-loss (Mutari and Debbie, 2011).

4.4.6 Fruit pH

Fruit pH increased between the start and the end the storage period for sample tomato fruit harvested and transported through the EM and ZZ routes in the summer. The pH of the fruit stored under ambient conditions also recorded slightly higher pH values compared to fruit stored under cold storage conditions. Fruit maturity at harvest and pre-storage treatments had varied effects on the changes in fruit pH across various transportation conditions. Table 4.8 and 4.9 shows a summary of the changes in fruit pH with storage for fruit harvested and transported in summer and winter, respectively.

Fruit transported through the PD route had higher pH values when they arrived in Pietermaritzburg than tomatoes transported through the EM and ZZ routes. Similarly, sample fruit transported through the EM route also had the lowest pH values when the fruit arrived at Pietermaritzburg (Table 8). There was also a slight increase in pH between Day 1 and 30 across all fruit maturities, transportation and storage conditions. Fruit harvested and transported through the EM (mean pH values of 4.31 to 4.66) route had the lowest pH values on arrival in Pietermaritzburg, with fruit harvested and transported through the PD (mean pH of 4.69 to 4.61) route recording the highest pH values. A MANOVA of the data showed the maturity at harvest, pre-storage treatments, storage environment and transportation conditions as the significant ($p \leq 0.05$) factors that influenced changes in fruit pH during summer.

Table 4.8 A summary of changes in tomato fruit pH of different maturity stages subjected to various disinfection, transportation and storage conditions during the summer season

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)
PD+Green	Control	4.600^{j}	4.600^{j}	4.550^{hijkl}	4.850^{opqr}	5.100^{klmn}	4.475^{defgh}	4.440^{de}	5.075^{A}	4.770^{ijklm}	4.425^{lmn}
	Chlorine	4.600^{j}	4.600^{j}	4.850^{qrst}	4.150^{defgh}	4.800^{fghij}	4.360^{cdefg}	4.360^{b}	4.670^{rs}	4.775^{jklmn}	4.405^{jkl}
	Biocontrol	4.600^{j}	4.600^{j}	4.450^{fghij}	5.000^{pqr}	4.750^{fghij}	4.290^{cdefg}	4.435^{d}	4.845^{uvw}	4.505^{a}	4.315^{de}
	HWT	4.600^{j}	4.600^{j}	4.850^{qrst}	4.550^{jklmn}	4.750^{fghij}	4.335^{cdefg}	4.655^{qrstu}	5.015^{zA}	4.950^{x}	4.245^{b}
	HWT+BIO	4.600^{j}	4.600^{j}	4.550^{hijkl}	4.550^{jklmn}	4.850^{ghijk}	4.275^{cdefg}	4.540^{ghijk}	4.680^{rs}	4.725^{efgh}	4.345^{fgh}
	CHL+BIO	4.600^{j}	4.600^{j}	4.450^{fghij}	5.150^{rs}	4.600^{cdefg}	4.265^{cdefg}	4.480^{f}	4.810^{uv}	4.600^{b}	4.400^{jkl}
	ANO+BIO	4.600^{j}	4.600^{j}	4.350^{defgh}	4.750^{nopq}	5.150^{lmno}	4.325^{cdefg}	4.385^{bc}	4.880^{uvwxy}	5.160^{A}	4.325^{ef}
PD+Pink	Control	4.500^{ij}	4.500^{ij}	5.000^{st}	4.350^{ghijk}	5.300^{mnop}	4.335^{cdefg}	4.475^{ef}	4.970^{yz}	4.575^{b}	4.500^{vw}
	Chlorine	4.500^{ij}	4.500^{ij}	4.950^{rst}	4.700^{mnopq}	4.800^{fghij}	4.425^{cdefg}	4.530^{ghij}	4.870^{uvwxy}	4.700^{cdef}	4.400^{jkl}
	Biocontrol	4.500^{ij}	4.500^{ij}	4.750^{opqrs}	5.400^{s}	4.600^{cdefg}	4.365^{cdefg}	4.620^{nopq}	4.875^{uvwxy}	4.725^{efgh}	4.425^{lmnop}
	HWT	4.500^{ij}	4.500^{ij}	4.700^{lnopq}	5.200^{rs}	4.750^{fghij}	4.445^{defgh}	4.705^{xyz}	4.940^{wxyz}	4.760^{ghijk}	4.260^{b}
	HWT+BIO	4.500^{ij}	4.500^{ij}	4.350^{defgh}	4.300^{fghij}	4.850^{ghijk}	4.445^{defgh}	4.525^{ghi}	4.935^{wxyz}	4.795^{klmn}	4.450^{nor}
	CHL+BIO	4.500^{ij}	4.500^{ij}	4.450^{fghij}	4.550^{jklmn}	4.500^{bcdef}	4.450^{defgh}	4.570^{jklm}	4.895^{vwxy}	4.850^{qstu}	4.365^{hi}
	ANO+BIO	4.500^{ij}	4.500^{ij}	4.700^{nopqr}	4.300^{fghij}	4.350^{bcdef}	4.425^{cdefg}	4.515^{fgh}	4.870^{uvwxy}	5.006^{y}	4.395^{jk}
PD+Red	Control	4.400^{i}	4.400^{i}	5.150^{t}	4.650^{lmnop}	4.700^{efghi}	4.475^{defgh}	4.515^{fgh}	5.020^{zA}	4.850^{qrstu}	4.500^{vw}
	Chlorine	4.400^{i}	4.400^{i}	4.550^{hijkl}	4.600^{klmno}	4.200^{bcde}	4.380^{cdefg}	4.505^{fg}	4.850^{uvw}	4.885^{uvw}	4.400^{jkl}
	Biocontrol	4.400^{i}	4.400^{i}	4.700^{nopqr}	5.000^{pqr}	4.450^{bcdef}	4.435^{defgh}	4.590^{lmno}	4.855^{uvwx}	4.770^{ijklm}	4.425^{lmno}
	HWT	4.400^{i}	4.400^{i}	4.600^{ijklm}	5.050^{qrs}	5.000^{jklm}	4.385^{cdefg}	4.880^{E}	4.880^{uvwxy}	4.992^{y}	4.260^{b}
	HWT+BIO	4.400^{i}	4.400^{i}	4.350^{defgh}	4.450^{ijklm}	5.000^{jklm}	4.535^{efghi}	4.635^{pqrst}	4.875^{uvwxy}	4.720^{defg}	4.450^{nopr}
	CHL+BIO	4.400^{i}	4.400^{i}	4.600^{ijklm}	4.350^{ghijk}	4.900^{hijkl}	4.370^{cdefg}	4.565^{ijklm}	4.955^{xyz}	4.785^{klmn}	4.365^{hi}
	ANO+BIO	4.400^{i}	4.400^{i}	4.800^{pqrst}	4.850^{opqr}	4.700^{efghi}	4.430^{defgh}	4.415^{cd}	4.895^{vwxy}	4.580^{b}	4.395^{jk}
EM+Green	Control	3.850^{b}	3.850^{b}	4.250^{cdefg}	4.250^{fghij}	4.150^{bcd}	4.850^{jk}	4.540^{ghijk}	4.450^{ijklm}	4.680^{cd}	4.425^{lmnop}
	Chlorine	3.850^{b}	3.850^{b}	3.550^{a}	3.700^{abc}	5.500^{nopq}	4.650^{ghijk}	4.505^{fg}	4.320^{defgh}	4.590^{b}	4.335^{efg}
	Biocontrol	3.850^{b}	3.850^{b}	4.150^{cdefg}	3.650^{ab}	4.200^{bcde}	4.400^{cdefg}	4.625^{nopqr}	4.435^{ijkl}	4.730^{efghi}	4.400^{jkl}
	HWT	3.850^{b}	3.850^{b}	4.150^{cdefg}	4.900^{opqr}	4.300^{bcdef}	3.850^{bc}	3.950^{a}	4.905^{vwxy}	4.695^{cdef}	4.490^{tv}
	HWT+BIO	3.850^{b}	3.850^{b}	4.150^{cdefg}	4.150^{defgh}	4.950^{ijklm}	4.550^{efghi}	4.605^{mnop}	4.355^{efghi}	4.956^{x}	4.455^{rs}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)
	CHL+BIO	3.850^{b}	3.850^{b}	4.385^{efghi}	3.950^{abcde}	4.550^{bcdef}	4.200^{cdefg}	4.665^{rstuv}	4.275^{abcde}	4.790^{klmn}	4.295^{cd}
	ANO+BIO	3.850^{b}	3.850^{b}	4.200^{cdefg}	4.150^{defgh}	4.100^{bc}	4.050^{bcdef}	4.550^{hijkl}	4.225^{abcd}	4.670^{c}	4.360^{h}
EM+Pink	Control	3.950^{b}	3.950^{b}	4.100^{bcdef}	4.300^{fghij}	$4.150b^{cd}$	4.600^{fghij}	4.575^{klm}	4.475^{jklmn}	4.690^{cde}	4.480^{stuv}
	Chlorine	3.950^{b}	3.950^{b}	3.950^{abcde}	4.550^{jklmn}	5.750^{q}	4.600^{fghij}	4.555^{hijkl}	4.385^{ghij}	4.730^{efghi}	4.465^{rst}
	Biocontrol	3.950^{b}	3.950^{b}	3.700^{ab}	4.050^{cdefg}	4.800^{fghij}	3.900^{bcd}	4.635^{pqrst}	4.445^{ijklm}	4.585^{b}	4.415^{kl}
	HWT	3.950^{b}	3.950^{b}	4.150^{cdefg}	4.400^{hijkl}	4.400^{bcdef}	4.000^{bcde}	4.635^{pqrst}	4.680^{rs}	4.795^{klmn}	4.520^{wx}
	HWT+BIO	3.950^{b}	3.950^{b}	4.050^{bcdef}	4.550^{jklmn}	4.200^{bcde}	4.650^{ghijk}	4.670^{stuvw}	4.355^{efghi}	4.780^{klmn}	4.750^{D}
	CHL+BIO	3.950^{b}	3.950^{b}	4.000^{bcdef}	3.800^{abcd}	4.550^{bcdef}	4.850^{jk}	4.630^{opqrs}	4.310^{defgh}	4.810^{nopqr}	4.405^{jkl}
	ANO+BIO	3.950^{b}	3.950^{b}	4.000^{bcdef}	4.400^{hijkl}	5.550^{opq}	3.950^{bcd}	4.500^{fg}	4.380^{fghij}	4.730^{efghi}	4.420^{klm}
EM+Red	Control	3.600^{a}	3.600^{a}	4.000^{bcdef}	4.650^{lmnop}	4.750^{fghij}	4.700^{hijk}	4.585^{lmn}	4.565^{opq}	4.820^{opqrs}	4.520^{wx}
	Chlorine	3.600^{a}	3.600^{a}	4.400^{efghi}	4.300^{fghij}	4.800^{fghij}	4.650^{ghijk}	4.515^{fgh}	4.500^{lmnop}	4.680^{cd}	4.355^{gh}
	Biocontrol	3.600^{a}	3.600^{a}	3.800^{abc}	3.800^{abcd}	4.800^{fghij}	4.550^{efghi}	4.675^{tuvwx}	4.475^{jklmn}	4.755^{ghijk}	4.590^{A}
	HWT	3.600^{a}	3.600^{a}	4.500^{ghijk}	4.150^{defgh}	3.150^{a}	4.750^{ijk}	4.480^{f}	4.395^{hijk}	5.046^{z}	4.615^{B}
	HWT+BIO	3.600^{a}	3.600^{a}	4.450^{fghij}	4.250^{fghij}	4.050^{b}	4.150^{cdefg}	4.515^{fgh}	4.400^{hijk}	5.460^{B}	4.395^{jk}
	CHL+BIO	3.600^{a}	3.600^{a}	4.250^{cdefg}	4.350^{ghijk}	4.230^{bcde}	3.600^{ab}	4.540^{ghijk}	4.305^{defgh}	4.710^{cdef}	4.385^{ij}
	ANO+BIO	3.600^{a}	3.600^{a}	4.650^{jlmno}	4.567^{jklmn}	5.600^{pq}	3.350^{a}	4.425^{d}	4.195^{a}	5.755^{C}	4.365^{hi}
ZZ+Green	Control	4.200^{c}	4.200^{c}	3.900^{abcd}	4.350^{ghijk}	4.950^{ijklm}	3.900^{bcd}	4.645^{pqrst}	4.605^{qr}	4.800^{lmno}	4.445^{mnopq}
	Chlorine	4.200^{cd}	4.200^{cd}	4.050^{bcdef}	4.050^{cdefg}	4.550^{bcdef}	4.200^{cdefg}	4.685^{uvwx}	4.290^{acdef}	4.565^{b}	4.245^{b}
	Biocontrol	4.200^{cde}	4.200^{cde}	4.350^{defgh}	4.250^{fghij}	4.350^{bcdef}	4.200^{cdefg}	4.660^{qrstu}	4.435^{ijklm}	4.755^{ghijk}	4.135^{a}
	HWT	4.200^{cdef}	4.200^{cdef}	4.150^{cdefg}	4.000^{bcdef}	4.200^{bcde}	4.250^{cdefg}	4.700^{wxyz}	4.205^{abc}	4.700^{cdef}	4.285^{c}
	HWT+BIO	4.200^{cdefg}	4.200^{cdefg}	3.950^{abcde}	4.250^{fghij}	4.550^{cdefg}	4.300^{cdefg}	4.750^{ABC}	4.285^{abcde}	4.850^{qrstu}	4.320^{e}
	CHL+BIO	4.200^{cdefg}	4.200^{cdefg}	4.150^{cdefg}	3.850^{abcde}	4.500^{bcdef}	4.450^{defgh}	4.675^{tuvwx}	4.195^{ab}	4.865^{tuvw}	4.325^{ef}
	ANO+BIO	4.200^{cdefg}	4.200^{cdefg}	4.200^{cdefg}	3.600^{a}	4.650^{defgh}	4.900^{k}	4.680^{uvwx}	4.335^{efgh}	4.725^{efgh}	4.450^{nr}
ZZ+Pink	Control	4.320^{cdef}	4.320^{cdef}	4.550^{hijkl}	4.300^{fghij}	4.600^{cdefg}	4.350^{cdefg}	4.620^{nopq}	4.715^{st}	4.730^{efghi}	4.535^{xy}
	Chlorine	4.320^{cdefg}	4.320^{cdefg}	4.550^{hijkl}	4.200^{efghi}	4.550^{bcdef}	4.350^{cdefg}	4.670^{stuvw}	4.590^{pqr}	4.735^{fghij}	4.395^{jk}
	Biocontrol	4.320^{cdefg}	4.320^{cdefg}	3.950^{abcde}	4.050^{cdefg}	4.650^{defgh}	4.650^{ghijk}	4.680^{uvwx}	4.670^{rs}	4.830^{pqrst}	4.485^{tuv}
	HWT	4.320^{cdefg}	4.320^{cdefg}	4.000^{bcdef}	4.250^{fghij}	4.500^{bcdef}	4.350^{cdefg}	4.715^{zAB}	4.535^{lnopq}	4.810^{nopq}	4.690^{C}
	HWT+BIO	4.320^{cdefg}	4.320^{cdefg}	4.200^{cdefg}	4.100^{defgh}	4.200^{bcde}	4.100^{bcdef}	4.800^{D}	4.500^{lmnop}	4.829^{pqrst}	4.580^{A}
	CHL+BIO	4.320^{cdefg}	4.320^{cdefg}	4.200^{cdefg}	4.300^{fghij}	4.950^{ijklm}	4.250^{cdefg}	4.755^{C}	4.385^{fghij}	4.790^{klmn}	4.420^{klm}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)
ZZ+Red	ANO+BIO	4.320^{cdefg}	4.320^{cdefg}	4.350^{defgh}	4.250^{fghij}	4.950^{ijklm}	4.200^{cdefg}	4.695^{vwxyz}	4.535^{lmnop}	4.850^{qrstu}	4.465^{rst}
	Control	4.385^{i}	4.385^{i}	4.300^{defgh}	4.650^{lmnop}	4.300^{bcdef}	4.850^{jk}	4.755^{AC}	4.860^{uvwx}	4.805^{mnop}	4.670^{C}
	Chlorine	4.385^{i}	4.385^{i}	4.050^{bcdef}	4.250^{fghij}	4.600^{cdefg}	4.250^{cdefg}	4.705^{xyz}	4.560^{opq}	4.765^{hijkl}	4.480^{tuv}
	Biocontrol	4.385^{ci}	4.385^{ci}	3.950^{bcde}	4.100^{defgh}	4.450^{bcdef}	4.750^{ijk}	4.715^{zA}	4.785^{tu}	5.010^{y}	4.555^{yz}
	HWT	4.385^{cdi}	4.385^{cdi}	4.350^{defgh}	4.050^{cdefg}	4.950^{ijklm}	4.250^{cdefg}	4.710^{yz}	4.510^{lmnop}	4.869^{tuvw}	4.540^{xy}
	HWT+BIO	4.385^{cdei}	4.385^{cdei}	4.150^{cdefg}	4.100^{defgh}	4.300^{bcdef}	4.400^{cdefg}	4.860^{E}	4.490^{klmno}	5.061^{z}	4.575^{zA}
	CHL+BIO	4.385^{cdefi}	4.385^{cdefi}	4.150^{cdefg}	4.600^{klmno}	4.550^{bcdef}	4.100^{bcdef}	4.625^{nopqr}	4.380^{fghij}	4.820^{opqrs}	4.465^{rstu}
	ANO+BIO	4.385^{cdefg}	4.385^{cdefg}	4.000^{bcdef}	4.290^{fghij}	4.550^{bcdef}	4.150^{cdefg}	4.695^{vwxyz}	4.470^{jklmn}	4.890^{uw}	4.570^{zA}

Significance level	
Treatments (A)	0.002
Storage (B)	<.001
Route (C)	<.001
Maturity stage (D)	0.001
AXB	<.001
AXC	0.041
BXC	0.107
AXD	0.336
BXD	0.432
CXD	0.002
AXBXC	<.001
AXBXD	0.448
AXCXD	0.354
BXCXD	0.154
AXBXCXD	0.008
CV (%)	7.8
SE	0.347
LSD	0.215

Means within the same column followed by the same letter are not significantly different (P>0.05). HWT signifies hot water treatment, BIO designates biocontrol treatment using B-13 yeast isolate, ANO anolyte water and CHL chlorinated water.PD signifies tomatoes transported through Point Drift-Pietermaritzburg route, EM through Mooketsi-Pietermaritzburg and ZZ through Esmefour-Pietermaritzburg. The transportation routes had varying road quality conditions and distances.

Table 4.9 A summary of changes in tomato fruit pH of different maturity stages subjected to various disinfection treatments, transportation and storage treatments during the winter season

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)
PD+Green	Control	4.230^{a}	4.230^{a}	4.905^{jklmn}	4.850^{fghi}	4.725^{abcde}	4.845^{E}	4.985^{bcdef}	5.040^{fg}	4.770^{ijklm}	4.615^{nopqr}
	Chlorine	4.230^{a}	4.230^{a}	4.595^{ab}	4.415^{abcde}	4.745^{abcde}	4.585^{hijkl}	4.900^{bcdef}	4.695^{abcde}	4.775^{jklmn}	4.510^{def}
	Biocontrol	4.230^{a}	4.230^{a}	4.580^{a}	4.565^{abcde}	4.745^{abcde}	4.610^{klmno}	4.855^{bcdef}	4.840^{abcde}	4.510^{a}	4.575^{ijkl}
	HWT	4.230^{a}	4.230^{a}	4.765^{cdefg}	4.925^{hi}	4.695^{abcd}	4.690^{uvwxy}	4.925^{bcdef}	4.990^{defg}	4.720^{fghij}	4.650^{rst}
	HWT+BIO	4.230^{a}	4.230^{a}	4.820^{defgh}	4.925^{hi}	4.700^{abcd}	4.660^{pqrst}	4.880^{bcdef}	4.680^{abcde}	4.725^{fghij}	4.655st
	CHL+BIO	4.230^{a}	4.230^{a}	4.910^{jklmn}	4.615^{bcdef}	4.765^{bcdef}	4.495^{cdefg}	4.875^{bcdef}	4.785^{abcde}	4.605^{bcd}	4.530^{fgh}
	ANO+BIO	4.230^{ab}	4.230^{ab}	4.695^{bc}	5.040^{i}	4.650^{abc}	4.480^{bcdef}	5.020^{cdefg}	4.880^{abcde}	5.210^{x}	4.545^{fghi}
PD+Pink	Control	4.465^{cdef}	4.465^{cdef}	4.865^{ghijk}	4.645^{bcdef}	4.840^{efghi}	4.785^{CDE}	5.025^{cdefg}	4.935^{cdefg}	4.745^{hijkl}	4.545^{fghi}
	Chlorine	4.465^{cdef}	4.465^{cdef}	4.870^{hijkl}	4.555^{abcde}	4.705^{abcd}	4.735^{wxyzA}	4.975^{bcdef}	4.825^{abcde}	4.715^{efghi}	4.675^{t}
	Biocontrol	4.465^{cdef}	4.465^{cdef}	4.825^{defgh}	4.635^{bcdef}	4.930^{lmnop}	4.770^{ACDE}	4.925^{bcdef}	4.875^{abcde}	4.705^{efghi}	4.580^{ijklm}
	HWT	4.465^{cdef}	4.465^{cdef}	4.720^{cde}	4.755^{efghi}	4.785^{defgh}	4.570^{ghijk}	4.980^{bcdef}	4.915^{cdefg}	4.750^{hijkl}	4.605^{lmnop}
	HWT+BIO	4.465^{cdef}	4.465^{cdef}	4.785^{cdefg}	4.710^{cdefg}	4.780^{defgh}	4.770^{CDE}	5.030^{defgh}	4.925^{cdefg}	4.780^{jklmn}	4.565^{hijk}
	CHL+BIO	4.465^{cdef}	4.465^{cdef}	4.865^{ghijk}	4.785^{efghi}	4.805^{defgh}	4.550^{efghi}	5.150^{ghi}	4.850^{abcde}	4.690^{defgh}	4.490^{cde}
	ANO+BIO	4.465^{cdef}	4.465^{cdef}	4.810^{cdefg}	4.625^{bcdef}	4.750^{bcdef}	4.565^{fghij}	5.035^{defgh}	4.840^{abcde}	4.580^{abc}	4.605^{lmnop}
PD+Red	Control	4.385^{cde}	4.385^{cde}	4.895^{jklmn}	4.725^{cdefg}	5.170^{s}	4.995^{F}	5.110^{fghi}	4.955^{cdefg}	4.845^{pqrs}	4.515^{def}
	Chlorine	4.385^{cde}	4.385^{cde}	4.805^{cdefg}	4.540^{abcde}	4.820^{defgh}	4.630^{mnopq}	4.935^{bcdef}	4.820^{abcde}	4.875^{rst}	4.520^{efg}
	Biocontrol	4.385^{cde}	4.385^{cde}	4.715^{cde}	4.580^{bcdef}	4.730^{abcde}	4.750^{xyzAB}	4.975^{bcdef}	4.820^{abcde}	4.775^{jklmn}	4.525^{efg}
	HWT	4.385^{cde}	4.385^{cde}	4.840^{efghi}	4.920^{ghi}	4.810^{defgh}	4.670^{qstuv}	4.965^{bcdef}	4.875^{abcde}	4.777^{jklmn}	4.620^{opqrs}
	HWT+BIO	4.385^{cde}	4.385^{cde}	4.840^{efghi}	4.780^{efghi}	4.760^{bcdef}	4.605^{klmno}	5.180^{hi}	4.880^{abcde}	4.745^{hijkl}	4.615^{mnopq}
	CHL+BIO	4.385^{cde}	4.385^{cde}	4.965^{qtuvw}	5.060^{i}	4.900^{jklmn}	4.605^{klmno}	5.220^{i}	4.945^{cdefg}	4.765^{ijklm}	4.480^{cd}
	ANO+BIO	4.385^{cde}	4.385^{cde}	4.965^{qrtuv}	4.755^{efghi}	4.625^{a}	4.495^{cdefg}	5.040^{defgh}	4.895^{bcdef}	4.580^{abc}	4.640^{qrst}
EM+Green	Control	4.480^{efg}	4.480^{efg}	4.905^{jklmn}	4.595^{bcdef}	4.820^{defgh}	4.495^{cdefg}	4.610^{b}	4.805^{abcde}	4.665^{cdefg}	4.435^{b}
	Chlorine	4.480^{efg}	4.480^{efg}	4.790^{cdefg}	4.520^{abcde}	4.760^{bcdef}	4.585^{hijkl}	4.650^{bcd}	4.915^{cdefg}	4.580^{abc}	4.615^{mnopq}
	Biocontrol	4.480^{efg}	4.480^{efg}	4.795^{cdefg}	4.555^{abcde}	4.810^{defgh}	4.590^{ijklm}	4.785^{bcdef}	4.780^{abcde}	4.745^{hijkl}	4.730^{u}
	HWT	4.480^{efg}	4.480^{efg}	4.955^{npqrs}	4.680^{bcdef}	5.465^{t}	4.540^{defgh}	4.850^{bcdef}	4.73^{5abcde}	4.685^{defgh}	4.925^{x}
	HWT+BIO	4.480$_{ef}^{g}$	4.480^{efg}	4.765^{cdefg}	6.220^{j}	4.805^{defgh}	4.665^{pqrst}	4.710^{bcde}	4.835^{abcde}	4.895st	4.545^{fghi}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)
	CHL+BIO	4.480^{efgh}	4.480^{efgh}	4.710^{cd}	4.625^{bcdef}	4.890^{ijklm}	4.425^{abc}	4.670^{bcde}	4.640^{abcde}	4.780^{jklmn}	4.625^{pqrs}
	ANO+BIO	4.480^{cefgh}	4.480^{cefgh}	4.750^{cdefg}	4.775^{efghi}	4.725^{abcde}	4.510^{defgh}	4.635^{bc}	4.940^{cdefg}	4.670^{defgh}	4.740^{u}
EM+Pink	Control	4.340^{ac}	4.340^{ac}	4.835^{defgh}	4.610^{bcdef}	4.785^{defgh}	4.475^{bcde}	4.685^{bcde}	4.625^{abcde}	4.705^{efghi}	4.365^{a}
	Chlorine	4.340^{abcd}	4.340^{abcd}	4.740^{cdefg}	4.615^{bcdef}	4.885^{hijkl}	4.515^{defgh}	4.680^{bcde}	4.760^{abcde}	4.765^{ijklm}	4.920^{x}
	Biocontrol	4.340^{abcd}	4.340^{abcd}	4.695^{c}	4.740^{defgh}	4.855^{ghijk}	4.410^{ab}	4.915^{bcdef}	4.925^{cdefg}	4.570^{ab}	4.835^{w}
	HWT	4.340^{abcd}	4.340^{abcd}	4.745^{cdefg}	4.565^{abcde}	5.165^{s}	4.525^{defgh}	4.910^{bcdef}	4.925^{cdefg}	4.780^{jklmn}	4.970^{y}
	HWT+BIO	4.340^{abcd}	4.340^{abcd}	4.985^{vw}	4.645^{bcdef}	4.810^{defgh}	4.675^{tuvwx}	4.675^{bcde}	4.935^{cdefg}	4.805^{nopqr}	4.470^{c}
	CHL+BIO	4.340^{abcd}	4.340^{abcd}	4.830^{defgh}	4.540^{abcde}	4.840^{efghi}	4.545^{defgh}	4.875^{bcdef}	4.655^{abcde}	4.810^{nopqr}	4.655^{st}
	ANO+BIO	4.340^{abcd}	4.340^{abcd}	4.795^{cdefg}	4.565^{abcde}	4.785^{defgh}	4.495^{cdefg}	4.750^{bcdef}	4.810^{abcde}	4.725^{fghij}	4.840^{w}
EM+Red	Control	4.410^{cde}	4.410^{cde}	4.900^{jklmn}	4.530^{abcde}	4.965^{qr}	4.495^{cdefg}	4.665^{bcde}	5.030^{efg}	4.805^{mnopq}	4.730^{u}
	Chlorine	4.410^{cde}	4.410^{cde}	4.985^{vw}	4.630^{bcdef}	4.925^{klmno}	4.505^{cdefg}	4.635^{bc}	4.735^{abcde}	4.680^{defgh}	4.640^{qrst}
	Biocontrol	4.410^{cde}	4.410^{cde}	4.945^{lmnop}	4.500^{abcde}	4.885^{hijkl}	4.370^{a}	6.190^{j}	4.665^{abcde}	4.730^{fghij}	4.740^{u}
	HWT	4.410^{cde}	4.410^{cde}	4.965^{tuvw}	4.540^{abcde}	5.205^{s}	4.585^{hijkl}	4.735^{bcdef}	4.630^{abcde}	5.015^{uv}	4.945^{xy}
	HWT+BIO	4.410^{cde}	4.410^{cde}	4.850^{fghij}	4.585^{bcdef}	4.800^{defgh}	4.680^{tuvwx}	4.500^{a}	4.880^{abcde}	5.405^{y}	4.555^{ghij}
	CHL+BIO	4.410^{cde}	4.410^{cde}	4.840^{efghi}	4.610^{bcdef}	4.885^{hijkl}	4.565^{fghij}	5.150^{ghi}	6.230^{h}	4.710^{efghi}	4.535^{fgh}
	ANO+BIO	4.410^{cde}	4.410^{cde}	5.115^{xy}	4.685^{bcdef}	4.790^{defgh}	4.460^{bcd}	4.620^{b}	4.680^{abcde}	5.695^{z}	4.940^{xy}
ZZ+Green	Control	4.550^{fghij}	4.550^{fghij}	4.805^{cdefg}	4.340^{abcd}	4.745^{abcde}	4.460^{bcd}	5.000^{bcdef}	4.470^{a}	4.717^{efghi}	4.525^{efg}
	Chlorine	4.550^{fghij}	4.550^{fghij}	4.925^{klmno}	4.430^{abcde}	4.730^{abcde}	4.525^{defgh}	4.775^{bcdef}	4.625^{abcde}	4.677^{defgh}	4.563^{hijk}
	Biocontrol	4.550^{fghij}	4.550^{fghij}	4.880^{ijklm}	4.330^{abc}	4.765^{bcdef}	4.720^{vwxyz}	4.805^{bcdef}	4.550^{abc}	4.627^{bcde}	4.653^{rst}
	HWT	4.550^{fghij}	4.550^{fghij}	4.795^{cdefg}	4.425^{abcde}	4.945^{pqr}	4.760^{yABCD}	4.955^{bcdef}	4.670^{abcde}	4.704^{efghi}	4.787^{v}
	HWT+BIO	4.550^{fghij}	4.550^{fghij}	4.725^{cdef}	4.570^{abcde}	4.770^{bcdef}	4.515^{defgh}	4.870^{bcdef}	4.675^{abcde}	4.782^{klmno}	4.600^{klmno}
	CHL+BIO	4.550^{fghij}	4.550^{fghij}	4.870^{hijkl}	4.350^{abcd}	4.625^{a}	4.560^{efghi}	4.795^{bcdef}	4.570^{abcd}	4.692^{defgh}	4.577^{ijklm}
	ANO+BIO	4.550^{fghij}	4.550^{fghij}	4.830^{defgh}	4.295^{ab}	4.645^{ab}	4.500^{cdefg}	4.770^{bcdef}	5.115^{g}	4.942^{tu}	4.643^{qrst}
ZZ+Pink	Control	4.610^{gj}	4.610^{gj}	4.880^{ijklm}	4.175^{a}	4.935^{mopqr}	4.610^{klmno}	5.055^{efghi}	4.575^{abcd}	4.725^{fghij}	4.455^{bc}
	Chlorine	4.610^{ghj}	4.610^{ghj}	4.830^{defgh}	4.350^{abcd}	4.760^{bcdef}	4.595^{jklmn}	4.760^{bcdef}	4.640^{abcde}	4.741^{ghijk}	4.797^{v}
	Biocontrol	4.610^{ghij}	4.610^{ghij}	4.800^{cdefg}	4.440^{abcde}	4.940^{opqr}	4.615^{lmnop}	4.835^{bcdef}	4.480^{ab}	4.637^{bcdef}	4.707^{u}
	HWT	4.610^{ghij}	4.610^{ghij}	4.905^{jklmn}	4.410^{abcde}	4.810^{defgh}	4.820^{DE}	4.745^{bcdef}	4.540^{abc}	4.779^{jklmn}	4.787^{v}
	HWT+BIO	4.610^{ghij}	4.610^{ghij}	4.755^{cdefg}	4.445^{abcde}	4.795^{defgh}	4.680^{tuvwx}	4.820^{bcdef}	4.870^{abcde}	4.794^{lmnop}	4.518^{efg}
	CHL+BIO	4.610^{ghij}	4.610^{ghij}	4.855^{ghijk}	4.385^{abcde}	4.775^{cdefg}	4.610^{klmno}	4.885^{bcdef}	4.655^{abcde}	4.751^{hijkl}	4.572^{ijkl}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)
	ANO+BIO	4.610^{ghij}	4.610^{ghij}	4.790^{cdefg}	4.445^{abcde}	4.715^{abcde}	4.555^{efghi}	4.785^{bcdef}	4.645^{abcde}	4.649^{bcdef}	4.722^{u}
ZZ+Red	Control	4.430^{cdef}	4.430^{cdef}	4.960^{qrstu}	4.475^{abcde}	4.970^{r}	4.570^{ghijk}	4.885^{bcdef}	4.655^{abcde}	4.827^{opqrs}	4.622^{opqrs}
	Chlorine	4.430^{cdef}	4.430^{cdef}	5.185^{y}	4.565^{abcde}	4.890^{ijklm}	4.580^{ghijk}	4.860^{bcdef}	4.640^{abcde}	4.779^{jklmn}	4.580^{ijklm}
	Biocontrol	4.430^{cdef}	4.430^{cdef}	4.925^{klmno}	4.460^{abcde}	4.925^{klmno}	4.680^{uvwxy}	4.905^{bcdef}	4.480^{ab}	4.754^{hijkl}	4.633^{pqrs}
	HWT	4.430^{cdef}	4.430^{cdef}	5.190^{y}	4.405^{abcde}	4.845^{fghij}	4.690^{uvwxy}	4.840^{bcdef}	4.615^{abcde}	4.868^{qrst}	4.782^{v}
	HWT+BIO	4.430^{cdef}	4.430^{cdef}	4.975^{uvw}	4.485^{abcde}	4.710^{abcd}	4.625^{lmnop}	4.850^{bcdef}	4.645^{abcde}	5.081^{vw}	4.585^{jklmn}
	CHL+BIO	4.430^{cdef}	4.430^{cdef}	4.950^{mnopq}	4.470^{abcde}	4.800^{defgh}	4.640^{opqrs}	4.925^{bcdef}	4.585^{abcd}	4.738^{ghijk}	4.508^{def}
	ANO+BIO	4.430^{cdef}	4.430^{cdef}	5.020^{wx}	4.470^{abcde}	4.785^{defgh}	4.635^{nopqr}	4.870^{bcdef}	4.725^{abcde}	5.143^{wx}	4.790^{v}

Significance level (p)	
Treatments (A)	0.139
Storage (B)	<.001
Route (C)	0.184
Maturity stage (D)	0.209
AXB	<.001
AXC	0.033
BXC	<.001
AXD	<.001
BXD	0.303
CXD	0.052
AXBXC	<.001
AXBXD	0.097
AXCXD	<.001
BXCXD	0.815
AXBXCXD	0.008
CV (%)	6.7
SE	0.315
LSD	0.195

Means within the same column followed by the same letter are not significantly different (p>0.05). HWT signifies hot water treatment, BIO designates biocontrol treatment using B-13 yeast isolate, ANO anolyte water and CHL chlorinated water. PD signifies tomatoes transported through Point Drift-Pietermaritzburg route, EM through Mooketsi-Pietermaritzburg and ZZ through Esmefour-Pietermaritzburg. The transportation routes had varying road quality conditions and distances.

Storage environment was the only significant ($p \leq 0.05$) factor affecting changes in fruit pH during the winter. Fruit treated with chlorinated water in combination with biocontrol had the lowest pH for fruit harvested and transported in the summer. In all seasons, control-treated fruit had the highest rise in pH, suggesting higher quality deterioration than other pre-storage treatments (Tigist *et al.*, 2013). Tomato fruit pH is also dependant on the variety, with cultivars that have an optimum pH of 4.5 when ripe being desirable (Tigist *et al.*, 2013).

Tomatoes are low pH foods that contain varying proportions of citric, malic and glutamic acids that contribute to the acid concentration of the fruit (Anthon *et al.*, 2011). Citric acid is the most abundant acid in tomatoes and is known to decrease with storage due to its conversion to sugars through gluconeogenesis (Anthon *et al.*, 2011). This results in an increase in the fruit pH (Taşdelen and Bayindirli, 1998). It is, however, undesirable to have the pH of tomatoes increase excessively, as it negatively affects its flavour (Anthon *et al.*, 2011). A rise in fruit pH observed in both seasons is therefore consistent with observations by Bhowmik and Pan (1992), Taşdelen and Bayindirli (1998) and Anthon *et al.* (2011). The fruit pH in the winter season however either remained relatively constant or changed only slightly. The lower temperatures during the winter season explains this difference as it may have considerably slowed down metabolic and enzymatic processes in the fruit. The lower pH values for fruit transported through the EM route compared to ZZ and PD routes, especially during the summer season may be attributed to the relatively good road quality, that led to reduced mechanical damage during transportation.

4.4.7 Subjective quality

4.4.7.1 Visual observations

The degree of damage to fruit under various transportation conditions upon arrival in Pietermaritzburg showed a higher level of damage to fruit harvested at the red maturity stage compared to other maturity stages. Similarly, fruit harvested at the green maturity stage depicted the least damage. This observation is consistent with conclusions made in the literature, that shows dependence of susceptibility to mechanical damage of tomatoes on their maturity stage (Mohammadi-Aylar *et al.*, 2010). Sample fruit at the bottom of the bins showed cracks, flattening and bruising especially for fruit sourced from the ZZ route. Fruit at the bottom of the bins also appeared redder than those at the top. Fruit transported through the EM route showed the least visual damage.

Pre-storage treatments had varied effects on the visual quality of the samples as the storage period progressed. Hot water treatment appeared to cause skin charring to fruit especially those harvested at the red maturity stage (Figure 4.4). However, it appeared to be effective in slowing down ripening of fruit harvested at the green maturity stage. Fruit treated with biocontrol treatment and HWT+Bio had white scum forming on the fruit surface. This may have been the biocontrol yeast growing over the fruit surface and creating a micro-coat. Figure 4.4 shows the effect of various pre-storage treatments on the visual quality of tomato fruit.

Figure 4.4 Effect of the pre-storage treatments on the visual appearance of tomato fruit after 24 days of storage. A is fruit treated using hot water, B chlorinated water, C Chl+Bio, D Ano+Bio and E biocontrol treatment using B-13 yeast isolate

Mould attack and decay occurred across all pre-storage treatments with varying levels. The control treatment, however, depicted higher prevalence of mould attack, and decay compared to other pre-storage treatments. Chl+Bio, and Ano+Bio appeared to be the best treatments in terms of appearance especially for fruit harvested at the pink and red maturity stages.

4.4.7.2 Marketability

Tables 4.10 and 4.11 show a summary of changes in marketability with storage for sample tomato fruit harvested and transported during the summer and winter, respectively. The marketability of fruit decreased with time under ambient and cold storage conditions, across all harvesting seasons, maturity stages and transportation conditions. A pronounced difference in marketability was noticeable between fruit stored in cold and ambient conditions, with those stored under cold storage recording higher marketability. The marketability of fruit harvested at red maturity stage was lower compared to those harvested at pink and green maturity stage. These trends were observed in fruit harvested and transported in both seasons. A comparison of the marketability of fruit subjected to the different transportation conditions depicted fruit transported through the EM route to have higher marketability compared to fruit transported through the PD and ZZ routes (Table 4.10 and 4.11). Fruit transported though the ZZ route had the lowest marketability across the summer and winter seasons.

Table 4.10 A summary of changes in marketability of tomato fruit with storage period for fruit harvested at the green, pink and red maturity stages, and transported in summer

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)
PD+Green	Control	99.26^{h}	99.26^{h}	95.79^{mnopq}	99.58^{qrs}	81.68^{qrs}	96.64^{AB}	31.50^{jklm}	81.25^{xyz}	0^{a}	74.75^{BCD}
	Chlorine	99.26^{h}	99.26^{h}	99.72^{t}	99.89^{s}	93.25^{ABCD}	96.73^{B}	53.25^{q}	81.75^{yz}	23.00^{t}	78.25^{CDE}
	Biocontrol	99.26^{h}	99.26^{h}	99.73^{t}	99.94^{s}	91.52^{yzABC}	96.8^{B}	34.50^{lmno}	83.00^{zAB}	8.62^{hi}	67.25^{xyz}
	HWT	99.26^{h}	99.26^{h}	99.78^{t}	97.96^{lmnop}	93.08^{zABCD}	89.66^{lmnop}	34.50^{lmno}	85.88^{ABC}	16.44^{opq}	48.00^{pq}
	HWT+BIO	99.26^{h}	99.26^{h}	98.46^{rst}	99.30^{pqrs}	89.52^{vwxyz}	95.63^{zAB}	68.75^{tuv}	86.50^{BC}	12.30^{lm}	80.00^{E}
	CHL+BIO	99.26^{h}	99.26^{h}	99.74^{t}	99.82^{s}	94.2^{8CD}	96.50^{AB}	33.88^{lmn}	87.00^{C}	11.50^{kl}	57.50st
	ANO+BIO	99.26^{h}	99.26^{h}	99.78^{t}	99.67^{qrs}	94.65^{CD}	95.27^{yzAB}	46.00^{p}	87.50^{C}	11.62^{kl}	79.75^{E}
PD+Pink	Control	98.93^{g}	98.93^{g}	99.40^{t}	99.76^{rs}	82.25^{qrs}	93.00^{stuvw}	35.00^{mno}	75.50^{stuv}	4.12^{cd}	61.00^{tuvw}
	Chlorine	98.93^{g}	98.93^{g}	98.01^{qrst}	99.83^{s}	84.50^{rstu}	94.91^{yzAB}	39.00^{o}	82.25^{yzA}	14.14^{mn}	57.25st
	Biocontrol	98.93^{g}	98.93^{g}	97.71^{qrst}	97.72^{klmno}	84.68^{rstu}	89.63^{lmnop}	28.88^{jk}	76.00^{stuvw}	17.77^{qr}	31.38^{ijk}
	HWT	98.93^{g}	98.93^{g}	99.40^{t}	98.05^{mnopq}	67.88^{gh}	91.21^{opqrs}	35.75^{mno}	71.00^{opqr}	3.79^{c}	49.75^{qr}
	HWT+BIO	98.93^{g}	98.93^{g}	73.34^{c}	99.63^{qrs}	41.25^{a}	93.23^{tuvwx}	18.75^{g}	67.50^{lmno}	14.90^{nop}	50.00^{qr}
	CHL+BIO	98.93^{g}	98.93^{g}	99.66^{t}	99.39^{pqrs}	86.88^{tuvw}	93.23^{tuvwx}	34.00^{lmn}	73.25^{rst}	11.75^{kl}	38.75^{mn}
	ANO+BIO	98.93^{g}	98.93^{g}	99.69^{t}	99.39^{pqrs}	84.62^{rstu}	94.78^{xyzAB}	31.25^{jklm}	70.00^{nopqr}	7.37^{ghi}	64.75^{vwxy}
PD+Red	Control	98.34^{b}	98.34^{b}	99.31st	99.26^{opqrs}	92.00^{yzABC}	90.38^{mnopq}	32.00^{klm}	61.75^{ijk}	6.34^{defgh}	31.50^{ijk}
	Chlorine	98.34^{b}	98.34^{b}	99.51^{t}	99.58^{qrs}	95.00^{D}	91.31^{opqrs}	51.25^{q}	67.25^{lmno}	23.80^{t}	15.13^{def}
	Biocontrol	98.34^{b}	98.34^{b}	95.42^{klmno}	99.48^{qrs}	91.50^{yzABC}	93.63^{vwxyz}	43.50^{p}	68.50^{nop}	5.62^{cdefg}	37.00^{lm}
	HWT	98.34^{b}	98.34^{b}	82.76^{e}	99.45^{qrs}	74.55^{lmn}	89.14^{lmnop}	30.00^{jkl}	60.75^{ijk}	11.57^{kl}	42.50^{no}
	HWT+BIO	98.34^{b}	98.34^{b}	67.04^{b}	98.04^{mnopq}	50.37^{c}	85.27^{ij}	24.50^{hi}	63.50^{jkl}	14.38^{mno}	17.50^{efg}
	CHL+BIO	98.34^{b}	98.34^{b}	99.58^{t}	99.31^{pqrs}	84.80^{rstu}	91.13^{opqrs}	27.00^{ij}	59.75^{ij}	11.50^{kl}	20.13^{gh}
	ANO+BIO	98.34^{b}	98.34^{b}	99.57^{t}	99.32^{pqr}s	91.17^{xyzAB}	94.50^{wxyzA}	38.25^{no}	60.75^{ijk}	13.12^{lmn}	18.88^{fgh}
EM+Green	Control	99.79^{p}	99.79^{p}	94.58^{jklmn}	97.75^{klmno}	93.50^{BCD}	90.73^{nopqr}	59.00^{r}	78.25^{uvwxy}	27.25^{u}	36.25^{klm}
	Chlorine	99.79^{ip}	99.79^{ip}	94.19^{jklm}	98.67^{nopqr}	92.03^{yzABC}	93.00^{stuvw}	77.25^{yz}	79.75^{wxyz}	18.50^{qrs}	53.50^{rs}
	Biocontrol	99.79^{ijp}	99.79^{ijp}	97.49^{pqrst}	97.22^{jklmn}	93.75^{BCD}	92.50^{rstuv}	66.75^{tu}	70.25^{nopqr}	37.00^{x}	59.25^{tu}
	HWT	99.79^{ijkp}	99.79^{ijkp}	95.32^{klmno}	98.68^{nopqr}	93.50^{BCD}	91.90^{qrstu}	61.25^{rs}	64.25^{klm}	30.13^{v}	49.00^{qr}
	HWT+BIO	99.79^{ijklp}	99.79^{ijklp}	94.23^{jklm}	97.32^{jklmn}	91.80^{yzABC}	93.50^{uvwxy}	71.38^{vwx}	63.63^{jkl}	20.12^{s}	51.38^{qr}
	CHL+BIO	99.79^{ijklm}	99.79^{ijklm}	97.67^{qrst}	98.77^{nopqr}	93.62^{BCD}	93.25^{tuvwx}	79.50^{z}	68.75^{nopq}	37.62^{x}	79.00^{DE}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)
	ANO+BIO	99.79^{ijklm}	99.79^{ijklm}	97.02^{mnopq}	97.00^{ijklm}	87.30^{tuvwx}	92.25^{qrstu}	53.75^{q}	76.25^{tuvw}	31.00^{v}	69.25^{yzA}
EM+Pink	Control	99.49^{hi}	99.49^{hi}	97.12^{nopqr}	96.78^{ijklm}	88.50^{uvwxy}	88.25^{jklmn}	69.50^{uvw}	83.00^{zAB}	23.00^{t}	67.00^{xyz}
	Chlorine	99.49^{hij}	99.49^{hij}	97.34^{opqrs}	96.83^{ijklm}	92.53^{yzABC}	92.25^{qrstu}	70.25^{uvwx}	88.25^{C}	5.50^{cdefg}	60.00^{tuv}
	Biocontrol	99.49^{hijk}	99.49^{hijk}	97.12^{nopqr}	96.70^{ijklm}	85.75^{stuv}	87.50^{ijklm}	61.50^{rs}	79.17^{uvwxy}	34.00^{w}	52.00^{qr}
	HWT	99.49^{hijkl}	99.49^{hijkl}	96.36^{mnopq}	95.98^{ghijk}	90.65^{wxyzA}	79.50^{fg}	72.00^{vwx}	75.75^{stuvw}	7.25^{fghi}	74.50^{BCD}
	HWT+BIO	99.49^{hijkl}	99.49^{hijkl}	95.67^{lmnop}	96.88^{ijklm}	71.75^{hijkl}	90.08^{mnopq}	77.00^{yz}	68.00^{mnop}	8.50^{hi}	64.75^{vwxy}
	CHL+BIO	99.49^{hijkl}	99.49^{hijkl}	96.36^{mnopq}	96.59^{ijklm}	89.13^{vwxyz}	90.50^{mnopq}	79.00^{z}	78.25^{uvwxy}	18.17^{qrs}	73.75^{ABC}
	ANO+BIO	99.49^{hijkl}	99.49^{hijkl}	95.95^{mnopq}	95.80^{fghij}	79.47^{opq}	92.13^{qrstu}	71.98^{vwx}	83.13^{zAB}	12.88^{lmn}	77.25^{CDE}
EM+Red	Control	98.70^{cg}	98.70^{cg}	90.92^{ghi}	95.16^{efghi}	84.00^{rst}	85.50^{ijk}	65.00st	76.50^{tuvw}	8.63^{hi}	31.25^{ij}
	Chlorine	98.70^{cdg}	98.70^{cdg}	95.30^{klmno}	93.65^{defg}	81.47^{qr}	81.25^{gh}	53.75^{q}	77.50^{uvwx}	4.50^{cd}	34.13^{jklm}
	Biocontrol	98.70^{cdeg}	98.70^{cdeg}	95.88^{mnopq}	94.53^{defgh}	89.00^{vwxyz}	86.50^{ijkl}	73.50^{wxy}	79.50^{vwxyz}	7.00^{efghi}	65.50^{wxy}
	HWT	98.70^{cdefg}	98.70^{cdefg}	88.92^{gh}	92.37^{cd}	77.12^{no}	78.25^{fg}	32.75^{klm}	67.25^{lmno}	0.88^{b}	49.13^{qr}
	HWT+BIO	98.70^{cdefg}	98.70^{cdefg}	92.97^{ijkl}	95.86^{fghij}	81.25^{pqr}	76.50^{f}	54.25^{q}	69.75^{nopqr}	0^{a}	29.00^{i}
	CHL+BIO	98.70^{cdefg}	98.70^{cdefg}	88.62^{g}	93.57^{defg}	81.00^{pqr}	81.50^{gh}	74.50^{xy}	71.25^{opqr}	4.62^{cde}	74.75^{BCD}
	ANO+BIO	98.70^{cdefg}	98.70^{cdefg}	96.6^{mnopqr}	97.01^{ijklm}	77.50^{nop}	79.50^{fg}	66.25^{tu}	69.75^{nopqr}	4.62^{cde}	36.50^{lm}
ZZ+Green	Control	99.2^{h}	99.2^{h}	92.54^{ij}	95.30^{efghi}	73.50^{klmn}	88.75^{klmno}	13.50^{f}	71.25^{opqr}	4.47^{cd}	47.00^{opq}
	Chlorine	99.25^{h}	99.25^{h}	96.67^{mnopq}	96.37^{hijkl}	68.75^{hi}	91.00^{opqrs}	33.00^{klm}	75.30^{stu}	23.12^{t}	67.00^{xyz}
	Biocontrol	99.25^{h}	99.25^{h}	95.45^{lmnop}	95.51^{efghi}	67.75^{gh}	90.55^{nopqr}	20.25^{gh}	73.25^{rst}	14.37^{mno}	63.25^{uvwx}
	HWT	99.25^{h}	99.25^{h}	91.33^{hi}	96.58^{ijklm}	82.12^{qrs}	91.75^{pqrst}	35.00^{mno}	70.00^{nopqr}	24.00^{t}	69.25^{yzA}
	HWT+BIO	99.25^{h}	99.25^{h}	86.15^{f}	95.78^{efghi}	69.69^{hijk}	87.05^{ijklm}	22.25^{gh}	66.50^{lmn}	19.50^{rs}	61.25^{tuvw}
	CHL+BIO	99.25^{h}	99.25^{h}	95.72^{lmnop}	94.54^{defgh}	75.56^{lmn}	87.92^{jklmn}	33.00^{klm}	72.00^{pqrs}	9.03^{ij}	43.50^{op}
	ANO+BIO	99.25^{h}	99.25^{h}	94.71^{jklmn}	96.00^{ghijk}	82.49^{qrs}	89.98^{mnopq}	30.00^{jkl}	72.75^{qrst}	20.37^{s}	71.75^{zAB}
ZZ+Pink	Control	98.42^{bc}	98.42^{bc}	94.26^{jklm}	95.50^{efghi}	72.55^{ijklm}	90.75^{nopqr}	12.73^{def}	46.75^{g}	13.38^{lmn}	22.55^{h}
	Chlorine	98.42^{bc}	98.42^{bc}	96.38^{mnopq}	95.75^{efghi}	75.88^{mno}	92.25^{qrstu}	10.75^{cdef}	54.75^{h}	6.50^{defgh}	20.53^{gh}
	Biocontrol	98.42^{bc}	98.42^{bc}	94.47^{jklmn}	94.06^{defgh}	71.69^{hijkl}	58.75^{b}	2.53^{a}	34.75^{de}	20.12^{s}	6.25^{b}
	HWT	98.42^{bc}	98.42^{bc}	92.69^{ijk}	94.56^{defgh}	69.29^{hij}	78.75^{fg}	19.50^{g}	29.75^{bc}	6.50^{defgh}	0.00^{a}
	HWT+BIO	98.42^{bcd}	98.42^{bcd}	76.31^{d}	95.22^{efghi}	54.55^{de}	72.40^{e}	20.50^{gh}	33.03^{cd}	16.92^{pq}	16.75^{defg}
	CHL+BIO	98.42^{bcde}	98.42^{bcde}	94.50^{jklmn}	95.75^{efghi}	58.38^{f}	86.25^{ijkl}	8.88^{cde}	60.75^{ijk}	4.88^{cdef}	29.63^{ij}
	ANO+BIO	98.42^{bcdef}	98.42^{bcdef}	86.05^{f}	93.44^{def}	51.25^{cd}	87.42^{ijklm}	20.38^{gh}	59.13^{i}	9.38^{ijk}	33.50^{ijkl}
ZZ+Red	Control	96.99^{a}	96.99^{a}	94.78^{jklmn}	90.68^{c}	69.47^{hijk}	84.25^{hi}	12.73^{def}	37.13^{e}	8.44^{hi}	12.25^{cd}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)
	Chlorine	96.99^{a}	96.99^{a}	89.11^{gh}	78.48^{a}	48.68^{bc}	72.88^{e}	10.75^{cdef}	34.50^{de}	11.14^{jkl}	8.63^{bc}
	Biocontrol	96.99^{a}	96.99^{a}	57.58^{a}	93.55^{defg}	64.88^{g}	54.38^{a}	2.53^{a}	25.38^{a}	6.50^{defgh}	14.38^{def}
	HWT	96.99^{a}	96.99^{a}	76.12^{d}	93.34^{de}	45.75^{b}	63.05^{c}	19.50^{g}	29.38^{bc}	11.61^{kl}	6.75^{b}
	HWT+BIO	96.99^{a}	96.99^{a}	57.14^{a}	87.46^{b}	56.00^{ef}	69.23^{d}	20.50^{gh}	27.25^{ab}	16.54^{opq}	16.55^{defg}
	CHL+BIO	96.99^{a}	96.99^{a}	95.25^{jklmn}	86.06^{b}	73.00^{jklm}	80.50^{g}	8.88^{cde}	42.50^{f}	7.08^{fghi}	13.88^{def}
	ANO+BIO	96.99^{a}	96.99^{a}	78.39^{d}	93.93^{defg}	74.52^{lmn}	68.98^{d}	20.38^{gh}	38.25^{e}	8.62^{hi}	13.63^{de}

Significance level (p)	
Treatments (A)	0.182
Storage (B)	<.001
Route (C)	<.001
Maturity stage (D)	<.001
AXB	0.979
AXC	0.981
BXC	0.018
AXD	0.928
BXD	0.202
CXD	0.012
AXBXC	0.996
AXBXD	0.951
AXCXD	1.000
BXCXD	0.145
AXBXCXD	1.000
CV (%)	42.5
SE	30.346
LSD	18.842

Means within the same column followed by the same letter are not significantly different ($p>0.05$). HWT signifies hot water treatment, BIO designates biocontrol treatment using B-13 yeast isolate, ANO anolyte water and CHL chlorinated water. PD signifies tomatoes transported through Point Drift-Pietermaritzburg route, EM through Mooketsi-Pietermaritzburg and ZZ through Esmefour-Pietermaritzburg. The transportation routes had varying road quality conditions and distances.

The mean marketability of fruit stored under ambient conditions was 58-64 % while fruit stored under cold storage conditions had a mean marketability of 76-79 %. Similarly, fruit transported through the EM route had the highest mean marketability of 71-77 %, while fruit transported through ZZ had the lowest marketability of 63-64 %. A MANOVA of the marketability of fruit harvested and transported during the summer showed storage environment, fruit maturity at harvest and transportation conditions as significant ($p \leq 0.05$) factors that influenced the marketability of stored fruit. The differences in the marketability of fruit subjected to different pre-storage treatments was, however, found not to be significant ($p > 0.05$).

Ano+Bio performed well in maintaining the marketability of fruit under various storage and transportation conditions, across the three maturity stages, for fruit harvested in the winter trial. The mean marketability of fruit treated with Ano+Bio was also found to be significantly (≤ 0.05) higher than that of fruit subjected to other treatments during the winter and summer trials (71-73 %). A MANOVA of the marketability of fruit harvested and transported during the winter season showed that the storage conditions, pre-storage treatments, fruit maturity at harvest and transportation conditions had a significant effect ($p \leq 0.05$) on the fruit marketability.

Fruit marketability aggregates the visual and tactile attributes of tomatoes. It closely mimics the approach that consumers use as a basis of making their buying decisions. Although it is a subjective attribute, it gives useful information on how appealing fresh tomatoes are to consumers, when they are at the market. A comparison of levels of marketability of tomato fruit with storage showed that the values achieved in this study were higher than some of those reported in the literature. For instance, a study by Workneh *et al.* (2009) where packaged and unpackaged tomato was stored under ambient conditions reported marketability of 57 and 30 %, respectively after 12 days of storage. In contrast, the percentage of marketable fruit in the present study was largely over 60 % after 16 days of storage. Another study by Linke and Geyer (2002) that assessed the loss in marketability of tomatoes due to different pre-storage treatments and packaging conditions reported fruit marketability of 62 % after 17 days of storage. The study, however, only used microbial spoilage as the criteria for assessing marketability. Their approach may have been less strict, hence the high marketability values. Delayed harvesting led to a lower marketability of fruit, as was the case when fruit was harvested at red maturity stage (Tolesa *et al.*, 2017). Transportation on roads of good quality improved fruit marketability due to decreased fruit damage (Mutari and Debbie, 2011).

Table 4.11 A summary of changes in marketability of tomatoes of different maturity stages with storage across different transportation and storage conditions, for fruit harvested and transported in winter

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)
PD+Green	Control	100.00^{a}	100.00^{a}	72.00^{i}	99.62^{opqr}	61.47^{klmn}	98.50^{zAB}	23.50^{efgh}	80.00^{xy}	1.34^{b}	8.00^{c}
	Chlorine	100.00^{a}	100.00^{a}	97.12t^{uvwx}	100.00^{r}	70.75^{tuv}	99.25^{B}	42.82st	84.13^{zA}	24.50^{zA}	41.33^{tuv}
	Biocontrol	100.00^{a}	100.00^{a}	95.88^{rstu}	100.00^{r}	63.25^{mno}	98.25^{xyzAB}	32.12^{lmno}	85.00^{A}	6.57^{def}	29.38^{hijkl}
	HWT	100.00^{a}	100.00^{a}	89.50^{lm}	100.00^{r}	64.75^{nopq}	97.75^{wxyzA}	22.60^{ef}	79.50^{wxy}	18.54^{tuvw}	27.75^{ghi}
	HWT+BIO	100.00^{a}	100.00^{a}	94.87^{qrst}	100.00^{r}	67.25^{qrs}	97.75^{wxyzA}	20.70^{de}	87.63^{ABCD}	15.98^{pqrst}	30.63^{hijkl}
	CHL+BIO	100.00^{a}	100.00^{a}	98.88^{vwxy}	100.00^{r}	72.75^{vw}	99.25^{B}	40.25^{qrs}	85.75^{ABC}	12.50^{klmno}	36.38^{pqrs}
	ANO+BIO	100.00^{a}	100.00^{a}	95.75^{rstu}	100.00^{r}	64.75^{nopq}	98.00^{wxyzA}	26.75^{fghij}	86.25^{ABCD}	13.20^{lmno}	36.75^{qrs}
PD+Pink	Control	100.00^{a}	100.00^{a}	63.00^{g}	98.88^{mnopq}	58.50^{ijk}	91.50^{klmno}	40.75^{rs}	75.12^{qrstu}	4.63^{cd}e	32.63^{lmnop}
	Chlorine	100.00^{a}	100.00^{a}	92.63^{nopq}	97.75^{jklmn}	61.50^{klmn}	94.75^{qrstu}	29.25^{jklm}	80.97^{yz}	17.04^{rstu}	44.03^{v}
	Biocontrol	100.00^{a}	100.00^{a}	73.25^{i}	98.50^{lmnop}	58.25^{ij}	94.00^{pqrst}	17.00^{d}	69.25^{mno}	16.57^{qrstu}	21.15^{e}
	HWT	100.00^{a}	100.00^{a}	77.50^{j}	92.38^{d}	64.00^{mnopq}	97.75^{wxyzA}	22.87^{efg}	78.12^{uvwxy}	6.73^{defg}	33.93^{mnopq}
	HWT+BIO	100.00^{a}	100.00^{a}	90.50^{mn}	94.75^{efg}	68.50^{rst}	97.75^{wxyzA}	38.77^{qrs}	85.75^{AB}	17.38^{stuv}	31.53^{ijklm}
	CHL+BIO	100.00^{a}	100.00^{a}	91.75^{mnop}	96.62^{ghijk}	74.00^{wx}	97.50^{wxyzA}	27.25^{hijk}	81.25^{yz}	12.32^{klmno}	33.48^{mnopq}
	ANO+BIO	100.00^{a}	100.00^{a}	93.38o^{pqr}	99.25^{nopqr}	66.75^{pqr}	95.50^{stuvw}	31.00^{klmn}	89.78^{BD}	9.55^{ghij}	36.20^{opqrs}
PD+Red	Control	97.00^{b}	97.00^{b}	58.38^{de}	95.50^{fghi}	52.00^{h}	87.75^{fghij}	20.37^{de}	64.00^{ijk}	9.00^{fghi}	20.80^{e}
	Chlorine	97.00^{b}	97.00^{b}	76.62^{j}	96.62^{ghijk}	62.00^{lmn}	91.75^{klmno}	38.87^{qrs}	79.10^{vwxy}	27.13^{B}	42.95^{uv}
	Biocontrol	97.00^{b}	97.00^{b}	73.38^{i}	96.37^{fghij}	61.00^{jklm}	67.75^{d}	28.36^{ijkl}	55.87^{f}	7.12^{efg}	39.28^{stu}
	HWT	97.00^{b}	97.00^{b}	53.12^{c}	94.37^{ef}	42.00^{f}	87.25^{efghi}	16.75^{d}	39.41^{c}	13.35^{lmnop}	3.85^{b}
	HWT+BIO	97.00^{b}	97.00^{b}	53.62^{c}	88.50^{c}	49.25^{gh}	90.75^{jklmn}	39.25^{qrs}	44.12^{d}	14.17^{nopq}	13.55^{d}
	CHL+BIO	97.00^{b}	97.00^{b}	73.12^{i}	95.87^{fghij}	62.50^{mn}	89.50^{ghijk}	40.52^{rs}	62.12^{hij}	10.92^{ijklm}	14.40^{d}
	ANO+BIO	97.00^{b}	97.00^{b}	63.50^{g}	97.62^{ijklm}	55.75^{i}	84.50^{e}	49.00^{uvw}	75.43^{rstuv}	11.95^{jklmn}	31.85^{jklmn}
EM+Green	Control	100.00^{a}	100.00^{a}	99.25^{xy}	99.50^{opqr}	81.50^{B}	97.25^{vwxyz}	57.50^{zA}	68.00^{lmn}	21.70^{xy}	15.13^{d}
	Chlorine	100.00^{a}	100.00^{a}	99.75^{y}	99.75^{pqr}	93.50^{D}	98.62^{AB}	54.38^{xyz}	71.38^{nopqr}	19.15^{uvwx}	36.13^{opqrs}
	Biocontrol	100.00^{a}	100.00^{a}	97.12^{tuvwx}	99.50^{opqr}	78.05^{yzA}	94.75^{qrstu}	60.75^{AB}	68.34^{lmno}	38.80^{E}	14.50^{d}
	HWT	100.00^{a}	100.00^{a}	99.25^{xy}	99.75^{pq}r	78.00^{yzA}	96.00^{tuvwx}	55.75^{yz}	60.38^{ghi}	31.12^{C}	41.38^{tuv}
	HWT+BIO	100.00^{a}	100.00^{a}	95.87^{rstu}	99.75^{pqr}	71.75^{uvw}	98.00^{wxyzA}	62.37^{BC}	49.50^{e}	20.77^{wxy}	42.63^{uv}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)
	CHL+BIO	100.00^{a}	100.00^{a}	99.38^{y}	99.75^{pqr}	77.50^{yz}	96.50^{uvwxy}	64.75^{C}	73.75^{pqrst}	37.92^{E}	28.50^{ghijk}
	ANO+BIO	100.00^{a}	100.00^{a}	98.87^{wxy}	99.50^{opqr}	81.25^{B}	98.50^{zAB}	60.52^{AB}	86.25^{ABCD}	32.65^{C}	43.15^{uv}
EM+Pink	Control	100.00^{a}	100.00^{a}	99.25^{xy}	99.25^{nopqr}	88.50^{C}	91.00^{jklmn}	51.00^{vwx}	71.12^{nopq}	23.00^{yz}	9.75^{c}
	Chlorine	100.00^{a}	100.00^{a}	98.88^{vwxy}	99.50^{opqr}	94.50^{D}	97.87^{wxyzA}	41.00^{rs}	74.75^{qrstu}	6.60^{def}	25.15^{fg}
	Biocontrol	100.00^{a}	100.00^{a}	97.75^{uvwxy}	97.88^{klmno}	80.00^{zAB}	96.87v^{wxyz}	29.00^{jklm}	58.75^{fgh}	35.00^{D}	14.35^{d}
	HWT	100.00^{a}	100.00^{a}	99.38^{y}	97.50^{ijklm}	69.25^{rstu}	97.75^{wxyzA}	49.87^{uvw}	59.75^{fgh}	8.40^{fghi}	16.15^{d}
	HWT+BIO	100.00^{a}	100.00^{a}	89.75^{lm}	98.50^{lmnop}	63.75^{mnop}	98.25^{xzAB}	42.00^{s}	70.00^{mnop}	8.05^{fgh}	43.90^{v}
	CHL+BIO	100.00^{a}	100.00^{a}	95.12^{qrstu}	98.50^{lmnop}	57.00^{i}	97.75^{wxyzA}	51.25^{vwx}	58.75^{fgh}	18.50^{tuvw}	28.25^{ghij}
	ANO+BIO	100.00^{a}	100.00^{a}	98.87^{wxy}	96.62^{ghijk}	59.00^{ijkl}	96.50^{uvwxy}	40.50^{rs}	73.75^{pqrst}	14.85^{opqrs}	32.25^{klmno}
EM+Red	Control	100.00^{a}	100.00^{a}	96.12^{rstuv}	98.50^{lmnop}	57.50^{i}	87.38^{efghi}	37.37^{pqr}	47.75^{e}	8.87^{fghi}	22.35^{ef}
	Chlorine	100.00^{a}	100.00^{a}	96.38^{stuvw}	98.63^{lmnop}	64.75^{nopq}	94.62^{qrstu}	38.87^{qrs}	59.25^{fgh}	4.82^{cde}	28.33^{ghijk}
	Biocontrol	100.00^{a}	100.00^{a}	94.38^{pqrst}	97.88^{klmno}	70.25^{stuv}	88.50^{ghijk}	33.00^{mno}	43.75^{d}	8.62^{fghi}	27.13^{gh}
	HWT	100.00^{a}	100.00^{a}	94.00^{opqrs}	97.12^{hijkl}	56.25^{i}	90.15^{hijkl}	27.75^{hijkl}	41.88^{cd}	0.92^{b}	25.13^{fg}
	HWT+BIO	100.00^{a}	100.00^{a}	87.62^{kl}	97.50^{ijklm}	71.47^{tuvw}	85.12^{ef}	0.00^{a}	34.25^{b}	0^{a}	20.90^{e}
	CHL+BIO	100.00^{a}	100.00^{a}	93.50^{opqr}	97.75^{jklmn}	66.25^{opqr}	95.00^{rstuv}	34.50^{nop}	64.50^{jkl}	4.10^{cd}	37.78^{rst}
	ANO+BIO	100.00^{a}	100.00^{a}	97.12^{tuvwx}	97.12^{hijkl}	71.25^{tuvw}	93.00^{nopqr}	24.50^{efghi}	72.00^{nopqr}	4.70^{cde}	32.78^{lmnop}
ZZ+Green	Control	99.00^{a}	99.00^{a}	66.50^{h}	99.25^{nopqr}	58.37^{ijk}	90.50^{ijklm}	9.87^{bc}	66.25^{klm}	3.85^{c}	32.90^{lmnop}
	Chlorine	99.00^{a}	99.00^{a}	97.00^{tuvwx}	99.75^{pqr}	81.12^{AB}	96.75^{uvwxy}	52.00^{wxy}	79.00^{vwxy}	25.12^{zAB}	43.00^{uv}
	Biocontrol	99.00^{a}	99.00^{a}	94.50^{qrst}	99.50^{opqr}	75.75^{xy}	94.62^{qrstu}	47.00^{uv}	78.75^{uvwxy}	16.50^{qrstu}	71.00^{z}
	HWT	99.00^{a}	99.00^{a}	77.25^{j}	99.88^{qr}	67.00^{pqr}	95.72^{tuvwx}	47.62^{uv}	75.50^{rstuv}	25.70^{AB}	50.63^{w}
	HWT+BIO	99.00^{a}	99.00^{a}	93.50^{opqr}	99.75^{pqr}	81.00^{AB}	97.25^{vwxyz}	41.50^{rs}	76.75^{tuvwx}	20.30^{wx}	62.53^{x}
	CHL+BIO	99.00^{a}	99.00^{a}	90.50^{mn}	99.75^{pqr}	86.50^{C}	88.75^{ghijk}	28.37^{ijkl}	68.87^{mno}	8.90^{fghi}	59.58^{x}
	ANO+BIO	99.00^{a}	99.00^{a}	86.50^{k}	99.75^{pqr}	80.50^{zAB}	95.37^{stuvw}	66.00^{C}	85.62^{A}	20.17^{wx}	66.86^{y}
ZZ+Pink	Control	95.00^{c}	95.00^{c}	54.12^{c}	95.00^{fgh}	42.37^{f}	89.75^{ghijk}	27.00^{ghijk}	49.13^{e}	13.31^{lmnop}	22.45^{ef}
	Chlorine	95.00^{c}	95.00^{c}	96.50^{stuvw}	99.50^{opqr}	82.37^{B}	92.37^{mnopq}	41.00^{rs}	76.25^{stuvw}	7.75^{fgh}	35.78^{nopqr}
	Biocontrol	95.00^{c}	95.00^{c}	91.50^{mno}	98.38^{lmnop}	75.87^{xy}	96.12^{tuvwx}	46.25^{tu}	79.75^{xy}	19.77^{vwx}	71.53^{z}
	HWT	95.00^{c}	95.00^{c}	67.25^{h}	97.75^{jklmn}	58.00^{ij}	93.38^{opqrs}	33.75^{nop}	56.62^{fg}	8.70^{fghi}	25.28^{fg}
	HWT+BIO	95.00^{c}	95.00^{c}	56.50^{d}	92.87^{de}	34.00^{e}	91.15^{klmno}	18.00^{d}	59.00^{fgh}	16.63^{qrstu}	28.43^{ghijk}
	CHL+BIO	95.00^{c}	95.00^{c}	72.62^{i}	95.87^{fghij}	62.50^{mn}	91.88^{lmnop}	31.12^{klmn}	66.12^{klm}	3.92^{c}	42.50^{uv}

Route+ Maturity stage	Pre-storage treatment	Days of storage and storage environment									
		0		8		16		24		30	
		Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)	Ambient	Cold (11^{o}C)
	ANO+BIO	95.00^{c}	95.00^{c}	73.38^{i}	97.37^{ijklm}	48.25^{g}	90.75^{jklmn}	35.97^{opq}	71.62^{nopqr}	9.05^{fghi}	59.28^{x}
ZZ+Red	Control	90.00^{d}	90.00^{d}	46.25^{a}	70.50^{a}	24.37^{c}	51.38^{a}	12.37^{c}	20.67^{a}	10.84^{ijkl}	0.00^{a}
	Chlorine	90.00^{d}	90.00^{d}	63.00^{g}	91.62^{d}	57.50^{i}	62.37^{b}	25.07^{fghij}	49.81^{e}	14.42^{nopqr}	25.33^{fg}
	Biocontrol	90.00^{d}	90.00^{d}	48.75^{b}	91.75^{d}	28.75^{d}	86.50^{efg}	20.37^{de}	60.20^{ghi}	7.80^{fgh}	49.49^{w}
	HWT	90.00^{d}	90.00^{d}	61.50^{fg}	79.75^{b}	13.75^{b}	49.12^{a}	11.15^{b}	39.28^{c}	11.17^{nopq}	20.45^{e}
	HWT+BIO	90.00^{d}	90.00^{d}	53.50^{c}	87.62^{c}	10.05^{a}	64.17^{bc}	10.47^{a}	33.37^{b}	9.58^{mnop}	16.30^{d}
	CHL+BIO	90.00^{d}	90.00^{d}	62.62^{g}	88.25^{c}	51.38^{h}	66.50^{cd}	35.87^{opq}	49.55^{e}	6.93^{efg}	51.94^{w}
	ANO+BIO	90.00^{d}	90.00^{d}	60.00^{ef}	95.62^{fghij}	44.53^{f}	87.00^{efgh}	28.90^{ijklm}	72.50^{opqrs}	9.97^{hijk}	51.15^{w}

Significance level (p).

Treatments (A)	<.001
Storage (B)	<.001
Route (C)	<.001
Maturity stage (D)	<.001
AXB	0.885
AXC	0.216
BXC	<.001
AXD	0.793
BXD	0.428
CXD	0.003
AXBXC	0.862
AXBXD	1.000
AXCXD	0.996
BXCXD	0.623
AXBXCXD	1.000
cv (%)	44.8
SE	30.276
LSD	18.774

Means within the same column followed by the same letter are not significantly different (p>0.05). HWT signifies hot water treatment, BIO designates biocontrol treatment using B-13 yeast isolate, ANO anolyte water and CHL chlorinated water. PD signifies tomatoes transported through Point Drift-Pietermaritzburg route, EM through Mooketsi-Pietermaritzburg and ZZ through Esmefour-Pietermaritzburg. The transportation routes had varying road quality conditions and distances.

4.5 Conclusions

This study investigated the effect of pre-storage treatments, transportation and storage conditions on the quality and shelf-life of tomatoes harvested and transported under typical commercial conditions. Based on the fruit hue angle, green fruit responded well to poor transportation conditions compared to fruit harvested at pink and red maturity stages. Poor road quality negatively affected fruit of green and red maturity stages compared to fruit harvested at pink maturity stage, with the firmness of fruit harvested at red maturity stage showing the worst response to rough roads. There was a 43, 20 and 17 % reduction in fruit firmness for fruit harvested at the green, pink and red maturity stages. Fruit transported through the EM had the highest firmness (19.65 N) compared to fruit transported through ZZ (18.48 N). Fruit transported through the EM route had the lowest weight-loss, while sample tomatoes transported through PD and ZZ having the highest weight-loss.. Fruit transported through EM had the highest mean marketability (77 %), while fruit transported through ZZ had the lowest mean marketability (64 %). Fruit treated with anolyte water in combination with biocontrol had significantly ($p \leq 0.05$) higher marketability than fruit subjected to other disinfection treatments. Combining fruit that was harvested at the green maturity stage, transported through EM, disinfected using anolyte water and stored in a cold storage environment gave, gave the fruit the highest quality and longest shelf-life. The significance of this study lies in the establishment of anolyte water and biocontrol as an environmentally-friendly and effective solution in maintaining tomato fruit shelf-life. Although PD route had a relatively higher proportion of its road length of rough road sections (58 % of its road length had IRR<2.5 m km^{-1}) than EM (70 % of its road length had IRR<2.5 m km^{-1}) and ZZ (63 % of its road length had IRR<2.5 m km^{-1}), fruit transported through ZZ showed more damage than those transported through EM and PD. This is attributed to the relatively longer distances fruit was transported through in the case of ZZ and the relatively rough road surface profiles. Significant differences in different quality attributes of fruit transported through EM, PD and ZZ signifies the importance of road quality and transportation distances on the quality of fresh tomatoes. The study has also shown that different tomato fruit qualities respond variedly to changes in transportation conditions. This implies that while tomatoes harvested at pink and green maturity stages responded well to roads of rough surface profiles compared to tomatoes harvested at red maturity stage, there is need for optimization of transportation conditions to maximize fruit quality and shelf-life. The study also brings out a clear link between road quality and distance, with need for optimization of the two variables based on the prevailing conditions.

4.6 Acknowledgements

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5. EFFECT OF PACKING UNITS DURING LONG DISTANCE TRANSPORTATION ON THE QUALITY AND SHELF-LIFE OF TOMATOES UNDER COMMERCIAL SUPPLY CONDITIONS

5.1 Abstract

The effect of various packing units on tomato fruit shelf-life and quality was studied, where fruit of three maturity stages (red, pink and green) were transported using plastic bulk bins (468 kg capacity) and carton boxes (8 kg capacity). The fruit was transported along three supply routes, with each route having varying distances and road quality. The fruit was thereafter stored under ambient or cold storage environment (11 ^{o}C) after treatment using chlorinated water or tap water. Sampling and analysis of fruit colour, firmness, weight loss, pH and marketability was carried out over a 30-day storage period. Fruit harvested at green maturity stage had a mean hue angle of 68 while fruit harvested at pink and red maturity stages had a hue angle of 55 and 49^{o}, respectively. Fruit maturity at harvest and storage environment had a significant ($p \leq 0.05$) effect on all the fruit quality parameters measured. Fruit stored in cold storage had significantly ($p \leq 0.05$) better physicochemical quality attributes compared to fruit stored in ambient conditions. The EM route had a shorter distance and the best road quality (70 % of road had IRI values less than 2.5 m km^{-1}) compared to PD (58 %) and ZZ (63 %) route. Fruit transported through EM had 5 and 10 % higher mean marketability compared to fruit transported through PD and ZZ, respectively. Handling using boxes rather than bins improved the fruit marketability by 8 % and reduced the cumulative weight loss by 1 %. The study recommends the use of modular bins made of softer materials to minimize tomato fruit damage. Similarly, the study has shown that timely maintenance of farm roads and maintenance of the cold chain as important avenues of mitigating postharvest losses in commercial tomato supply chains.

Keywords: *handling conditions; IRI; postharvest quality; road quality; tomato fruit injuries*

5.2 Introduction

Tomatoes are among some of the most popular fresh fruits and vegetables (FFV) globally with diverse uses. It has numerous culinary uses, and can be eaten in fresh forms as salads, salsas or processed into juices (Raiola *et al.*, 2014). In the current global fresh food market environment, tomato production, including other FFV, are increasingly produced in areas far away from the markets due to the restructuring of agricultural food systems globally in response to rising urbanisation (Jedermann *et al.*, 2014).

Tomatoes are climacteric in nature and their physiological characteristics make them some of the most perishable fresh foods (Robinson and Kolavalli, 2010). They are also some of the most fragile agricultural commodities, whose perishability is exacerbated by poor harvesting, handling, and transportation practices (Li and Thomas, 2014). In tomato supply chains, loss of quality due to poor handling practices become only apparent downstream the supply chain, and in other cases, after the products have reached the market leading to huge economic losses (Jedermann *et al.*, 2014).

Although the exact level of tomato postharvest losses due to handling and transportation is not well documented, estimates show that poor handling and transportation practices can be as high as 20 % (Arah *et al.*, 2015). Sibomana *et al.* (2016) and Arah *et al.* (2015) reported the overall postharvest losses in tomato supply chains in sub-Saharan Africa to be between 10-40 %. These losses are higher in African nations and emerging markets with poor road infrastructure (Macheka *et al.*, 2017). It has been reported for instance, that logistical and transportation activities in Ghana and Nigeria are the major causes of postharvest losses in fresh tomatoes (Macheka *et al.*, 2017). Adepoju (2014) reported that tomatoes in Nigeria are often transported to the markets by using small, open trucks, over poor roads, which leads to mechanical damage to the fruit and exposes it to high temperature conditions. Similar observations have been made with respect to transportation infrastructure and practices of tomatoes in Ghana (Addo *et al.*, 2015). The quantification of the losses caused by transportation is therefore important, in order for the necessary and most suitable measures necessary to mitigate these losses to be put in place.

Packing units of fresh tomatoes play the role of containment, give structural support, protection and ease handling during transport (Vigneault *et al.*, 2009). Packaging units also influence fruits' heat transfer properties (Kitinoja and Kader, 2002), and need to be designed to effectively dissipate accumulated heat and prevent mechanical damage to the fruit (Zhou *et al.*, 2007). Depending on the materials used, they interact with road-vehicle systems during transportation to provide cushioning of fruit against vibrations, and excessive static loads. Studies by Aba *et al.* (2012) have explored the load and vibration transmissivity of some of the packing materials used to transport tomatoes. They concluded that the material surface type is an important attribute that affected fruit damage during transportation. The study was, however, simulated and did not account for practicalities of handling and transportation during normal supply operations. This is especially important in commercial supply chains, where excessive loadings are often subjected to the fruit due to the bulk handling operations.

The aim of this study was to investigate the effect of two packing units commonly-used in South African commercial supply chains on the quality and shelf-life of tomatoes transported through three supply chains with varying distances and road quality.

5.3 Materials and Methods

5.3.1 Tomato fruit samples

Tomato fruit (*Solanum lycopersicum*) of Nemo-Netta variety was obtained from three farms in Limpopo Province located in Esmefour (22^{o}19’48.7” S 30^{o}28’21.3” E), Pont drift (22^{o}11’52.7” S 29^{o}11’30.7” E) and Mooketsi (23^{o}26’05.2” S 30^{o}26’47.5” E). The fruit was harvested at three maturity stages (red, pink and green), graded, and non-defective fruit packed in either plastic bins 2 m in length, 1 m wide and 0.4 m deep or carton boxes 0.4 m long, 0.3 m wide and 0.25 m deep.

5.3.2 Transportation conditions

The fruit was transported to the fresh produce market in non-refrigerated trucks along three supply routes, namely, Point Drift to Pietermaritzburg (PD), Mooketsi to Pietermaritzburg (EM) and Esmefour to Pietermaritzburg (ZZ), which had varying road surface profiles. On arrival in Pietermaritzburg, the fruit was taken to the Bioresources Engineering laboratory of the University of KwaZulu-Natal for application of pre-storage treatments, storage and analysis. Each route had varying distances of both rough and asphalt roads. The trucks were driven at a speed of 80 km h^{-1} on the highways and 60 km h^{-1} on rough roads.

5.3.3 Experimental design

A Schematic representation of the experimental design are shown in Figure 5.1. The experiment was arranged in a factorial design with the three transportation routes (PD, EM and ZZ), three maturity stages (red, pink and green), two storage conditions (cold and ambient) and the two packing units (boxes and bins) as experimental factors. The pre-storage treatments were replicated three times, with sampling and analysis on Day 1 and after 8, 16, 24 and 30 days of storage.

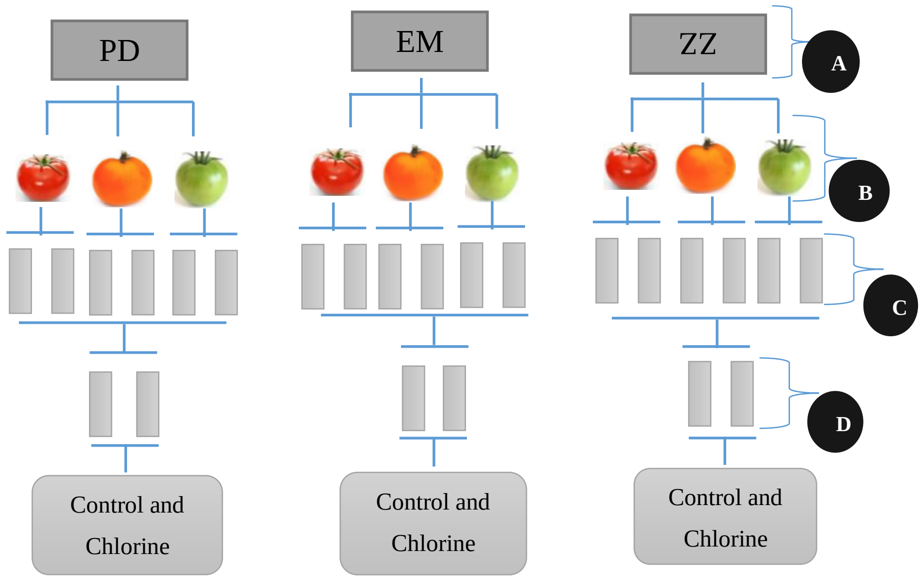

Figure 5.1 A schematic representation of the experimental design with (A) as the transportation conditions, (B) the fruit maturities at harvest and (C) the packaging units (bins and boxes) during transport. The two disinfection treatments (chlorinated water and tap water) were applied on fruit and sampling and analysis carried out over a 30-day storage period. (D) designates cold (11 ^{o}C) and ambient storage conditions.

5.3.4 Data collection

5.3.4.1 Measurement of road quality

During transportation, the road quality, which signified the quality of ride induced on the tomatoes was measured using a road surface laser profilometer (PaveProf V2.0, Pavetesting, UK).

5.3.4.2 Colour

Fruit colour was measured using a Minolta Chroma meter (Model CR-400, Narachi Pty, South Africa). Readings were made at an observer angle of 2^{o} after standardizing the instrument with a white tile (Y = 93.8, X = 0.3030, y = 0.3191). Illuminant C was used to measure the L*a*b*c and h values, where readings were taken from three fruits, for each replicate (Kerkhofs *et al.*, 2005; Pinheiro *et al.*, 2015). The fruit colour was assessed before (Day 1) and after 8, 16, 24 and 30 days of storage.

5.3.4.3 Fruit firmness

Tomato fruit firmness was tested using Instron universal testing machine (model 3345, Advanced Laboratory Solutions, South Africa) attached to a 6.1 mm flat end stainless steel probe at a cross-head speed of 20 mm min^{-1}. The force-deformation curves were automatically recorded by the Bluhill® software (Batu, 2004), which also reported the maximum force required to puncture the tomato skin. Three fruits was tested per replicate, and results reported as the maximum puncture force in N (Batu, 2004).

5.3.4.4 pH

Product pH was measured using a pH meter (Orion Star A210, Thermo Scientific, South Africa) with a probe designed to measure solids (Favati *et al.*, 2009). The instrument was first standardized using 4.01, 10.00 and 7.00 pH buffers. Two tomato fruits were macerated using a food processor (Philips Model HR2106/01, Makro, Pietermaritzburg, South Africa) for 1 minute and the juice was extracted into a 50 mL beaker, using a cheesecloth. The pH of the extracted aliquot was then determined using the pH meter. Readings were repeated for each replication for the selected sampling days.

5.3.4.5 Physiological weight-loss

Weight-loss was determined at selected storage intervals using the method proposed by Pinheiro *et al.* (2013). A batch of 3 tomatoes per replication were marked and weighed at Day 1 and the percentage weight-loss reported on day 8, 16, 24 and 30, relative to Day 1.

5.3.4.6 Subjective quality evaluation

Subjective tests were performed to ascertain the proportion of the sample that was marketable under shelf-life studies. The overall visual appearance was the primary criterion used to judge if samples were still marketable during sampling. Fruit that was perceived to have shrivelled excessively, to have decayed or to have been physiologically damaged in any way, and that could not be sold at the local markets, was considered unmarketable and was therefore removed from the test sample during sampling. This procedure followed the method used by Tadesse *et al.* (2012).

5.3.5 Data analysis

Data analysis was carried out using Genstat 18 (VSI international, UK). multivariate analysis of variance (MANOVA) was used to analyse the effect of packing units, transportation conditions, storage conditions and disinfection treatments on the quality of tomato fruit of various maturities at harvest.

5.4 Results and Discussion

5.4.1 Colour

A Comparison of the effect of handling conditions on the changes in the fruit hue angle of tomato fruit across various transportation conditions is shown in Figure 5.2.

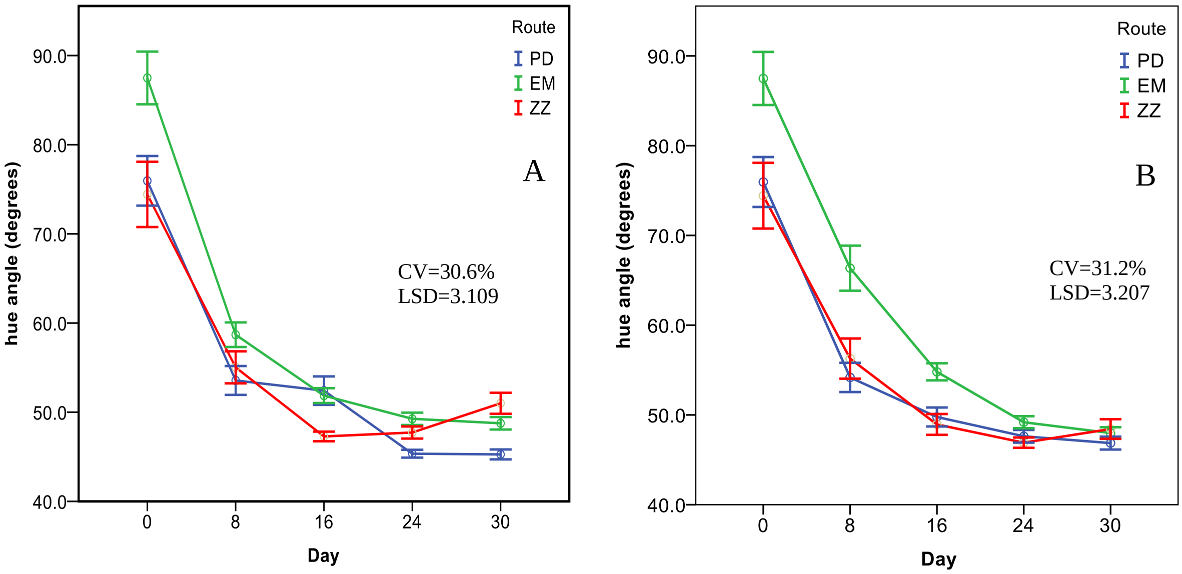

Figure 5.2 Effect of handling conditions on the changes in hue angle with storage across various transportation conditions. (A) designates fruit handled using bins and (B) fruit handled using boxes

It was observed that the mean hue angle decreased with storage duration from 86.49 to 45.27 and 86.49 to 46.86, for fruit handled using bins and boxes, respectively. The reduction in h was greatest between Day 1-8 for both handling conditions, with the h values of fruit handled using boxes being slightly higher than those of bins. With respect to transportation conditions, fruit transported through the EM route had higher h compared to that transported through the PD and ZZ route. A MANOVA of the data showed the fruit maturity at harvest and storage conditions as significant ($p \leq 0.05$) factors affecting changes in h of the fruit. The pre-storage treatments, transportation and handling conditions (bins or boxes) had no significant ($p > 0.05$) effect on the changes in fruit hue angle.

Tomato hue angle indicates colour change from green (hue angle of 180) to red (hue angle of 0) as fruit ripens (Pathare *et al.*, 2013). A decrease in hue angle signifies changes in colour due to accumulation of lycopene and degradation of chlorophyll as ripening progresses (Canene-Adams *et al.*, 2005). Higher hue angles signify better maintenance of tomato fruit quality. The

EM route had better road quality, with 70 % of its road length having International roughness index values <2.5 m km^{-1} compared to PD (58 %) and ZZ (63 %) route. These results suggest that fruit transported using bins suffered higher bruising levels and mechanical damage due to excessive static loading and accumulation of field heat compared to fruit transported using boxes (Opara and Pathare, 2014). It has also been shown that impact damage causes tomatoes to ripen faster due to inducement of a burst of ethylene, a phyto-hormone that regulates tomato fruit ripening (Mutari and Debbie, 2011).

5.4.2 Firmness

Fruit firmness decreased with the storage period across all transportation conditions. Fruit transported using boxes had higher firmness values compared to that of fruit transported using bins. The mean firmness of tomatoes transported using bins decreased from 22.0 N to 12.33 N over the storage period, while that of fruit transported using boxes dropped from 26.18 N to 13.08 N. Figure 5.3 shows the changes in tomato fruit firmness with storage across various transportation conditions for fruit handled using bins and boxes.

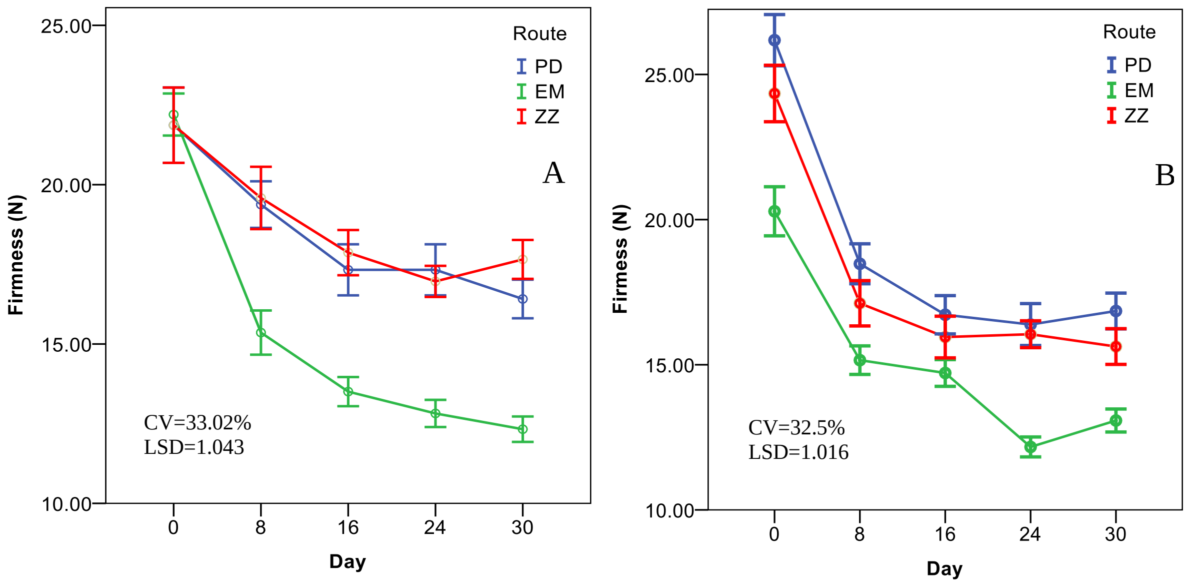

Figure 5.3 Effect of different handling and transportation conditions on the changes in tomato fruit firmness. (A) represents fruit handled in bins and (B) those handled using boxes

Transportation conditions had varied effects on the changes in fruit firmness with storage time. Fruit transported through PD had higher firmness values than those transported through EM and ZZ, especially for fruit handled using bins (Figure 3 B). The analysis of data showed the fruit maturity at harvest and storage conditions as the significant ($p \leq 0.05$) factors influencing the changes in fruit firmness over the storage period. However, the effect of disinfection treatments, handling (bins or boxes), transportation and storage conditions was not significant ($p>0.05$) on changes in tomato fruit firmness during storage.

A decrease of tomato fruit firmness occurs as a result of the progression of fruit ripening. This process is accompanied by fruit softening as a consequence of the combined effect of hydrolytic enzymes and changes in the hydrostatic pressure within the fruit cells (Tran *et al.*, 2017). The firmness of the tomato fruit influences the purchasing decisions of consumers, with softer fruit being less desirable due to their mealy texture (Batu, 2004). Tomato fruit firmness also effects their susceptibility to mechanical damage, with firmer fruit able to withstand handling during freight (Kader, 1984). Poor road quality and packing units during the transportation and handling operations of tomatoes results in fruit bruising and mechanical damage. The cumulative effects of poor handling, transportation and packaging are higher ripening rates, loss of quality and market value of fruit.

5.4.3 pH changes

Table 5.1 shows a comparison of the changes in fruit pH with storage duration for fruit handled using bins and boxes across various transportation conditions. Fruit pH showed varying trends with storage time, with fruit transported through PD showing a slight increase in pH. This rise in fruit pH was higher for fruit transported through the EM route than those transported through the ZZ route. Comparison of the effect of handling conditions on the changes in fruit firmness shows that the pH of fruit handled using bins was higher that of fruit handled using boxes. The mean pH of fruit transported using bins increased from 4.58 to 4.68, while the pH of fruit transported using boxes increased from 4.42 to 4.64. This observation implies that handling tomato fruit in bulk bins caused a comparatively higher rate of ripening, which could be attributed to fruit damage, accumulation of respiration or field heat around the fruit during transportation.

A MANOVA of the data showed that the changes in fruit pH with storage were significantly ($p\leq0.05$) influenced by the fruit maturity at harvest, storage, transportation and handling conditions (using boxes or bins). The disinfection treatments, however, had no significant ($p>0.05$) effect on the changes in tomato fruit pH during storage.

Tomato fruit is a low acid food with pH values commonly greater than 4.6, depending on the variety (Anthon *et al.*, 2011). Normal tomato fruit ripening processes causes its pH to rise due to the conversion of acids to sugars by gluconeogenesis (Anthon *et al.*, 2011). Excessive rise in fruit pH negatively affects the sensory quality of the fruit and upsets its sugar to acid ratio (Tigist *et al.*, 2013). Fruit damage causes higher ripening rates as discussed by Mutari and Debbie (2011). Higher pH levels in fruit transported using bins suggests a higher level of fruit bruising and mechanical damage compared to fruit handled using boxes.

Table 5.1 Effect of handling conditions on changes in tomato fruit pH with storage

Routes	Packaging units	Days of storage				
		0	8	16	24	30
PD	Bin	4.38±0.02[a]	4.48±0.01[a]	4.50±0.03[a]	4.58±0.01[a]	4.61±0.06[a]
	Box	4.28±0.01[b]	4.39±0.04[b]	4.41±0.01[b]	4.48±0.02[b]	4.56±0.03[b]
EM	Bin	4.44±0.05[c]	4.49±0.02[a]	4.54±0.02[c]	4.66±0.01[c]	4.68±0.02[c]
	Box	4.35±0.02[d]	4.40±0.01[d]	4.44±0.04[d]	4.56±0.02[d]	4.59±0.08[d]
ZZ	Bin	4.45±0.04[e]	4.49±0.03[a]	4.49±0.02[a]	4.61±0.03[e]	4.67±0.04[c]
	Box	4.34±0.03[f]	4.39±0.05[b]	4.44±0.01[d]	4.56±0.01[d]	4.58±0.03[d]

Means in the same column with different letters are significantly different at 95 % significance level based on Fisher's Least Significant Difference (LSD)

5.4.4 Physiological weight-loss

Cumulative fruit weight-loss increased over the storage period across the transportation conditions, and for fruit handled using boxes and bins. The cumulative weight-loss for the entire storage period was generally higher for fruit handled using bulk bins compared to fruit transported using boxes. It increased over the 30-day storage period to 14.22, 13.9 and 12.42 %, for fruit transported using bins through EM, PD and ZZ route, respectively. Similarly, fruit transported using boxes had a cumulative, 30-day weight-loss of 12.79, 12.02 and 10.21 % for fruit transported through the EM, PD and ZZ route, respectively. A comparison of the effect of transportation conditions on the fruit weight loss shows the ZZ route to have lower weight-loss compared to the PD and EM route. The mean weight-loss of fruit transported using bins and boxes was 7.38 and 6.34 %, respectively. The PD route comparatively had the highest mean weight-loss compared to the EM and the ZZ route (Figure 5.4). A MANOVA of the data showed that the handling (bins or boxes), storage and transportation conditions significantly ($p \leq 0.05$) influenced the changes in fruit weight-loss over the storage period. The disinfection treatments and fruit maturity at harvest did not have a significant effect ($p > 0.05$) on changes in fruit weight-loss. Figure 5.4 shows the changes in fruit weight-loss with storage for fruit handled using bins and boxes across various transportation conditions.

Fruit weight-loss is linked to the rate of ripening in tomatoes driven by physiological and metabolic processes in the fruit (Javanmardi and Kubota, 2006). It is primarily driven by respiratory processes and transpiration (Tigist *et al.*, 2013). The rate of these reactions in the fruit are influenced by environmental conditions, and partly by mechanical and chemical systems that can interact with the fruit to induce increased ripening (Mutari and Debbie, 2011). Bruising and other forms of mechanical damage have been shown to increase fruit ripening, which, in turn, increases fruit weight loss (Aba *et al.*, 2012). Increased weight-loss is not only undesirable to producers and retailers of tomatoes who sell their fruit per weight basis, but also to consumers. Excessive weight-loss results in tomatoes that have shrivelled, making them unattractive to consumers.

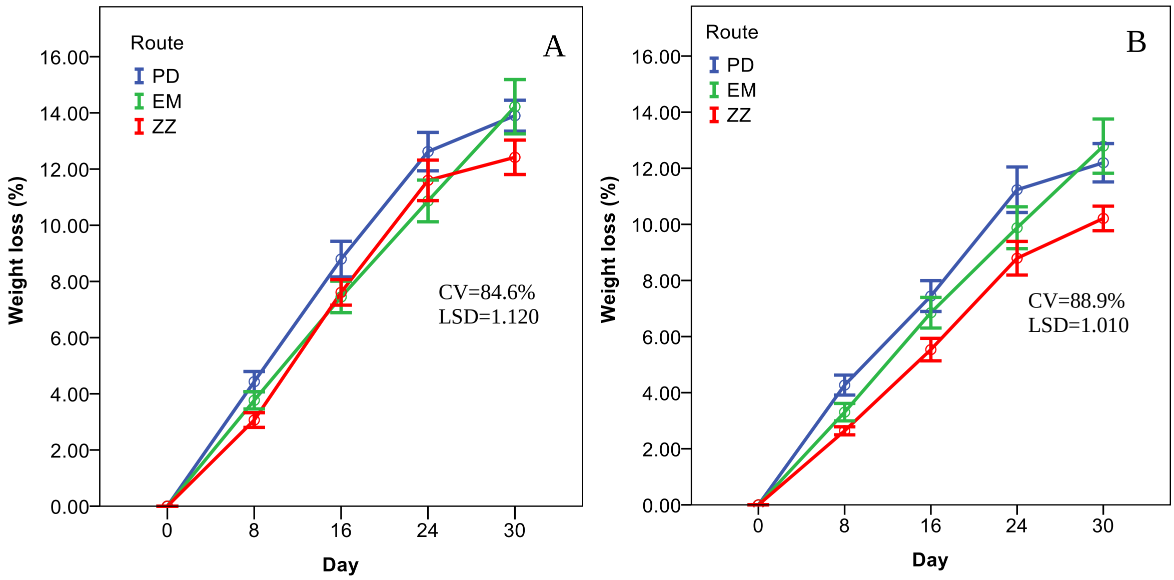

Figure 5.4 Variation in tomato fruit weight-loss with storage period for fruit transported using bins (A) and boxes (B), across, PD, EM and ZZ routes from Limpopo to Pietermaritzburg

5.4.5 Subjective quality and marketability

The bottom layer of tomatoes transported using bins showed signs of mechanical damage due to excessive compression resulting in cracking of fruit. Bruising also occurred due to the rubbing action of fruit on the lower surface of the bulk bin, which had been loaded with layers of fruit above it. Samples fruit transported using boxes had no signs of mechanical damage.

Figure 5.5 shows a side-by-side comparison of the visual appearance of fruit transported using bins and boxes.

Visual comparison of fruit transported using bins and boxes showed the colour of fruit transported using bins to be redder than those transported using boxes upon their arrival to Pietermaritzburg (Figure 5.5). This difference was pronounced especially for fruit that was harvested at the red maturity stage.

Figure 5.5 Visual appearance of tomatoes harvested at red maturity stage and transported using boxes (A) and bins (B)

The mean marketability of tomato fruit decreased with storage period from 100 % on the first day of storage to 34.04 % and 26.35 % for fruit transported using boxes and bins, respectively. The marketable fruit was comparatively higher for fruit transported using boxes. The effect transportation conditions on the marketability of fruit showed fruit transported through PD having higher marketability than those transported through ZZ and EM. Fruit transported through ZZ recorded the lowest percentage marketable fruit over the storage period. Figure 5.6 shows the effect of handling conditions on the changes in tomato fruit marketability with storage across various transportation conditions.

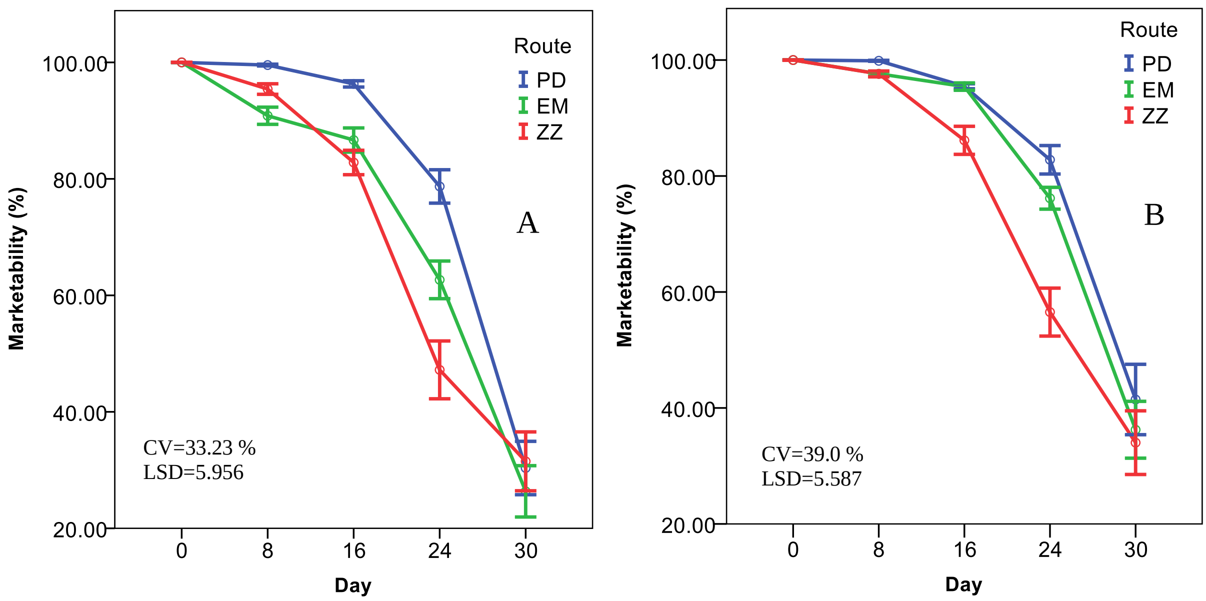

Figure 5.6 Effect of handling conditions on the changes in marketability of tomatoes with storage. (A) designates fruit transported using bins, while (B) designates tomatoes transported using boxes

A MANOVA of the fruit marketability showed the fruit maturity at harvest, storage, handling (boxes or bins) and transportation conditions as significant ($p \leq 0.05$) factors affecting changes in fruit marketability during storage. The disinfection treatments however, had no significant ($p > 0.05$) effect on the changes in fruit marketability.

The physicochemical parameters of tomatoes are important quality indicators that determine their market value, shelf-life and nutritional quality (Ceballos Aguirre and Vallejo Cabrera, 2012). These parameters are influenced by various factors, some of which relate to the prevailing temperature conditions, maturity at harvest, handling and transportation conditions (Workneh *et al.*, 2012). The fruit responded to varying transportation conditions differently, with fruit transported through the PD route showing comparatively higher percentage of marketable fruit than those transported through EM and ZZ. This may be attributed to the shorter distance that was taken for the fruit to reach the market, in the case of PD (894 km), compared to the fruit transported through EM (934 km) and ZZ (1157 km). Transportation using boxes reduced accumulation of heat, minimized fruit damage due to minimal inter-layer loading and gave fruit better containment. In contrast, fruit transported using bins showed damage, especially to fruit at the bottom. This may be attributed to excessive loading, accumulation of field, environmental and respiration heat leading to rapid ripening. Tomato bruising and other mechanical injuries have also been shown to trigger physiological responses that increases ethylene production, resulting in a rise in deteriorative processes causing higher loss in quality compared to intact fruit (Mutari and Debbie, 2011). The reverse relationship between marketability and weight-loss may be attributed to differences in the agro-climatic growing zones. ZZ farms were located far north compared to PD and EM. Water stress and higher growing temperatures may have affected fruit from ZZ. It was noticed in some instances that most fruit from ZZ were smaller than fruit harvested from PD and EM.

5.5 Conclusion

This study investigated the effect of packing units during long distance transportation under typical commercial conditions on the quality of fresh tomatoes. Transportation of tomatoes using boxes as opposed to bins was shown to comparatively have a beneficial effect in decreasing the rate of fruit quality changes during storage. Fruit transported through PD had the highest firmness (18.9 N), lowest rise in pH (4.40), and the highest marketability (82 %), while fruit transported through EM had the highest hue angle (60). Fruit harvested at green maturity stage and those stored under cold storage environment had significantly ($p \leq 0.05$) higher physicochemical quality attributes compared to tomatoes stored under ambient conditions and harvested at red maturity stage. A combination of harvesting at green maturity stage, transportation through PD, handling fruit in boxes and storage in cold storage gave the best treatment combination with a mean marketability of 97 %. Fruit marketability increased by 8 % when fruit was transported using boxes as opposed to bulk bins. Fruit transported through the EM and PD had comparatively lower quality loss compared to fruit transported through the ZZ route. This observation suggests that long distance transportation of tomatoes over slightly rough road conditions leads to higher quality losses compared to shorter distances through rougher road conditions. Handling units are clearly important avenues that can be targeted to reduce postharvest losses and improve the quality of tomato fruit supplied in South African supply chains. Handling using boxes rather than bins is recommended as it significantly ($p \leq 0.05$) reduced the fruit weight loss, improved fruits' visual appearance, reduced the rise in fruit pH and increased fruit marketability. Minimizing the use of bulk bins or redesigning them to improve airflow and reduce inter-layer loading should also be explored.

5.6 Acknowledgement

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6. APPLICATION OF LOGISTIC STATISTICAL MODELLING IN EVALUATION OF SUITABLE CONDITIONS FOR THE SUPPLY OF FRESH TOMATOES IN SELECTED SOUTH AFRICAN SUPPLY CHAINS

6.1 Abstract

In this study, a novel statistical modelling approach was employed to develop tomato quality models based on their physicochemical and subjective quality changes during transportation and storage, to predict the chances of fruit marketability. Seven disinfection treatments, two storage environments and three transportation conditions were subjected to tomatoes of three maturities harvested in summer and winter seasons. A binary variable based on fruit marketability was used to predict the probability of fruit marketability under various disinfection treatments, storage and transportation conditions. The probability of fruit marketability was comparatively lower for fruit transported on rough roads compared to fruit transported over smoother roads. However, fruit transported through moderately rough roads, that were furthest from the market had the lowest probability of marketability. Fruit harvested at green maturity stage, transported through the shortest, smoothest road (designated by low international roughness index values), stored under refrigerated environment and treated with anolyte water combined with biocontrol resulted in fruit with the highest probability of marketability. The hue angle (h), firmness, pH and weight-loss of the tomatoes were good predictors of the probability of marketability of tomatoes. The firmness and h of the tomatoes, however, contributed heavily to the model's predictive ability. Humidifying ambient storage rooms during winter was also shown to be a critical operation that can potentially increase the probability of marketability of tomatoes harvested during winter. The models developed can be used by tomato industry players to aid the selection of appropriate fresh tomato supply conditions when supplying fruit to different markets.

Keywords: *anolyte water; binary variable; International Roughness Index (IRI); marketability; pre-storage treatments; transportation effect*

6.2 Introduction

Tomatoes (*Solanum lycopersicum*) are climacteric fruit whose popularity and economic importance among fresh fruit and vegetables (FFV), is second to potatoes (Dorais *et al.*, 2008). In South Africa, tomatoes apart from being s key contributor to the country's GDP growth, they are also a source of healthy diets to consumers (DAFF, 2015).

The physiological nature of tomato fruit makes it susceptible to mechanical damage during transportation, distribution and storage (Kays, 1999). It is also a high-moisture food that is rich in nutrients and sugars, making it an attractive source of nutrients for a host of microorganisms (Dugassa *et al.*, 2015). This not only pre-disposes it to postharvest spoilage, but also poses food safety issues, as some of the microorganisms known to contaminate tomatoes are pathogenic (CDC, 2007; Ahmed and Shimamoto, 2015). In addition to these factors, biochemical processes and metabolic reactions that continually occur even after harvest, that causes the fruit to ripen and rapidly reach their senescence, makes tomatoes some of the most perishable FFVs (Antonious and Snyder, 1994). For these reasons, post-harvest losses of tomatoes are among the highest of all FFVs supplied globally. It is estimated that tomato fruit losses in some regions in Africa are as high as 40 % (Moneruzzaman *et al.*, 2009). Although accurate information is unavailable, postharvest losses of tomatoes in South Africa are estimated to be 10.2 % (Sibomana *et al.*, 2016).

The use of sub-optimal transportation, storage and handling conditions in tomato supply chains could be a further source of postharvest losses, which are often manifested by the fruit being either damaged or overripe, resulting in low marketable quality. Spoilage microorganisms can further cause serious problems downstream of the supply chain, if a rigorous disinfection regime is not implemented. Chlorinated water is a common industry disinfectant used in the tomato industry as a fruit surface disinfectant (Guo *et al.*, 2014). Chlorine inactivates microorganisms principally through oxidative reactions with compounds on the cell surface and with RNA of the microbial cell (WHO, 1998; Ramos *et al.*, 2013). The high oxidative potential of chlorine makes it a key disinfectant of FFV. The FFV industry is, however, currently facing challenges in replacing chlorinated water as a surface disinfectant as it has been shown to have harmful effects to the environment and produce, including triggering tomato postharvest disorders as the fruit approaches senescence (Venta *et al.*, 2010). Numerous FFV disinfectants have been reported in the literature including thermal, chemical and radioactive forms (Venta *et al.*, 2010; Mukhopadhyay *et al.*, 2013). However, the practical application of some of these treatments as tomato fruit disinfectants is questionable.

Anolyte water is a promising disinfectants that has recently been tested on carrots and tomatoes (Workneh *et al.*, 2009; Workneh *et al.*, 2012). It is a novel disinfectant that is environmentally-friendly and has no harmful effects on human health. Integrating it with other pre-storage treatments could improve its effectiveness in maintaining tomato fruits' postharvest quality. It has been shown that integrated treatments tap into their synergistic effects to better improve postharvest quality of FFV, as compared to using each treatment singularly (Workneh and Osthoff, 2010). Various biocontrol treatments have been tested on tomatoes, although not commercially (Wang *et al.*, 2008; Sangwanich *et al.*, 2013). Hot water treatment (HWT) has also been shown to be effective in not only inducing physiological responses in tomatoes that increase the concentration of important bioactive compounds, but also triggering fruit defences that lead to the extension of its shelf-life (Ali *et al.*, 2004). These novel surface disinfectants and pre-storage treatments can be therefore integrated to yield a postharvest management system and test its effectiveness in maintaining fruit quality across varying transportation and storage conditions. The maturity at harvest of tomato fruit also influences the fruits' response to different pre-storage treatments, storage and handling conditions (Getinet *et al.*, 2008; Moneruzzaman *et al.*, 2008). For instance, fruit harvested at the red maturity stage is known to be more susceptible to mechanical damage than fruit harvested at the green maturity stage (Mohammadi-Aylar *et al.*, 2010).

Studies that combine all these factors involve vast amounts of data and therefore, robust statistical analysis and data interpretation methods should be explored in order to adequately understand the intricate relationships between various experimental factors and fruit quality parameters. In addition, assessment of the combination of postharvest parameters that best preserve fruit quality cannot be effectively achieved in experiments that combine numerous factors when conventional statistical analysis methods are used. The need for information on predictability of the product quality over varying levels of postharvest treatment conditions is especially important to the farmers, processors and suppliers who would implement such systems. In this regard, generic statistical methods such as ANOVA have significant limitations. Statistical modelling of food quality data has only been recently used by different researchers (Ortega *et al.*, 2011). One approach involved the use of logistic regression to analyse the quality of tomato fruit treated with different disinfection treatments, packaging, storage and pre-harvest biocatalyst (Melesse *et al.*, 2016). The study built a logistic regression model to assess the effect of these parameters on the probability of fruit marketability. The range of pre-storage treatments explored in that study was, however, limited in terms of the integrated treatments involved. It also, did not consider the effect of transportation conditions, which play an important role in the quality changes of tomato products, once they reach their markets. This is especially important in South Africa and other regions of the world where commercial supply chains dominate the fresh tomato value chains. In this case, transportation operations play a critical role due to the integration of production and processing operations in areas that are far from the markets.

The theory of logistical regression has been adequately described by Melesse *et al.* (2016). In this study, a binary logistic model was used to evaluate the effect of various transportation conditions on the quality of tomato supplied under typical commercial conditions. The model was also used to predict the marketability of the tomato fruit of various maturities at harvest subjected to a combination of different pre-storage treatments, transportation and storage conditions.

6.3 Materials and Methods

6.3.1 Tomato fruit production

Tomato fruit (*Solanum lycopersicum)* of Nemo-Netta variety was sourced from three farms in Limpopo Province. The farms were located in Esmefour (22^{o}19’48.7” S 30^{o}28’21.3” E), Pont drift (22^{o}11’52.7” S 29^{o}11’30.7” E) and Mooketsi (23^{o}26’05.2” S 30^{o}26’47.5” E). The fruit was harvested at three maturity stages, namely, red, pink and green, during the winter (June) and summer (September) seasons.

6.3.2 Transportation conditions

The harvested tomato was then transported from each harvesting site to Pietermaritzburg using non-refrigerated trucks to mimic normal supply operations. Each route (Esmefour-Pietermaritzburg (ZZ), Mooketsi-Pietermaritzburg (EM) and Point Drift-Pietermaritzburg (PD)) had varying road quality conditions and distances. The samples were then taken to the Bioresources laboratory for application of pre-storage treatments. Each route had varying proportions of both rough and asphalt roads. The road quality, which signified the quality of ride induced on the tomatoes, was measured using a road surface laser profilometer (PaveProf

V2.0, Pavetesting, UK). The trucks were driven at a speed of 80 km h^{-1} on the highways and 60 km h^{-1} on rough roads.

6.3.3 Experimental design

A schematic representation of the experimental design is shown in Figure 6.1.

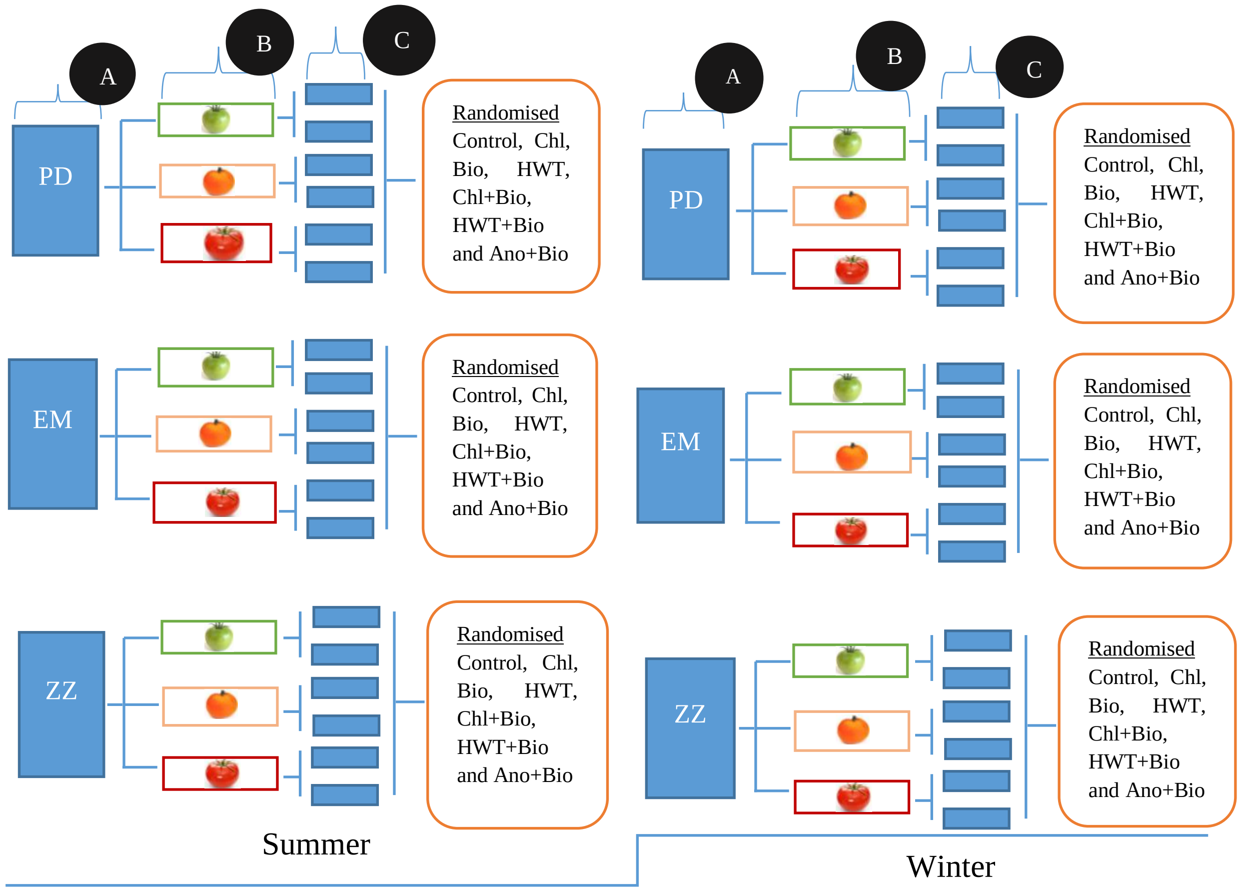

Figure 6.1 Schematic representation of the experimental design. (A)=transportation conditions, (B) = fruit maturities at harvest and (C) = ambient and cold storage conditions (11 ^{o}C). The experiment was carried out in summer and winter. The seven pre-storage treatments were triplicated in a full factorial experiment. Chl= chlorinated water, Bio=biocontrol using B-13 yeast, HWT=hot water treatment and Ano=anolyte water

6.3.4 Application of pre-storage treatments

At the laboratory, the damaged and defective fruit was removed from the test samples and seven pre-storage treatments applied on the fruit. These were, dipping in chlorinated water (100 ppm, for 20 min), hot water (42.5 ^{o}C, for 30 min), biocontrol (B-13 yeast 1g l^{-1}, for 30 sec), control (dipping tap water, for 1 min), hot water in combination of biocontrol, chlorine in combination with biocontrol and biocontrol in combination with anolyte water (for 5 min) in combination of biocontrol. Although B-13 yeast isolate has not been tested on tomatoes, it has been shown to be completely effective in inhibiting certain microorganisms in fruit (Abraha, 2010). The treated fruit was then stored in ambient or cold storage conditions (11 ^oC). Hobo loggers (U12-012, C.W. Price & Co., Midrand, South Africa) were used to monitor the temperature and RH conditions of the ambient and cold storage rooms during the storage period. The experiment was carried out in summer and winter to account for seasonal effects.

6.3.5 Data collection

Fruit quality parameters of stored tomatoes were assessed over a 30-day storage period. All the quality attributes were assessed on Day 1 and after 8, 16, 24 and 30 days of storage. The quality attributes analysed are described briefly as follows:

6.3.5.1 Fruit colour

Fruit colour was measured using a Minolta Chroma meter (Model CR-400, Narachi Pty, South Africa). Readings were made at an observer angle of 2^o after standardizing the instrument with a white tile (Y = 93.8, X = 0.3030, y = 0.3191). Illuminant C was used to measure the L*a*b*c and h values, where two readings per fruit were taken from three fruits, from each replicate (Kerkhofs *et al.*, 2005; Pinheiro *et al.*, 2015).

6.3.5.2 Subjective quality evaluation

Subjective tests were performed to ascertain the proportion of the sample that was marketable. The overall visual appearance was the primary criterion used to judge if samples were still marketable during sampling. Fruit that was perceived to have shrivelled excessively, to have decayed or to have been physiologically damaged in any way, and that could not be sold at the local markets, was considered unmarketable and was therefore removed from the test sample during sampling. This procedure followed the method used by Tadesse *et al.* (2012).

6.3.5.3 Fruit firmness

Tomato fruit firmness was tested using Instron universal testing machine (model 3345, Advanced Laboratory Solutions, South Africa) attached to a 6.1 mm flat end stainless steel probe at a cross-head speed of 20 mm min^{-1}. The force-deformation curves were automatically recorded by the Bluhill® software (Batu, 2004), which also reported the maximum force required to puncture the tomato skin. Three fruits was tested from each replication, and results reported as the maximum puncture force (N) (Batu, 2004).

6.3.5.4 Fruit pH

Product pH was measured using a pH meter (Orion Star A210, Thermo Scientific, South Africa) with a probe designed to measure solids (Favati *et al.*, 2009). The instrument was first standardized using 4.01, 10.00 and 7.00 pH buffers. Two tomato fruits were macerated using a food processor (Philips Model HR2106/01, Makro, Pietermaritzburg, South Africa) for 1 minute and the juice was extracted into a 50 mL beaker, using a cheesecloth. The pH of the extracted aliquot was then determined using the pH meter. Readings were repeated thrice per replication for the selected sampling days.

6.3.5.5 Physiological weight-loss

Weight loss was determined at selected storage intervals using the method proposed by Pinheiro *et al.* (2013). Three batches of three tomatoes per treatment were marked and weighed on Day 1 and the percentage weight-loss reported on day 8, 16, 24 and 30, relative to Day 1.

6.3.6 Logistic modelling of tomato quality data

A logistic model was build based on the binary variable related to fruit marketability. This variable can be expressed using Equation 6.1 given by Melesse *et al.* (2016) as,

$$y_i = \begin{cases} 1 \;\; if \;\; y^* > \tau \\ 0 \;\; if \;\; y^* \leq \tau \end{cases} \tag{6.1}$$

Where y_i is a latent binary variable based on product marketability and returns a marketable or unmarketable result based on selected threshold τ.

A logistic model was build using the quality data, based on the linear function given by Melesse *et al.* (2016) as shown in Equation 6.2.

$$y^* = \alpha + \beta x + \varepsilon \tag{6.2}$$

Where y* is the probability of marketability of the fruit based on a quality attribute x, with distribution of errors ε, given by Tolesa *et al.* (2017) in Equation 6.3 as,

$$ln\left(\frac{p_i}{1 - p_i}\right) = \sum_{k=0}^{k=n} (\beta_k x_{ik}) \tag{6.3}$$

The probability of marketability was expressed by Tolesa *et al.* (2017) using Equation 6.4 as,

$$logit\big(\pi(x)\big) = \alpha + \beta x \tag{6.4}$$

Equation 6.1 was used to covert fruit marketability data into a binary variable that was used as a surrogate that holistically represented the quality of the fruit at a given time period x, with x expressed as the days of tomato fruit storage. A marketability threshold τ was selected based on acceptability criteria given by Batu (2004). The model in Equation 6.4 was implemented using SPSS 24 (IBM, USA) in three steps. The probability of marketability of the fruit was modelled as function of the storage period. The quality data that included weight loss, firmness, pH, L*, a* and b* were used as predictors (independent variables) of the marketability of the fruit and best predictors chosen. A comparison of combinations of various storage, disinfection and transportation conditions that gave the best quality was also carried out by comparing the odds ratio between each group of treatments.

6.4 Results and Discussion

6.4.1 Transportation conditions

Table 6.1 presents a summary of the observed road conditions during transportation. The ZZ route was 263.44 and 223.81 km further than the PD and the EM route, respectively.

The drive time was related to the distance and the road quality. In sections with rough roads, the trucks were driven at 60 km h^{-1} compared to speeds of 80 km h^{-1} in highways. The PD route had a larger proportion of its road length comprising rough roads (Table 6.1). Similarly, the EM route had a higher proportion of its road length comprising smoother road surface compared to both the PD and ZZ routes. Based on international road classification using IRI values, thresholds of 2.7 m km^{-1} and 1.5 m km^{-1} have been set for acceptable and good quality roads, respectively (Arhin *et al.*, 2015). These values, however, relate to road comfort and are not related to damage to produce during transport.

Table 6.1 A summary of road conditions during transportation of tomatoes from three commercial farms in Limpopo to Pietermaritzburg

Route	Distance (km)	Drive time (h)	IRI values (m km^{-1})	
			% less than	% less than
EM	934.12	10.43	70	91
PD	894.49	9.33	58	90
ZZ	1157.93	12.76	63	95

Although these IRI values in this study gives an indication of the relationship between road roughness and effect on tomato quality, classification and guidance threshold values should be developed for fragile agricultural commodities.

6.4.2 Storage conditions

Figure 6.2 shows the variation in temperature and RH conditions with storage period in ambient and cold storage environments.

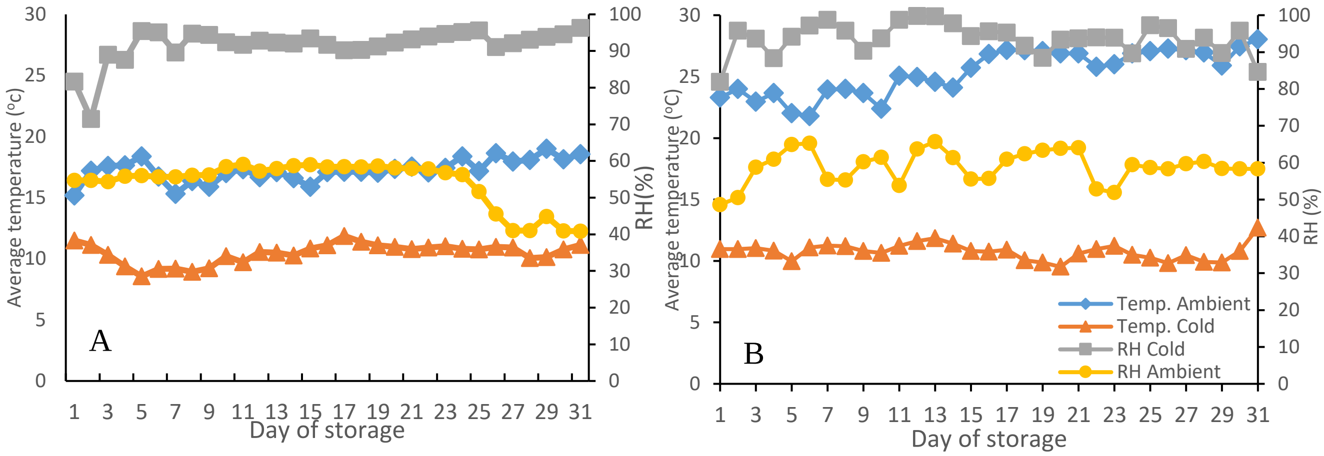

Figure 6.2 A side-by-side comparison of the temperature and RH conditions during storage of tomato fruit during winter (A) and summer season (B)

Cold storage conditions were generally within a close range of values for both RH and temperature across the summer and winter seasons. On the other hand, ambient temperature conditions were generally higher in the summer compared to the winter season. The ambient RH conditions during the summer season were also higher than RH conditions in the winter season for the entire storage period. The RH conditions in ambient storage conditions fluctuated more in the summer than in the winter (Figure 6.2). This can be attributed to higher temperature fluctuations in the summer compared to the winter season (Figure 6.2). Optimum storage temperature and RH conditions for tomatoes and other horticultural produce have been widely reported in the literature. For instance, tomatoes require an optimal RH of 90-95 % and temperatures of 13-22 ^{o}C depending on the fruit maturity at harvest (Kitinoja and Kader, 2002). It has however, been reported by Nunes *et al.* (2009) that fluctuating storage temperatures in combination with low RH conditions leads to significant water loss in fruits and vegetables within the first few days of storage. The control of RH and temperature is therefore becoming increasingly important from a postharvest quality perspective of horticultural produce.

However, the control of RH in storage units requires precise instrumentation, making it an endeavour with prohibitive cost implications (Paull, 1999).

6.4.3 Changes in fruit marketability with storage period

The probability of marketability of sample tomato decreased with storage over the 30-day period, with a noticeable drop in the chances of marketability between day 8 and 16. This was a drop of over 50 % for this storage interval and a further 40 % drop between day 16 and 24. Figure 6.3 shows the variation in the probability of tomato fruit marketability with the days of storage (dos).

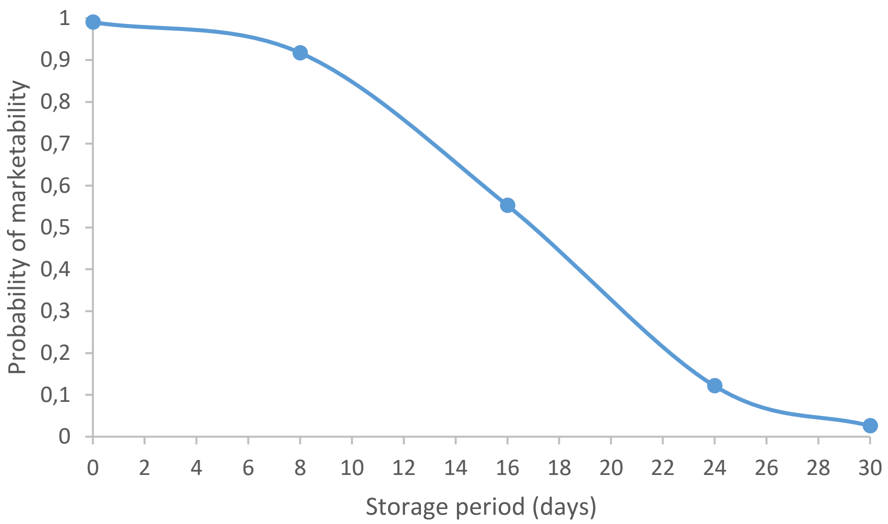

Figure 6.3 Variation in tomato fruit marketability with days of storage

The probability of marketability (p̂) was estimated using Equation 6.5, given by,

$$\hat{p} = \frac{e^{(4.595-0.274dos)}}{1+e^{(4.595-0.274dos)}} \tag{6.5}$$

Where dos designates the days of storage. Based on the degree of risk that growers are willing to take, Equation 6.5 can be used to estimate the expected shelf life of tomato fruit. For instance, if a grower supplies fruit to Woolworths, a market that is strict on quality, a probability of 85% can be adopted, giving an approximate shelf-life of 11 days.

6.4.4 Effect of categorical variables on the probability of marketability

The changes in the probability of marketability with days of storage (dos) as a function of categorical variables is shown in Table 6.2. The trends in changes in probability of marketability with dos across all the variables (Table 6.2), closely followed trends in changes in the probability of marketability with dos, shown Figure 6.3. Fruit supplied in the summer showed a better chance of marketability. This may be attributed to fluctuations in ambient temperature conditions, accompanied with lower ambient RH during the beginning of storage in the winter season compared to the summer season. This has been shown by Nunes *et al.* (2009) to cause rapid moisture loss during the first few days of storage, leading to lower chances of marketability. This renders cooler ambient temperatures during the winter not to be beneficial to the fruit, hence the importance of control of RH during the winter season. Although fruit is generally kept longer in the winter season, the bulk marketable threshold of tomatoes declined more rapidly in winter compared to the summer season.

Table 6.2 Variation of the probability of marketability of tomato fruit of various maturity stages with days of storage across different seasons, transportation and storage conditions

Day of storage (dos)	Probability of marketability ($\hat{p}$)									
	Season		Maturity at harvest			Transportation			Storage environment	
	summer	winter	green	pink	red	PD	EM	ZZ	Cold	Ambient
0	0.997	0.986	0.997	0.993	0.982	0.994	0.995	0.981	0.990	0.987
8	0.968	0.913	0.968	0.935	0.841	0.949	0.957	0.837	0.987	0.808
16	0.745	0.599	0.745	0.576	0.332	0.643	0.685	0.332	0.741	0.184
24	0.215	0.173	0.215	0.113	0.044	0.148	0.174	0.045	0.134	0.011
30	0.044	0.028	0.044	0.021	0.007	0.029	0.035	0.008	0.018	0.001

Tomato fruit harvested at the green maturity stage had a higher probability of being marketable, compared to fruit harvested at the pink or red maturity stage. This is expected from a physiological perspective since as the biological age of tomatoes increases, the cumulative physiological changes that will have occurred such as weight-loss, respiration and transpiration are comparatively larger in quantity at a later time than an earlier time. It has also been established that as tomatoes ripen, their susceptibility to mechanical damage increases (Mohammadi-Aylar *et al.*, 2010). These aspects therefore result in decreased consumer appeal, hence a reduction in the fruits' probability of marketability. The transportation conditions especially the road quality had a clear effect on the probability of fruit marketability. Tomatoes harvested and transported through the EM route had a higher chance of marketability compared to fruit supplied through the PD and ZZ route. Similarly, fruit harvested and transported through the ZZ route had the lowest odds of being marketable for all routes. These observations can be corroborated by the road quality conditions shown in Table 6.1. The EM route had smoother road profile compared to the PD and ZZ route, translating to a better ride quality, hence minimal vibrations transmitted to the fruit through the road-vehicle system, hence a reduced risk of mechanical damage to the fruit. Mechanical damage in tomato fruit has been shown to trigger an increase in ethylene production leading to increased fruit ripening rates (Mutari and Debbie, 2011; Aba *et al.*, 2012). Although the ZZ route also had a larger proportion of relatively better road surface profile than PD, it was much further than EM and PD. Studies have also shown that longer transportation distances under moderately rough road conditions cause far more serious mechanical damage to tomatoes than shorter transportation distances under much poorer roads (Linke and Geyer, 2002; Scheerlinck *et al.*, 2006; Aba *et al.*, 2012). Ambient storage also had lower odds of yielding marketable fruit compared to cold storage conditions. Higher storage temperature of fruit results in higher rate of metabolic processes leading to a rapid decline in tomato quality. Temperature control is one of the principal means of maintaining the postharvest quality of FFV (Mutari and Debbie, 2011). Maintaining the cold chain during the transportation, distribution and storage of tomatoes is therefore one of the single, most important practices necessary for the maintenance of tomato fruit quality (de Castro *et al.*, 2005). Figure 6.4 shows the effect of different pre-storage treatments on the probability of marketability of tomato fruit.

Fruit treated with HWT and HWT+Bio had the lowest probability of marketability, with fruit treated with chlorinated water and anolyte water combined with biocontrol (Ano+Bio) having the highest probability of marketability. Although chlorinated water showed the best performance in maintaining the probability of marketability of the fruit, it was marginally better than Ano+Bio, and other results have shown that the performance of the pre-storage treatments in maintaining tomato fruits' quality, is dependent on the fruit maturity at harvest. For instance, fruit treated with Ano+Bio had the highest probability of marketability for fruit harvested at the red maturity stage.

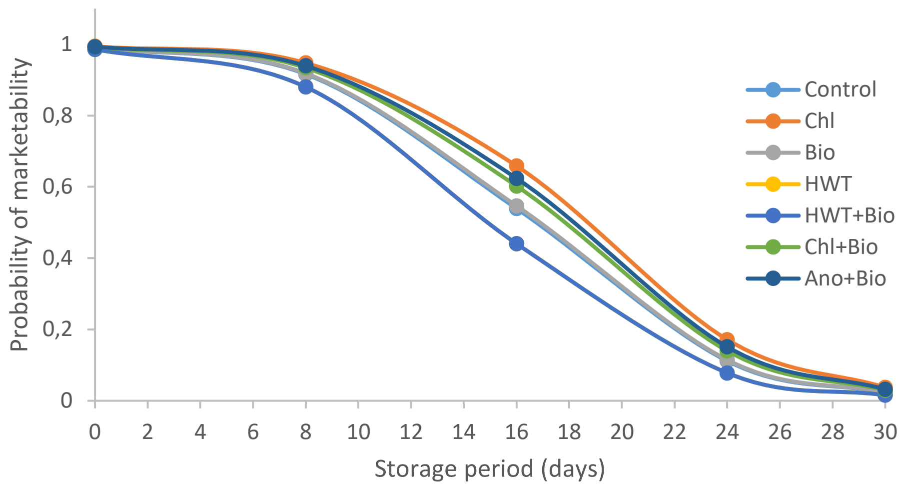

Figure 6.4 Effect of pre-storage treatments on the probability of marketability of tomato fruit

6.4.5 Prediction of tomato fruits' probability of marketability from their quality parameters

The measured quality parameters that included hue angle, pH, weight-loss and fruit firmness were entered together as predictors of the probability of tomato fruit marketability. The result yielded a model that gave an accuracy of 82.9 % in correctly classifying the marketability of tomato fruit based on these quality parameters. The model depicted the fruit hue angle and firmness as important parameters that contribute more to the odds of the fruit being marketable. Each of the quality parameters were significant ($p \leq 0.05$) in the overall model, hence these parameters are good predictors of the chances of marketability of tomatoes. A unit reduction in the hue angle resulted in a 1.107 times reduction in the odds of the fruit being marketable. A unit reduction in firmness, also lead to a 1.048 times reduction in the fruits' probability of marketability. Similarly, a unit increase in weight-loss and pH resulted in a 0.741 and 0.524 reduction in tomato fruits' probability of marketability, respectively.

6.4.6 Combination of factors in the model

The selection of suitable pre-storage treatments, transportation and storage conditions for tomato fruit harvested at various maturity stages was done by selecting from the logistic model, a combination of factors that yielded fruit with the highest probability of marketability. A logistic model shown in Equation 6.6 combined all the categorical variables and estimated the probability of marketability of fruit ($\hat{p}$) based on the treatments fruit was subjected to.

$$\hat{p} = e^{\wedge}((7.619 - 0.452dos - 1.126pin - 2.675red + 0.287EM - 1.987ZZ + 0.8cl + 0.049bi - 0.636hwt - 0.636hwb + 0.414clb + 0.56anb))/(1 + e^{\wedge}((7.619 - 0.452dos - 1.126pin - 2.675red + 0.287EM - 1.987ZZ + 0.8cl + 0.049bi - 0.636hwt - 0.636hwb + 0.414clb + 0.56anb))) \quad (6.6)$$

Where dos is the days of storage, pin is fruit of pink maturity stage, red is fruit of red maturity stage, EM is fruit transported through EM route, ZZ is fruit transported through ZZ route, cl is fruit treated with chlorinated water, bi is fruit treated with biocontrol, hwt is fruit treated with hot water, hwb is fruit treated with hot water in combination with biocontrol, clb is fruit treated with chlorinated water in combination with biocontrol and anb is fruit treated with anolyte water in combination with biocontrol.

The model in Equation 6.6 was used to generate the parameters shown in Table 6.3, which shows the statistical parameters of the model with combined independent variables. When these factors were entered into the model, the days of storage, storage conditions, transportation conditions and maturity at harvest were all statistically significant predictors ($p \leq 0.05$) of the probability of marketability of fruit. Some of the pre-storage treatments (biocontrol treatment and Chl+Bio) were not significant ($p > 0.05$) predictors of fruit marketability in the model.

Table 6.3 Model parameters when all categorical factors are used as predictors of probability of marketability of tomato fruit

Experimental factor	Model coefficient	Wald χ^2	Significance	Odds ratio	95% CI	
					Lower	Upper
Constant	7.619	563.608	0.000	2036.544		
dos	-0.452	939.339	0.000	0.637	0.618	0.655
Green		249.610	0.000			
Pink	-1.126	58.759	0.000	0.324	0.243	0.432
Red	-2.675	249.021	0.000	0.069	0.049	0.096
PD route		219.110	0.000			
EM route	0.287	4.003	0.045	1.333	1.006	1.766
ZZ route	-1.978	154.630	0.000	0.138	0.101	0.189
Control		71.714	0.000			
Chlorine	0.800	13.025	0.000	2.226	1.441	3.438
Biocontrol	0.049	0.049	0.825	1.050	0.681	1.619
HWT	-0.636	8.201	0.004	0.529	0.342	0.818
HWT+Bio	-0.636	8.201	0.004	0.529	0.342	0.818
Chl+Bio	0.414	3.503	0.061	1.512	0.981	2.332
Ano+Bio	0.560	6.405	0.011	1.750	1.135	2.700

Where dos = days of storage, HWT = hot water treatment, Bio = biocontrol treatment, chl = chlorinated water and Ano = anolyte water.

Fruit harvested at the green maturity stage, transported through the EM route to Pietermaritzburg, stored in the cold storage, and treated with chlorinated water or Ano+Bio had the highest odds of marketability. Fruit treated with chlorinated water had only slightly better chances of marketability than those treated using Ano+Bio. Ano+Bio can therefore be considered as a potential replacement of chlorinated water when the environmental and health concerns of using chlorinated water to disinfect FFV are considered.

6.4.7 Validation of the overall model

Table 6.4 shows a summary of statistical parameters of the validated model. In terms of the overall significance, the likelihood ratio was 4863.4982 with a p value of 0.0001. This therefore implies that the model adequately predicted the probability of marketability of tomatoes based on the storage, transportation and pre-storage treatment conditions, and the associated quality parameters.

Table 6.4 The statistical parameters for validation of the overall model

Model evaluation measure	Wald χ^2	Degrees of freedom	Significance
Overall significance			
Likelihood ratio test	4863.49	14	<.0001
Score test	3138.66	14	<.0001
Wald test	847.89	14	<.0001
Goodness of fit test			
Hosmer and Lemeshow	11.76	8	0.162
Pearson χ^2	5461.35	4017	
Deviance χ^2	1728.65	4017	1.0000
Association of predicted probabilities and observed response			
Sommers's D	0.96		
Goodman Kruskal Gamma	0.96		
c-statistic	0.98		

The Hosmer and Lemeshow test also gave a statistically non-significant result (p = 0.162) which strengthens the validity of the model in predicting the probability of marketability of the fruit. The model correctly classified 86.9 % of marketable fruit (specificity) and 86.3 % of unmarketable fruit (sensitivity). This also implies that the model gave good predictions and only gave 13.1 % as false positives and 13.7 % as false negatives. Other measures of the model's validity (Sommers's D, Goodman Kruskal Gamma and c-statistic) also gave values close to one, implying a close association between observed responses and predicted probabilities. A comparison of these parameters with those reported in study by Melesse *et al.* (2016) shows good similarities, although the measures of model specificity and sensitivity were slightly lower in the present study. This may be attributed to the fact that the present study involved a larger number of experimental factors compared to the study by Melesse *et al.* (2016).

6.5 Conclusion

In this study, a novel statistical modelling procedure was applied to assess and recommend a combination of tomato supply chain parameters that are most suitable for maintaining the quality of tomato fruit harvested and transported at maturity stages. Transportation conditions was shown to affect the probability of marketability of fruit, with the route that had a high proportion of rough profile having fruit with the lowest probability of marketability. All the measured tomato quality parameters were good predictors of the probability of fruit marketability. The model that combined categorical variables showed that Ano+Bio closely gave comparable probabilities of fruit marketability with chlorinated water. It was also found that a combination of harvesting fruit at green maturity stage, transportation through the EM supply route, storing in cold storage conditions and treatment with chlorinated water maximized the odds of tomato fruit marketability. Ano+Bio can potentially be used as a replacement for chlorinated water when negative effects exerted by chlorinated water to the environment and human health are considered. With the different models that were developed, a range of parameters can be used to adequately predict the chances of marketability of the tomato fruit through various supply routes. This information is potentially useful to commercial growers and suppliers at different levels of the tomato supply chain.

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6.7 References

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7. CHEMICAL AND NUTRITIVE QUALITY CHANGES OF FRESH TOMATOES SUBJECTED TO VARIOUS TRANSPORTATION AND DISINFECTION TREATMENTS UNDER COMMERCIAL CONDITIONS IN SOUTH AFRICAN SUPPLY CHAINS

7.1 Abstract

This study investigated the effect of disinfection treatments, storage and transportation conditions on the chemical and nutritional quality of tomatoes harvested and transported under typical commercial conditions. The experimental design consisted of tomatoes of three maturity stages (red, pink and green), two harvesting seasons (winter and summer), three transportation conditions, four disinfection treatments (tap water as the control, hot water, anolyte water in combination with biocontrol and chlorinated water in combination with biocontrol) and two storage conditions (11 ºC and ambient storage) over a 30-day storage period. Fruit dipped in hot water and anolyte water in combination with biocontrol showed the least loss in AA compared to fruit subjected to other treatments. Fruit transported through the route with the longest distance (1157 km) and moderately rough road profile (63 % of road length with IRI values<than 2.5 m km^{-1}) lost the highest ascorbic acid (AA) among all the routes. A 9 % decrease in AA content was observed for fruit harvested and transported in winter, then stored in ambient and cold storage environment. However, fruit harvested and transported in the summer showed 85 % and 35 % decrease in AA concentration for ambient and cold stored fruit, respectively, over the 30-day storage period. Fruit transported through the shortest, smoothest road that had 70 % of its road length having IRI values less than 2.5 m km^{-1} had a mean lycopene content of 40.9 mg kg^{-1}. In contrast, fruit transported the longest distance with moderately rough surface profile had a mean lycopene content of 37.6 mg kg^{-1}. The disinfection treatments and harvesting season had a significant ($p \leq 0.05$) effect on the sugar content of stored tomatoes. The study shows that tomato postharvest nutrient losses in commercial supply chains are not only affected by environmental and postharvest practices, but also road quality, as established for the first time in this study. Based on the results obtained, maintenance of cold chain during storage of tomatoes, disinfection with anolyte water in combination with biocontrol, timely maintenance of roads in and around farms, as well as transportation planning that minimizes distances to the markets are recommended as industry best practices.

Keywords: *anolyte water; fruit quality; international roughness index (IRI); postharvest losses; postharvest treatments; road quality*

7.2 Introduction

Tomatoes are some of the most popular fresh fruit and vegetables (FFV) globally, whose importance is only second to potato (Dorais et al., 2008; Pinheiro *et al.,* 2014). The nutritional composition of tomatoes makes them a valuable source of health-promoting compounds that are known to boost the human immune system and prevent the occurrence of degenerative heath conditions (Canene-Adams et al., 2005). Some of these compounds include vitamins, bioactive compounds, antioxidants, sugars, fiber and flavonoids (Canene-Adams et al., 2005).

Ascorbic acid (AA) is one of the most abundant nutrients and a key antioxidant in tomatoes that contributes a majority of the overall antioxidant capacity of tomatoes (Stevens et al., 2008). For this reason, the Mediterranean diet which is associated with a menu rich in tomato fruit has been attributed to lower risks of occurrence of cancers and heart diseases (Ioannidi et al., 2009). The accumulation of AA in tomatoes, therefore, has a profound importance on their nutritive quality, as it has been cited as one of the important fresh fruits and vegetables that humans rely on as a source AA (Lee and Kader, 2000). I addition, AA has agronomic and postharvest physiological functions. Lycopene is another important antioxidant in tomatoes that accumulates during ripening, and gives in tomatoes their red colour (Toor and Savage, 2005). Lycopene is known to have numerous disease-prevention and immune-boosting benefits on human health (Brandt et al., 2006). Sugars contribute over 50 % of tomato fruits' dry-weight and have important attributes that determine tomato fruit quality (Davies and Kempton, 1975). Tomato fruit sugars predominantly consist of glucose and fructose with slight concentrations of sucrose (Davies and Kempton, 1975). They have been reported to initially increase under normal storage conditions and are later used up for growth and terminal metabolic processes (Beckles, 2012). Significant alterations in the sugar concentrations in tomatoes negatively affect flavor. Of key importance is the balance of sugars and acid in the fruit, which has been shown to shift in favour of accumulation of the latter as ripening progresses (Malundo et al., 1995).

AA and sugars are important nutrients in tomatoes. Changes in their concentrations can occur due to a range of postharvest factors (Lee and Kader, 2000). For instance, fluctuation in temperature conditions during storage, transportation or distribution, can cause losses in AA, as it is one of the most thermo-sensitive nutrient (Goula and Adamopoulos, 2006). Sub-optimal handling and transportation conditions can further trigger losses of these nutrients in tomato. It is no surprise that commercial conditions during production, distribution and storage of tomatoes have been singled out as the source of tomato fruit with altered flavour (Boukobza and Taylor, 2002). Restructuring of the fresh fruit and vegetable production systems globally has led to the consolidation and vertical integration of tomato production and distribution operations (Louw et al., 2008). This has brought about the concentration of production and processing operations in sites that are distant from their markets. This necessitates long distance transportation of fruit to their markets. South Africa is home to the largest commercial tomato producers in the Southern hemisphere (Lee et al., 2012). Commercial producers are mainly concentrated in Limpopo Province where production and central processing operations are carried out before transporting tomato fruit to markets as far as Cape Town through roads with varied surface profiles (DAFF, 2013).

Transportation conditions (environmental conditions and road quality) can greatly affect the quality of tomatoes through fluctuations in ambient conditions and fruit damage induced through the road-vehicle system, which can trigger physical losses as well as undesirable nutrient changes (Çakmak et al., 2010). The efficacy of tomato surface disinfection treatments can also affect the nutrient quality of tomatoes. Inadequate disinfected tomato fruit may exhibit altered nutrient composition, due to the microbial breakdown of sugars and other structural compounds forming fruit tissues. The postharvest quality of tomatoes under commercial settings is often assessed on the basis of physical attributes such as fruit color, firmness, prevalence of mechanical damage or decay. Although these parameters may give a good indication of the overall fruit quality, nutrient losses may not be entirely apparent. Minor changes in postharvest handling conditions including the transportation conditions may have a huge impact on the nutritive quality of tomatoes, occasioning losses that may not be physically discernable. Nutrient changes of tomato during transportation and distribution has not been well studied and reported in the literature. The quantification of nutrient losses of tomato during transportation is therefore important as it would enable the selection and use of suitable transportation conditions that minimize these losses. It would also give tomato producers and suppliers insight into the factors that lead to changes in important nutrients in fresh tomatoes, in order to formulate postharvest management systems that deliver tomatoes of highest nutritive quality. The aim of this study was to investigate changes in some of the key nutrient and health-promoting components of fresh tomatoes, which were subjected to various transportation, storage and disinfection treatments under commercial supply conditions.

7.3 Materials and Methods

7.3.1 Tomato fruit production

Tomato fruit *(Solanum lycopersicum*) of Nemo-Netta variety was grown in three farms situated in Limpopo Province. The farms were situated in Esmefour (22º19’48.7” S 30º28’21.3” E), Pont Drift (22º11’52.7” S 29º11’30.7” E) and Steve Mohale’s farm in Mooketsi (23º26’05.2” S 30º26’47.5” E). Good agricultural practice (GAP) and sustainable soil and water management practices were implemented throughout the production cycle using Natuurboerdey® technology (Taurayi, 2011). The fruit was harvested at three maturity stages namely, red, pink and green during the winter (June) and summer (September) seasons.

The harvested tomato was graded, and non-defective fruit packed in plastic bins 2 m in length, 1 m wide and 0.4 m deep in pack-houses situated near each farm. Harvesting and transportation was carried out early in the morning to minimize accumulation of field and respiration heat. Pre-cooling was also done in the pack-houses for three to four hours using forced air coolers (Model K3738, Carrier, USA).

7.3.2 Transportation conditions

The sample tomatoes were transported in non-refrigerated trucks through three supply routes with varying road conditions to Pietermaritzburg fresh produce market, where they were immediately taken to the Bioresources Engineering laboratory of the University of KwaZulu-Natal for pre-treatment and thereafter, storage under ambient and cold storage conditions (11 ºC). Each route (Esmefour-Pietermaritzburg (ZZ), Mooketsi-Pietermaritzburg (EM) and Point Drift-Pietermaritzburg (PD)) had varying road quality conditions, as well as varying proportions of both rough and asphalt roads. The road quality, which signified the quality of ride induced on the tomatoes, was measured using a road surface laser profilometer (PaveProf V2.0, Pavetesting, UK). The trucks were driven at a speed of 80 km h^{-1} on the highways and 60 km hr^{-1} on rough roads.

7.3.3 Disinfection and storage treatments

The disinfection treatments involved dipping the fruit in hot water (42.5 ^{o}C, for 30 min), dipping in tap water for 1 min (control), dipping in chlorinated water (100 ppm, for 20 min) in combination with biocontrol (1g of B-13 yeast lit^{-1} tap water, for 30 sec) and dipping fruit in anolyte water (for 5 min) (Workneh et al., 2012) in combination with biocontrol. The treated sample tomatoes were then stored in ambient or cold storage conditions (11 ^{o}C).

7.3.4 Temperature and relative humidity measurement

Hobo loggers (U12-012, C.W. Price & Co., Midrand, South Africa) were used to log the temperature and relative humidity (RH) conditions of the ambient and cold storage rooms during the storage period. Each of the storage rooms (cold and ambient storage room) had three Hobo loggers. The temperature and RH of each storage room was averaged from the logs of the three Hobos.

7.3.5 Experimental design

The experiment was arranged in a full factorial design with tomato fruit of three maturity stages (red, pink and green), three transportation conditions (PD, EM and ZZ) two storage conditions (ambient and cold storage at 11 ^{o}C), two harvesting seasons (summer and winter) and four disinfection treatments (hot water, anolyte water in combination with biocontrol, control and chlorinated water in combination with biocontrol) as the factors. The disinfection treatments were triplicated.

7.3.6 Analysis of changes in nutrient and antioxidant levels

All analyses were carried from each replicate of fruit sampled on Day 1, and after 8, 16, 24 and 30 days of storage. These analyses are briefly described as follows:

7.3.6.1 Sugar analysis

The analysis of sugars followed the method suggested by Baldwin et al. (1991) with modification. In summary, three-quarters of three frozen tomato samples per treatment was crushed in liquid nitrogen, and then 0.1 g of the crushed sample weighed into a test tube and 10 mL of 80 % ethanol added to it. The mixture was then sonicated using ultraturrax mixer (model IKA T25D, Cole-Parmer, South Africa) at 8600 rpm for one minute. The homogenate was thereafter incubated in a water bath at 80 ^{o}C for an hour, removed and left to stand overnight at 4 ^{o}C. This homogenate was then filtered through glass wool into 20 mL scintillation vials then dried in a vacuum evaporator (Genvac personal evaporator, model EZ2.3, SP Scientific, England) set at 45 ^{o}C for 6 hours. Two mL of ultra-pure water were then added to the dried extract and filtered through a 0.45 μm nylon syringe filter (Merck Pty, Durban, South Africa). Exactly 20 μL of the filtrate was finally injected into a HPLC column set at 85 ^{o}C, with ultra-pure water as the mobile phase flowing at 0.6 mL min^{-1}. The sugars were detected by differential refraction using a RID detector (RID-10A, Shimadzu, South Africa). Standards were run and their retention times ascertained.

7.3.6.2 Ascorbic acid

Ascorbic acid (AA) content of the tomato samples was analysed titrimetrically using the method described by Marfil et al. (2008). In summary, 25 g of fruit tissue was homogenized in 50 g of oxalic acid (containing 2 g of oxalic acid per 100 g of solution) in a food blender (Philips Model HR2106/01, Makro, South Africa) for one minute. Accurately, 20g of the extracted homogenate was then diluted with to 50 mL using the extracting solution and vacuum filtered through a Whiteman's filter paper to a 100 mL volumetric flask. 10 mL of the aliquot was thereafter titrated against DCIP solution (0.01 g per 100 g of solution) to a rose-pink end point. The volume of DCIP used for each titration run was then used to calculate the AA content of the tomato samples.

7.3.6.3 Lycopene estimation

Lycopene content was determined using the method described by Davis et al. (2003). In brief, approximately 25 g of tomato was added to distilled water (W/V) and blended for 30 sec using a food chopper (Philips Model HR2106/01, Makro, South Africa). Accurately, 0.6 g of the puree was then weighed and put in a 40 mL amber screw top vial containing 5 mL 0.05 % HBT, 5 mL 85 % ethanol and 10 mL hexane. The mixture was then shaken in ice at 180 RPM for 15 min using an orbital shaker (KS 130 orbital shaker, IKA, Staufen, Germany) and thereafter, 3 mL of deionized water added and shaken in ice for an additional 5 min. The mixture was finally left for 5 min to allow phase separation, then the absorbance of the upper hexane layer was measured at 503 nm in a 1 cm path glass cuvette against hexane as the blank. Lycopene content was calculated using Equation 7.1.

$$\text{Lycopene}\left(\frac{\text{mg}}{\text{kg of tissue}}\right) = \frac{\text{A}_{503}\times 31.2}{\text{g of tissue used}} \tag{7.1}$$

Where A_{503} is the absorbance at 503 nm.

All determinations for tomato fruit sugar content, AA and lycopene were triplicated for each of the treatments.

7.3.7 Data analysis

Multiple analysis of variance (MANOVA) was used to assess the effect of various disinfection treatments, storage and transportation conditions on the chemical and nutritive quality changes of fresh tomato fruit supplied under typical commercial conditions. SPSS version 24 (IBM, USA) was used for all statistical analyses and results reported at 0.05 significance level.

7.4 Results and Discussion

7.4.1 Road quality conditions

A summary of the road surface profile conditions measured during transportation are presented in Table 7.1. The ZZ route was 263.44 and 223.81 km further than the PD and EM route, respectively.

Table 7.1 A summary of road conditions during transportation of tomatoes from three commercial farms in Limpopo to Pietermaritzburg

Route	Distance (km)	Drive time (h)	International roughness index (IRI) values in m km^{-1}	
			% less than 2.5	% less than 5
EM	934.12	10.43	70	91
PD	894.49	9.33	58	90
ZZ	1157.93	12.76	63	95

As discussed in chapter four, five and six, the drive time was related to the road quality and the distance from the farms to Pietermaritzburg. In sections with rough roads, the trucks were driven at 60 km h^{-1} while speeds of 80 km h^{-1} were maintained in tarmacked road sections. The PD route had a larger proportion of its road length comprising rough roads (Table 7.1). Similarly, the EM route had a higher proportion of its road length comprising smoother road surface compared to both the PD and ZZ routes. Although the PD route had the highest proportion of its road length comprising of rough roads, the slight difference in drive time between ZZ and EM suggests that ZZ had comparatively the longest section of its road section comprising of rough roads of the three routes. International road classification using IRI values have set thresholds of 2.7 m km^{-1} and 1.5 m km^{-1} as acceptable and good quality roads, respectively (Arhin et al., 2015). These values, however, relate to human comfort and are not related to the degree of damage to produce during transport. Although the IRI values in this study give an indication of the relationship between road roughness and its effect on tomato quality, guidance threshold values should be developed for fragile agricultural commodities as stated previously in chapter four, five and six (Fischer *et al.*, 1990).

7.4.2 Air temperature and RH during transportation and storage

The air temperature and RH varied inside the truck depending on the season and the transportation route of each trial. Figure 7.1 and 7.2 depicts variation in air temperature and RH in the trucks with time during the summer and winter transportation runs. The air temperature during the summer transportation run was higher than that of the winter trial (Figure 7.1). Similarly, there were rapid fluctuations in RH conditions compared to the temperature conditions. Relatively higher RH also prevailed during the winter trial compared to the summer trial (Figure 7.2). These conditions can be generally explained by the higher ambient temperature conditions in the summer compared to winter, and the observed trends were, therefore, expected. The differences in temperature and RH between different routes was minor with the air temperature across all the routes gradually decreasing overnight. Higher temperature conditions during transportation increases their respiration rates, hence increasing their ripening and in turn, reduces fruit shelf-life downstream the supply chain. It has also been widely reported that warmer temperature conditions increase the risk of mechanical damage, especially when fruit is transported across long distances over rough roads (Fischer *et al.*, 1990).

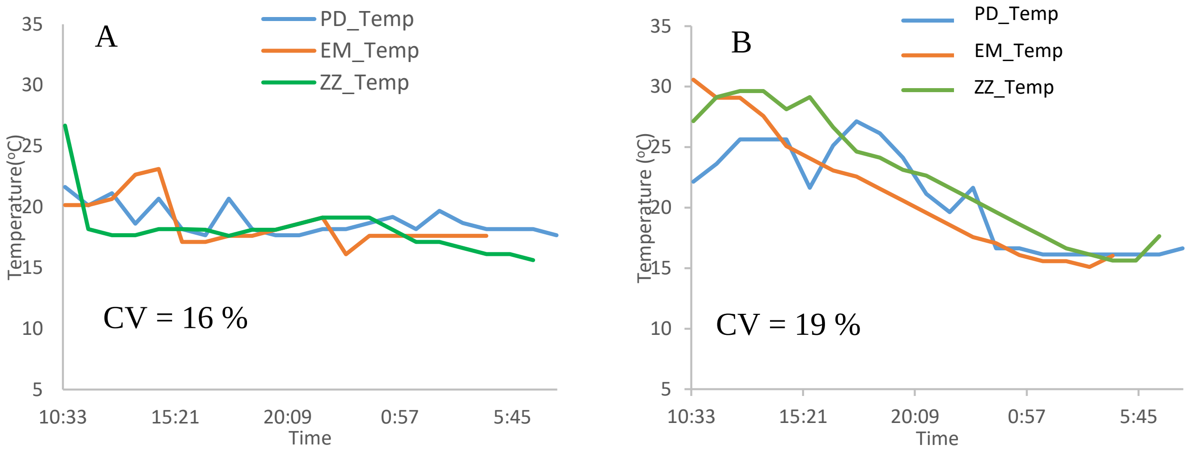

Figure 7.1 Average temperature conditions in the trucks during transportation of tomatoes. Winter conditions are depicted in (A) and summer conditions in (B) (n = 3)

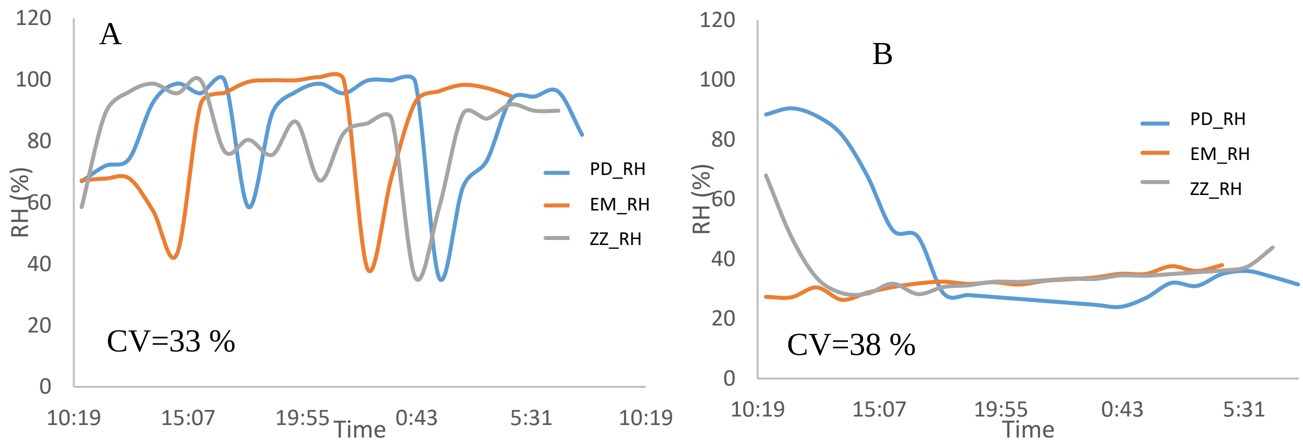

Figure 7.2 Relative humidity (RH) conditions in the trucks during transportation of tomatoes. Winter conditions are depicted in (A) and summer conditions in (B) (n = 3)

Figure 7.3 shows the variation in temperature and RH over the 30-day storage period in ambient and cold storage environments. Cold storage conditions were maintained within a close range of values temperature across the summer and winter seasons. On the other hand, ambient temperature conditions were found to be higher in the summer compared to the winter season. The ambient RH conditions during the summer season were also higher than RH conditions in the winter season for the entire storage period. Optimum storage temperature and RH conditions for tomatoes and other horticultural produce have been widely reported in the literature. For instance, tomatoes require an optimal RH of 90-95 % and temperatures of 13-22 ^{o}C depending on the fruit maturity at harvest (Kitinoja and Kader, 2002). It has however, been reported by Nunes et al. (2009) that fluctuating storage temperatures in combination with low RH conditions leads to significant water loss in fruits and vegetables within the first few days of storage. The control of ambient RH conditions is, therefore, becoming increasingly important from a postharvest quality perspective of horticultural produce. However, the control of RH in storage units requires a precisely-controlled system, making it unaffordable to emerging farmers due to the high manufacturing costs (Paull, 1999).

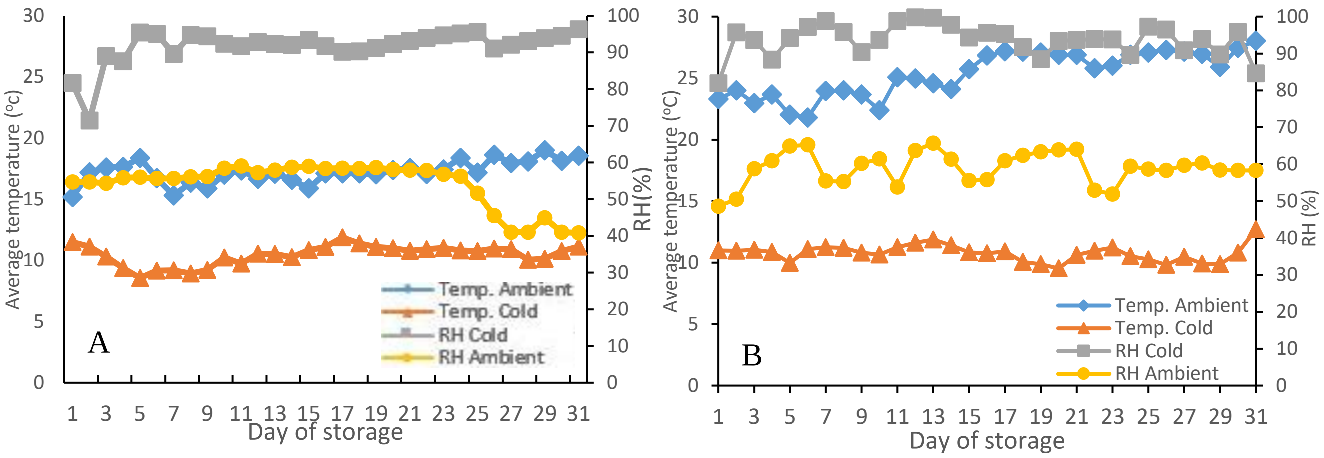

Figure 7.3 Side by side comparison of the variation in temperature and RH conditions in ambient and cold storage rooms during storage of tomato fruit in winter (A) and summer season (B) (n = 3)

7.4.3 Changes in ascorbic acid (AA) content

Ascorbic acid (AA) concentration in the sample tomato fruit on fresh weight basis, had an overall mean of 19.09 mg $100g^{-1}$ and ranged from 2.70 to 47 mg $100g^{-1}$. The changes in AA concentration varied depending on the storage environment, transportation conditions, season and maturity at harvest, during the 30-day storage period. A slight increase in AA during the first few days of storage followed by sharp decrease in the subsequent days of storage was observed (Figure 7.4). The AA concentration for tomato fruit stored under cold storage environment was found to be significantly ($p \leq 0.05$) higher than that of tomatoes stored under ambient conditions. Changes in AA content of fruit harvested during different seasons showed higher accumulation of AA in fruit harvested in the summer season compared to that of the winter season, at the beginning of the storage period. The AA concentration of summer harvested fruit, however, decreased faster than that of fruit harvested in the winter season especially towards the end of the storage period. Fruit of the red maturity stage had the lowest AA concertation throughout the storage period. Fruit harvested at the green maturity stage had the highest AA concentration compared to fruit harvested at the red and pink maturity stages at the beginning of storage. Slight differences in AA were also observed in fruit transported through different routes with the fruit transported through PD route having the highest AA content (19.30±0.34 mg $100g^{-1}$) compared to the EM (19.12±0.30 mg $100g^{-1}$) and ZZ (19.01±0.37 mg $100g^{-1}$) routes. Table 7.2 and 7.3 presents a summary of changes in AA with storage for tomatoes of various maturity stages that were harvested and transported during summer and winter, respectively.

Statistical analysis of the AA data showed the AA content of fruit stored in the cold storage environment was significantly ($p \leq 0.05$) higher than that of fruit stored under ambient storage conditions for fruit harvested and transported during summer and winter (Table 7.2 and 7.3). Similarly, the differences in the AA content of sample tomato fruit harvested and transported through PD, EM and ZZ was significant ($p \leq 0.05$) for fruit harvested and transported in summer and winter (Table 7.2 and 7.3). The differences in AA content of fruit harvested at different maturity stages and fruit subjected to different disinfection treatments was significant ($p \leq 0.05$) for fruit harvested and transported in the winter. An analysis of the pooled data for both seasons showed that the harvesting season is a significant ($p \leq 0.05$) factor affecting changes in AA concentration of fruit, with fruit harvested in the winter having significantly ($p \leq 0.05$) higher AA concentration than that of fruit harvested in the summer.

Table 7.2 A summary of changes in ascorbic acid concentration of tomatoes harvested at different maturity stages and transported through various supply routes during the summer

Route+maturity stage	Disinfection treatments	Storage environment and storage period									
		0		8		16		24		30	
		Ambient	Cold (11ºC)	Ambient	Cold (11ºC)	Ambient	Cold (11ºC)	Ambient	Cold (11ºC)	Ambient[‡]	Cold (11ºC)
PD+Green	Control	25.65^{c}	25.65^{c}	30.51^{cdefg}	21.60^{abcdef}	19.98^{ab}	22.68^{abcde}	18.63^{f}	14.31^{bcdef}	-	15.93^{bcd}
	HWT	25.65^{c}	25.65^{c}	33.75^{fg}	28.62^{fg}	20.25^{abc}	17.01^{abcd}	18.09^{ef}	19.71^{fghij}	-	13.91^{abcd}
	CHL+BIO	25.65^{c}	25.65^{c}	26.19^{bcdefg}	22.41^{bcdefg}	17.55^{ab}	15.93^{ab}	12.29^{abcdef}	9.05^{abc}	-	12.29^{abcd}
	ANO+BIO	25.65^{c}	25.65^{c}	19.98^{abc}	12.15^{a}	14.58^{a}	12.15^{a}	12.02^{abcdef}	10.80^{abcd}	-	9.72^{abc}
PD+Pink	Control	21.60^{bc}	21.60^{bc}	25.11^{bcdefg}	26.46^{defg}	19.44^{ab}	22.68^{abcde}	17.55^{def}	14.58^{bcdefg}	-	15.12^{abcd}
	HWT	21.60^{bc}	21.60^{bc}	18.36^{ab}	16.20^{abc}	36.18^{e}	37.80^{i}	18.23^{ef}	22.14^{hij}	-	13.37^{abcd}
	CHL+BIO	21.60^{bc}	21.60^{bc}	21.60^{abcde}	19.17^{abcdef}	24.03^{abcd}	$26.73^{bcdefgh}$	9.32^{abc}	12.29^{abcde}	-	13.10^{abcd}
	ANO+BIO	21.60^{bc}	21.60^{bc}	34.83^{g}	31.86^{g}	27.81^{bcde}	31.86^{efghi}	14.04^{abcdef}	12.29^{abcde}	-	10.80^{abcd}
PD+Red	Control	24.30^{c}	24.30^{c}	24.17^{bcdefg}	24.84^{bcdefg}	23.22^{abcd}	23.22^{abcde}	13.23^{abcdef}	12.69^{abcdef}	-	12.42^{abcd}
	HWT+BIO	24.30^{c}	24.30^{c}	25.65^{bcdefg}	22.41^{bcdefg}	24.84^{abcde}	26.19^{bcdef}	17.55^{def}	19.58^{fghij}	-	14.58^{abcd}
	CHL+BIO	24.30^{c}	24.30^{c}	31.86^{defg}	25.65^{cdefg}	20.52^{abc}	23.76^{bcde}	14.04^{abcdef}	14.85^{bcdefg}	-	15.53^{abcd}
	ANO+BIO	24.30^{c}	24.30^{c}	$24.03^{abcdefg}$	27.28^{efg}	26.19^{abcde}	22.28^{abcde}	13.50^{abcdef}	14.04^{bcdef}	-	15.66^{abcd}
EM+Green	Control	23.76^{c}	23.76^{c}	20.52^{abcd}	20.25^{abcdef}	25.65^{abcde}	22.68^{abcde}	15.39^{bcdef}	16.34^{defghi}	-	10.94^{abcd}
	HWT	23.76^{c}	23.76^{c}	30.51^{cdefg}	23.76^{bcdefg}	32.13^{cde}	32.40^{efghi}	16.07^{bcdef}	26.19^{j}	-	18.09^{d}
	CHL+BIO	23.76^{c}	23.76^{c}	21.60^{abcde}	18.90^{abcdef}	32.67^{de}	25.65^{bcde}	8.10^{a}	10.94^{abcd}	-	11.88^{abcd}
	ANO+BIO	23.76^{c}	23.76^{c}	32.40^{efg}	21.60^{abcdef}	22.41^{abcd}	22.41^{abcde}	16.34^{cdef}	11.07^{abcd}	-	13.10^{abcd}
EM+Pink	Control	20.52^{bc}	20.52^{bc}	24.84^{bcdefg}	19.44^{abcdef}	21.60^{abcd}	$27.00^{bcdefghi}$	9.18^{ab}	$16.20^{cdefghi}$	-	14.31^{abcd}
	HWT	20.52^{bc}	20.52^{bc}	27.27^{bcdefg}	19.44^{abcdef}	32.94^{de}	$27.00^{bcdefghi}$	16.47^{def}	21.33^{ghij}	-	12.29^{abcd}
	CHL+BIO	20.52^{bc}	20.52^{bc}	22.14^{abcde}	20.79^{abcdef}	28.08^{bcde}	21.33^{abcde}	11.48^{abcde}	10.13^{abcd}	-	10.80^{abcd}
	ANO+BIO	20.52^{bc}	20.52^{bc}	21.06^{abcde}	17.28^{abcd}	27.00^{bcde}	$27.54^{cdefghi}$	12.83^{abcdef}	6.48^{a}	-	12.56^{abcd}
EM+Red	Control	10.80^{a}	10.80^{a}	22.41^{abcdef}	25.11^{cdefg}	21.60^{abcd}	25.65^{bcde}	14.04^{abcdef}	19.17^{efghi}	-	14.58^{abcd}
	HWT	10.80^{a}	10.80^{a}	25.38^{bcdefg}	22.41^{bcdefg}	21.33^{abcd}	26.19^{bcdefg}	10.67^{abcd}	22.95^{ij}	-	16.34^{bcd}
	CHL+BIO	10.80^{a}	10.80^{a}	28.35^{bcdefg}	24.03^{bcdefg}	26.73^{bcde}	37.26^{fhi}	12.29^{abcdef}	11.21^{abcd}	-	10.40^{abcd}
	ANO+BIO	10.80^{a}	10.80^{a}	20.25^{abc}	18.63^{abcde}	21.33^{abcd}	18.90^{abcd}	10.67^{abcd}	9.86^{abcd}	-	10.40^{abcd}

Route+maturity stage	Disinfection treatments	Storage environment and storage period									
		0		8		16		24		30	
		Ambient	Cold (11ºC)	Ambient	Cold (11ºC)	Ambient	Cold (11ºC)	Ambient	Cold (11ºC)	Ambient‡	Cold (11ºC)
ZZ+Green	Control	21.87^{bc}	21.87^{bc}	25.11^{bcdefg}	22.95^{bcdefg}	16.74^{ab}	25.11^{bcde}	18.63^{f}	12.42^{abcde}	-	9.45^{ab}
	HWT	21.87^{bc}	21.87^{bc}	12.69^{a}	22.95^{bcdefg}	22.95^{abcd}	18.09^{abcd}	15.39^{bcdef}	11.61^{abcd}	-	17.55^{cd}
	CHL+BIO	21.87^{bc}	21.87^{bc}	24.84^{bcdefg}	22.41^{bcdefg}	20.25^{abc}	$27.27^{bcdefghi}$	13.50^{abcdef}	11.48^{abcd}	-	8.51^{ab}
	ANO+BIO	21.87^{bc}	21.87^{bc}	26.73^{bcdefg}	15.12^{ab}	26.19^{abcde}	16.20^{abc}	12.15^{abcdef}	8.37^{ab}	-	7.83^{a}
ZZ+Pink	Control	15.93^{ab}	15.93^{ab}	19.85^{abc}	24.84^{bcdefg}	25.38^{abcde}	25.38^{bcde}	14.58^{abcdef}	15.66^{cdefgh}	-	15.12^{abcd}
	HWT	15.93^{ab}	15.93^{ab}	22.14^{abcde}	20.79^{abcdef}	19.98^{ab}	21.06^{abcde}	13.23^{abcdef}	14.04^{bcdef}	-	7.83^{a}
	CHL+BIO	15.93^{ab}	15.93^{ab}	24.84^{bcdefg}	22.41^{bcdefg}	21.60^{abcd}	22.68^{abcde}	15.93^{bcdef}	11.61^{abcd}	-	11.48^{abcd}
	ANO+BIO	15.93^{ab}	15.93^{ab}	21.33^{abcde}	22.41^{bcdefg}	25.11^{abcde}	23.22^{abcde}	13.50^{abcdef}	12.83^{abcdef}	-	10.94^{abcd}
ZZ+Red	Control	21.87^{bc}	21.87^{bc}	20.25^{abc}	23.49^{bcdefg}	26.73^{bcde}	21.06^{abcde}	12.69^{abcdef}	13.23^{abcdef}	-	17.55^{cd}
	HWT	21.87^{bc}	21.87^{bc}	21.60^{abcde}	22.95^{bcdefg}	20.52^{abc}	28.35^{defghi}	14.85^{abcdef}	10.94^{abcd}	-	12.96^{abcd}
	CHL+BIO	21.87^{bc}	21.87^{bc}	22.14^{abcde}	17.28^{abcd}	19.17^{ab}	21.87^{abcde}	14.31^{abcdef}	14.18^{bcdef}	-	10.13^{abcd}
	ANO+BIO	21.87^{bc}	21.87^{bc}	22.68^{abcdef}	15.93^{abc}	24.03^{abcd}	26.19^{bcdefg}	13.23^{abcdef}	14.18^{bcdef}	-	13.10^{abcd}

Significance level (p)		
Treatments (A)	0.054	**
Storage (B)	<.001	*
Route (C)	0.004	*
Maturity stage (D)	0.514	ns
AXB	0.220	ns
AXC	0.196	ns
BXC	0.997	ns
AXD	0.493	ns
BXD	0.184	ns
CXD	0.001	*
AXBXC	0.986	ns
AXBXD	0.900	ns
AXCXD	0.181	ns
BXCXD	0.771	ns
AXBXCXD	1.000	ns

CV (%)	33.0
SE	6.491
LSD	5.701

‡designates missing values. No samples were available under ambient conditions during summer after 30 days of storage. Means within the same column followed by the same letter are not significantly different based on Duncan's multiple range test at 5 % significance level. HWT signifies hot water treatment, BIO designates biocontrol treatment, ANO anolyte water and CHL chlorinated water. PD signifies tomatoes transported through Point Drift-Pietermaritzburg route, EM through Mooketsi-Pietermaritzburg and ZZ through Esmefour-Pietermaritzburg. The routes had varying road quality conditions and distances. Treatments marked * and ** are significant at 5 % and 10 % significance level, respectively.

Table 7.3 A summary of changes in ascorbic acid concentration during the storage of tomatoes harvested and transported during the winter

Route+maturity stage	Disinfection treatments	Storage environment and storage period									
		0		8		16		24		30	
		Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)	Ambient	Cold (11°C)
PD+Green	Control	25.11^{b}	25.11^{b}	18.90^{abc}	25.38^{cdef}	19.17^{abcdef}	25.65^{bcdefg}	9.45^{ab}	15.39^{abcd}	9.18^{ab}	31.86^{kl}
	HWT	25.11^{b}	25.11^{b}	25.65^{bcd}	38.07^{g}	16.20^{abcd}	21.60^{abcdef}	14.58^{abcdefg}	18.09^{abcd}	25.11^{ijklmno}	24.84^{efghij}
	CHL+BIO	25.11^{b}	25.11^{b}	17.82^{abc}	9.72^{a}	23.22^{cdef}	17.55^{abc}	27.27^{hij}	25.11^{bcd}	15.39^{abcdefgh}	8.91^{a}
	ANO+BIO	25.11^{b}	25.11^{b}	21.68^{abcd}	12.42^{ab}	20.52^{abcdef}	14.58^{a}	25.38^{ghij}	28.89^{d}	20.25^{defghijklm}	24.03^{efghij}
PD+Pink	Control	17.82^{ab}	17.82^{ab}	17.01^{abc}	18.36^{abcd}	16.74^{abcde}	17.55^{abc}	10.53^{abc}	18.36^{abcd}	10.53^{abc}	19.17^{abcdef}
	HWT	17.82^{ab}	17.82^{ab}	26.19^{bcd}	24.57^{cdef}	19.71^{abcdef}	29.16^{defgh}	18.90^{abcdefg}	22.14^{abcd}	19.98^{defghijkl}	22.14^{cdefgh}
	CHL+BIO	17.82^{ab}	17.82^{ab}	24.03^{bcd}	19.17^{abcd}	20.25^{abcdef}	17.28^{abc}	12.15^{abcde}	13.77^{abc}	15.39^{abcdefgh}	14.04^{abcde}
	ANO+BIO	17.82^{ab}	17.82^{ab}	25.11^{bcd}	18.09^{abcd}	27.27^{def}	20.25^{abcdef}	20.52^{cdefghi}	19.98^{abcd}	32.94^{o}	29.43^{ijkl}
PD+Red	Control	12.42^{a}	12.42^{a}	17.55^{abc}	21.87^{bcdef}	17.82^{abcde}	21.60^{abcdef}	10.80^{abcd}	9.18^{a}	12.42^{abcd}	18.09^{abcdef}
	HWT+BIO	12.42^{a}	12.42^{a}	26.19^{bcd}	26.73^{def}	16.20^{abcd}	16.47^{abc}	21.60^{defghij}	21.60^{abcd}	17.82^{bcdefghij}	18.90^{abcdef}
	CHL+BIO	12.42^{a}	12.42^{a}	22.14^{bcd}	15.93^{abc}	18.36^{abcde}	21.33^{abcdef}	15.93^{abcdefg}	12.96^{ab}	12.69^{abcde}	16.20^{abcdef}
	ANO+BIO	12.42^{a}	12.42^{a}	17.82^{abc}	21.33^{bcde}	18.09^{abcde}	18.36^{abcd}	19.98^{bcdefgh}	22.41^{abcd}	30.24^{no}	26.46^{ghijkl}
EM+Green	Control	15.93^{ab}	15.93^{ab}	14.04^{ab}	27.00^{def}	9.99^{abc}	14.85^{ab}	18.63^{abcdefg}	21.33^{abcd}	8.10^{a}	14.58^{abcde}
	HWT	15.93^{ab}	15.93^{ab}	27.00^{bcd}	24.30^{cdef}	19.98^{abcdef}	26.19^{cdefgh}	21.87^{efghij}	17.82^{abcd}	16.74^{abcdefghi}	34.56^{l}
	CHL+BIO	15.93^{ab}	15.93^{ab}	17.28^{abc}	24.03^{cdef}	25.92^{def}	25.11^{abcdef}	27.54^{hij}	27.54^{cd}	25.65^{jklmno}	21.06^{cdefgh}
	ANO+BIO	15.93^{ab}	15.93^{ab}	17.28^{abc}	22.22^{bcdef}	15.93^{abcd}	28.74^{defgh}	19.17^{abcdefg}	26.19^{bcd}	26.46^{jklmno}	24.57^{efghij}
EM+Pink	Control	20.52^{ab}	20.52^{ab}	13.50^{ab}	20.25^{bcde}	7.02^{a}	31.59^{gh}	17.28^{abcdefg}	16.20^{abcd}	16.74^{abcdefghi}	12.42^{abcd}
	HWT	20.52^{ab}	20.52^{ab}	28.89^{cd}	31.59^{fg}	26.19^{def}	28.62^{defgh}	28.62^{j}	22.41^{abcd}	23.76^{hijklmn}	31.05^{jkl}
	CHL+BIO	20.52^{ab}	20.52^{ab}	24.57^{bcd}	25.65^{cdef}	19.98^{abcdef}	21.33^{abcdef}	15.12^{abcdefg}	20.25^{abcd}	21.60^{fghijklmn}	9.99^{ab}
	ANO+BIO	20.52^{ab}	20.52^{ab}	33.48^{d}	23.76^{cdef}	32.40^{f}	21.06^{abcdef}	21.60^{defghij}	24.03^{bcd}	21.60^{efghijklmn}	20.25^{bcdefg}
EM+Red	Control	23.90^{ab}	23.90^{ab}	7.56^{a}	15.93^{abc}	9.99^{abc}	15.12^{ab}	8.91^{a}	9.45^{a}	8.91^{a}	21.33^{cdefgh}
	HWT	23.90^{ab}	23.90^{ab}	17.55^{abc}	24.30^{cdef}	19.71^{abcdef}	31.05^{fgh}	16.20^{abcdefg}	15.66^{abcd}	13.77^{abcdef}	16.20^{abcdef}
	CHL+BIO	23.90^{ab}	23.90^{ab}	20.52^{abcd}	17.82^{abcd}	8.10^{ab}	22.95^{abcdef}	19.17^{abcdefg}	23.22^{abcd}	15.12^{abcdefgh}	17.28^{abcdef}
	ANO+BIO	23.90^{ab}	23.90^{ab}	24.38^{bcd}	18.66^{abcd}	23.22^{cdef}	29.43^{efgh}	17.01^{abcdefg}	18.63^{abcd}	27.00^{klmno}	15.12^{abcdef}

Route+maturity stage	Disinfection treatments	Storage environment and storage period									
		0		8		16		24		30	
		Ambient	Cold (11ºC)	Ambient	Cold (11ºC)	Ambient	Cold (11ºC)	Ambient	Cold (11ºC)	Ambient	Cold (11ºC)
ZZ+Green	Control	23.22^{ab}	23.22^{ab}	23.49^{bcd}	13.23^{ab}	8.64^{ab}	16.20^{abc}	$19.17^{abcdefg}$	25.38^{bcd}	14.31^{abcdef}	15.93^{abcdef}
	HWT	23.22^{ab}	23.22^{ab}	28.89^{cd}	13.23^{ab}	27.81^{def}	20.52^{abcdef}	24.03^{fghij}	26.19^{bcd}	$22.14^{fghijklmn}$	25.65^{fghijk}
	CHL+BIO	23.22^{ab}	23.22^{ab}	24.84^{bcd}	23.49^{cdef}	26.46^{def}	16.47^{abc}	24.30^{fghij}	22.68^{abcd}	$20.52^{defghijklm}$	16.20^{abcdef}
	ANO+BIO	23.22^{ab}	23.22^{ab}	17.55^{abc}	30.24^{efg}	19.71^{abcdef}	32.40^{h}	28.08^{ij}	20.25^{abcd}	$23.49^{ghijklmn}$	27.81^{hijkl}
ZZ+Pink	Control	20.52^{ab}	20.52^{ab}	18.90^{abc}	21.06^{bcde}	10.80^{abc}	16.20^{abc}	14.04^{abcdef}	11.88^{ab}	$19.98^{defghijkl}$	24.84^{efghij}
	HWT	20.52^{ab}	20.52^{ab}	23.22^{bcd}	21.06^{bcde}	17.55^{abcde}	18.90^{abcde}	$18.90^{abcdefg}$	14.58^{abcd}	$14.85^{abcdefg}$	14.58^{abcde}
	CHL+BIO	20.52^{ab}	20.52^{ab}	30.51^{cd}	26.46^{def}	21.87^{bcdef}	20.52^{abcdef}	$17.01^{abcdefg}$	22.14^{abcd}	$16.74^{abcdefghi}$	18.09^{abcdef}
	ANO+BIO	20.52^{ab}	20.52^{ab}	28.62^{cd}	23.76^{cdef}	30.78^{ef}	22.95^{abcdef}	$19.44^{abcdefg}$	24.30^{bcd}	27.81^{lmno}	29.43^{ijkl}
ZZ+Red	Control	19.98^{ab}	19.98^{ab}	16.20^{abc}	18.63^{abcd}	15.66^{abcd}	17.28^{abc}	$17.82^{abcdefg}$	18.36^{abcd}	14.31^{abcdef}	11.34^{abc}
	HWT	19.98^{ab}	19.98^{ab}	28.89^{cd}	18.63^{abcd}	19.44^{abcdef}	21.33^{abcdef}	$17.28^{abcdefg}$	19.17^{abcd}	$18.63^{cdefghijk}$	22.95^{defghi}
	CHL+BIO	19.98^{ab}	19.98^{ab}	18.09^{abc}	20.79^{bcde}	26.73^{def}	16.47^{abc}	$17.82^{abcdefg}$	18.90^{abcd}	14.04^{abcdef}	17.82^{abcdef}
	ANO+BIO	19.98^{ab}	19.98^{ab}	20.79^{abcd}	26.81^{def}	17.82^{abcde}	25.38^{abcdef}	$21.06^{cdefghi}$	22.14^{abcd}	28.89^{mno}	27.54^{hijkl}

Significance level (p)

Treatments (A)	<.001	*
Storage (B)	0.017	*
Route (C)	0.028	*
Maturity stage (D)	<.001	*
AXB	0.001	*
AXC	0.009	*
BXC	0.124	ns
AXD	0.448	ns
BXD	0.417	ns
CXD	0.066	**
AXBXC	0.084	**
AXBXD	0.200	ns
AXCXD	0.242	ns
BXCXD	0.740	ns
AXBXCXD	0.872	ns

CV (%)	28.7
SE	5.825
LSD	5.116

Means within the same column followed by the same letter are not significantly different based on Duncan's multiple range test at 5 % significance level. HWT signifies hot water treatment, BIO designates biocontrol treatment, ANO anolyte water and CHL chlorinated water. PD signifies tomatoes transported through Point Drift-Pietermaritzburg route, EM through Mooketsi-Pietermaritzburg and ZZ through Esmefour-Pietermaritzburg. The routes had varying road quality conditions and distances. Treatments marked * and ** are significant at 5 % and 10 % significance level, respectively.

Figure 7.4 shows changes in AA with storage for fruit subjected to various disinfection treatments. Tomato fruit samples subjected to HWT showed high AA concentrations of AA compared to other treatments. Fruit treated with anolyte water in combination with biocontrol also showed high AA towards the end of the storage period with control-treated fruit showing the least AA content.

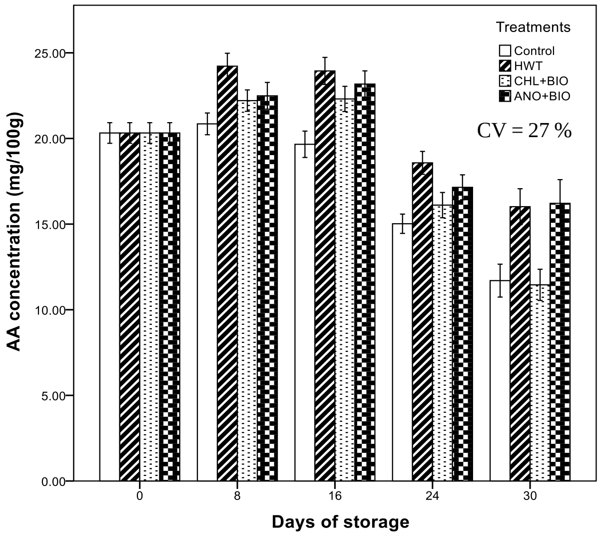

Figure 7.4 Changes in AA concentration during storage of tomatoes subjected to different disinfection treatments

Figure 7.5 shows the effect of seasonal changes on the variation in AA concentration of sample tomato fruit harvested at different maturity stages and stored in cold and ambient storage conditions. Fruit harvested at the green maturity stage generally had higher AA concentration than fruit harvested at the pink and red maturity stages, with fruit harvested at the red maturity stage having the lowest AA concentration.

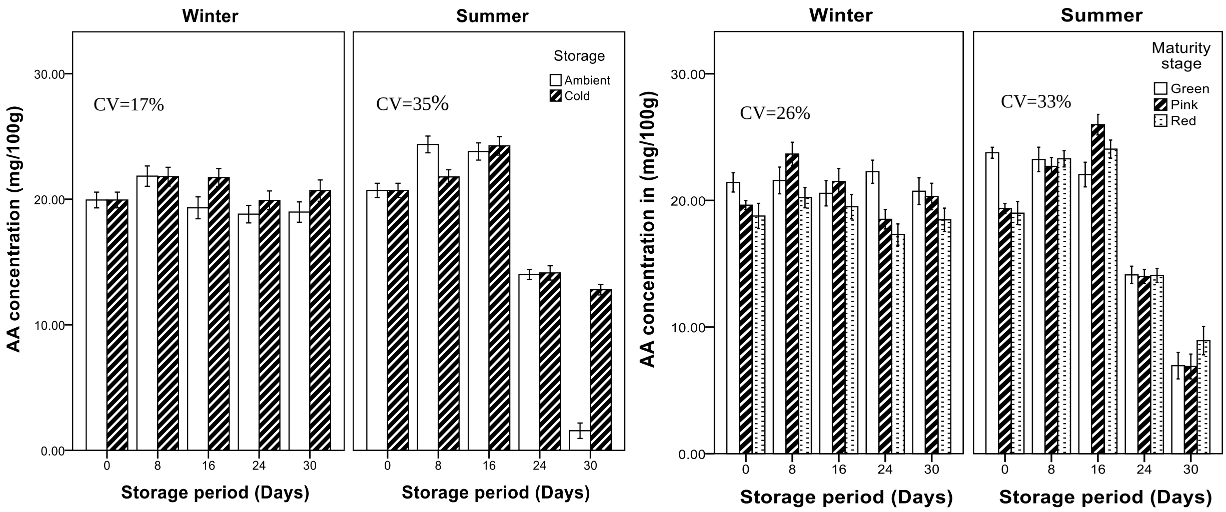

Figure 7.5 Changes in sample tomato fruit AA content during storage of tomatoes harvested at different maturity stages and transported in the summer and winter season.

AA is one of the important nutrients in tomatoes that contributes the highest proportion of the fruit's total antioxidant capacity. It has been shown by Tigist *et al.* (2013) that treatment conditions, affect the changes in AA concentration of tomatoes during storage. Tomato handling, storage and transportation, particularly under commercial conditions has been shown to yield fruit of inferior taste and flavor (Maul *et al.*, 2000). The understanding of the influence of treatment factors on the changes in AA in commercial conditions is therefore important for the development of handling, storage and transportation guidelines. The range in AA concentration of fruit in this study varied widely due to the wider range of treatment conditions. For instance, Tigist *et al.* (2013) and Toor and Savage (2006) reported AA of 9.21-21.7 mg 100^{-1}g during storage of green harvested tomatoes. The study by Chang *et al.* (2006) reported AA contents of up to 80 mg 100^{-1}g. AA in tomatoes has also been shown to vary widely depending on the harvesting seasons and the cultivar in question (Saltveit, 1999). Other studies have shown that the AA of tomatoes does not vary significantly among fruit harvested at red green maturity stages (Saltveit, 1999). It was, however, observed in the present study that fruit harvested at red, pink and green maturity stages had significantly ($p \leq 0.05$) different AA concentrations over the storage period when the fruit is harvested in winter. It has also been reported that AA degradation increases with higher storage temperature and long storage periods (Lee and Kader, 2000). This explains the changes in AA concentration for samples harvested in the summer and stored in ambient, as well as cold storage conditions, where a rapid drop in AA was observed after 16 days of storage (Figure 7.5), compared to fruit stored in the winter. The road quality and distance of transportation had an effect on the changes in the AA content of the fruit. Shorter transport distances appeared to produce tomatoes that had better AA retention, than fruit transported through longer distances. Fruit transported through ZZ route had the highest degree of mechanical damage hence the lower AA content. Although the PD route had the roughest road surface profile, the shorter distance helped reduce fruit injuries since tomato fruit injuries have been shown to be comparatively worse for fruit transported through slightly rough roads over long distances (Mutari and Debbie, 2011). It has also been shown that bruising and other mechanical injuries on tomato fruit results in high losses in AA (Lee and Kader, 2000).

7.4.4 Lycopene content

Figure 7.6 shows side-by-side comparisons of the mean lycopene content of sample tomato fruit subjected to different treatments. The lycopene content varied widely depending on the treatments applied to the fruit.

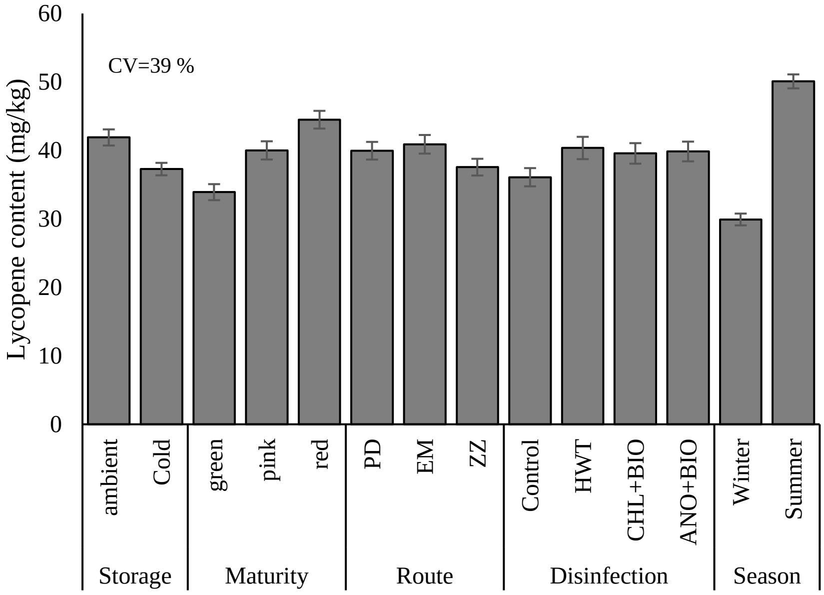

Figure 7.6 Comparison of the mean lycopene content of tomato fruit harvested at different maturity stages, subjected to different transportation, disinfection and storage conditions during the summer and winter

Accumulation of lycopene in tomato fruit stored under ambient conditions was 11.03 % higher than that of tomato fruit stored under cold storage. The mean lycopene content of tomatoes harvested at the red maturity stage was 23.78 % and 10.06 % higher than that of fruit harvested at the green and pink maturity stages, respectively, with fruit harvested at the green maturity stage having the lowest mean lycopene content. The mean lycopene content of fruit harvested and transported in the summer was 40.26 % higher than that of fruit harvested and transported in the winter. Similarly, fruit transported through the EM route had 5.37 % and 8.17 % higher mean lycopene concentration compared to fruit transported through the PD and ZZ routes, respectively, with fruit transported through the ZZ route having the lowest lycopene content. Tomato samples stored under ambient temperature had significantly ($p \leq 0.05$) higher lycopene content when compared to those stored under cold storage conditions. Tomatoes harvested and transported during the summer also had significantly ($p \leq 0.05$) higher lycopene content when compared to the lycopene concentration of fruit harvested and transported in the winter. The lycopene content of fruit harvested at the green maturity stage was significantly ($p \leq 0.05$) lower than that of fruit harvested at the pink and green maturity stage, with differences in lycopene content of fruit harvested at pink and red maturities not being significant ($p > 0.05$). Fruit transported through EM also had significantly ($p \leq 0.05$) higher lycopene content that those transported through EM and ZZ. The disinfection treatments also had a significant ($p \leq 0.05$) effect on the lycopene content of the stored tomatoes. The lycopene content of the fruit generally increased during the first 16 days of storage, with a slight drop being observed towards day 30 (Figure 7.7).

Accumulation of lycopene in tomatoes occurs as a consequence of the normal ripening process. This process is a genetically-controlled process that is triggered by phyto-hormones and regulated by other environmental factors (Toor and Savage, 2006). Accumulation of lycopene influenced by temperature and light, with higher storage temperature favoring its accumulation than cold storage conditions (Brandt *et al.*, 2006). Similarly, lycopene is known to give tomatoes their red colour, hence as expected, tomatoes of red maturity at harvest had higher lycopene content than the pink and green maturity stages. Figure 7.7 shows changes in lycopene content with storage of tomatoes subjected to different disinfection treatments.

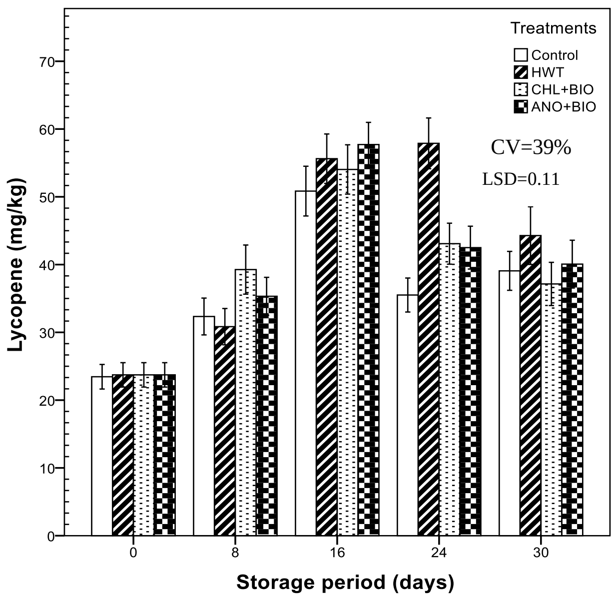

Figure 7.7 Changes in lycopene content during storage of tomatoes subjected to different disinfection treatments

Tomato fruit that was subjected to HWT had a mean lycopene content of 9-15 % higher than all the other disinfection treatments towards the end of the storage period, with the control fruit having the least lycopene content. The accumulation of lycopene in tomatoes treated with HWT could be related to the inducement of fruit defense responses that caused the formation of heat shock proteins known to trigger accumulation of lycopene (Paull and Jung Chen, 2000). It is, however, known that heat treatment of tomato also disrupts the activity of lycopene synthase, but its activity is restored after normal temperature conditions are restored during the storage period. This may explain the low lycopene content of sample tomato fruit during the earlier stages of fruit storage (Lurie, 1998). Other researchers have also demonstrated that hot treatment of tomato fruit prior to storage reduces the occurrence of chilling injury, and that the lycopene content increases with increase in water temperature (Hakim *et al.*, 1997).

The transportation conditions also influenced accumulation of lycopene in the tomatoes, with fruit transported through the EM route having the highest mean lycopene content compared to fruit transported through the PD and ZZ routes. Fruit transported through the ZZ route had the lowest mean lycopene content. These differences may be explained by higher level of mechanical damage observed in fruit transported through ZZ route occasioned by a relatively poor road surface profile and a long distance of transportation. This observation is consistent with results reported by Buccheri and Cantwell (2014) that showed mechanically damaged cut tomatoes to have lower lycopene content than intact, cut tomato fruit. Their experiment was, however, simulated, and did not consider practical aspects in commercial tomato supply and distribution that evolve around the fruit being transported over long distances with varying road conditions.

7.4.5 Sugars (Glucose and Fructose)

Fructose and glucose content increased during the first 16 days of storage and decreased in the remaining storage period for sample fruit stored in cold storage environment. These sugars increased during the first 8 days of storage, and decreased for the remaining period for tomato fruit stored under ambient conditions. The mean fructose content was 24 % higher than glucose content with the fructose to glucose ratio being generally greater 1. Table 7.4 shows a summary of changes in the mean glucose and fructose concentration with storage for tomatoes subjected to different storage, transportation and disinfection treatments.

Although the glucose and fructose content of tomatoes stored in ambient storage peaked higher than that of tomatoes stored in cold storage environment, the subsequent trend depicts comparatively lower concentrations of both sugars for fruit stored in ambient conditions.

Table 7.4 A summary of changes in glucose and fructose contents with storage for tomato fruit subjected to various disinfection treatments, storage and transportation conditions

Experimental factors		Glucose ($g\ kg^{-1}$)					Fructose ($g\ kg^{-1}$)				
		0	8	16	24	30	0	8	16	24	30
Storage (A)	Ambient	8.53±0.36	16.71±0.81	14.39±0.38	13.56±0.64	7.14±0.68	10.21±0.43	20.65±1.01	18.74±1.01	19.11±0.83	9.32±0.96
	Cold	8.53±0.36	15.92±0.97	15.04±0.74	13.97±0.53	11.14±0.54	10.21±0.43	20.49±1.16	20.33±0.99	20.22±0.84	15.69±0.76
Fruit maturity (B)	Green	8.44±0.64	15.93±1.00	14.55±1.04	13.13±0.69	9.49±0.83	9.85±0.73	20.54±1.28	19.96±1.46	20.13±1.18	13.24±1.16
	Pink	8.74±0.32	16.71±1.14	14.99±0.85	14.33±0.78	9.92±0.76	10.64±0.41	20.60±1.36	19.46±1.11	20.06±0.98	13.97±1.07
	Red	8.41±0.26	16.32±1.09	14.62±0.90	13.84±0.69	10.01±0.74	10.15±0.37	20.58±1.36	19.19±1.09	18.81±0.89	13.67±1.06
Transport conditions (C)	PD	9.59±0.45	13.54±1.13	14.16±1.08	14.47±0.68	10.07±0.77	10.98±0.49	17.60±1.38	18.66±1.37	20.93±1.10	14.48±1.08
	EM	7.06±0.35	17.06±1.00	16.03±0.87	12.53±0.77	10.58±0.77	8.58±0.46	21.20±1.27	21.62±1.21	17.69±1.01	14.64±1.12
	ZZ	8.94±0.47	18.33±1.03	13.97±0.81	14.29±0.69	8.76±0.76	11.09±0.58	22.91±1.28	18.33±1.06	20.37±0.93	11.58±1.05
Disinfection (D)	Control	8.53±0.51	12.03±0.96	10.71±0.71	13.19±0.77	10.45±0.83	10.22±0.61	15.23±1.18	15.98±1.09	19.19±1.07	13.75±1.09
	HWT	8.53±0.51	16.85±1.01	16.65±1.01	14.17±0.94	10.36±0.88	10.22±0.61	22.54±1.58	21.45±1.22	20.69±1.54	15.57±1.35
	Chl+Bio	8.53±0.51	18.87±1.32	15.02±1.03	13.52±0.90	9.40±0.96	10.21±0.61	22.34±1.56	19.85±1.38	18.32±1.12	12.30±1.32
	Ano+Bio	8.53±0.51	17.51±1.02	16.49±1.32	14.16±0.71	9.02±0.91	10.21±0.61	22.18±1.64	20.86±1.81	20.46±0.91	12.66±1.26
Season (E)	Winter	6.42±0.21	22.30±0.87	19.67±0.73	14.81±0.65	8.97±0.52	7.62±0.28	28.34±1.03	26.26±0.97	21.88±0.97	16.36±1.09
	Summer	10.64±0.39	10.33±0.55	9.76±0.53	12.72±0.50	11.47±0.82	12.81±0.44	12.78±0.67	12.81±0.65	17.45±0.63	12.17±0.76
Significance level (p)											
Storage (A)						0.26					0.019
Maturity at harvest (B)						0.471					0.806
Route (C)						0.596					0.796
Disinfection (D)						<.001*					<.001*
Season (E)						<.001*					<.001*
AB						0.243					0.337
AC						0.059**					0.054**
BC						0.392					0.857
AD						0.293					0.026*
BD						0.875					0.778
CD						0.72					0.828

AD	0.698	0.568
BE	0.356	0.367
CE	0.657	0.269
DE	0.007**	0.073**
ABC	0.818	0.788
ABD	0.762	0.777
ACD	0.136	0.061**
BCD	0.848	0.626
ABE	0.535	0.78
ACE	0.199	0.094**
BCE	0.473	0.675
ADE	0.451	0.374
BDE	0.861	0.85
CDE	0.639	0.747
ABCD	0.823	0.892
ABCE	0.814	0.937
ABDE	0.956	0.936
ACDE	0.56	0.572
BCDE	0.487	0.188
ABCDE	0.997	0.992
LSD	0.725	0.888
SE	4.265	4.735
CV (%)	35.351	32.458

HWT signifies hot water treatment, Bio designates biocontrol treatment, Ano anolyte water and Chl chlorinated water. PD signifies tomatoes transported through Point Drift-Pietermaritzburg route, EM through Mooketsi-Pietermaritzburg and ZZ through Esmefour-Pietermaritzburg. The routes had varying road quality conditions and distances. Treatments marked * and ** are significant at 5 % and 10 % significance level, respectively.

This observation agrees with that of Workneh *et al.* (2012) who reported that sugars tend to accumulate and peak after 8 days of storage, and decrease with further storage, with sugars in tomatoes stored in ambient conditions depleting faster than in fruit stored under cold storage. Similarly, fruit harvested and transported during the winter season experienced lower rate of decrease in fructose and glucose content compared to tomatoes harvested and transported in the summer. Comparison of the sugars of fruit harvested at different maturity stages only showed slight differences during storage. Sugar metabolism in ripening fruit is driven by complex biosynthetic pathways that are partly controlled by the physiological ripening processes and stimuli. Higher ripening rates imply sugars that fuel these pathways are used up faster hence explaining the quick accumulation and depletion of these sugars under ambient conditions than cold storage conditions.

The EM route showed comparatively lower decline glucose and fructose compared to both the ZZ and PD routes. The disinfection treatments had varied effects on the changes in sugars during storage. It is apparent that the control-treated fruit had lower accumulation of sugars than the treated group. Fruit treated with hot water and fruit treated with anolyte water in combination with biocontrol, appeared to have a higher concentration of fructose and glucose, compared to other treatments.

Statistical analysis of the glucose and fructose data showed the disinfection treatments and season of harvest to be significant factors ($p \leq 0.05$) affecting changes in the glucose and fructose content of tomatoes. However, the fruit maturity at harvest, storage and transportation conditions had no significant ($p > 0.05$) effect on the glucose and fructose content of stored fruit.

The mean sucrose equivalent of fruit samples during storage was found to be 38.65 ± 3.65 g kg^{-1}, and tomato sample fruit stored under cold storage was found to have significantly ($p \leq 0.05$) higher sucrose equivalent sample fruit stored under ambient conditions. The route conditions and maturity at harvest were found not to have a significant effect on the differences in sucrose of the fruit. Tomato fruit samples treated using HWT and Anolyte water combined with biocontrol also had significantly ($p \leq 0.05$) higher sucrose equivalent than fruit treated with other treatments. Tomato fruit samples harvested and transported during the winter were also found to have significantly ($p \leq 0.05$) higher sucrose equivalent than fruit harvested and transported during the summer. Table 7.5 presents a summary of changes in sucrose equivalent of tomato fruit samples with storage period.

Table 7.5 A summary of changes in sucrose equivalent of tomato fruit samples with storage period

Category of treatments	Treatments	Treatments Sucrose equivalent (g kg^{-1})				
		0	8	16	24	30
Storage (A)	Ambient	23.99±1.01[a]	48.11±2.34[a]	43.07±2.02[a]	43.09±1.90[a]	21.41±2.16[a]
	Cold	23.99±1.01[a]	47.22±2.72[a]	46.31±2.26[a]	45.32±1.84[a]	35.40±1.71[b]
Fruit maturity (B)	Green	24.88±1.73[b]	47.33±2.95[a]	45.29±3.29[a]	44.55±2.55[a]	29.94±2.62[c]
	Pink	23.30±0.94[a]	48.00±3.19[a]	44.76±2.54[a]	45.30±2.27[a]	31.21±2.41[d]
	Red	23.79±0.83[a]	47.67±3.15[a]	44.02±2.55[a]	42.78±2.05[ab]	31.06±2.38[d]
Transport conditions (C)	PD	26.11±1.18[c]	40.46±3.22[a]	42.75±3.16[a]	46.94±2.40[a]	32.51±2.43[bd]
	EM	20.06±1.05[d]	49.32±2.93[a]	49.94±2.73[ab]	39.87±2.31[bc]	33.17±2.50[bd]
	ZZ	25.80±1.35[b]	53.21±2.75[b]	42.05±2.43[a]	45.82±2.11[a]	26.53±2.37[c]
Disinfection (D)	Control	23.99±1.43[a]	35.25±3.48[c]	35.57±2.41[c]	42.95±2.42[ab]	31.52±2.49[d]
	HWT	23.99±1.43[a]	51.46±3.67[b]	49.43±2.85[ab]	46.29±3.35[a]	34.61±2.98[bd]
	Chl+Bio	23.99±1.42[a]	51.46±3.59[b]	45.47±3.14[a]	41.70±2.60[abc]	28.24±2.99[c]
	Ano+Bio	23.99±1.42[a]	51.33±2.42[b]	48.28±4.10[a]	45.88±2.09[a]	28.59±2.85[c]
Season (E)	Winter	17.94±0.63[e]	65.54±2.97[d]	59.98±2.21[c]	48.82±2.15[a]	36.79±2.27[b]
	Summer	30.04±1.04[f]	29.79±1.56[e]	29.40±1.51[d]	39.59±1.45[bc]	27.71±1.92[c]
Significance level (p)						
Storage (A)						0.037*
Maturity at harvest (B)						0.790
Route (C)						0.743
Disinfection (D)						<.001*
Season (E)						<.001*
AB						0.305
AC						0.051**
BC						0.791
AD						0.052**
BD						0.819
CD						0.802
AD						0.593
BE						0.378
CE						0.364
DE						0.042*
ABC						0.828
ABD						0.776
ACD						0.071**
BCD						0.698
ABE						0.719
ACE						0.108
BCE						0.621
ADE						0.431
BDE						0.854
CDE						0.726
ABCD						0.895
ABCE						0.934
ABDE						0.942
ACDE						0.566
BCDE						0.247
ABCDE						0.996
LSD						0.925
SE						4.665
CV (%)						39.59

Means within the same column with different letters are significantly different (p>0.05). HWT = hot water treatment, Bio = biocontrol treatment, Ano = anolyte water and Chl = chlorinated water. PD signifies tomatoes transported through Point Drift-Pietermaritzburg route, EM through Mooketsi-Pietermaritzburg and ZZ through Esmefour-Pietermaritzburg. The routes had varying road quality conditions and distances. Treatments marked * and ** are significant at 5 % and 10 % significance level, respectively.

It has been well established that sugars accumulate during the initial stages of the post-harvest period of tomatoes due to breakdown of carbohydrate polymers, and later drops due to respiratory metabolism (Missio *et al.*, 2015). Glucose and fructose concentration in tomatoes determines the fruits' flavor intensity and aroma evolution, with fruit that have high concentration of these sugars exhibiting superior flavor than those with lower concentrations (Georgelis *et al.,* 2004; Missio *et al.*, 2015). The study by Missio *et al.* (2015) that involved storage of tomatoes for a period four months showed glucose and fructose to decrease sharply during the first three months and a gradual decline between the third and the fourth month. The concentration of sugars in their study ranged from 11.62 to 29.64 g kg^{-1}, and compared well to those reported in the present study (8.12-23.85 g kg^{-1}).

The fructose to glucose ratio has also been reported to increase due to differences in the biosynthetic pathways sugar metabolism follow in tomatoes, with more glucose than fructose being consumed with longer periods of storage (Missio *et al.*, 2015). This observation is in agreement with the findings made in the present study. Studies by Davies and Kempton (1975) reported the differences in glucose and fructose content between fruit of different maturity at harvest not to be significant, an observation that is also in agreement with observations made in the present study. Biochemical processes that lead to depletion of fruit sugars are linked to fruit ripening. Higher storage and ripening temperatures lead to higher ripening rates, thus explaining the higher depletion of sugars in fruit stored under ambient conditions compared to cold storage, as well as higher losses in the sugar content of fruit harvested in summer compared to winter. In this respect, it has been widely shown that relatively higher temperature and light conditions (typically in the summer season) lead to higher accumulation of sugars in tomatoes than lower temperature and light conditions (winter) (Beckles, 2012) .The EM route had smoother road surface profile signifying less damage to fruit during transportation. The ZZ route had the longest distance with a moderately rough road surface conditions, and fruit transported through this route showed relatively higher levels of mechanical damage compared to fruit transported through the other routes. Bruising and other mechanical injuries have been shown to trigger a surge in ethylene production in tomatoes resulting in higher ripening rates than intact fruit (Mutari and Debbie, 2011). Mechanical injury occurs when tomatoes are subjected to forces exceeding their bio-yield point, causing cell breakdown that leads to undesirable chemical reactions, upsurge of ethylene production, increased respiration and transpiration, as well as pathogen infestation (Beckles, 2012). While visible injuries can be managed upon detection, internal injuries may often go undetected leading to massive losses (Beckles, 2012). Damaged fruit would therefore have depleted sugar reserves hence explaining the differences in fructose and glucose content in fruit transported through different routes.

7.5 Conclusion

This study investigated changes in the chemical and nutritive quality of tomatoes transported through roads of varying distances and road surface profile. The study showed that transportation conditions had a significant effect ($p \leq 0.05$) on the differences in ascorbic acid content in tomato fruit samples, with fruit transported through PD having 2 % higher AA than tomato samples transported through ZZ. The mean ascorbic acid content of tomato fruit samples stored under cold storage conditions was found to have 60 % higher than that of tomato fruit that was stored under ambient conditions. Ascorbic acid was therefore, quantitatively affected more by temperature conditions than mechanical damage during transportation. The study highlights the importance of maintaining the cold chain to minimize losses in ascorbic acid content. The lycopene content of transported fruit was dependent upon the road quality, with tomatoes transported though roads with smooth surface profile showing the least loss in lycopene. Lycopene content of fruit transported through EM was 7.5 % higher than that of tomatoes transported through ZZ. Transportation routes were found not to have a significant ($p > 0.05$) effect on the fruit sugars. Disinfection treatments had varied effects on the nutrient changes. However, hot water treatment and anolyte water in combination with biocontrol were both found to be effective in maintaining fruit's nutritional quality. The maintenance of cold chain in tomato supply chains, adequate disinfection and timely maintenance of rough road sections in and around commercial farms were found to be the best practices that will yield fruit of high nutritional quality. The study recommends HWT to emerging farmers due to the ease of use and application to tomatoes, while anolyte water in combination with biocontrol is recommended to commercial growers, due to its effectiveness in maintaining tomato quality, even though it requires higher investment costs than HWT. As established for the first time under practical supply chain conditions, long transportation distances and poor road quality negatively affected the chemical and nutritional quality of tomatoes. Logistical planning in commercial supply chains that minimizes transportation distances would therefore reduce loss in nutritional quality of tomatoes.

7.6 Acknowledgement

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8. MULTIVARIATE ANALYSIS OF QUALITY ATTRIBUTES OF TOMATO FRUIT SUBJECTED TO DIFFERENT DISINFECTION TREATMENTS, TRANSPORTATION AND STORAGE CONDITIONS USING PRINCIPAL COMPONENTS ANALYSIS

8.1 Abstract

This study sought to establish the complex relationships between numerous physicochemical quality attributes of tomatoes subjected to different disinfection, storage and transportation conditions. The experimental design involved tomatoes of three maturity stages (red, pink and green), three transportation routes from Limpopo to Pietermaritzburg (PD, EM and ZZ), two storage conditions (cold and ambient), two harvesting seasons (summer and winter) and four disinfection treatments. Various physicochemical, nutritive and chemical quality attributes of the tomato fruit were measured during storage. Principal component analysis (PCA) was used to establish the complex relationships between categorical variables and quality attributes. The nine physical and subjective quality attributes were grouped into three principal components. Fruit hue angle, firmness, marketability and consumer acceptability heavily loaded on PC1, which was also significantly ($p \leq 0.05$) affected by fruit maturity at harvest, storage environment and transportation route. This component was inferred to be related to the tomato fruit tactile and visual attributes that influence consumer buying decisions. Components relating to fruit ripening and chemical processes were strongly linked to season of harvest, fruit maturity at harvest and storage environment. The components accounted for 74.32 % of the variability in the data for physical and subjective quality attributes, while accounting for 80.66 % of variability of chemical and nutritive quality data. Maturity at harvest, route and storage conditions were the main driving factors accounting for most of the variability in the data. The components developed adequately explained the tomato fruit quality data.

Keywords: *PCA; pre-storage treatments; processing parameters; route conditions*

8.2 Introduction

The processing operations that food materials are subjected to before they are sent to the market, are important for preserving perishable food products, as well as meeting legal, consumer or safety requirements (Woodroof, 2012). During processing of fresh foods such as tomatoes, different handling and processing operations occur in the supply chain (Ramos *et al.*, 2013). Some of these operations include storage, transportation, disinfection, packaging and precooling. These operations have diverse effects on the quality attributes required from tomato fruit. The understanding of the effect of these operations on different quality attributes is necessary for process design and control to be implemented that ensures that the fruit supplied meets the required criteria (Ramos *et al.,* 2013). This necessitates the collection and analysis of a vast amount of fruit quality data that often presents hazy and non-coherent conclusions (Sobratee and Workneh, 2015b).

Analysis of data related to multiple processing parameters and accompanying changes in tomato fruit quality attributes requires an in-depth approach beyond the traditional ANOVA, which has been criticized for its limitations in establishing complex interrelationships between different factors (Melesse *et al.*, 2016). Approaches used to assess process conditions and their effect on food quality parameters has been a subject that has recently attracted huge research interest, especially for perishable fresh foods (Sobratee and Workneh, 2015b; Melesse *et al.*, 2016; González-Tejedor *et al.*, 2017). The use of principal components in a study by Sobratee and Workneh (2015a), effectively isolated the quality parameters that were most important during processing of tomatoes using a range of disinfection and storage treatments. Although the study by Sobratee and Workneh (2015a) involved the analysis of pre- and post-harvest processing operations of tomatoes, it did not account for practicalities in their supply and distribution, which can exacerbate quality degradation of fresh tomatoes.

In the present study, tomato fruit is transported over road sections with varying road surface profiles to mimic typical transportation operations by commercial growers. Various disinfection treatments, storage environments and fruit of different maturities were tested across two harvesting seasons. Nine fruit quality parameters were assessed under typical commercial supply conditions, and used to extract the principal components of the fruit quality data. The study seeks to establish the relationships between different physicochemical quality attributes of tomato fruit, as a result of different supply chain operations, in selected South African supply chains.

8.3 Materials and Methods

8.3.1 Tomato fruit production

Tomato fruit (*Solanum lycopersicum)* of Nemo-Netta variety was produced from three farms in Limpopo Province, South Africa. The farms were located in Esmefour (22°19’48.7” S

30°28'21.3" E), Pont Drift (22°11'52.7" S 29°11'30.7" E) and Mooketsi (23°26'05.2" S 30°26'47.5" E). The crop was trained and drip irrigation implemented throughout the growing season, to meet the crop water requirement. For the entire growing season, the crop was grown under sustainable soil and water management practices (compost use, crop rotation, minimum tillage), as well as soft pest control practices. This production system is known as Natuurboerdey® system (Taurayi, 2011). Through this system, inorganic fertilizers are replaced by carbon-loaded fertilizers with additional foliar spray, bio-stimulants and nutrient supplements depending on the growing stage of the crop. The fruit was harvested at three maturity stages namely, red, pink and green, during the winter (June) and summer (September) seasons.

8.3.2 Transportation conditions

The tomato fruit was harvested in the morning and transported in bulk bins to the respective pack-house located near each of the farms, where the fruit was pre-cooled to remove field heat using forced air coolers for three to four hours. The fruit was then transported overnight from each of the pack-houses to Pietermaritzburg using non-refrigerated trucks to mimic normal supply operations. Each route (Esmefour-Pietermaritzburg (ZZ), Mooketsi-Pietermaritzburg (EM) and Point Drift-Pietermaritzburg (PD)) had varying road surface profile and distances to the Pietermaritzburg. Each route also had varying proportions of rough roads and asphalt roads. On arrival in Pietermaritzburg, the samples were immediately taken to the nearby Food Engineering laboratory of the University of KwaZulu-Natal for application of disinfection treatments and storage. The trucks were driven at a speed of 80 km h^{-1} on the highways and 60 km hr^{-1} on dirt roads.

8.3.3 Disinfection treatments

At the laboratory, the damaged and defective tomato fruit was removed from the test samples and four disinfection treatments applied to the fruit. These disinfection treatments were; dipping in chlorinated water (100 ppm, for 20 min) in combination with biocontrol (1g of B-13 yeast L^{-1} tap water, for 30 sec), dipping in hot water (42.5 °C, for 30 min), control (dipping in tap water, for 1 min) and a combination of dipping in anolyte water (Workneh *et al.*, 2012) for 5 min with biocontrol. The treated fruit was then stored in ambient and cold storage conditions (11 °C).

8.3.4 Experimental design.

The experiment was set up in a full factorial design, with three transportation routes (PD, EM, and ZZ), three fruit maturities at harvest (red, pink, green), four disinfection treatments (control, hot water, chlorinated water combined with biocontrol (described previously) and anolyte water combined with biocontrol), two storage environments (ambient storage and cold storage at 11 °C) and two harvesting seasons (Figure 8.1). Each disinfection treatment was replicated three times and sampling was carried out from each replicate over a 30-day storage period. The physicochemical, chemical and nutritive quality of tomato fruit were analysed at selected storage intervals.

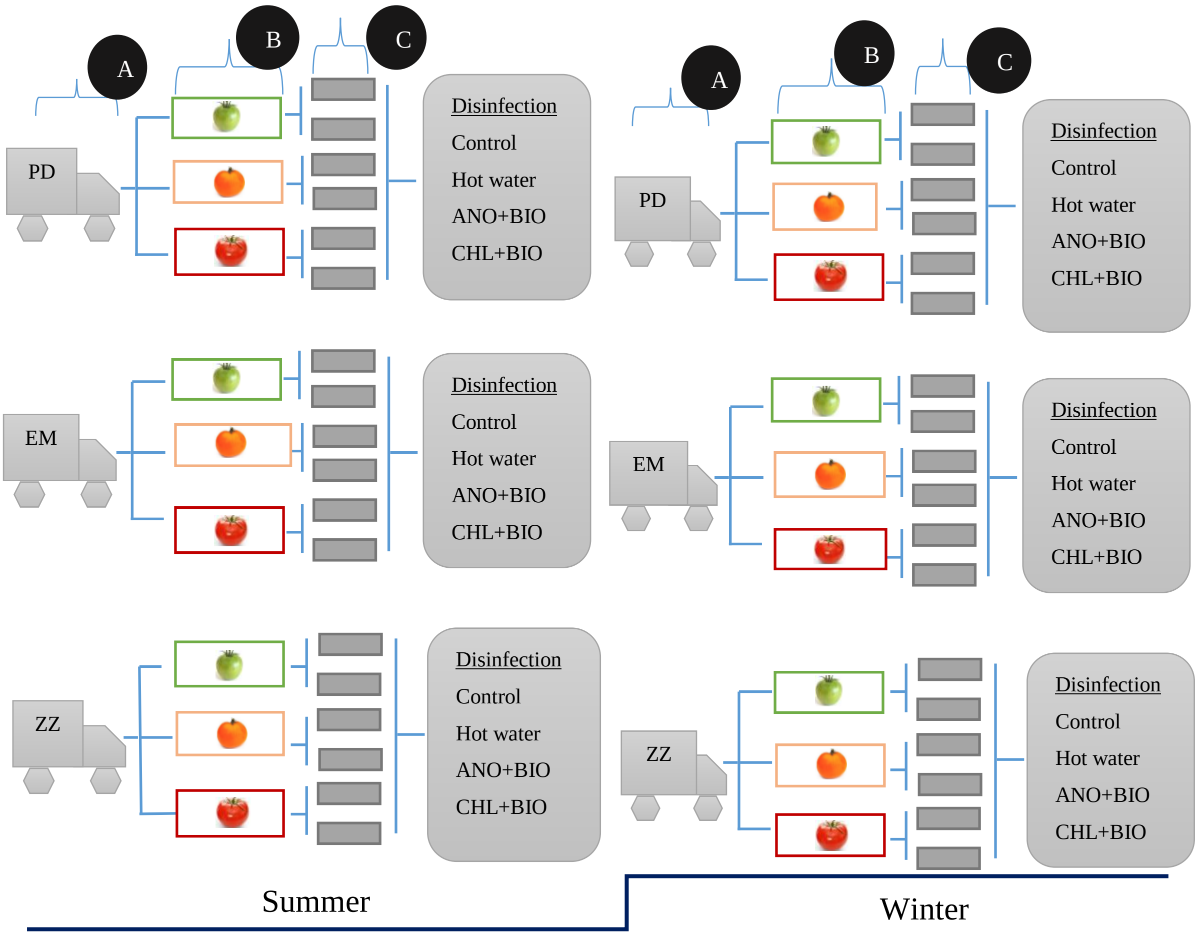

Figure 8.1 A schematic representation of the experimental design with (A) designating transportation of fruit from three farms with varying road surface profile and distances to the market, (B) the fruit maturities at harvest and (C) designating ambient and cold storage conditions (11 °C). The experiment was carried out in summer and winter. Fruit was sampled and analysed from each replicate on Day 1 and after 8, 16, 24 and 30 days of storage

8.3.5 Analysis of tomato fruits' physicochemical quality

8.3.5.1 Fruit colour

Fruit colour was measured using a Minolta Chroma meter (Model CR-400, Narachi Pty, South Africa). Readings were taken at an observer angle of 2^o, after standardizing the instrument with a white tile (Y = 93.8, X = 0.3030, y = 0.3191). Illuminant C was used to measure the L*a*b*c and h values, where two readings per fruit were taken from three fruits from each replication (Kerkhofs *et al.*, 2005; Pinheiro *et al.*, 2015).

8.3.5.2 Firmness

Tomato fruit firmness was tested using Instron universal testing machine (model 3345, Advanced Laboratory Solutions, South Africa) attached to a 6.1 mm flat end stainless steel probe at a cross-head speed of 20 mm min^{-1}. The force-deformation curves were automatically recorded by the Bluhill® software (Batu, 2004), which also reported the maximum force required to puncture the tomato skin. The slope of the force-deformation curves (secant modulus) were used to assess the consumer acceptability of the samples at selected storage intervals, based on the criteria developed by Adegoroye *et al.* (1989), where samples with a firmness >1.48 N mm^{-1} are acceptable for sale in supermarkets, those >1.28 and <1.48 N mm^{-1} are suitable for home use for making salads and those below 1.28 N mm^{-1} unacceptable for commercial or home use. Three fruits was tested per replication, and results reported as the maximum puncture force (N) (Batu, 2004).

8.3.5.3 pH

Product pH was measured using a pH meter (Orion Star A210, Thermo Scientific, South Africa) with a probe designed to measure solids (Favati *et al.*, 2009). The instrument was first standardized using 4.01, 10.00 and 7.00 pH buffers. Two tomato fruits were macerated using a food processor (Philips Model HR2106/01, Makro, Pietermaritzburg, South Africa) for 1 minute and the juice extracted into a 50 mL beaker, using a cheesecloth. The pH of the extracted aliquot was then determined using the pH meter. Readings were taken from six fruits per replication, for the selected sampling days.

8.3.5.4 Weight-loss

Weight-loss was determined at selected storage intervals using the method proposed by Pinheiro *et al.* (2013). Three batches of three tomatoes per treatment were marked and weighed on Day 1 and the percentage weight-loss reported on day 8, 16, 24 and 30, relative to Day 1.

8.3.5.5 Fruit marketability

Subjective quality tests were performed to ascertain the proportion of the sample that was marketable. The overall visual appearance was the primary criterion used to judge if samples were still marketable during sampling. Fruit that was perceived to have shrivelled excessively, to have decayed or to have been physiologically damaged in any way, and that could not be sold at the local markets, was considered unmarketable and was therefore removed from the test sample during sampling. This procedure followed the method used by Tadesse *et al.* (2012).

8.3.6 Analysis of chemical and nutritive quality

Chemical and nutritive quality analyses were carried out for each treatment in triplicate, for fruit sampled on Day 1, and after 8, 16, 24 and 30 days of storage. These analyses are briefly described as follows:

8.3.6.1 Sugars

The analysis of tomato sugars followed the method suggested by Baldwin et al. (1991) with modification. In summary, a quarter of three frozen tomato samples per replication was crushed in liquid nitrogen, and then 0.1 g of the crushed sample weighed into a test tube and 10 mL of 80 % ethanol added to it. The mixture was then sonicated using ultraturrax mixer (model IKA T25D, Cole-Parmer, South Africa) at 8600 rpm for one minute. The homogenate was thereafter incubated in a water bath set at 80 ^oC for an hour, removed and left to stand overnight at 4 ^oC. This homogenate was then filtered through glass wool into 20 mL scintillation vials then dried in a vacuum evaporator (Genvac personal evaporator, model EZ2.3, SP Scientific, England) set at 45 ^oC for 6 hours. Two mL Ultra-pure water was then added to the dried extract and filtered through a 0.45 µm nylon syringe filter (Merck Pty, Durban, South Africa). The 20 µL of the filtrate was finally injected into a HPLC column set at 85 ^oC, with ultra-pure water as the mobile phase flowing at 0.6 mL min^{-1}. The sugars were detected by differential refraction using a RID detector (RID-10A, Shimadzu, South Africa). Standards were run and their retention times ascertained.

8.3.6.2 Ascorbic acid

Ascorbic acid (AA) content of the tomato samples was analysed titrimetrically using the method suggested by Marfil et al. (2008). In summary, 25 g of fruit tissue was homogenized in 50 g oxalic acid (containing 2 g of oxalic acid per 100 g of solution) in a food blender (Philips Model HR2106/01, Makro, South Africa) for 1 minute. The extracted aliquot (20 g) was then diluted to 50 mL using the extracting solution and vacuum filtered through a Whiteman's filter paper to a 100 mL volumetric flask. The aliquot (10 mL) was thereafter titrated against DCIP solution (0.01g per 100 g of solution) to a rose-pink end-point. The volume of DCIP used for each titration run was then used to calculate the AA content of the tomato samples based on molar ratios and concentrations of reacting solutions.

8.3.6.3 Lycopene

Lycopene content was determined using the method reported by Davis et al. (2003). In brief, approximately 25 g of tomato was added to distilled water (W/V) and blended for 30 sec using a food blender (Philips Model HR2106/01, Makro, South Africa). The puree (0.6 g) was then weighed and put in a 40 mL amber screw top vial containing 5 mL 0.05 % HBT, 5 mL 85 % ethanol and 10 mL hexane. The mixture was then shaken in ice at 180 RPM for 15 min using an orbital shaker (KS 130 orbital shaker, IKA, Staufen, Germany) and thereafter, 3 mL of deionized water added and shaken in ice for an additional 5 min. The mixture was finally left for 5 min to allow phase separation, then the absorbance of the upper hexane layer was measured at 503 nm in a 1 cm path glass cuvette against hexane as the blank. Lycopene content was calculated using Equation 8.1.

$$\text{Lycopene}\left(\frac{\text{mg}}{\text{kg of tissue}}\right)=\frac{\text{A}_{503}\times 31.2}{\text{g of tissue used}} \tag{8.1}$$

Where A_{503} is the absorbance at 503 nm.

8.3.7 Data reduction using principal component analysis

8.3.7.1 Theoretical background of principal components analysis

Principal Components Analysis (PCA) is a modern data analysis tool that has recently gained popularity in the analysis of food quality data (O'farrell *et al.*, 2005; Sobratee and Workneh, 2015b; Sobratee and Workneh, 2015a). The theoretical application of PCA to the analysis of food quality data has been adequately described by Sobratee and Workneh (2015a).

In summary, PCA involves the extraction of relevant information from large and confusing data (Jolliffe, 1986). It provides a means through which complex and latent relationships in a dataset are revealed by reducing the data to a lower dimension (Sobratee and Workneh, 2015a). In this way, the data is expressed in a form that ensures that the important dynamics of the data are expressed, while compartmentalizing sections of it that are redundant (Shlens, 2014). It involves re-expression of the dataset in a linear combination of its basis vectors in the form of Equation 8.2, given by,

$$Y = PX \tag{8.2}$$

Based on a dataset X, a matrix m by n dimensions is developed, with m being the number of observation types in the experiment and n the sample size. P is the principal components of X. An orthogonal matrix P in the form Y=PX can be found such that,

$$C_Y = \frac{1}{n} YY^T \tag{8.3}$$

In Equation 8.3, C_Y is a diagonal matrix that relates to the principal components by Equation 8.4 given by,

$$C_Y = PC_XP^T \tag{8.4}$$

With C_X being a square symmetric m by m matrix.

PCA assumes that the dataset has high signal to noise ratio, with components that have large variances (Shlens, 2014). It also assumes that principal components are orthogonal hence solvable using linear algebra decomposition methods such as Eigen vector decomposition and Singular value decomposition (Shlens, 2014).

8.3.7.2 Principal components analysis of tomato fruit quality data

All the dependent variables were assessed using multiple principal component analysis (PCA) in order to establish the interrelationships of the measured quality changes in tomato fruit during transportation and storage. The approach used in the analysis followed the method described by Sobratee and Workneh (2015a). SPSS version 24 (IBM, USA) was used for the analysis.

8.4 Results and Discussion

The disinfection treatments had a significant ($p \leq 0.05$) effect on tomato fruit marketability. Fruit marketability also decreased with storage period across all disinfection treatments. The mean fruit marketability after 8 days of storage was well above 80 % across all the disinfection treatments. Figure 8.2 shows the changes in fruit marketability with storage across the disinfection treatments.

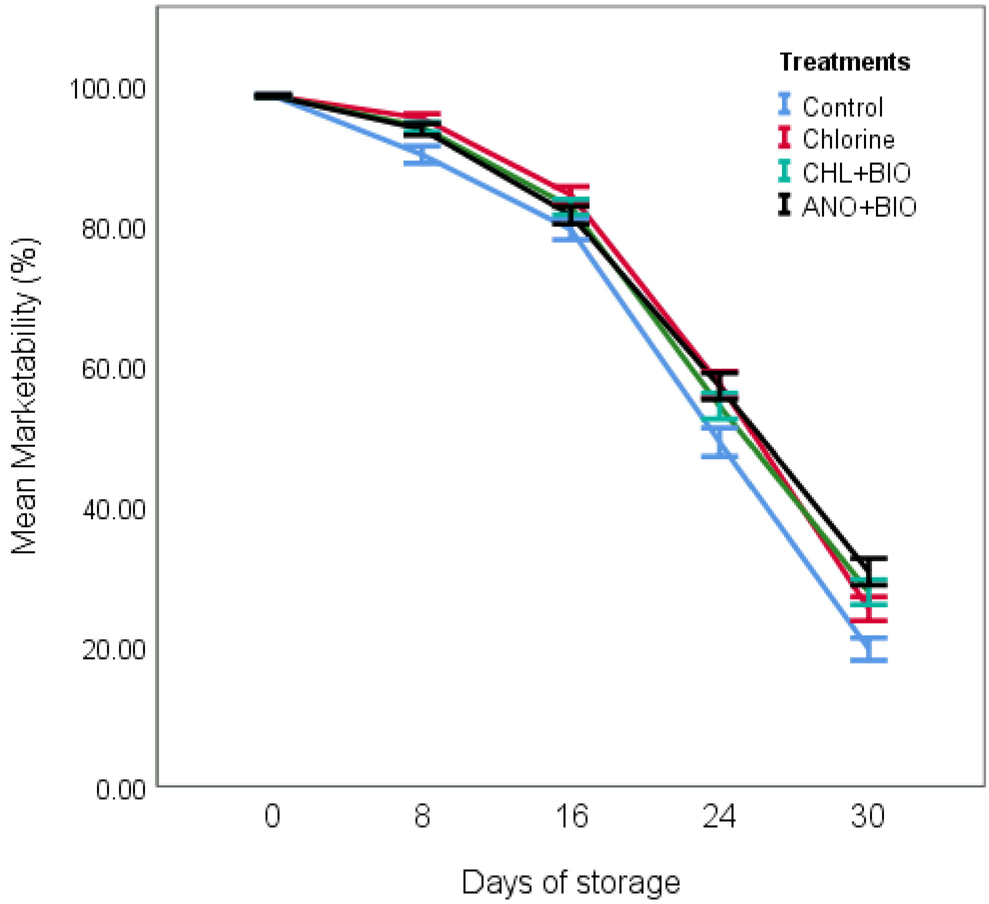

Figure 8.2 Changes in the marketability of fruit subjected to various disinfection treatments

Fruit treated with hot water and control-treated fruit had the lowest marketability values over the 30-day storage period. Anolyte water combined with biocontrol appeared to give fruit with highest marketability over the storage period.

Marketability of fruit is a subjective quality attribute that aggregates the visual and tactile cues as perceived by tomato consumers, and are used to judge if fruit salable or not (Workneh *et al.*, 2012). It is one of the widely-used subjective quality test on a range of fresh fruit and vegetables (Workneh *et al.*, 2012). Fruit marketability is a useful measure in judging the overall quality of tomatoes and it mimics the procedure used by consumers at the market, when deciding whether or not to buy a batch of tomato fruit.

Figure 8.3 shows the changes in consumer acceptability of tomato fruit with storage. The disinfection treatments were found not to have a significant ($p>0.05$) effect on consumer acceptability. It can also be seen that changes in fruit marketability and consumer acceptability with storage showed similar trends (Figure 8.2 and 8.3), with anolyte water combined with biocontrol recording the highest marketability and consumer acceptability. All the fruit subjected to the disinfection treatments were acceptable for sale in supermarkets after eight days of storage. The selected treatments also show that tomatoes treated using ANO+BIO were acceptable for home use for up to 30 days of storage.

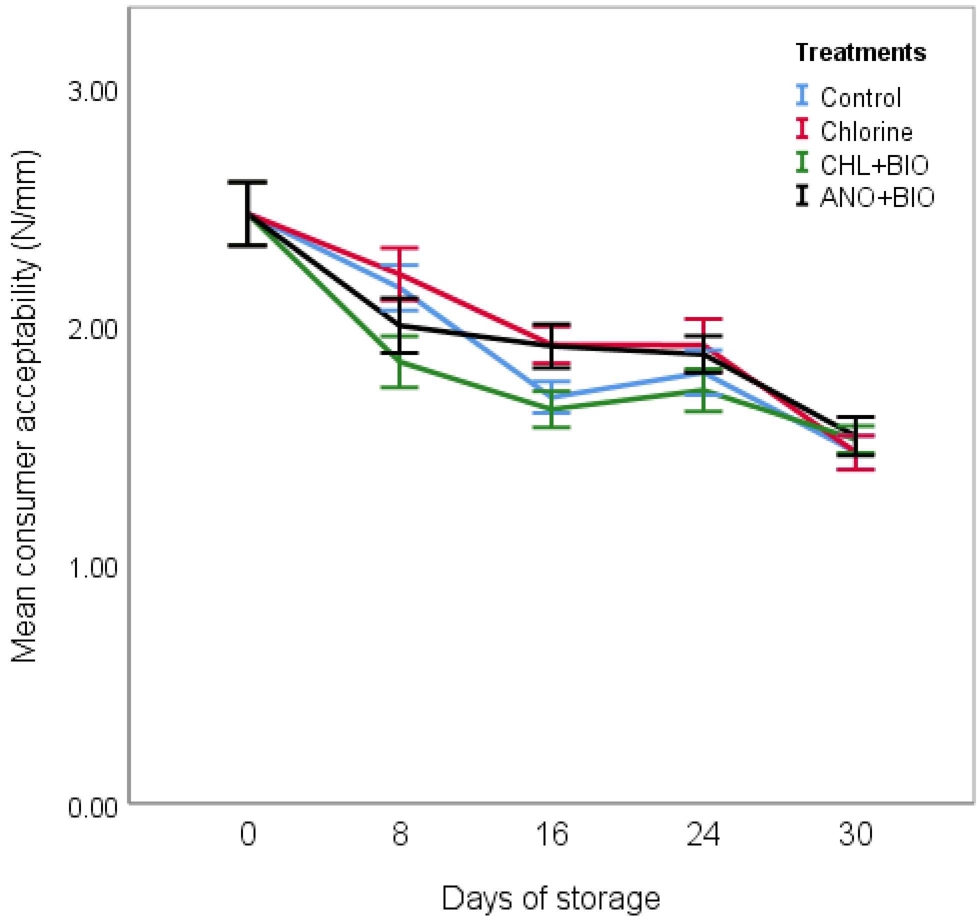

Figure 8.3 Changes in the consumer acceptability of fruit subjected to various disinfection treatments

Consumer acceptability is a sensory attribute linked to tomato fruit firmness that categorizes uses of fruit based on the slope of their force-deformation curves. The disinfection of tomatoes is linked to the control of microbial contaminants on the fruit. Microbial contaminants in FFVs cause the decay of fruit and other forms of fruit spoilage that alters their appearance (Workneh *et al.*, 2012; Sobratee and Workneh, 2015a). This may explain why the disinfection treatments had a significant ($p \leq 0.05$) effect on marketability and not the consumer acceptability. The results suggest that tomato appearance, which seemed affected mainly by microbial quality, had a higher impact on marketability than firmness.

8.4.1 Classification of tomato fruit quality data using PCA

8.4.1.1 Physicochemical quality parameters

Exploratory principal component analysis (EPCA) is used as a data reduction technique to explore the complex relationship among variables. Nine variables were transformed into principal components. A value of 0.741 was obtained for the Kaiser -Meyer-Olkin Measure of Sampling Adequacy (KMO). The Bartlett's Test of Sphericity was also found to be significant (p-value < 0.001). About 74.32 % of the variation in the data was explained by the first three principal components. The Monte Carlo Parallel Analysis, also supported the idea that three components must be retained as shown in the Scree-parallel plot (Figure 8.4). The three components, PC1, PC2 and PC3 explained 46.45 %, 14.84 % and 13.03 % of the variability in the data, respectively.

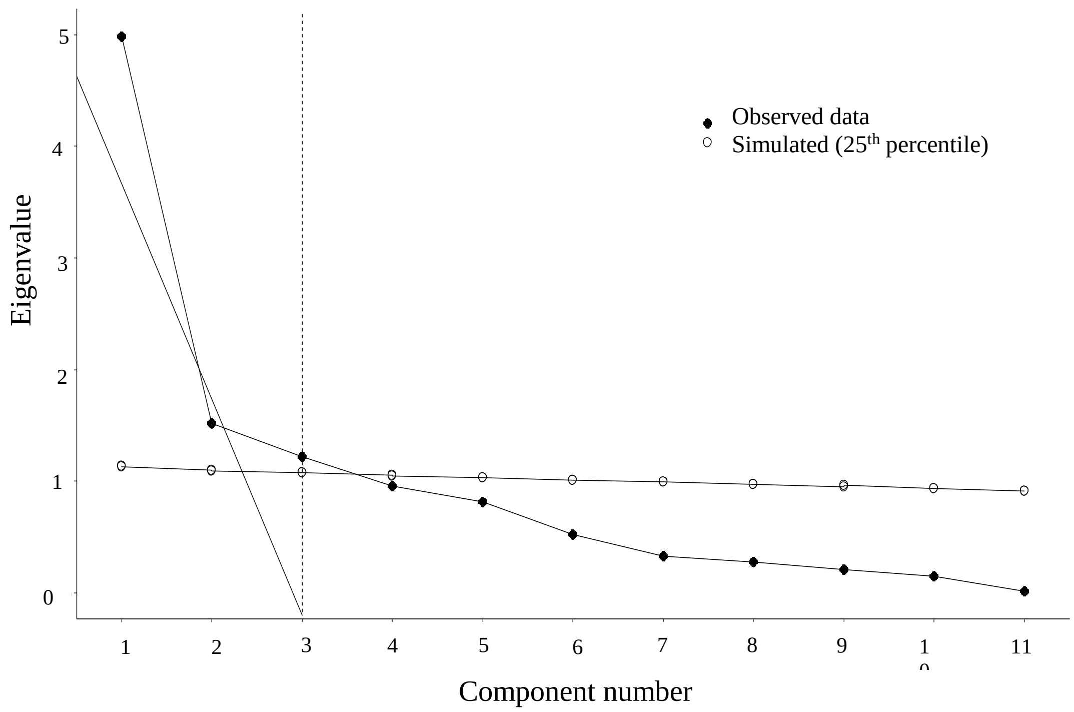

Figure 8.4 Scree-parallel plot with observed and parallel analysis-derived and estimated eigenvalues

The component loadings indicate how much of the variation in a variable is explained that the component. The larger the component loadings, the more important the variable is to that component, irrespective of the sign of the loading. In Table 8.1, Principal Component 1 (PC1) is strongly positively correlated to the variables, colour, L*, firmness, marketability and Consumer acceptability (p-value <0.001). PC1 is also strongly negatively correlated to the variables a* and weight-loss (p-value <0.001). PC1 can therefore be considered as a contrast between the set of Group 1 variables (firmness, colour, L*, marketability and Consumer acceptability) and Group 2 variables (a*, and weight-loss). Moreover, the same component is characterized by categorical variables maturity stage, storage and route (p-value <0.001). This result is obtained by performing a one-way analysis of variance with the coordinates of the individual factors, and then for each category of the categorical variable. A Student's t- test is used to compare the average of the category with the general mean (Husson *et al.*, 2010).

Table 8.1 Correlation between variables and the three principal components (Component loadings)

Correlation with PC1			Correlation with PC2			Correlation with PC3		
Variables	R^2	P-Value	Variables	R^2	P-Value	Variables	R^2	P-Value
Colour	0.923	< 0.001	b*	0.72	< 0.001	pH	0.678	< 0.001
L*	0.849	< 0.001	Marketability	0.388	< 0.001	b*	0.516	< 0.001
Firmness	0.814	< 0.001	a*	0.33	< 0.001	L*	0.286	< 0.001
Marketability	0.681	< 0.001	L*	0.057	< 0.001	a*	0.087	< 0.001
Consumer acceptability	0.587	< 0.001	Consumer acceptability	0.042	0.005	Consumer acceptability	-0.401	< 0.001
pH	0.154	< 0.001	Firmness	-0.049	< 0.001	Weight loss	-0.053	0.005
b*	0.108	< 0.001	Colour	-0.218	< 0.001	Firmness	-0.191	< 0.001
Weight loss	-0.700	< 0.001	Weight loss	-0.306	< 0.001			
a*	-0.887	< 0.001	pH	-0.625	< 0.001			
Categorical variables								
Maturity	0.173	< 0.001	Season	0.081	< 0.001	Season	0.162	< 0.001
Storage	0.036	< 0.001	Route	0.071	< 0.001	Route	0.033	< 0.001
route	0.003	< 0.001	storage	0.02	< 0.001	Maturity	0.004	< 0.001
			Maturity	0.01	< 0.001	storage	0.001	0.03
Coordinates of quality measures								
Dimension of category	Estimate	P-value	Dimension of category	Estimate	P-value	Dimension of category	Estimate	P-value
Green	1.153	< 0.001	Summer	0.327	< 0.001	Winter	0.406	< 0.001
Cold	0.398	< 0.001	EM	0.407	< 0.001	PD	0.146	< 0.001
EM	0.14	0.002	Cold	0.227	< 0.001	EM	0.118	< 0.001
PD	-0.097	0.022	Red	0.108	< 0.001	Pink	0.084	< 0.001
Pink	-0.21	< 0.001	Pink	-0.053	0.03	Ambient	0.032	0.03
Ambient	-0.398	< 0.001	Green	-0.054	< 0.001	Cold	-0.033	0.043
Red	-0.942	< 0.001	ZZ	-0.095	< 0.001	Green	-0.075	< 0.001
			Ambient	-0.227	< 0.001	ZZ	-0.263	< 0.001
			PD	-0.312	< 0.001	Summer	-0.406	< 0.001
			Winter	-0.327	< 0.001			

The coordinates of the quality measures for the green maturity stage are significantly higher than average on the first component, whereas the coordinates of the other two maturity stages (pink and red) are lower than the average (See estimates in Table 8.1). The coordinates of quality measures for fruit stored in cold storage conditions are significantly higher than average on the first component, while the coordinates of ambient storage are lower than average. With reference to the route, the coordinates of quality measures for the EM route are higher than the average on the first component, whereas the coordinates of the ZZ are lower than average.

The second Principal Component (PC2) mainly contrasted tomato b* and pH (p-value <0.001) values. The second component has significant positive correlation with marketability and b*, while negatively correlating with weight-loss. Moreover, this component is characterized by categorical variables, season, route, storage and maturity stage (p-value <0.001). The coordinates of the quality measures for the summer season are also significantly higher than average on the second component, whereas the coordinates of the winter season are lower than the average (See estimates on Table 8.1). The coordinates of quality measures for cold storage environment are significantly higher than average on the second component, while the coordinates of ambient storage are lower than average. With reference to the route, the coordinates of quality measures for the EM route are higher than the average on the second component, whereas the coordinates of the ZZ route are lower than average.

The third Principal Component PC3 is also positively correlated with b* and pH (p-value < 0.001). PC3 is characterized by categorical variables, season, route, maturity stage and storage. The coordinates of quality measures for winter are significantly higher than average on the third component, while the coordinates of summer are lower than average. With reference to the route, the coordinates of quality measures for PD and EM routes are higher than the average on the third component, whereas the coordinates of the ZZ route are lower than average. From the above description, we can see that all three components are affected by maturity stage, storage and route. A graphical representation of the components and their correlation with the variables is presented in Figure 8.5 and 8.6.

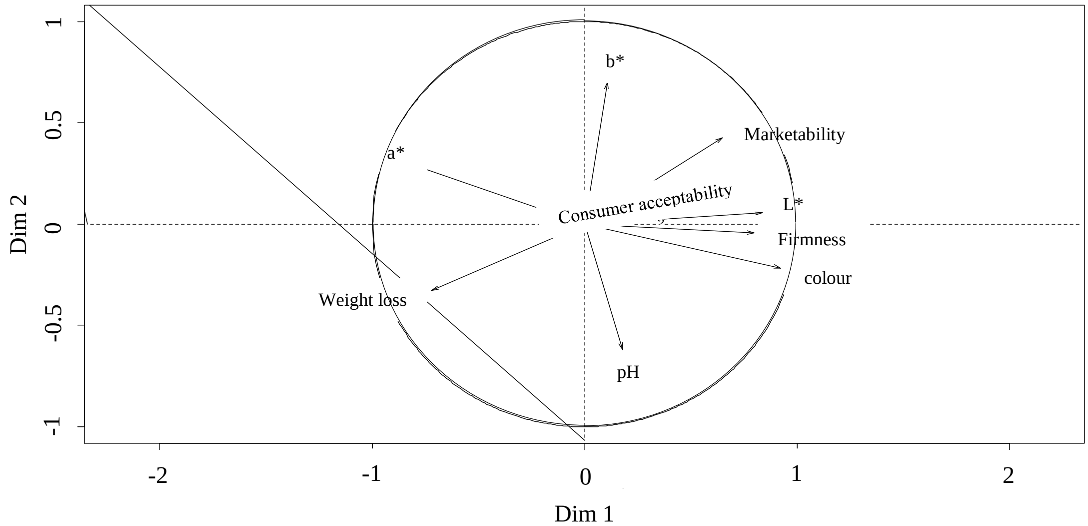

Figure 8.5 Visualization of the correlation coefficients between variables and the principal components, PC1 and PC2

In the Figures each, variable was presented on a graph using its correlation coefficient with the Principal Components as coordinates. That means each variable is represented within a circle of radius 1. The representation of a variable in each plane is obtained directly on the graph by looking at its distance from the circle of radius one. For instance, the large correlation between color and PC1 (see Figure 8.5) is indicated by the arrow that extends from the center to the right-hand side of the circle. This indicates that there is strong positive relationship between PC1 and color.

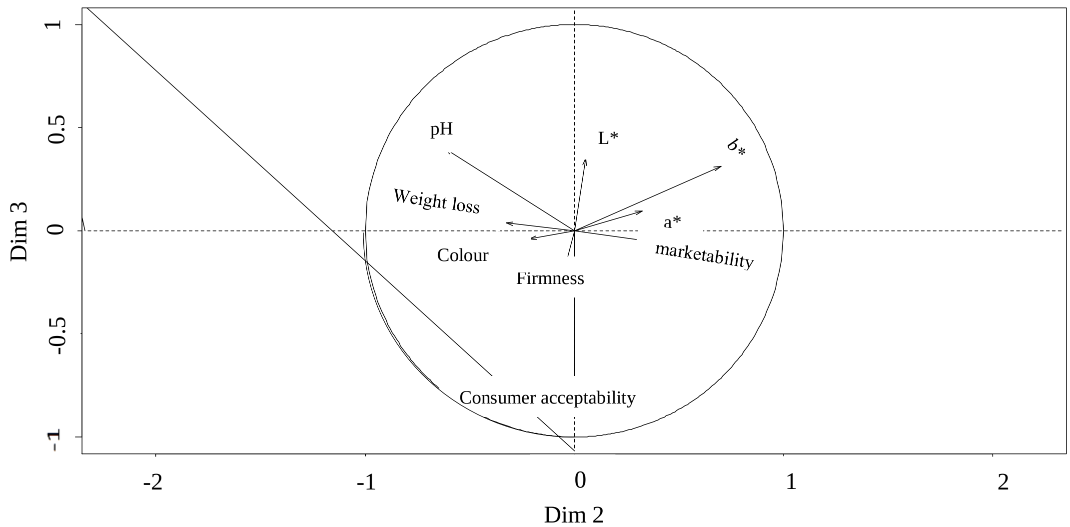

Figure 8.6 Visualization of the correlation coefficients between variables and the principal components, PC2 and PC3

PC1 is therefore related to the tactile and visual appearance (objective and subjective) that consumers commonly base their buying decisions upon, due to the high loadings of marketability, colour, consumer acceptability and firmness on this component. Similarly, PC2 relates to tomato fruit ripening processes due to its link in the weight-loss and a*. Weight-loss and a* in tomatoes are parameters driven by respiration, accumulation of lycopene and climacteric processes in tomatoes that modulate the ripening process. PC3 relates to the chemical and biochemical processes in tomatoes due to its high loadings on pH, L* and b*. PC1 was also related to fruit of green maturity stage, that were stored in cold conditions and transported through the EM due to the positive dimensions' estimates given in Table 1. Combination of these process parameters from previous analysis, depict it as fruit with minimal mechanical damage and the longest shelf-life. PC2 was related to fruit of red maturity stage, fruit harvested in the summer, transported through the EM route and stored in cold storage conditions. This combination of supply chain parameters from our previous analysis, had comparatively the shortest shelf-life with minimal mechanical damage during transportation. Similarly, PC3 relates to fruit of pink maturity stage, harvested and transported in the winter through PD or EM and stored in ambient storage. This combination of parameters from previous analysis was fruit that had slight mechanical damage and medium shelf-life.

8.4.1.2 Chemical and nutritive quality parameters

PCA of nutritive and chemical quality data during the storage of tomato fruit subjected to various transportation, disinfection and storage treatments showed that the data can be reduced to three components PC1, PC2 and PC3. PC1, PC2 and PC3 explained 38.96, 21.14 and 20.67 % of the variance in the data, respectively. The three components accounted cumulatively for 80.67 % of the total variance in the data. Both KMO and Bartlett's test supported the analysis, with a KMO value of 0.62 and a significant p ($p < 0.01$) value for Bartlett's test. Figure 8.7 shows a scree plot that supports retaining the three components.

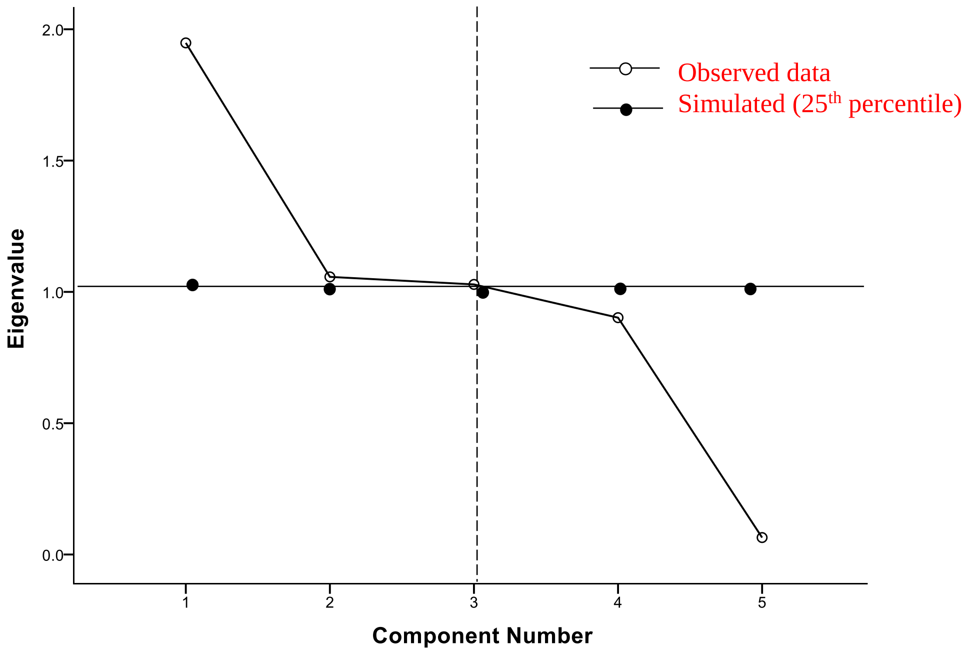

Figure 8.7 Scree-parallel plot with observed and parallel analysis -derived estimated eigenvalues

Glucose and fructose heavily loaded on PC1, while glucose to fructose ratio heavily loaded on PC2. Lycopene and AA heavily loaded on PC3. PC1 can be interpreted as a parameter that relates to the overall sugar system in the fruit. This parameter could be important in determining the sensory quality of the fruit, particularly the sweetness as, fructose loaded heavier than glucose on this component. This component could also be related to the ease of spoilage of fruit due to the relative abundance of substrates for microbial growth and spoilage. This could be a risk loading factor, especially in tomato fruit postharvest systems with inadequate disinfection regime. Glucose to fructose ratio heavily loaded on PC2, and could be interpreted as a parameter that represents tomato fruit sugar metabolism, as this quality attribute changes during fruit ripening (Davies and Kempton, 1975). AA and lycopene content heavily loaded on PC3, and could be grouped as biochemical factors of the fruit that contribute to fruit's antioxidant capacity. This component could be used as an overall measure of the fruit's contribution to consumer's health as the two quality attributes are known for their immune- and health-boosting properties on human health. Plots of each pair of components in a two-dimensional space, with the distance from the center of the circle giving the correlation coefficient of each quality attribute to each component are shown in Figure 8.8 and 8.9.

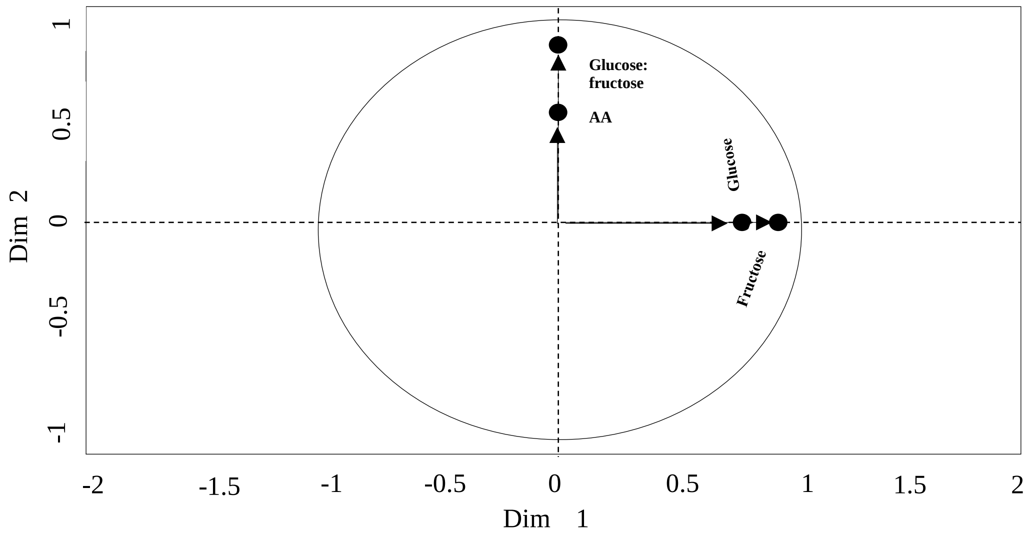

Figure 8.8 Visualization of the correlation coefficients between variables and the principal components PC1 and PC2

In a study by Sobratee and Workneh (2015a) that used PCA to analyze the relationships between different tomato fruit quality parameters during storage, three principal components were extracted, with one components consisting of glucose, fructose, total sugar and sucrose equivalent. They also concluded that this component was related to fruit sweetness and fuels metabolic processes such as respiration and related metabolic processes. This observation is in agreement with findings reported in the present study.

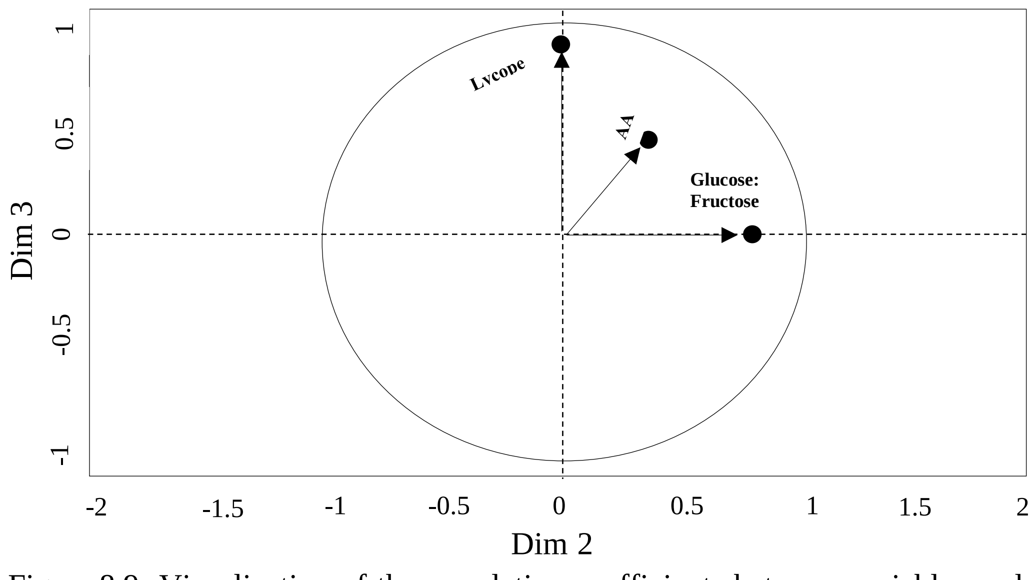

Figure 8.9 Visualization of the correlation coefficients between variables and the principal components PC2 and PC3

8.5 Conclusion

In this study, a multivariate analysis approach was used to establish the relationships between various physicochemical, nutritive and chemical quality parameters of tomato fruit subjected to different disinfection, transportation and storage treatments. Based on the PCA of physicochemical quality attributes, three components (PC1, PC2 and PC3) were extracted that were related to the visual appearance of fruit, the fruit ripening processes, as well as the chemical and biochemical processes in the fruit. Similarly, three components were extracted from the chemical and nutritive quality attributes related to the sugar composition of the fruit, sugar metabolic pathways and antioxidant capacity of the fruit. In the two data sets, the components (PC1, PC2 and PC3) explained 74.32 % and 80.66 % of data relating to the physicochemical quality parameters and chemical and nutritive quality attributes, respectively. The study has brought forth components that have the following underlying attributes: i) PC1 describes fruit with a long shelf-life and minimal damage during transportation; ii) PC2 describes fruit with the shortest shelf-life and minimal damage during transportation; and iii) PC3 describes fruit with a moderate shelf-life and slight mechanical damage during transportation. Based on factor loadings of samples on the principal components, the quality and shelf life of fruit can be predicted. The developed models can therefore, be trained and used for the prediction of the shelf life of tomato fruit quality data.

8.6 Acknowledgement

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9. MODELING QUALITY KINETICS OF TOMATO FRUIT SUBJECTED TO VARIOUS TRANSPORTATION, DISINFECTION AND STORAGE TREATMENTS

9.1 Abstract

In this study, models for the prediction of tomato fruit quality changes under commercial supply conditions were developed, based on their physicochemical quality attributes during transportation, distribution and storage. The experimental design involved tomatoes of three maturity stages (red, pink and green), three transportation routes from Limpopo to Pietermaritzburg (PD, EM and ZZ), two storage conditions (cold storage at 11 ^{o}C and ambient storage), two harvesting seasons (summer and winter) and four disinfection treatments. Various tomato fruit physicochemical, nutritive and chemical quality attributes were measured during storage. Quality kinetic models were also developed and used to estimate fruit shelf-life under four storage temperature regimes (winter-cold, winter-ambient, summer-cold and summer-ambient). Fruit hue angle and firmness followed second-order degradation kinetics, while tomato fruit marketability and weight loss followed zero-order quality degradation kinetics. The coefficient of determination (R^2) of models developed to predict fruit weight loss were above 0.94, while those of models developed to predict marketability ranged from 0.52 to 0.97. Based on the fruit hue angle, the kinetic models estimated the shelf-life of tomatoes stored under ambient and cold storage conditions, to be 10 and 21 days, respectively. The developed models are potentially useful tools for process control and design for the supply, distribution and storage of tomatoes under commercial conditions.

Keywords: *anolyte water; model functions; predicted shelf-life; processing parameters; transportation conditions*

9.2 Introduction

Tomatoes are important fresh fruits globally with many culinary uses (Beckles *et al.*, 2012). Their popularity is not only linked to the wide range of uses tomatoes are put to, including preparation of salads, salsa or processing into juices, but also the numerous health benefits derived by the consumers (Dorais *et al.*, 2008). Tomatoes are also known to be among some of the most perishable fresh commodities, whose quality starts declining immediately after harvest (Sammi and Masud, 2007). Their perishable nature is associated to a host of pre- and post-harvest factors. The ripening of tomatoes, depict a climacteric peak that is controlled at the biochemical and genetic level (Tucker *et al.*, 2007). Their perishability is also linked to external and environmental factors that are significant, from a post-harvest quality management perspective (Paull, 1999). Other microbial and enzymatic processes also occur during the post-harvest phase of fresh tomatoes that lead to changes in different quality parameters (Moneruzzaman *et al.*, 2008; Liu *et al.*, 2015). These changes can be modulated using different process operations. For instance, temperature control has been cited as one of the most important unit operations for maintenance of the quality of fresh fruits and vegetables (FFV)(de Castro *et al.*, 2005).

Cold chain management in tomato commercial supply chains is a standard practice that is implemented during storage and at different phases of transportation and distribution (Kumar *et al.*, 2008). Other processing operations occur in commercial supply chains that have to be carefully selected and optimized in order to have fruit of high quality and lengthened shelf-life. Control of microbial contamination using a range of disinfection treatments, packaging to manage respiration and gas exchange, as well as careful handling during transportation to minimize fruit damage, are all important processing operations in tomato fruit commercial supply chains (Workneh *et al.*, 2012; Sibomana *et al.*, 2016). The effect of these operations in maintaining tomato fruit quality and shelf-life should be well understood and predicted accurately in order for processors, distributors and transporters in tomato commercial value chains to adequately design systems that meet their objectives. This is especially important in the case where alternative combinations of integrated agro-technologies are available for selection. However, conventional laboratory procedures are required to obtain data on different quality changes during transportation and storage. The analytical laboratory techniques and procedures used to obtain the experimental quality data are costly, time-consuming and require technical knowledge and instrumentation.

Approaches used to assess process conditions and their effect on food quality parameters have recently attracted huge research interest, especially for perishable fresh foods (Sobratee and Workneh, 2015; Melesse *et al.*, 2016; González-Tejedor *et al.*, 2017). In a study by Sobratee and Workneh (2015), the kinetics of quality degradation of carrot were represented using first and second order kinetic functions involving eleven different microbial and biochemical quality attributes of carrot. These functions are especially important in predicting changes in physicochemical and nutritive quality of FFV, including tomatoes. Prediction of the quality changes of tomatoes under different processing conditions is important especially in commercial supply chains, where profit margins are volume driven, and minute improvements in quality and shelf-life translates into improved margins. Although the study by Sobratee and Workneh (2015) involved the analysis of pre- and post-harvest processing operations of carrots, it did not account for practicalities in their supply and distribution, which can exacerbate quality degradation of FFV.

In the present study, tomato fruit was transported through road sections with varying surface profiles to mimic normal transportation conditions. Various disinfection treatments, storage environments and fruit of different maturities were tested across two harvesting seasons. Ten quality parameters were assessed during storage and models developed using experimental data for the first time. The study sought to develop models for the prediction of kinetics of quality degradation of fresh tomatoes during their transportation and storage. These models would be used by processors, retailers and other tomato supply chain actors in designing their operations based on the predicted tomato fruit quality and shelf-life.

9.3 Materials and Methods

9.3.1 Tomato fruit production

Tomato fruit (*Solanum lycopersicum)* of Nemo-Netta variety was produced from three farms in Limpopo Province, South Africa. The farms were located in Esmefour (22^{o}19'48.7" S 30^{o}28'21.3" E), Pont Drift (22^{o}11'52.7" S 29^{o}11'30.7" E) and Mooketsi (23^{o}26'05.2" S 30^{o}26'47.5" E). Throughout the growing season, the crop was trained and drip irrigation implemented to the meet crop water requirement. For the entire growing season, the crop was grown under sustainable soil and water management practices (compost use, crop rotation, minimum tillage), as well as soft pest control practices. This production system is known as Natuurboerdey® system (Taurayi, 2011). The fruit was harvested at three maturity stages namely, red, pink and green, during the winter (June) and the summer (September) seasons.

9.3.2 Transportation conditions

The tomato fruit was harvested in the morning and transported in bulk bins to the respective pack-house located near each of the farms, where the fruit was precooled to remove field heat using forced air coolers for three to four hours. The fruit was then transported from each pack-houses overnight to Pietermaritzburg using non-refrigerated trucks to mimic normal supply operations. Each route (Esmefour-Pietermaritzburg (ZZ), Mooketsi-Pietermaritzburg (EM) and Point Drift-Pietermaritzburg (PD)) had varying road surface profile and distances. Each route also had varying proportions of both rough and asphalt roads. On arrival in Pietermaritzburg, the samples were immediately taken to the nearby Food Engineering laboratory of the University of KwaZulu-Natal for application of disinfection treatments and storage. The trucks were driven at a speed of 80 km h^{-1} on the highways and 60 km hr^{-1} on dirt roads.

9.3.3 Disinfection treatments

Upon arrival at the laboratory, the damaged and defective tomato fruit was removed from the test samples and four disinfection treatments applied on the fruit. The disinfection treatments involved dipping the fruit in anolyte water for 5 min (Workneh *et al.,* 2012) in combination with biocontrol. Anolyte water in combination with biocontrol was used as a typical disinfection treatment due to its effectiveness in maintaining the overall fruit quality. The treated fruit was then stored in ambient and cold storage conditions (11 ^{o}C).

9.3.4 Experimental design

The experiment was set up in a full factorial design with three transportation routes (PD, EM, and ZZ), three fruit maturities at harvest (red, pink, green), four disinfection treatments (control, hot water, chlorinated water combined with biocontrol and anolyte water combined with biocontrol), two storage environments (room storage and cold storage at 11 ^{o}C) and two harvesting seasons (Figure 9.1). Sampling was carried out from each replicate over a 30-day storage period and the physicochemical, chemical and nutritional quality attributes of the fruit analysed at selected storage intervals. The disinfection treatments were replicated three times.

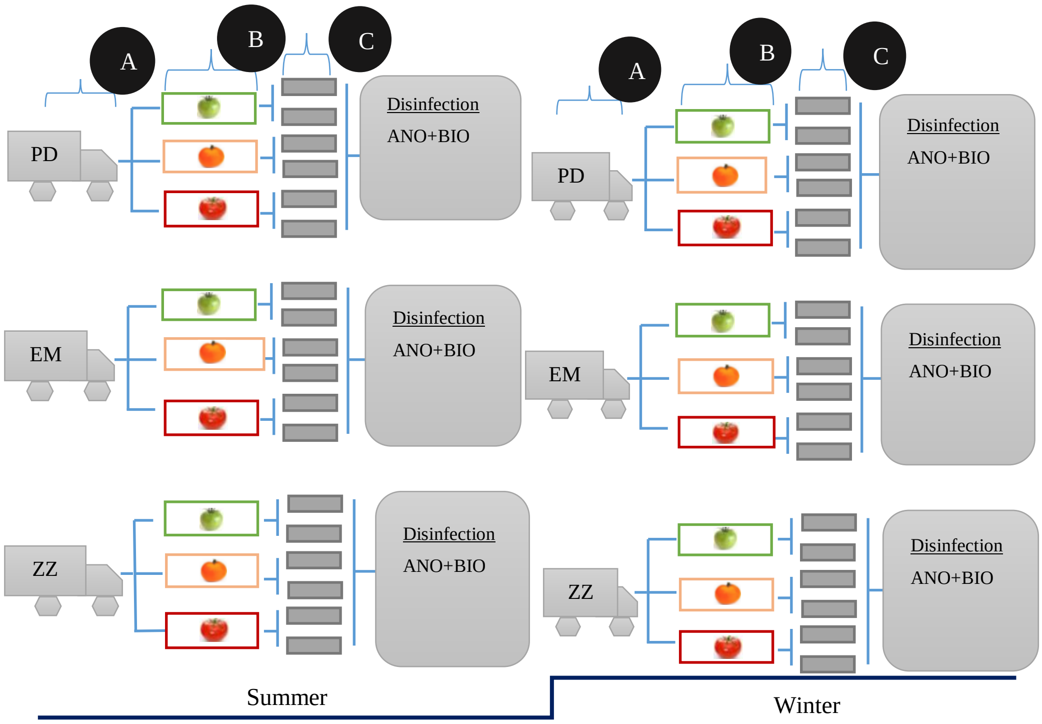

Figure 9.1 A schematic representation of the experimental design with (A) designating transportation of fruit from three farms with varying road surface profile and distances to the market, (B) designating fruit maturities at harvest and (C) representing ambient and cold storage conditions (11°C). The experiment was carried out in summer and winter. Fruit was sampled and analysed from each replicate on Day 1 and after 8, 16, 24 and 30 days of storage. ANO+BIO designates integrated treatment using biocontrol (B-13 yeast isolate) and anolyte water

9.3.5 Analysis of tomato fruits' physicochemical quality

9.3.5.1 Fruit colour

Fruit colour was measured using a Minolta Chroma meter (Model CR-400, Narachi Pty, South Africa). Readings were taken at an observer angle of 2° after standardizing the instrument with a white tile (Y = 93.8, X = 0.3030, y = 0.3191). Illuminant C was used to measure the L*a*b*c and h values, where two readings per fruit were taken from three fruits for each replication (Kerkhofs *et al.*, 2005; Pinheiro *et al.*, 2015).

9.3.5.2 Firmness

Tomato fruit firmness was tested using Instron universal testing machine (model 3345, Advanced Laboratory Solutions, South Africa) attached to a 6.1 mm flat end stainless steel probe at a cross-head speed of 20 mm min^{-1}. The force-deformation curves were automatically recorded by the Bluhill® software (Batu, 2004), which also reported the maximum force required to puncture the tomato skin. Six fruits was tested per treatment, and results reported as the maximum puncture force (N) (Batu, 2004).

9.3.5.3 pH

The pH of tomato samples was measured using a pH meter (Orion Star A210, Thermo Scientific, South Africa) with a probe designed to measure solids (Favati *et al.*, 2009). The instrument was first standardized using 4.01, 10.00 and 7.00 pH buffers. Two sample tomato fruits were macerated using a food processor (Philips Model HR2106/01, Makro, Pietermaritzburg, South Africa) for 1 minute and the juice was extracted into a 50 mL beaker, using a cheesecloth. The pH of the extracted aliquot was then determined using the pH meter. Readings were repeated thrice per treatment for the selected sampling days.

9.3.5.4 Weight-loss

Weight-loss was determined at selected storage intervals using the method proposed by Pinheiro *et al.* (2013b). Three batches of three tomatoes per treatment were marked and weighed on Day 1 and the percentage weight-loss reported on day 8, 16, 24 and 30, relative to Day 1.

9.3.5.5 Fruit marketability

Subjective quality tests were performed to ascertain the proportion of the sample that was marketable. The overall visual appearance was the primary criterion used to judge if samples were still marketable during sampling. Fruit that was perceived to have shrivelled excessively, to have decayed or to have been physiologically damaged in any way, and that could not be sold at the local markets, was considered unmarketable and was therefore removed from the test sample during sampling. This procedure followed the method used by Tadesse *et al.* (2012).

9.3.6 Analysis of chemical and nutritional quality

Chemical and nutritional quality analyses of sample tomato fruit were carried out for each treatment in triplicate on Day 1, and after 8, 16, 24 and 30 days of storage. These analyses are briefly described as follows:

9.3.6.1 Sugars

The analysis of tomato sugars followed the method suggested by Baldwin et al. (1991) with modification. In summary, a quarter of three frozen tomato samples per treatment was crushed in liquid nitrogen, then 0.1 g of the crushed sample weighed into a test tube and 10 mL of 80 % ethanol added to it. The mixture was then sonicated using ultraturrax mixer (model IKA T25D, Cole-Parmer, South Africa) at 8600 rpm for one minute. The homogenate was thereafter incubated in a water bath set at 80 ^{o}C for an hour, removed and left to stand overnight at 4^{o}C. This homogenate was then filtered through glass wool into 20 mL scintillation vials then dried in a vacuum evaporator (Genvac personal evaporator, model EZ2.3, SP Scientific, England) set at 45 ^{o}C for 6 hours. Two mL Ultra-pure water was then added to the dried extract and filtered through a 0.45 μm nylon syringe filter (Merck Pty, Durban, South Africa). The filtrate (20 μL) was finally injected into a HPLC column set at 85 ^{o}C, with ultra-pure water as the mobile phase flowing at 0.6 mL min^{-1}. The sugars were detected by differential refraction using a RID detector (RID-10A, Shimadzu, South Africa). Standards were run and their retention times ascertained. This procedure had been described previously on chapter eight.

9.3.6.2 Ascorbic acid

The ascorbic acid (AA) content of the tomato samples was analysed titrimetrically using the method described by Marfil et al. (2008). In summary, 25 g of fruit tissue was homogenized in 50 g oxalic acid (containing 2 g of oxalic acid per 100 g of solution) in a food blender (Philips Model HR2106/01, Makro, South Africa) for 1 minute. The extracted aliquot (20 g) was then diluted to 50 mL using the extracting solution and vacuum filtered through a Whiteman's filter paper to a 100 mL volumetric flask. The aliquot (10 mL) was titrated against DCIP solution (0.01g/100 g of solution) to a rose-pink end-point. The volume of DCIP used for each titration run was then used to calculate the AA content of the tomato samples.

9.3.6.3 Lycopene

Lycopene content was determined using the method described by Davis et al. (2003). In brief, approximately 25 g of tomato was added to distilled water (W/V) and blended for 30 sec using a food blender (Philips Model HR2106/01, Makro, South Africa). The puree (0.6 g) was then weighed and put in a 40 mL amber screw top vial containing 5 mL 0.05 % HBT, 5 mL 85 % ethanol and 10 mL hexane. The mixture was then shaken in ice at 180 RPM for 15 min using an orbital shaker (KS 130 orbital shaker, IKA, Staufen, Germany) and thereafter, 3 mL of deionized water added and shaken in ice for an additional 5 min. The mixture was finally left for 5 min to allow phase separation, then the absorbance of the upper hexane layer measured at 503 nm in a 1 cm glass cuvette against hexane as the blank. Lycopene content was calculated using Equation 9.1.

$$\text{Lycopene}\left(\frac{\text{mg}}{\text{kg of tissue}}\right) = \frac{\text{A}_{503} \times 31.2}{\text{g fresh of tissue used}} \tag{9.1}$$

Where A_{503} is the absorbance at 503 nm.

9.3.7 Modeling tomato fruit quality degradation kinetics

9.3.7.1 Theoretical considerations

Foods are complex mixtures of various biological materials that react together over time to yield species that influence the foods' quality (taste, texture, chemical, nutritional quality). These reactions determine the amount of time food can be stored, distributed or transported before it reaches the end of its shelf-life, where it can no longer be consumed and therefore, needs to be removed from the market (Taoukis *et al.*, 1997). Quality changes of food are controlled by compositional (enzymatic, microbiological and concentration of chemical constituents) and environmental (temperature, light, mechanical stresses, relative humidity and pressure) factors. These changes can be described in Equation 9.2, given as,

$$\frac{dQ}{dt} = F(C_i, E_j) \tag{9.2}$$

Where C_i are compositional factors and E_j environmental factors that drive quality degradation in foods.

Quality degradation in food products can be represented using Equations 9.3, 9.4, 9.5 and 9.6 described by Martins *et al.* (2008) as zero-, first-, second-order and fractional reaction kinetics, respectively.

$$C = C_o - kt \tag{9.3}$$

$$C = C_o . e^{-kt} \tag{9.4}$$

$$C = \frac{C_o}{1 + C_o kt} \tag{9.5}$$

$$\frac{C - C_{eq}}{C_0 - C_{eq}} = -e^{-kt} \tag{9.6}$$

Where C is the concentration of a quality component at time t, C_o is the initial concentration of the quality component, C_{eq} is the concentration of the final quality component at equilibrium and k (day^{-1}) is the kinetic rate of reaction.

The rate constant is influenced by the concentration of the reactant species and the temperature conditions of the reaction (van Boekel, 2008). The temperature dependence of the reaction constant is expressed by the Arrhenius Law (Taoukis *et al.*, 1997). In zero-order reaction kinetics, the concentration of reactant species in a huge excess, such that that its concretion remains largely constant throughout (van Boekel, 2008). Therefore, in this way, the k in zero-order reactions is independent of the concentration of the reactants (van Boekel, 2008).

Kinetic functions are modeled using differential or integration approaches (Taoukis *et al.*, 1997). Differential methods are, however, not preferred due to amplification of the noise ratio, hence integration methods are mostly used (Martins *et al.*, 2008). A robust approach of developing reaction kinetics of food products has been suggested by Martins *et al.* (2008), which first explores the kinetics and selects appropriate kinetic models, then uses statistical approaches to validate selected models. Such tests include goodness of fit or Student's t-analysis.

9.3.7.2 Modeling approach

The eight tomato fruit quality attributes that were measured during selected storage intervals were used to develop the fruits' kinetic models. The approach suggested by Amodio *et al.* (2015) was followed, where kinetic functions were optimized using Matlab's Curve Fitting Toolbox (Matlab version R2010a, MathWorks Inc, USA). The least squares method was used to establish the model constants. The goodness of fit was also evaluated using the correlation coefficient, significance (p-value) and confidence intervals. The value of root mean square error (RMSE) was also used to evaluate the accuracy of the models. The developed models assumed four constant storage temperature regimes. These are cold storage during the summer (Su_cold), ambient storage during the summer (Su_amb), cold storage in the winter (Wi_cold) and ambient storage in the winter (Wi_amb). It was also assumed that the quantitative changes of the quality parameters with time are due to chemical reactions of reactant species to yield new products. Integrated kinetics equations given in Equations 9.3, 9.4 and 9.5 were used and the behavior of the specific quality parameter characterized and selected using the first two replicates of the data. The third replicate was used to validate the selected models. This approach has been suggested by Sobratee and Workneh (2015).

9.4 Results and Discussion

9.4.1 Identifying kinetics of quality degradation of tomatoes

The sample tomato fruit colour, firmness, pH, marketability and weight-loss was significantly ($p \leq 0.05$) influenced by the storage and transportation temperature regimes of the tomatoes. Similarly, these transportation and storage temperature regimes had also had a significant ($p \leq 0.05$) effect on the changes in fructose, glucose, AA and lycopene content of the fruit. The four temperature regimes as averaged were; Su_amb (23.4 ^{o}C), Su_cold (16.1 ^{o}C), Wi_amb (17.9 ^{o}C) and Wi_cold (14.5 ^{o}C). The data of the nine quality parameters were fitted to zero-, first- and second-order kinetic reaction functions and showed varied degrees of goodness of fit. Table 9.1 defines the notations used to develop the model kinetic functions.

Table 9.1 Nomenclature of the developed models

Col_{S_C}	Colour for summer in cold storage	ASA_{S_A}	AA for summer in cold storage
Col_{S_A}	Colour for summer in ambient storage	ASA_{S_A}	AA for summer in ambient storage
Col_{W_C}	Colour for winter in cold storage	ASA_{W_C}	AA for winter in cold storage
Col_{W_A}	Colour for winter in ambient storage	ASA_{W_A}	AA for winter in ambient storage
Frm_{S_C}	Firmness for summer in cold storage	Fru_{S_C}	Fructose for summer in cold storage
Frm_{S_A}	Firmness for summer in ambient storage	Fru_{S_A}	Fructose for summer in ambient storage
Frm_{W_C}	Firmness for winter in cold storage	Fru_{W_C}	Fructose for winter in cold storage
Frm_{W_A}	Firmness for winter in ambient storage	Fru_{W_A}	Fructose for winter in ambient storage
Mar_{S_C}	marketability for summer in cold storage	Glu_{S_C}	Glucose for summer in cold storage
Mar_{S_A}	marketability for summer in ambient storage	Glu_{S_A}	Glucose for summer in ambient storage
Mar_{W_C}	marketability for winter in cold storage	Glu_{W_C}	Glucose for winter in cold storage
Mar_{W_A}	marketability for winter in ambient storage	Glu_{W_A}	Glucose for winter in ambient storage
pH_{S_C}	pH for summer in cold storage	Lyc_{S_C}	Lycopene for summer in cold storage
pH_{S_A}	pH for summer in ambient storage	Lyc_{S_A}	Lycopene for summer in ambient
pH_{W_C}	pH for winter in cold storage	Lyc_{W_C}	Lycopene for winter in cold storage
pH_{W_A}	pH for winter in ambient storage	Lyc_{W_A}	Lycopene for winter in ambient storage
Wtl_{S_C}	Weight loss for summer in cold storage		
Wtl_{S_A}	Weight loss for summer in ambient storage		
Wtl_{W_C}	Weight loss for winter in cold storage		
Wtl_{W_A}	Weight loss for winter in ambient storage		

9.4.1.1 Fruit colour (Hue angle)

The degradation kinetics of fruit colour (hue angle) followed second order reaction kinetics. The second-order kinetic equations had better goodness of fit as described by the coefficient of determination (R^2) than the first- and zero-order kinetic functions, as well as the fractional kinetics model. The R^2 values for these functions ranged from 0.13-0.97. Table 9.2 present typical model functions for kinetic models developed to predict the colour change of tomatoes harvested at green maturity stage across the three transportation routes and each of the storage and transportation temperature regimes. Model R^2 values and coefficients for all treatments are presented in Appendix 3.

Table 9.2 Kinetic equations for colour degradation of tomato fruit

PD			EM			ZZ		
Equation	Eq. No.	R^2	Equation	Eq. No.	R^2	Equation	Eq. No.	R^2
$Col_{S\_A} = \frac{104.6}{1+0.06276t}$	(9.7)	0.97	$Col_{S\_A} = \frac{105.4}{1+0.07378t}$	(9.11)	0.93	$Col_{S\_A} = \frac{108.7}{1+0.08696t}$	(9.16)	0.94
$Col_{S\_C} = 104.6\exp(-0.00241)$	(9.8)	0.97	$Col_{S\_C} = \frac{105.4}{1+0.06324t}$	(9.12)	0.85	$Col_{S\_C} = \frac{108.7}{1+0.04348t}$	(9.17)	0.56
$Col_{W\_A} = \frac{108.4}{1+0.07588t}$	(9.9)	0.92	$Col_{W\_A} = \frac{109.7}{1+0.08776t}$	(9.14)	0.89	$Col_{W\_A} = \frac{106.9}{1+0.07483t}$	(9.18)	0.75
$Col_{W\_C} = \frac{108.4}{1+0.01084t}$	(9.10)	0.88	$Col_{W\_C} = \frac{109.7}{1+0.05485t}$	(9.15)	0.87	$Col_{W\_C} = \frac{106.9}{1+0.04276t}$	(9.20)	0.97

Based on the model functions developed in Table 9.2, the shelf-life of ambient stored fruit harvested and transported in the summer season for fruit transported through PD, EM and ZZ was 21, 18 and 16 days, respectively. Tomato fruit hue angle threshold of 45^o has been suggested by Thai and Shewfelt (1991) as the lower limit of saleable fruit, hence this limit was used in calculating the maximum shelf-life of the fruit. The calculated shelf-life values accurately depict the reality as no samples were available beyond day 24 for fruit harvested and transported in the summer season. Similarly, from previous investigations, fruit transported through ZZ showed the highest quality degradation. Figure 9.2 shows a plot of experimental and predicted hue angle plots based on Equation 9.8. From Figure 9.2, the model fits well to the data. Based on the calculated and the predicted hue angle, it is can be deduced that the second-order kinetic functions represent the changes in hue angle of tomato fruit.

Changes in tomato fruit colour is one of the most widely modeled quality attribute used as a surrogate to predict tomato fruit quality (Schouten *et al.*, 2007; Pinheiro *et al.*, 2013b). A study by Thai *et al.* (1990) reported that the changes in tomato fruit colour follow second-order reaction kinetics. Their observations are consistent with the findings reported in the present study.

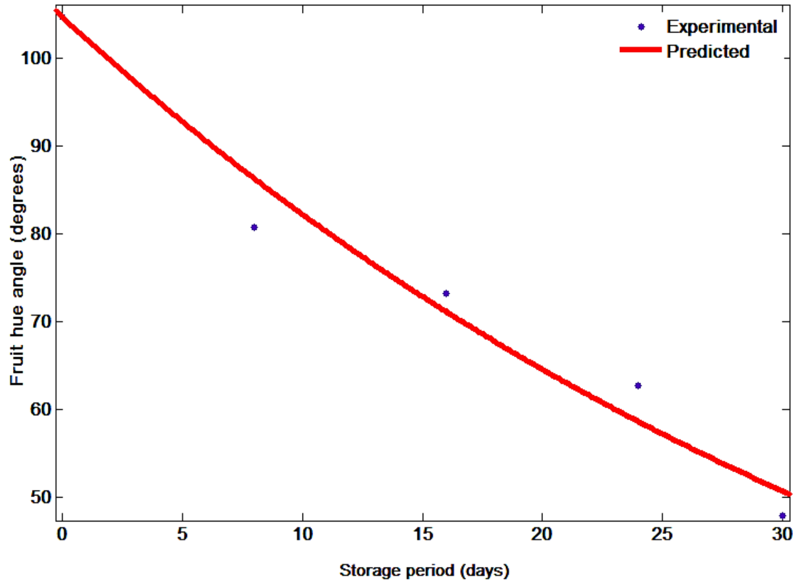

Figure 9.2 A typical plot of the experimental and predicted hue angle of tomato fruit based on Equation 9.8

9.4.1.2 Fruit firmness

Tomato fruit firmness data showed a good fit to second order kinetic equations, with most of the treatments having high R^2 values when the model was fitted to the data. The selection of the second order kinetic functions was based on the models' coefficient of determination (R^2) that ranged from 0.09 to 0.99. Table 9.3 presents a summary of typical tomato fruit firmness kinetic models for tomato fruit harvested at the green maturity stage, across the three harvesting and transportation routes.

Table 9.3 Model functions for tomato fruit firmness degradation kinetics

PD			EM			ZZ		
Equation	Eq. No.	R^2	Equation	Eq. No.	R^2	Equation	Eq. No.	R^2
$Frm_{S\_A} = \frac{32.36}{1+0.0421t}$	(9.21)	0.87	$Frm_{S\_A} = \frac{35.93}{1+0.0431t}$	(9.25)	0.96	$Frm_{S\_A} = \frac{29.98}{1+0.0479t}$	(9.29)	0.99
$Frm_{S\_C} = \frac{32.36}{1+0.0258t}$	(9.22)	0.42	$Frm_{S\_C} = \frac{35.94}{1+0.0215t}$	(9.26)	0.92	$Frm_{S\_C} = \frac{29.98}{1+0.0209t}$	(9.30)	0.47
$Frm_{W\_A} = \frac{29.09}{1+0.0329t}$	(9.23)	0.13	$Frm_{W\_A} = \frac{31.55}{1+0.0094t}$	(9.27)	0.18	$Frm_{W\_A} = \frac{34.09}{1+0.0409t}$	(9.31)	0.70
$Frm_{W\_C} = \frac{29.09}{1+0.0261t}$	(9.24)	0.80	$Frm_{W\_C} = 31.55 - 0.4532t$	(9.28)	0.85	$Frm_{W\_C} = \frac{34.09}{1+0.0238t}$	(9.32)	0.19

Based on the developed model functions and a minimum acceptable firmness of 17 N (Ali, 1998), the calculated shelf-life of tomato fruit was 34, 48 and 36 days for fruit transported through PD, EM and ZZ, respectively, for samples harvested and transported in the summer and stored in cold storage conditions. Figure 9.3 shows a plot of model fit to the data based on Equation 9.26.

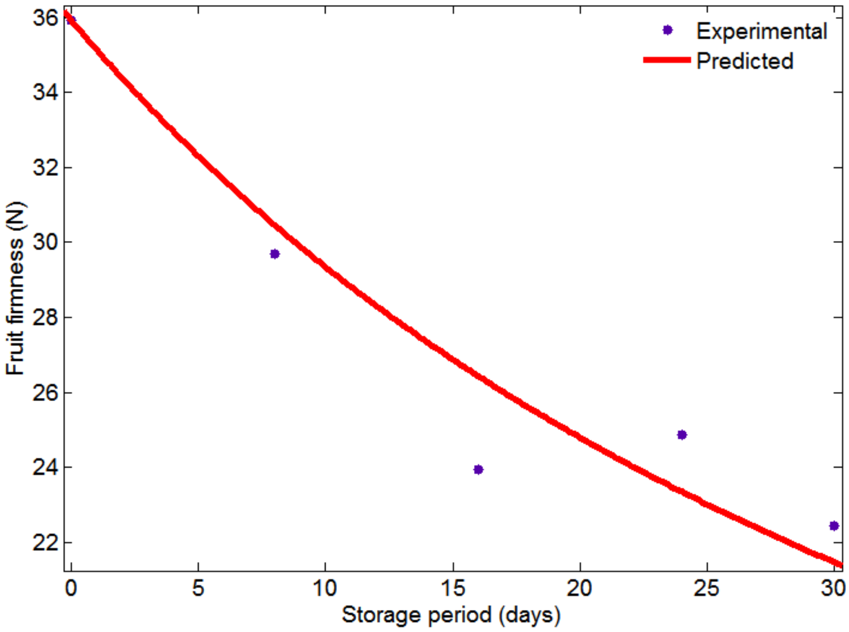

Figure 9.3 A plot of predicted and observed tomato firmness based on Equation 9.26

The models overestimated fruit shelf-life, in this case due to hardening of fruit towards the end of the storage period. This is however, as a result of physiological processes of the fruit and not a limitation on the part of the model. This phenomenon was observed in other results in the present study and reported in the literature by Mishra (2002), that post-harvest treatments that utilize heat treatment can cause Ca^{2+} to form salt-bridge cross-links, making pectins inaccessible to enzymes that cause tomato fruit softening.

9.4.1.3 pH changes

The fruit pH followed the second- and zero-order degradation kinetics, with the models' fits to the data, being selected based on their R^2. Fruit R^2 values ranged from 0.04 to 0.91. Although the model fits were equally good for both the zero- and second-order kinetic functions, the zero-order reaction kinetic function had slightly higher R^2 values for some of the samples. Similarly, some of the pH data for some samples did not follow kinetic law. Table 9.4 shows a summary of model functions developed for tomato fruit harvested at green maturity stage and transported through PD, EM and ZZ routes.

Table 9.4 Model functions for the degradation kinetics of tomato fruit pH

PD			EM			ZZ		
Equation	Eq. No.	R^2	Equation	Eq. No.	R^2	Equation	Eq. No.	R^2
$pH_{S\_A} = \frac{4.60}{1-0.0023t}$	(9.33)	0.17	$pH_{S_A} = \frac{3.85}{1-0.0057t}$	(9.34)	0.88	$pH_{S_A} = 4.20 + 0.0993$	(9.37)	0.86
$pH_{S_C} = 4.60 - 0.0025t$	(9.34)	0.40	$pH_{S_C} = 3.85 - 0.0284t$	(9.35)	0.22	$pH_{S\_C} = \frac{4.20}{1-0.0008t}$	(9.38)	0.28
$pH_{W_A} = 4.32 + 0.0328t$	(9.35)	0.91	pH_{W_A}	‡	–	$pH_{W\_A} = \frac{4.55}{1-0.0427\,t}$	(9.39)	0.71
pH_{W_C}	‡	–	$pH_{W_C} = 4.48 + 0.0121t$	(9.36)	0.28	$pH_{W\_C} = \frac{4.55}{1-0.0036\,t}$	(9.40)	0.91

‡ does not follow kinetic law

Two of the selected treatments did not follow kinetic law as shown in Table 9.4. The models in Equation 9.34 and 9.35 depict a decrease in pH with time for these treatments. These models truly reflect the data; however, in the two instances, there was a slight increase in pH for the first eight and 16 days of storage for pH_{S_C} (PD) and pH_{S_C} (EM), respectively, followed by a decline for the subsequent period. These changes could not be accurately represented by these models hence the lower R^2 values than those of other models presented in Table 9.4. These observations suggest that pH during storage of tomatoes are not adequately represented by kinetic laws. Titratable acidity (TA) could be a more reliable parameter, as suggested by the study by Bancel *et al.* (2012), where the TA and pH of banana fruit were modeled. The study showed poor prediction of pH with an R^2 values of 0.34 compared to TA that had R^2 values of 0.8 (Bancel *et al.*, 2012). The authors suggested that the model did not account for all reactant species in the predicted pH values.

9.4.1.4 Weight-loss

The cumulative weight-loss of tomato fruit followed zero-order quality degradation kinetics. The zero-order kinetic model had the highest R^2 values compared to the first-, second-order and fractional kinetics model, when fitted to the data, and were selected on this basis. The R^2 values of the models ranged from 0.94 to 0.99. Table 9.5 shows typical tomato fruit weight-loss kinetic functions for fruit harvested at the green maturity stage and transported through PD, EM and ZZ routes.

Table 9.5 Kinetic functions for degradation kinetics of tomato fruits' weight-loss

PD			EM			ZZ		
Equation	Eq. No.	R^2	Equation	Eq. No.	R^2	Equation	Eq. No.	R^2
$Wtl_{S\_A} = 0.854t$	(9.41)	0.99	$Wtl_{S\_A} = 0.495t$	(9.45)	0.98	$Wtl_{S\_A} = 0.578t$	(9.49)	0.97
$Wtl_{S\_C} = 0.303t$	(9.42)	0.99	$Wtl_{S\_C} = 0.253t$	(9.46)	0.99	$Wtl_{S\_C} = 0.319t$	(9.50)	0.97
$Wtl_{W\_A} = 0.624t$	(9.43)	0.99	$Wtl_{W\_A} = 0.411t$	(9.47)	0.99	$Wtl_{W\_A} = 0.578t$	(9.51)	0.94
$Wtl_{W\_c} = 0.622t$	(9.44)	0.95	$Wtl_{W\_c} = 0.407t$	(9.48)	0.99	$Wtl_{W\_C} = 0.575t$	(9.52)	0.99

The weight-loss of fruit harvested and transported in the summer and stored ambient storage environment had the highest cumulative weight-loss due to the high rate constants shown in Table 9.5. Based on the kinetic functions developed, there was marginal difference in the weight-loss for fruit harvested and transported in the winter when fruit stored in cold and ambient storage environments. The predicted weight-loss for Wtl_{S_A} samples for fruit transported through PD, EM and ZZ at day 24 were 20.496, 11.88 and 13.858 %, respectively. The corresponding, observed values of Wtl_{S_C} samples for the same period for fruit transported through PD, EM and ZZ was 20.576, 11.679 and 13.872 %, respectively. The models were therefore accurate in predicting the changes in cumulative weight-loss of the tomato fruit during storage. In a study by Pinheiro *et al.* (2013a), the kinetics of tomato fruit weight-loss were reported to fit well to fractional kinetics model with Arrhenius equation, where the weight-loss of tomato fruit harvested at green maturity stage was evaluated at temperatures of 2, 5, 10 15 and 20 ^{o}C. The study, however did not consider other kinetic models. In the present study four kinetic models including fractional kinetic models were tested.

9.4.1.5 Marketability

Tomato fruit marketability followed the zero-order reaction kinetics and the models were selected on the basis of their R^2 values. The model's R^2 values in this case ranged, from 0.52 to 0.97. The zero-order kinetic model had higher R^2 values compared to the first, second and fractional kinetics models. Table 9.6 presents typical zero-order model functions developed for predicting marketability of tomato fruit harvested at green maturity stage and transported though the EM, PD and ZZ routes.

Table 9.6 Kinetic model functions of tomato fruit marketability

PD			EM			ZZ		
Equation	Eq. No.	R^2	Equation	Eq. No.	R^2	Equation	Eq. No.	R^2
$Mar_{S\_A} = 99.78 - 2.196t$	(9.53)	0.70	$Mar_{S_A} = 99.79 - 1.896t$	(9.57)	0.84	$Mar_{S_A} = 99.25 - 2.412t$	(9.61)	0.85
$Mar_{S\_C} = 99.67 - 0.601t$	(9.54)	0.85	$Mar_{S_C} = 99.79 - 0.904t$	(9.58)	0.88	$Mar_{S_C} = 99.25 - 0.919t$	(9.62)	0.90
$Mar_{W\_A} = 100 - 2.762t$	(9.55)	0.92	$Mar_{W_A} = 100 - 1.824t$	(9.59)	0.85	$Mar_{W_A} = 99 - 2.021t$	(9.63)	0.79
$Mar_{W_c} = 100 - 1.275t$	(9.56)	0.53	$Mar_{W_c} = 100 - 1.149t$	(9.60)	0.55	$Mar_{W_C} = 100 - 0.788t$	(9.64)	0.73

Ali (1998) developed guidelines for acceptability of tomato fruit for sale in supermarkets based on the percentage fruit that is marketable. In their study, a minimum marketability of 60 % has been suggested as the lower threshold for acceptability of tomatoes for sale in supermarkets. Based on the developed models functions given in Table 6, and the threshold of acceptable marketability of 60 % given by Ali (1998), a shelf-life of 19, 21 and 17 days was calculated based on Mar_{S_A} equations for fruit transported through PD, EM and ZZ routes, respectively. The calculated fruit shelf-life accurately represented the data. Model checks based on the criteria used by van Dijk *et al.* (2006) showed that the models fitted well to the data and met the assumptions made.

9.4.1.6 Ascorbic acid content

Tomato fruit ascorbic acid (AA) changes with storage followed first-, second- and zero-order kinetic models, with a majority of the treatments following zero-order reaction kinetics. However, some of the treatments did not follow any of the kinetic functions. The models were selected on the basis of their R^2 values with the models that best fitted the data from all treatments ranging from 0.09 to 0.99. Table 9.7 presents kinetic model functions developed to predict changes in AA of tomato fruit harvested at green maturity stage and transported through PD, EM and ZZ routes. Based on the developed equations in Table 9.7, the calculated AA content of fruit transported through PD, EM and ZZ for the case of ambient storage, summer transportation and storage temperature regime (ASA_{S_A}) after 24 days of storage was 11.62, 20.28 and 18.53 mg $100g^{-1}$. The average AA content of tomato fruit has been reported by Salunkhe *et al.* (1974) to be about 25 mg $100g^{-1}$, suggesting higher losses in fruit transported through PD. There appears to be no agreement in the literature as to the kinetic model that best describes changes of AA content in fresh fruits and vegetables during storage. Odriozola-Serrano *et al.* (2009) reported the kinetics of AA of fresh-cut strawberries to follow first order kinetics.

Table 9.7 Kinetic model equations developed to predict changes in ascorbic acid content of tomato fruit

PD			EM			ZZ		
Equation	Eq. No.	R^2	Equation	Eq. No.	R^2	Equation	Eq. No.	R^2
$ASA_{S_A} = 25.65\exp(-0.033t)$	(9.65)	0.99	$ASA_{S_A} = 23.76 - 0.145t$	(9.68)	0.15	$ASA_{S_A} = 21.87 - 0.139t$	(9.72)	0.13
$ASA_{S\_C} = \frac{25.65}{1+0.74385t}$	(9.66)	0.87	$ASA_{S_C} = 23.76 - 0.369t$	(9.69)	0.74	$ASA_{S_C} = 21.87 - 0.476t$	(9.73)	0.88
$ASA_{W\_A} = \frac{25.11}{1+0.0052t}$	(9.67)	0.44	$ASA_{W\_A} = \frac{15.93}{1+0.0095t}$	(9.70)	0.68	ASA_{W_A}	‡	–
ASA_{W_c}	‡	–	$ASA_{W_c} = 15.93\exp(0.0195t)$	(9.71)	0.35	ASA_{W_c}	‡	–

‡ does not follow kinetic law

In another study by Sobratee and Workneh (2015) where microbial and chemical degradation kinetics of carrots stored under room temperature (22 °C) and refrigerated (1°C) temperature regimes were developed. It was reported that changes in AA with time followed second order reaction kinetics. In the present study, however, degradation AA kinetics of tomato fruit followed zero and second reaction kinetics, with a majority of the samples following zero-order reaction kinetics. Fruit subjected to summer transportation and storage temperature regimes (Su_cold and Su_ambient) appeared to follow the zero-order kinetics, while tomatoes subjected to winter transportation and storage temperature regimes (Wi_cold and Wi_ambient) appeared to follow second-order kinetics. This suggest that the kinetics of AA are temperature related, and at higher storage temperatures, degradation kinetics of tomatoes follow zero-order reaction kinetics. The models' assumptions were validated using the method described by van Dijk *et al.* (2006).

AA also showed a decreasing trend for fruit stored in the summer (positve k values) while those stored in the winter showed increased accumulation of AA with storage period due to the negative kinetic constants. This can be explained by the temperature differences in the summer and winter, as it is known that AA is one of the most thermos-sensitive nutrient component in tomato fruit (Dumas *et al.*, 2003; Toor and Savage, 2006). Higher storage temperatures are known to increase losses in AA during storage (Toor and Savage, 2006). It has also been reported that AA is un unstable nutrient that is susceptible to losses, especially when fruit is stored under ambient conditions (Singh *et al.*, 2001). The present study therefore suggests that AA content in tomatoes is relatively stable when tomatoes are stored under cold storage temperature conditions.

9.4.1.7 Glucose content

The changes in glucose content during summer conditions followed first-, zero- and second-order kinetic functions, depending on the storage environment and the route the samples were transported through. A majority of the fruit harvested and transported during the summer followed second-order reaction kinetics. The kinetics of fruit subjected to winter transportation and storage conditions did not follow kinetic law. The R^2 values of the models, for all the treatments, ranged from 0.15-0.99. Table 9.8 presents the kinetic model functions developed to predict changes in glucose content for tomato fruit harvested at green maturity stage and transported through PD, EM and ZZ routes.

Table 9.8 Model functions developed to predict changes of glucose content of tomato fruit during transportation and storage

PD			EM			ZZ		
Equation	Eq. No.	R^2	Equation	Eq. No.	R^2	Equation	Eq. No.	R^2
Glu_{S_A}	‡	–	$Glu_{S_A} 10 - 0.1155t$	(9.75)	0.42	$Glu_{S_A} = \frac{16.2}{1+2.6503t}$	(9.76)	0.99
$Glu_{S\_C} = \frac{16}{1+0.0144t}$	(9.74)	0.62	Glu_{S_c}	‡	–	$Glu_{S_C} = \frac{16.2}{1+0.00648t}$	(9.77)	0.15
Glu_{W_A}	‡	–	Glu_{W_A}	‡	–	Glu_{W_A}	‡	–
Glu_{W_c}	‡	–	Glu_{W_c}	‡	–	Glu_{W_c}	‡	–

‡ does not follow kinetic laws so far established

The kinetics of glucose degradation in tomatoes during storage has received minimal attention due to the limited number of studies that have been reported in the literature, yet it is one of the major substrates that fuels many of the chemical reactions in the fruit. In a study by Sobratee and Workneh (2015), the degradation kinetics of glucose in carrot were developed during storage at room temperature and under cold storage conditions. They reported the kinetics of glucose not to follow any of the kinetic models. The developed equations in Table 9.8 and reported studies in the literature suggests that glucose content in tomatoes and other fresh fruits and vegetables can be represented by kinetic laws to a limited extent. Other quality models therefore have to be developed to predict changes of glucose in tomato fruit.

9.4.1.8 Fructose content

The degradation of fructose in tomato fruit harvested and transported in the summer followed zero- and second-order reaction kinetics, with some of the treatments not following any of the kinetic models tested. Changes in the fructose content of fruit subjected to winter conditions did not follow any of the kinetic models tested. The models were selected based on their R^2 values, that ranged from 0.07 to 0.97. Table 9.9 presents kinetic model functions of tomato fruit harvested at green maturity stage and transported through PD, EM and ZZ routes.

Table 9.9 Model functions for the degradation of fructose in tomato fruit during transportation storage

PD			EM			ZZ		
Equation	Eq. No.	R^2	Equation	Eq. No.	R^2	Equation	Eq. No.	R^2
Fru_{S_A}	‡	–	Fru_{S_A}	‡	–	$Fru_{S\_A} = \frac{19.3}{1+t0.08106}$	(9.78)	0.91
Fru_{S_C}	‡	–	Fru_{S_C}	‡	–	$Fru_{S\_C} = \frac{19.3}{1+0.00193t}$	(9.79)	0.70
Fru_{W_A}	‡	–	Fru_{W_A}	‡	–	Fru_{W_A}	‡	–
Fru_{W_C}	‡	–	Fru_{W_C}	‡	–	Fru_{W_C}	‡	–

‡ does not follow kinetic law

From Table 9.9, the degradation kinetics of fructose in tomatoes can also be represented using kinetic models to a limited extent. Similarly, as was the case for glucose, there are limited reports in the literature on the kinetic functions used to represent the degradation kinetics of fructose in tomatoes. The study by Sobratee and Workneh (2015) reported the degradation kinetics of fructose during storage of carrot to follow first-order kinetics. Sobratee and Workneh (2015) also reported an initial increase (for the first 8-10 days) in sugars during the storage of carrot, followed by a sustained decline in the remaining storage period.

9.4.1.9 Lycopene content

Lycopene content followed zero- and second-order kinetics, with a majority of the treatments subjected to summer storage and transportation conditions, following the zero-order reaction kinetics. The R^2 values for the models ranged from 0.02 to 0.96, with some of the treatments not following any of the kinetic models tested. Table 9.10 presents kinetic model functions for lycopene degradation in tomato fruit harvested at green maturity stage and transported through PD, EM and ZZ routes.

Table 9.10 Kinetic functions for lycopene degradation in tomato fruit during storage

PD			EM			ZZ		
Equation	Eq. No.	R^2	Equation	Eq. No.	R^2	Equation	Eq. No.	R^2
$Lyc_{S_A} = 19.42 + 0.884t$	(9.80)	0.02	$Lyc_{S_A} = 4.91 + 0.583t$	(9.84)	0.42	$Lyc_{S_A} = 27.83 - 1.851t$	(9.86)	0.77
$Lyc_{S_C} = 19.42 + 0.594t$	(9.81)	0.07	Lyc_{S_C}	‡	−	$Lyc_{S\_C} = \frac{27.83}{1-0.0139t}$	(9.87)	0.26
$Lyc_{W\_A} = \frac{20.41}{1-0.0204}$	(9.82)	0.54	Lyc_{W_A}	‡	−	Lyc_{W_A}	‡	−
$Lyc_{W_C} = 20.41 + 0.13t$	(9.83)	0.47	$Lyc_{W_C} = 2.31\exp(1.114t)$	(9.85)	0.75	$Lyc_{W_C} = 3.2 + 0.467t$	(9.88)	0.48

‡ does not follow kinetic law

The model assumptions were verified using the approach suggested by van Dijk *et al.* (2006). The developed equations in Table 9.10 also depict lower lycopene concentration in fruit from EM route and higher lycopene in fruit stored under ambient conditions compared to fruit stored in cold storage environment. These observations are consistent with the data and findings reported in the literature (Davies and Kempton, 1975; Batu, 2004; Sammi and Masud, 2007; Workneh *et al.*, 2012; Pinheiro *et al.*, 2013b).

Modeling of the kinetics of lycopene in fresh tomatoes has also received little attention based on the reported studies in the literature. A majority of studies have mainly focused on kinetics of lycopene during the thermal processing of tomato fruit products and by-products. In a study involving the evaluation of the kinetics of lycopene in ketchup under different storage temperature conditions, Rajchl *et al.* (2010) reported the kinetics of lycopene to follow zero-order kinetics. However, they reported inconsistencies in the kinetics of different treatments, and suggested that the inconsistencies were a result of the thermal and compositional history of the products. The study also recommended colour parameters as a more robust attribute that can be used to predict the shelf-life of tomato ketchup. This was largely in agreement with observations made in the present study. Similar studies have also been reported by Goula *et al.* (2006).

9.5 Conclusion

In this study, the quality degradation kinetics of tomato fruit were developed based on changes in their physicochemical, nutritive and chemical quality during transportation and storage. The models developed for tomato fruit colour accurately predicted the changes in fruit hue angle using second-order kinetic functions, with R^2 values ranging from 0.13 to 0.97. Fruit firmness followed second-order reaction kinetics with the models overestimating the fruit shelf-life towards the end of the storage period. Fruit weight-loss and marketability followed zero-order kinetics, with the developed models having R^2 values ranging from 0.52 to 0.99. It was found that the pH and glucose in tomato fruit were not well-modeled, using kinetic functions. Tomato fruit lycopene content followed zero-order reaction kinetics with some treatments having inconsistencies that may be attributed to the storage conditions of the fruit as well as their thermal history. The developed models can be used to predict a range of fruit quality parameters under similar storage and transportation conditions. The kinetic models are potentially useful to commercial tomato producers for improving of their supply and distribution operations to various markets by enabling improved handling and storage of fruit, as well as optimal transportation planning.

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10. TRANSPORTATION PLANNING MODEL FOR THE SUPPLY OF FRESH TOMATOES: AN APPLICATION TO SOUTH AFRICAN CONDITIONS WHILE CONSIDERING TOMATO FRUIT OF DIFFERENT MATURITY STAGES

10.1 Abstract

A transportation planning model was developed based on transportation, vehicle maintenance, and production costs against revenue from tomato fruit of different maturity stages supplied by different growers in a commercial farmers' sourcing network. Fruit quality kinetics of different maturities, transportation and storage conditions were integrated into the model, and quality constraints implemented to allow the selection of fruit that meet the requirements of different markets. The model output was selected quantities of fruit to be supplied by different farms situated in different growing zones of the farmers' sourcing network, as well as the amount of fruit of each maturity stage. The objective function is to maximize profits from the quantity of fruit demanded while meeting the quality constraints of different markets. The kinetics of fruit firmness, hue angle and ascorbic acid content were selected as the quality attributes to be built into the model. The model was run under two configurations, with one configuration being strict on enforcing the quality constraints and the other configuration relaxing the quality constraints, while allowing the selection of fruit of each maturity stages Different quantities of fruit were selected, based on each transportation and storage temperature regimes. In a typical scenario, the model was shown to improve the profits of the commercial growers by over 8000 ZAR per truckload of fruit, while ensuring that fruit quality requirements of consumers were met. The relaxed model configuration can be implemented in cases where fruit is sent to the open markets that are less strict on quality. Additional farms can be integrated into the model from a pool of farms in the grower's supply network. The model is potentially beneficial from a transportation planning perspective and its implementation will likely improve tomato fruit grower's profits, reduce food waste and allow competitive integration of emerging growers into the commercial growers' sourcing network.

Keywords: *fruit quality heterogeneity; multi-criteria optimization; optimal supply parameters; supply strategy; transportation conditions*

10.2 Introduction

Globally, the fresh fruit industry has been growing steadily over the last two decades, and is projected to expand further due to the rise in household incomes (Regmi, 2001). It has been well documented that an increase in family incomes results in a shift of diets from dry foods such as cereals, to fresh foods that have higher water content (Jedermann *et al.*, 2014). Coupled with the ever-increasing urbanization of global populations to cities in search of opportunities, these phenomena continue to put pressure on existing fresh food systems to efficiently supply quality food products to consumers. These consumers will make their purchase decisions based on their own dietary needs, individual preferences and perceptions (Jedermann *et al.*, 2014). Careful planning of production processes and distribution of fresh foods, including fresh fruits is necessary in order to meet the dynamic demands of an informed and health-conscious consumer population (Macheka *et al.*, 2017).

The fresh fruit supply presents unique challenges, unlike those of other conventional consumer goods and foods (Aung and Chang, 2014). Freshness, for instance in tomatoes, is a risk loading factor that has to be managed, in order to prevent food losses due to spoilage and demand mismatch, which can lead to a loss of revenue for the growers, suppliers and retailers (Ahumada and Villalobos, 2011a). Conventional methods of overcoming these problems involved their oversupply in order to meet the diverse needs of sets of potential consumers, leading to food losses due to quality and demand mismatch. Some of the other conventional approaches used to supply fresh fruits and vegetable have been described in detail by Macheka *et al.* (2017). In most fresh food supply systems, the shelf-life of the product is dependent upon the environmental conditions (temperature, gaseous composition, relative humidity) and the transit time between each node of the supply system (Jedermann *et al.*, 2014). Variations in these conditions causes deviations in the expected shelf-life of fresh foods (Ahumada and Villalobos, 2011b). It has been, however, widely reported that temperature is one of the most important environmental driver that affects the quality of fresh foods (Jedermann *et al.*, 2014). The biological age of fresh foods, in a batch or individually, also brings variability in their behavior (Macheka *et al.*, 2017).

In commercial fresh fruit enterprises, complex decisions have to be made with regard to what quantities and different qualities to produce in different zones, what modes of transportation to use between specific nodes of the supply chain and what the maximum allowable distances are for the transportation of produce (Ahumada and Villalobos, 2011b; Ahumada and Villalobos, 2011a). These are just but some of the decisions that require detailed information about the costs associated with each selection, degradation of quality due to interaction with environmental conditions as well as other fruits in the batch, the production, transportation and distribution constraints. All these factors have to be to be integrated and trade-offs made to meet desirable production and distribution objectives (Ahumada and Villalobos, 2011a). In many of such problems, cost minimization is the primary objective, while meeting consumer demand at acceptable levels of fruit quality (Ahumada and Villalobos, 2011b; Ahumada and Villalobos, 2011a).

In the present study, a transportation model of fresh tomatoes was developed based on practical commercial supply conditions of fresh tomatoes by commercial growers in South Africa. From the literature, fresh fruits' production and distribution planning models have a limited number of quality attributes involved (Ahumada and Villalobos, 2011b; Ahumada and Villalobos, 2011a; Ahumada *et al.*, 2012). This limits the capacity of these models to give reasonably accurate predictions of the quality of the product, upon which all other decisions and costs hinge on. This study also uses detailed kinetic data from shelf-life experiments making it practical and with minor adjustments, it can be retrofitted to model other fresh fruit supply chains. The nature of tomato fruit harvesting makes it difficult to accurately sort fruit according to their maturity at harvest (Macheka *et al.*, 2017). This inherent biological heterogeneity makes it difficult to make general assumptions on fruit quality, as fruit of different maturities behave differently, respond differently to storage conditions and have varied susceptibilities to mechanical damage. They also attract different clientele in the markets. In the coming sections, a detailed background of the problem is given, followed by the model formulation. The formulated model is then implement in a modeling environment. The results are then viewed based on a practical application during transportation of tomatoes under commercial conditions.

10.3 Related Work and Context of Problem

In the recent years, there has been increased interest in the development and application of planning models in the supply of fresh fruits and vegetables (Munhoz and Morabito, 2014; Mateo *et al.*, 2016). This interest is expected to increase due to the pressure on commercial farming entities to remain profitable and operate in efficient and sustainable circumstances. These models take the burden of reliance on past experiences and reduce the time and risks involved in making fruit supply chain decisions, that are complex and involve many conflicting variables (Okabe *et al.*, 2012). One of such models was developed by Ahumada *et al.* (2012), that maximized the revenue of tomato and pepper growers, subject to water, land and capital constraints. The model considered only fruit colour as the attribute that indicated its quality. The developed model also incorporated uncertainties in the production and distribution operations, hence its complexity was substantially increased, which limited farmers when it came to retrofitting this model to their conditions. Similar observations could be also made on the work by Mateo *et al.* (2016). In another study by Ahumada and Villalobos (2011a), an operational model was developed to aid decisions in the supply of tomatoes to different markets with the objective of maximizing revenue, while imposing quality constraints on the allowable quality in terms of fruit colour, for different markets. The challenge, therefore, is to balance complexity against ease of use in practical situations, as well as capturing and predicting as accurately as possible the important variables in the supply network.

In the context of south African tomato industry, fruit of different maturity stages often get mixed-up in batches, even though manual fruit sorting is done at the pack-house and in the field during harvesting. This heterogeneity is inherent in tomato bulk handling operations in most commercial supply chains (van der Vorst *et al.*, 2007). Installation of a computer vision sorting system by one of the largest growers proved problematic due to the complexity of the system, and the unavailability of prompt technical support, when it failed. However, information on the economic gains and quality maximization through such a system could have been first analyzed. Supply decisions in terms of what routes to use to the markets, based on the road characteristics, and taking into account the distance and time constraints, often need to be made. At the same time, depending on the fruit quality and market characteristics, growers and suppliers target different markets or review their pricing policies according to the consumer demands. The value of investment on in-field pre-cooling units need to be also assessed to establish their impact on fruit quality and their return on investment. Decisions have to be made on the benefits of using such pre-cooling units in place of the bulk pre-cooling units at the pack-houses. Similarly, growers also grapple with choosing between centralization of pack-house operations in giant pack-houses serving several farms or having smaller pack-houses near each farm. Both of these decisions will have an impact on the quality of fruit delivered to the market and the accompanying net returns.

These are some of the complex decisions that confront tomato producers on a daily basis. The decisions made in each case have cost implications that affect the revenues and profit margins of the growers. These decisions also have an impact on the quality of the fruit as it moves through the supply chain. In the context of this study a focus is first made on the fruit maturity at harvest as a basis of choosing consumers and quantities of fruit to be supplied, which will indirectly have an impact on the profitability of these establishments.

10.4 Model Formulation

10.4.1 Problem description

In South African tomato supply chains, commercial farmers form a majority of all the growers, contributing 95 % of the total tomato fruit output (DAFF, 2015). Many growers sell their tomatoes through agents that auction the fruit in fresh produce markets. The fresh produce markets also double-up as distribution centers to nearby markets (DAFF, 2013). Emerging farmers struggle to push their produce through organized formal marketing chains that commercial farmers enjoy (DAFF, 2013). Such farmers are exposed to greater risks of the market forces, and often suffer losses when the market collapses. These farmers also have inadequate capital to install fruit pre-cooling facilities. Disinfection is often inadequate as fruit is only cleaned with tap water. Their fruit handling and processing conditions, however, limits the degree of multiple handling that often causes fruit injuries in commercial tomato processing facilities. For both commercial and emerging growers, fruit is transported from their farms through dirt roads to the pack-houses, with these roads varying in distances and road surface conditions. The emerging farmers however, have limited capital and their roads around the farms tend to be poorly maintained, unlike the commercial growers, whose roads are well maintained. There are varying needs for both sets of farmers, although consensus has been reached that emerging farmers should be gradually integrated into the formal supply chains, to improve their capacity and standards of production (Sibomana *et al.*, 2017). It is also known that harvested fruit is heterogeneous (mixed maturity stages) and will behave differently during handling, transportation and storage, depending on the maturity at harvest. Similarly, markets have different quality requirements. The biggest challenge often encountered by farmers, beyond integrating emerging farmers, is to determine the quantities that should be produced from each site (farms) to meet the demand required by different markets. These farmers often process and consolidate produce in their pack-houses and distribution centers as buffers against the market demand. In this way, non-optimal decisions are made that often erode profitability, increases food losses due to mismatched quality or demand. In this study, we formulate a simple transportation planning model that can aid these farmers decide the best tomato fruit production and distribution strategy, from a mix of farming sites (growers), so that profits will maximized and food losses minimized. The formulation of the model will primarily be based on knowledge gathered from previous tomato fruit shelf-life and quality studies. Figure 10.1 shows a schematic of processing operations during the supply of fresh tomatoes in typical commercial supply chains in South Africa. In Figure 10.1, Tp Designates transportation from the farms from which tomatoes have been harvested to the respective pack-houses for processing. RQ_1 designates road quality and distance during transport of fruit from of emerging farmer's farm to the pack-house. RQ_2 and RQ_3 designates the road quality and distances during transportation of tomatoes from the farms to the pack-houses of the commercial grower. T_L designates long distance transportation using non-refrigerated trucks to distribution centres (DC) near the markets. The fruit is stored in the distribution centres before transporting them to the markets (T_M). Based on the demand from various markets and the quality requirements, the fruit may be disposed as a result of not meeting these requirements. The fruit may then be supplied to different markets (Export, supermarket, open market or be disposed) depending on the fruit quality requirement of each market. During tomato fruit supply, four transportation and storage temperature regimes prevailed designated as; summer ambient (SA), summer cold (SC), winter ambient (WA) and winter cold (WC). Fruit from the farms are harvested at green, pink and red maturity stages.

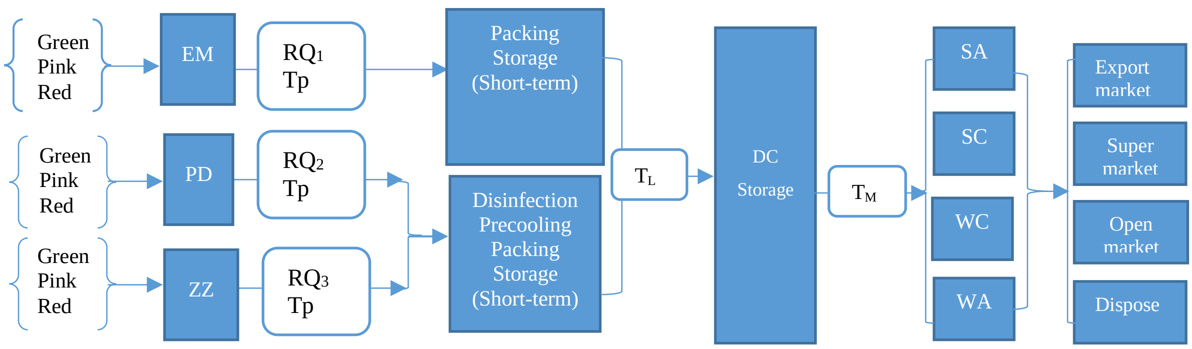

Figure 10.1 Framework for the supply for tomato fruit by commercial and emerging farmers to different markets

10.4.2 Mathematical formulation

The notation used to formulate the transportation planning model is presented in Table 10.1. Equation 10.1 is the objective function of the model that involves the maximization of the profit derived from the difference in proceeds from sales of fruit against production costs, transportation costs with respect to each route, and the vehicle maintenance costs associated with the different routes. Routes associated with emerging farmers typically hire trucks for transportation of their fruit, hence incurring slightly higher transportation costs than commercial farmers and no associated vehicle maintenance costs. Equations 10.2, 10.3 and 10.4 are kinetic functions associated with fruit hue angle, fruit firmness and ascorbic acid content, respectively for each maturity stage and transport route.

Table 10.1 Nomenclature of tomato fruit transportation planning model

P_i	Price per kg of tomato fruit of *i* maturity stage
SL_{ij}	Shelf-life of fruit of *i* maturity stage harvested and transported through route *j*
Tr_j	Transportation cost per km for fruit transported through route *j*
Pr_{ij}	production of a kg of fruit of *i* maturity stage transported through route *j*
Mt_j	Cost of vehicle maintenance for fruit transported through *j* route
X_{ij}	Quantity in kg of fruit of *i* maturity stage harvested and transported through route *j*
Y_{ij}	Shelf-life of fruit of *i* maturity stage harvested and transported through route *j*
m	Number of fruit maturity stages
n	Number of farms and routes through which tomato fruit were supplied through
AA_{ij}	Ascorbic acid content of *i* maturity stage transported through route *j*
AA_{min}	Minimum acceptable ascorbic acid content of tomato fruit demanded by consumers
f_{ij}	Firmness of tomato fruit of *i* maturity stage transported through route *j*
f_{min}	Minimum acceptable tomato fruit firmness demanded by consumers
h_{ij}	Hue angle of tomatoes of *i* maturity stage transported through route *j*
h_{min}	Minimum acceptable tomato fruit hue angle demanded by consumers
di_j	Distance in km of route *j* from which fruit is harvested and transported to the market
de	Quantity of fruit in kg demanded by either retail, supermarket or export market
Rt_{cap}	Maximum amount of tomato fruit in kg that can be supplied from each route *i*

$$Max\left[\sum_{j\in n}\sum_{i\epsilon m}P_iX_{ij}-\sum_{j\in n}\sum_{i\epsilon m}Pr_iX_{ij}-\sum_{j\in n}di_j\left(\sum_{i\epsilon m}Tr_i-\sum_{i\epsilon m}Mt_j\right)\right] \tag{10.1}$$

Subject to,

$$h_{ij}=f\left(SL_{ij}\right)\ all\ ij \tag{10.2}$$

$$f_{ij}=f\left(SL_{ij}\right)\ all\ ij \tag{10.3}$$

$$AA_{ij}=f\left(SL_{ij}\right)\ all\ ij \tag{10.4}$$

$$AA_{ij} \geq AA_{min} \qquad \forall i \in m, \forall j \in n \qquad (10.5)$$

$$h_{ij} \geq h_{min} \qquad \forall i \in m, \forall j \in n \qquad (10.6)$$

$$f_{ij} \geq f_{min} \qquad \forall i \in m, \forall j \in n \qquad (10.7)$$

$$\sum_{j \in m} \sum_{i \in n} X_{ij} = de \qquad (10.8)$$

$$\sum_{all\ n} X_{ij} \leq Rt_{cap} \qquad (10.9)$$

These kinetic functions had been developed in the transportation experiments and tomato fruit shelf-life life studies. All the kinetic functions represent changes in fruit quality parameters with time. The maximum shelf-life selected to meet the consumer constraints is designated as SL_{ij}. The Equations 10.5 to 10.7 are consumer quality constraints that are enforced based on the market and consumer requirements. Equation 10.8 is the constraint that ensures that the quantity of fruit demanded equates to the summation of the optimum quantities of tomato fruit selected from each of the n transportation routes, as well as each of the m tomato fruit maturities at harvest. Equation 10.9 enforces the maximum capacities of fruit that can be transported from each route (see Appendix 1). It also enforces production capacity constraints from each of the farms. The model was implemented in CPLEX optimization studio 12.7 (IBM, USA).

10.4.3 Implementation of model in selected tomato supply chains

The model was implemented under four transportation and storage temperature regimes. These included; ambient storage and transportation under summer conditions, cold storage and transportation under summer conditions, ambient storage and transportation under winter conditions, and cold storage and transportation under winter conditions. The model output is the quantities of fruit of each maturity stage, to be transported through PD, EM and ZZ routes in order to meet the consumer quality requirements for a given demand. The model assumes that emerging farmers do not utilize pre-cooling facilities and only hot water treatment is the feasible disinfection treatment (Figure 10.1). Transportation from the farms of the three growers to the market takes into account varied road surface conditions and transportation distances. The algorithm of the developed model is presented in Appendix 2.

10.4.4 Modelled quantities fruit required to be meet market demand

Transportation experiments established the quality kinetics of tomato fruit of different maturity stages under different transportation and storage temperature regimes. The model was implemented under the assumption that a truckload supplies a maximum of 5000 kg of fruit, and this demand must be satisfied to adequately utilize the transportation capacity. Other parameters relating to supply chain costs given in Table 10.1 were sourced from the commercial grower, and an emerging farmer involved in the study. The quality constraints were implemented based on the quality requirements of the market the fruit is to be supplied to. For purposes of this study, fruit hue angle is constrained to be ≥50, fruit firmness≥17 N and AA content to be≥16 mg 100^{-1}g. These quality attributes have been given by Ali (1998) and Batu (2004) as minimum acceptable quality thresholds of fresh tomato fruit for home consumption. Export markets, supermarket chains and open markets could impose quality constraints depending on their customer requirements.

Table 10.2 shows a summary of quantities of fruit of each maturity stage selected to be transported from each grower in order to maximize profit while meeting consumer quality constraints. The optimum quantities selected and presented in Table 10.2 relate to transportation of fruit under summer conditions and storage under ambient conditions. The maximum allowed shelf-life, or best-before days, is also presented.

Table 10.2 Modelled quantities of tomato fruit in kg to be supplied under summer transportation conditions and storage in ambient storage conditions

Model configuration	Fruit maturity	Maximum shelf-life and transportation routes											
		8			16			24			30		
		PD	EM	ZZ	PD	EM	ZZ	PD	EM	ZZ	PD	EM	ZZ
Strict on quality	Green	-	-	-	-	2000	-	-	-	-	-	-	-
	Pink	4000	-	1000	-	-	3000	-	-	-	-	-	-
	Red	-	-	-	-	-	-	-	-	-	-	-	-
Selects fruit from all maturities	Green	-	2000	-	-	2000	-	-	2000	-	-	2000	-
	Pink	2000	-	-	-	-	2000	-	-	2000	-	-	2000
	Red	1000	-	-	1000	-	-	1000	-	-	1000	-	-

Two model configuration settings were evaluated. One configuration was strict on the quality constraints, while the other configuration relaxed these constraints at the same time ensuring the selection of fruit of each maturity stage at selected maximum capacities. From Table 10.2, the model selected fruit of pink maturity on day 8 under strict quality settings due to the higher prices of fruit of pink maturity stages. South African consumers prefer fruit at the pink maturity stage, due to its longer keeping quality (Zeithaml, 1988). At and beyond day 24, fruit did not meet any of the quality constraints and no quantities were selected. When the quality constraints were relaxed, the model selected fruit from each maturity stage while respecting both production capacities from each route and fruit maturity stages. The quality could, however, not be guaranteed under this setting but the profitability will be maximized. Table 10.3 presents modeled quantities of tomato fruit to be supplied from the different farms under summer transportation conditions and storage of fruit under cold storage conditions.

Table 10.3 Modelled quantities in kg of tomatoes to be transported under summer conditions and storage in cold storage conditions

Model configuration	Fruit maturity	Maximum shelf-life and transportation routes											
		8			16			24			30		
		PD	EM	ZZ	PD	EM	ZZ	PD	EM	ZZ	PD	EM	ZZ
Strict on quality	Green	-	-	-	-	2000	-	-	-	-	-	-	-
	Pink	4000	-	1000	-	-	3000	-	-	3000	-	-	-
	Red	-	-	-	-	-	-	-	2000	-	-	-	-
Selects fruit from all maturities	Green	-	2000	-	-	2000	-	-	2000	-	-	-	2000
	Pink	-	-	2000	-	-	2000	2000	-	-	2000	-	-
	Red	1000	-	-	1000	-	-	1000	-	-	1000	-	-

The selected quantities of fruit to be supplied under cold storage conditions during the summer similarly shows no fruit being selected if fruit has a maximum shelf-life of 30 days, when the model is strict on quality. However, when the model is set to relax the quality constraints and enforce maximization of profit, fruit from each of the three maturity stages was selected in all the days of expected shelf-life. In the configuration of relaxed quality constraints, the quality constraints are relaxed and therefore, quality is not guaranteed. From Table 10.2 and 10.3, when the model is set to be strict on quality, the only limiting factor is the expected shelf-life of the fruit, with ambient storage having fruit that do not conform to quality constraints beyond 16 days.

Table 10.4 presents the modelled quantities of tomatoes to be supplied under winter transportation conditions and storage in ambient storage environment. During winter, storage of tomato fruit under ambient conditions (Table 10.4) depicts quality as a limiting factor only after day 24. The model selected the same quantities to be supplied if fruit has to be consumed within 16 and 8 days. This suggests that no appreciable quality changes occurred when tomatoes are transported and stored under similar conditions for up to 16 days.

Table 10.4 Modelled quantities of tomato fruit in kg to be supplied under winter transportation conditions and storage in ambient storage conditions

Model configuration	Fruit maturity	Maximum shelf-life and transportation routes											
		8			16			24			30		
		PD	EM	ZZ	PD	EM	ZZ	PD	EM	ZZ	PD	EM	ZZ
Strict on quality	Green	-	-	-	-	-	-	-	-	-	-	-	-
	Pink	4000	-	1000	4000	-	1000	-	-	3000	-	-	
	Red	-	-	-	-	-	-	-	2000	-	-	-	-
Selects fruit from all maturities	Green	-	1000	1000	-	2000	-	-	2000	-	-	2000	-
	Pink	2000	-	-	2000	-	-	2000	-	-	2000	-	-
	Red	-	1000	-	1000	-	-	1000	-	-	1000	-	-

In contrast, under relaxed settings on quality constraints of fruit, different quantities of fruit were selected for different periods of expected shelf-life. In this case, the quality was not strictly enforced and quality could not be entirely guaranteed. Table 10.5 presents the modelled quantities of fruit to be supplied under winter transportation conditions and storage under cold storage environment.

Table 10.5 Modelled quantities of fruit in kg to be supplied under winter transportation conditions and storage in cold storage environment

Model configuration	Fruit maturity	Maximum shelf-life and transportation routes											
		8			16			24			30		
		PD	EM	ZZ	PD	EM	ZZ	PD	EM	ZZ	PD	EM	ZZ
Strict on quality	Green	-	-	-	-	-	-	-	-	-	-	-	3000
	Pink	4000	-	1000	4000	-	1000	4000	-	1000	-	-	-
	Red	-	-	-	-	-	-	-	-	-	-	2000	-
Selects fruit from all maturities	Green	-	2000	-	-	2000	-	-	2000	-	-	-	2000
	Pink	2000	-	-	2000	-	-	2000	-	-	2000	-	-
	Red	1000	-	-	1000	-	-	1000	-	-	1000	-	-

From Table 10.5, and from the quantities of tomato fruit selected by the model under the strict quality configuration, there was no difference in quantities of fruit selected for shelf-life of 8, 16 and 24 days. This suggests that there were no appreciable changes in fruit quality for up to 24 days of storage under cold storage conditions. On day 30, the cost-effective source of fruit meeting the required quality conditions were fruit from the ZZ and EM routes that supplied fruit from the commercial growers. Modeled quantities under relaxed configuration could similarly, not guarantee conformity to the quality requirements. However, the profits for the growers were maximized.

10.5 Benefits of Implementation of the Model

The implementation of the developed model will potentially improve the earnings to commercial growers by improving profit margins due to selection of fruit matching the shelf-life and quality requirements of consumers. To highlight this fact, if fruit of green maturity stages (PD = 2000 kg, EM = 1000 kg, and ZZ = 2000 kg) is selected compared to optimum quantities selected by the model (pink fruit, PD = 4000 kg and ZZ = 1000 kg), profits would be improved by 8685.5281 ZAR for a truckload of fruit. These calculations are based on the industry data of costs and revenue associated with each decision. The enforcement of the quality required by consumers would also eliminate food spoilage and food waste by matching demanded quantities and qualities with that which is supplied. The model that relaxes quality constraints could be used for fruit sent to open markets. The developed model can easily be configured to further include any number of farms from which fruit is sourced, other quality parameters, costs and quality constraints.

10.6 Discussion

A review by Ahumada and Villalobos (2009) shows that many of the supply chain planning models developed have not been practically applied in production and distribution processes in agri-food supply chains. This may be attributed to the complexity and impracticality in their adoption by farmers, growers and managers of such supply chains. Transportation planning of fresh fruits and vegetables have received interest in the recent past with many of the models developed focusing on the economic aspects of the processes (Apaiah and Hendrix, 2005; Munhoz and Morabito, 2014).

In a study by Apaiah and Hendrix (2005), a supply chain planning model whose aim is to supply protein-based food products as cheaply as possible, by integrating farm production processes, ingredient formulation operations and manufacture of the products. The objective function of their model was minimization of production costs. Quality requirements of the products and ingredients were, however, not controlled in their model. Transportation operations in fresh fruit supply chains are critical operations since losses of up to 15 % are known to occur during transportation and distribution, most of which are hidden and show up further downstream the supply chain (Jedermann *et al.*, 2014). Integrating quality characteristics of fresh fruits and vegetables in transportation planning models would make such models important tools in improving earnings to growers and eliminating food losses. A study by Blackburn and Scudder (2009) developed a hybrid model that strived to minimize loss of value in melon and sweetcorn supply chains by using the marginal value time of the products. The developed model, however, assumed different rates of quality loss at various phases of distribution. The accuracy of such a model is therefore questionable.

The transportation planning model developed in the present study integrated both the quality characteristics of the fruit and the economic outcomes of selecting fruit from each of the supply routes. Integrating quality kinetics of the fruit improved their usefulness in holistically encompassing the quality changes of tomatoes due to different handling and transportation conditions. Similarly, the transportation planning model developed in the present study also accounted for heterogeneity in supplied tomatoes occasioned by differences in their maturities at harvest.

10.7 Conclusion

This study sought to develop a transportation planning model based on the shelf-life of tomato fruit of various maturity stages under various transportation and storage temperature regimes. The model was developed based on quality kinetics of fruit under different transportation and storage conditions. Fruit firmness, hue angle and ascorbic acid concentration were used as quality attributes that would be imposed on the constraints and used as a basis for selecting fruit that would be of acceptable quality for different consumers. Based on industry data on production costs and revenue, the model was implemented in two configurations. One configuration strictly enforced the quality constraints, while the other configuration relaxed quality constraints. In both configurations, the model maximized revenue from the quantities of fruit of different maturity stages selected from each of the growers. The developed models will potentially improve revenue to growers as established in this study, with the model in some cases improving profits by 8685.5281 ZAR for a truckload of fruit. The major limitation of the developed model is that it requires vast amounts of data, and at the technical level requires high level of expertise to adjust it. However, the model is easily usable by farmers when their production data is linked to the model using excel sheet. The model can be further adjusted to incorporate other farms in the growers’ sourcing networks, costs and quality constraints. There is also room to incorporate in the model uncertainty in demand and risks of unmarketability of tomatoes based on fruit characteristics and supply chain conditions.

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11. CONCLUSIONS AND RECOMMENDATIONS

This study sought to develop a post-harvest management system for handling, transportation and storage of fresh tomatoes in South African commercial supply chains through an assessment of supply chain processes from the farm to the market. Transportation of fruit was used as the focal point of the study based on gaps in information on the effect of transportation on the quality changes on fresh tomatoes under practical commercial supply conditions. The study also assessed the key processes during the supply of tomatoes, tested and developed data-driven models suitable for improving the quality and market value of fruit supplied to various markets. The developed supply chain parameters were further optimized in a transportation planning model developed to aid supply decisions by commercial growers in South African tomato industry. Based on the results obtained in this study, the following sections presents the conclusions and recommendations made.

11.1 Conclusions

Reduction of time to pre-cooling and maintaining the cold chain during in-field handling of tomatoes was shown to be beneficial in maintaining tomato fruit quality. Similarly, the synergistic effects of harvesting in the morning, shortening the time to pre-cooling and proper handling of tomatoes on their quality was established. These practices are suggested to tomato growers and pack-house operators as they have been shown to improve tomato fruit marketability and reduce weight-loss by up to 20 % and 75 kg ton^{-1}, respectively. Adherence to these practices would have a profound improvement on market value of fruit downstream the supply chain, which would in turn improve profits of tomato growers.

The tested disinfection treatment treatments significantly ($p \leq 0.05$) improved the marketability, subjective, chemical and nutritive quality of fruit. Anolyte water in combination with biocontrol (B-13 yeast isolate) was effective in maintain the subjective, chemical and nutritive quality attributes of tomatoes and was only comparable to chlorinated water, an industry standard in disinfection of fruit and vegetables. Fruit treated with anolyte water in combination with biocontrol had significantly ($p \leq 0.05$) higher marketability compared to fruit subjected to other treatments. Hot water treatment and anolyte water in combination with biocontrol gave fruit with comparable chemical and nutritional quality, with the mean AA content of fruit subjected to the two treatments being 18.29 and 17.17 mg 100g^{-1}, respectively. Based on the observations from this study, anolyte water in combination with biocontrol is suggested to commercial growers as a novel integrated treatment for improving tomato quality. Hot water treatment can be used by emerging farmers due to the minimal investment costs involved in adopting and integrating this treatment into their fruit processing operations.

Fruit harvested at green maturity stage responded well to poor road conditions compared to fruit harvested at red and pink maturity stages. This is suggested by the reduction in fruit firmness by 45, 41 and 42 % for fruit harvested at green maturity stages and transported through rough (58% of road having IRI values < 2.5 km m^{-1}), smooth (70% of road having IRI values < 2.5 km m^{-1}) and moderately rough roads (63% of road having IRI values < 2.5 km m^{-1}), respectively. These marginal differences in the hue angle for fruit handled through different road conditions proposes harvesting at green maturity stage in instances where road surfaces are poorer. Harvesting at the green maturity stage can be used as the first line of defense against fruit damage in instances where adequate road maintenance is not practiced.

Packaging of fruit in plastic bins during long distance transportation was shown to negatively affect the fruits' physicochemical quality compared to when fruit is transported in carton boxes. Fruit transported using bins and boxes had a mean firmness of 22 N and 26 N, respectively, when the fruit on when they reached Pietermaritzburg. Transportation using boxes rather than bins improved fruit marketability by 8%. In-field transportation of fruit in bins was also shown to negatively affect fruits' quality as opposed to transportation in smaller lugs. For instance, fruit at the bottom of the bins and lugs showed 30 % and 2 % mechanical damage, respectively, during transportation of fruit from the field to the pack-house. The industry should reconfigure packaging units during transportation at different levels of the supply chain to address these realities. It also provides incentives for the industry to develop packaging units using suitable materials and with geometrical configurations that improve the shelf-life and quality of transported fruit.

The logistic model developed to predict fruit marketability highlighted the processing path that resulted in fruit with the highest quality. The study reaffirmed earlier observations that fruit transported through moderately rough road surface profile over the longest distance had the lowest quality. The logistic model showed that such fruit had the lowest probability of marketability compared to fruit transported through shorter and smoother roads. The logistic model further highlighted the importance of regulating the humidity in tomato fruits' storage environment during winter. Lower humidity during winter was shown to negatively affect tomato fruits' marketability.

AA was shown to be not only a thermo-sensitive nutrient, but also sensitive to poor transportation conditions. Lycopene and AA losses was shown to be the greatest in fruit transported through moderately rough roads over the longest distances. Quantitatively, fruit transported along smoother road surface profile had 8.17 and 1.6 % higher lycopene and AA content, respectively, than fruit transported over the road with a moderately rough surface profile and the longest distance. Losses in tomato fruit sugars was not significantly ($p>0.05$) influenced by road quality. Adequate maintenance of roads in and around farms is also suggested to growers as one of the means through which nutritional losses in tomato can be managed.

Hot water treatment and anolyte water in combination with biocontrol were shown to be effective treatments that gave tomatoes with the best nutritional and chemical quality. The mean AA content of fruit treated using Anolyte water in combination with biocontrol, hot water treatment and control were 17.17, 18.29 and 16.8 mg 100 g^{-1}, respectively. Similarly, fruit treated with Anolyte water in combination with biocontrol, hot water treatment and control were 39.85, 40.36 and 36.09 mg kg^{-1}, respectively. Based on the acceptable mean AA content in tomatoes, the treatments extended the shelf-life of fruit by up to 14 days. Anolyte water in combination with biocontrol is recommended to commercial growers due to the higher investment costs in implementing the system, while hot water treatment is recommended to emerging farmers due to the simplicity in implementing such a system and the lower investment costs.

Multivariate analysis of the data to establish the complex interrelationships between different variables showed that the nine physicochemical attributes (hue angle, pH, L*, a*, b*, firmness, marketability, weight-loss and consumer acceptability) of tomato fruit can be decomposed into three principal components. One of the components was interpreted to be linked to fruit's tactile and visual quality attributes that drove consumer buying decisions. This component was strongly linked to fruit maturity at harvest, storage and transportation conditions. Therefore, these factors have to be carefully managed in tomato supply chains. These observations further underscore the importance of road quality during transportation of tomato fruit.

The developed kinetic models adequately modelled the kinetics of tomato fruits' colour, firmness, ascorbic acid content, marketability and weight-loss. Fruit firmness and hue angle followed second order reaction kinetics, with models having R^2 values of 0.13-0.97, while the kinetics of marketability and weight-loss followed zero order reaction kinetics, with the models having R^2 values of 0.52-0.99. Based on the fruit hue angle, the models predicted a shelf-life of 21, 18 and 16 days for fruit transported along PD, EM and ZZ routes, respectively. Similarly, the kinetic models of tomato fruit marketability predicted the shelf-life of fruit transported along the PD, EM and ZZ routes to be 19, 21 and 17 days, respectively. Validation of the models with the data showed that the developed models accurately predicted changes in tomato hue angle, firmness, weight-loss and marketability during storage and transportation of the fruit.

The developed transportation planning model would be useful in aiding decision making by growers in selecting the quantities of tomato fruit to transport from each fam to maximize profit while meeting consumer quality constraints. In some instances, the model improved profits by over 8000 ZAR per truckload of transported fruit.

11.2 Recommendations

1. Further microbial analysis of the biocontrol yeast (B-13) should be carried out to improve its potency in controlling spoilage microorganisms in tomato fruit.
2. Analysis of different packaging materials on tomato quality should be studied to establish the suitable materials properties and surfaces that offer adequate protection and cushioning to fruit during transportation. Similarly, material geometries should be investigated to establish suitable configurations that optimize space use in trucks while carrying the largest amount of fruit.
3. During pre-cooling in the cold rooms, the spatial and temporal distribution of cooling air should be further studied using computational fluid dynamics (CFD). This would help to establish optimum stalking patterns in cold rooms that maximize removal of field heat from fruit, as well as optimizing air flow patterns to achieve the highest cooling efficiencies.
4. Further development of the transportation planning model should be carried out to include more farms, as well as production and transportation costs and constraints.

APPENDIX A

Required fruit capacities from different growers

Table A.1 Maximum capacities of fruit of each maturity stage that can be supplied from each supply route

Maturity stages and transportation routes of tomato fruit	Capacities in kg
PD route	4000
EM route	1000
ZZ route	3000
Green fruit	2000
Pink fruit	2000
Red fruit	1000

APPENDIX B

CPLEX code for the developed transportation planning model

Tomato supply chain model.dat   Tomato supply chain model.mod

```
2    * OPL 12.7.0.0 Model
3    * Author: User
4    * Creation Date: 24 Oct 2017 at 12:54:17 PM
5    *********************************************/
6   //parameters
7   int n=...;
8   range routes=1..n;
9   int m=...;
10  range maturity=1..m;
11  //data
12  float distances[maturity][routes]=...;
13  float TransCosts[maturity][routes]=...;
14  float MaintCosts[maturity][routes]=...;
15  float demand=...;
16  float ProdCosts[maturity][routes]=...;
17  float prices[maturity][routes]=...;
18  float capacity[routes]=...;
19  float fruitcapacity[maturity]=...;
20  //decision variable
21  dvar float+ x[maturity][routes];
22  //objective function
23  maximize
24  sum(i in maturity, j in routes)prices[i][j]*x[i][j]-
25  sum(i in maturity, j in routes)TransCosts[i][j]*x[i][i]-
26  sum(i in maturity, j in routes)MaintCosts[i][j]*x[i][i]-
27  sum(i in maturity, j in routes)ProdCosts[i][j]*x[i][i];
28  subject to{
29  forall(i in maturity, j in routes)
30    sum(i in maturity,j in routes)x[i][j]==demand;
31  forall(j in routes)
32   sum(i in maturity)x[i][j]<=capacity[j];
33  forall(i in maturity)
34  sum(j in routes)x[i][j]<=fruitcapacity[i];
35  };
```

Figure B.1 Suggested algorithm for the models implemented in CPLEX. Under the strict quality configuration, line 32-34 is excluded. The .dat file links cost data and quality kinetics data to the model

APPENDIX C

Developed kinetic model parameters of fresh tomatoes

Table 0.1 Model fits for tomato quality degradation kinetics under four transportation and storage temperature regime

Temp. Regime	Fruit supply conditions	Colour (hue angle)		Firmness		pH		weight loss		Marketability		AA		Fructose		Glucose		Lycopene	
		R^2	Model	R^2	Model	R^2	Model	R^2	Model	R^2	Model	R^2	Model	R^2	Model	R^2	Model	R^2	Model
Su_Amb	PD+Green	0.97	2nd	0.87	2nd	0.17	2nd	0.99	Zero	0.70	Zero	0.99	1st	<0.1	‡	<0.1	‡	0.02	Zero
	PD+Pink	0.81	2nd	0.92	2nd	<0.1	‡	0.98	Zero	0.81	Zero	<0.1	‡	0.69	Zero	<0.1	‡	0.15	Zero
	PD+Red	0.76	2nd	0.61	Zero	<0.1	‡	0.99	Zero	0.77	Zero	0.38	Zero	0.48	2nd	0.25	2nd	0.15	Zero
	EM+Green	0.93	2nd	0.96	2nd	0.88	2nd	0.98	Zero	0.84	Zero	0.15	Zero	<0.1	‡	0.15	Zero	0.42	Zero
	EM+Pink	0.85	2nd	0.73	2nd	0.23	Zero	0.99	Zero	0.71	Zero	0.09	Zero	0.93	Zero	0.80	Zero	<0.1	‡
	EM+Red	0.56	2nd	<0.1	‡	0.44	Zero	0.98	Zero	0.72	Zero	<0.1	‡	0.58	Zero	0.51	Zero	0.92	Zero
	ZZ+Green	0.94	2nd	0.99	2nd	0.86	Zero	0.97	Zero	0.85	Zero	0.13	Zero	0.91	2nd	0.99	2nd	0.77	Zero
	ZZ+Pink	0.93	2nd	0.56	2nd	0.61	Zero	0.97	Zero	0.97	Zero	<0.1	‡	0.56	2nd	0.99	2nd	0.40	Zero
	ZZ+Red	0.90	2nd	0.93	2nd	0.45	2nd	0.98	Zero	0.87	Zero	0.32	Zero	<0.1	‡	<0.1	‡	0.18	Zero
Su_Cold	PD+Green	0.97	1st	0.42	2nd	0.04	Zero	0.99	Zero	0.85	Zero	0.87	2nd	<0.1	‡	0.62	2nd	0.07	Zero
	PD+Pink	0.85	2nd	0.67	Zero	0.02	2nd	0.99	Zero	0.80	Zero	0.12	Zero	0.07	Zero	0.05	Zero	<0.1	‡
	PD+Red	0.87	2nd	0.09	Zero	<0.1	‡	0.99	Zero	0.71	Zero	0.64	Zero	0.85	Zero	0.97	2nd	<0.1	‡
	EM+Green	0.85	2nd	0.92	2nd	0.22	Zero	0.99	Zero	0.88	Zero	0.74	Zero	<0.1	‡	<0.1	‡	<0.1	‡
	EM+Pink	0.63	2nd	0.94	2nd	0.17	2nd	0.96	Zero	0.95	Zero	0.26	Zero	0.94	1st	0.89	2nd	0.12	Zero
	EM+Red	0.85	2nd	0.15	Zero	0.06	Zero	0.97	Zero	0.82	Zero	<0.1	‡	0.97	2nd	0.97	1st	<0.1	‡
	ZZ+Green	0.94	2nd	0.91	2nd	0.06	2nd	0.95	Zero	0.90	Zero	0.88	Zero	0.07	2nd	0.15	2nd	0.26	2nd
	ZZ+Pink	0.56	2nd	0.07	2nd	0.28	2nd	0.97	Zero	0.82	Zero	<0.1	‡	0.31	2nd	0.39	2nd	<0.1	‡
	ZZ+Red	0.17	2nd	0.67	2nd	0.03	2nd	0.98	Zero	0.91	Zero	0.29	Zero	0.71	Zero	0.29	Zero	<0.1	‡
Wi_Amb	PD+Green	0.92	2nd	0.13	2nd	0.91	Zero	0.94	Zero	0.92	Zero	0.04	2nd	<0.1	‡	<0.1	‡	0.54	2nd
	PD+Pink	0.77	2nd	0.89	2nd	<0.1	‡	0.96	Zero	0.93	Zero	0.41	Zero	<0.1	‡	<0.1	‡	<0.1	‡
	PD+Red	0.72	2nd	0.86	2nd	<0.1	‡	0.96	Zero	0.88	Zero	0.88	2nd	<0.1	‡	<0.1	‡	0.02	Zero
	EM+Green	0.89	2nd	0.18	2nd	<0.1	‡	0.99	Zero	0.85	Zero	0.68	2nd	<0.1	‡	<0.1	‡	<0.1	‡
	EM+Pink	0.85	2nd	0.88	2nd	<0.1	‡	0.98	Zero	0.92	Zero	<0.1	‡	<0.1	‡	<0.1	‡	0.03	2nd
	EM+Red	0.62	2nd	0.82	2nd	0.38	2nd	0.98	Zero	0.88	Zero	0.08	2nd	<0.1	‡	<0.1	‡	0.17	Zero
	ZZ+Green	0.90	2nd	0.26	2nd	0.24	Zero	0.99	Zero	0.79	Zero	<0.1	‡	<0.1	‡	<0.1	‡	<0.1	‡
	ZZ+Pink	0.75	2nd	0.70	2nd	0.71	Zero	0.94	Zero	0.98	Zero	<0.1	‡	<0.1	‡	<0.1	‡	<0.1	‡
	ZZ+Red	0.73	2nd	0.59	2nd	0.15	Zero	0.99	Zero	0.96	1st	0.39	2nd	<0.1	‡	<0.1	‡	<0.1	‡
Wi_Cold	PD+Green	0.88	2nd	0.80	2nd	<0.1	‡	0.95	Zero	0.53	Zero	<0.1	‡	<0.1	‡	<0.1	‡	0.47	Zero
	PD+Pink	0.89	2nd	0.96	1st	<0.1	‡	0.96	Zero	0.52	Zero	0.68	2nd	<0.1	‡	<0.1	‡	0.98	2nd
	PD+Red	0.78	2nd	0.64	2nd	0.15	Zero	0.96	Zero	0.69	Zero	0.72	1st	<0.1	‡	<0.1	‡	<0.1	‡
	EM+Green	0.87	2nd	0.85	Zero	0.28	Zero	0.99	Zero	0.55	Zero	0.35	1st	<0.1	‡	<0.1	‡	0.75	1st
	EM+Pink	0.79	2nd	0.68	Zero	0.86	1st	0.98	Zero	0.66	Zero	<0.1	‡	<0.1	‡	<0.1	‡	0.83	2nd

	EM+Red	0.78	2^{nd}	0.90	2^{nd}	0.59	2^{nd}	0.98	Zero	0.71	Zero	0.22	Zero	<0.1	‡	<0.1	‡	0.96	Zero
	ZZ+Green	0.97	2^{nd}	0.19	2^{nd}	0.56	2^{nd}	0.99	Zero	0.73	Zero	<0.1	‡	<0.1	‡	<0.1	‡	0.48	Zero
	ZZ+Pink	0.78	2^{nd}	0.74	Zero	0.22	2^{nd}	0.93	Zero	0.83	Zero	0.79	2^{nd}	<0.1	‡	<0.1	‡	0.58	Zero
	ZZ+Red	0.13	2^{nd}	0.38	Zero	0.91	2^{nd}	0.99	Zero	0.82	Zero	0.04	Zero	<0.1	‡	<0.1	‡	<0.1	‡

Table 0.2 Model coefficients for tomato quality degradation kinetics under four transportation and storage temperature regime

Temp. Regime	Fruit supply conditions	Colour (hue angle)		Firmness		pH		weight loss		Marketability		AA		Fructose		Glucose		Lycopene	
		k (d^{-1})	A_0	k (d^{-1})	A_0	k (d^{-1})	A_0	k (d^{-1})	A_0	k (d^{-1})	A_0	k (d^{-1})	A_0	k (d^{-1})	A_0	k (d^{-1})	A_0	k (d^{-1})	A_0
Su_Amb	PD+Green	0.0006	104.6	0.0013	32.36	-0.0005	4.60	-0.854	0	2.196	99.78	0.033	25.65	_	_	_	_	-0.884	19.42
	PD+Pink	0.0003	61.07	0.0006	17.41	_	_	-0.679	0	2.595	99.69	_	_	-0.316	15.6	_	_	-2.349	29.56
	PD+Red	0.0002	52.59	0.1071	15.83	_	_	-0.907	0	2.344	99.57	0.258	24.3	-0.001	13.3	-0.0009	11.3	-1.131	36.31
	EM+Green	0.0007	105.4	0.0012	35.93	-0.0015	3.85	-0.495	0	1.896	99.79	0.145	23.76	_	_	0.1155	10	-0.583	4.91
	EM+Pink	0.0004	65.63	0.0009	31.41	-0.0349	3.95	-0.507	0	2.009	99.5	0.107	20.52	-0.723	8.51	-0.5383	7.94	_	_
	EM+Red	0.0002	50.98	_	_	-0.0697	3.60	-0.757	0	2.203	98.7	_	_	-0.151	12.0	-0.1069	9.03	-1.394	46.43
	ZZ+Green	0.0008	108.7	0.0016	29.98	-0.0193	4.20	-0.578	0	2.412	99.25	0.139	21.87	-0.0042	19.3	0.1636	16.2	-1.851	27.83
	ZZ+Pink	0.0004	66.34	0.0009	20.21	-0.0197	4.32	-0.746	0	3.005	98.42	_	_	-0.0005	14.8	0.154	10.0	-1.643	27.87
	ZZ+Red	0.0002	54.89	0.0022	22.71	-0.0006	4.39	-0.730	0	3.030	97	0.185	21.87	_	_	_	_	-1.530	29.57
Su_Cold	PD+Green	0.0241	104.6	0.0008	32.36	0.00251	4.60	-0.303	0	0.601	99.67	0.029	25.65	_	_	0.00097	16	-0.594	19.42
	PD+Pink	0.0002	61.07	0.0853	17.41	-0.0007	4.50	-0.315	0	1.028	99.39	0.167	21.6	0.0255	15.6	0.0481	12.8	_	_
	PD+Red	0.0001	52.59	0.0457	15.83	_	_	-0.378	0	1.917	99.32	0.286	24.3	-0.317	13.3	-0.0014	11.3	_	_
	EM+Green	0.0006	105.4	0.0006	35.94	-0.0284	3.85	-0.253	0	0.904	99.79	0.369	23.76	_	_	_	_	_	_
	EM+Pink	0.0003	65.63	0.0005	31.41	-0.0009	3.95	-0.298	0	0.673	99.5	0.273	20.52	-0.043	8.51	-0.0028	7.94	-0.710	33.85
	EM+Red	0.0001	50.98	-0.172	15.44	-0.0229	3.60	-0.300	0	1.603	98.7	_	_	-0.0012	12.0	-0.0199	9.03	_	_
	ZZ+Green	0.0004	108.7	0.0007	29.98	-0.0002	4.20	-0.319	0	0.919	99.25	0.496	21.87	-0.0001	19.3	0.0004	16.2	-0.0005	27.83
	ZZ+Pink	0.0003	66.34	-0.0001	20.21	-0.0002	4.32	-0.332	0	1.730	98.42	_	_	-0.0006	14.8	-0.0008	10.0	_	_
	ZZ+Red	0.0001	54.98	0.0009	22.71	-0.0008	4.39	-0.288	0	2.442	97	0.237	21.87	-0.0001	13.1	-0.1531	11.3	_	_
Wi_Amb	PD+Green	0.0007	108.4	0.0011	29.02	-0.0328	4.32	-0.622	0	2.762	100	0.0002	25.11	_	_	_	_	-0.001	20.41
	PD+Pink	0.0004	74.25	0.0011	24.32	_	_	-0.597	0	2.759	100	-0.405	17.82	_	_	_	_	_	_
	PD+Red	0.0003	63.68	0.0011	20.28	_	_	-0.422	0	2.579	97	-0.001	12.42	_	_	_	_	-0.249	43.05
	EM+Green	0.0008	109.7	0.0003	31.55	_	_	-0.411	0	1.824	100	-0.0006	15.93	_	_	_	_	_	_
	EM+Pink	0.0007	86.09	0.0010	24.54	_	_	-0.403	0	2.588	100	_	_	_	_	_	_	-0.0003	27.41
	EM+Red	0.0004	61.8	0.0013	22.01	-0.0001	4.41	-0.372	0	2.870	100	-0.0004	23.9	_	_	_	_	-0.328	14.06
	ZZ+Green	0.0007	106.9	0.0012	34.09	-0.0094	4.55	-0.579	0	2.021	99	_	_	_	_	_	_	_	_
	ZZ+Pink	0.0004	67.42	0.0009	24.26	-0.0095	4.61	-0.618	0	2.841	95	_	_	_	_	_	_	_	_
	ZZ+Red	0.0002	53.86	0.0008	19.55	-0.0209	4.43	-0.506	0	0.055	90	-0.0003	19.98	_	_	_	_	_	_
Wi_Cold	PD+Green	0.0001	108.4	0.0009	29.02	_	_	-0.622	0	1.275	100	_	_	_	_	_	_	-0.613	20.41
	PD+Pink	0.0003	74.25	0.0131	24.32	_	_	-0.597	0	1.246	100	-0.0006	17.82	_	_	_	_	-0.002	14.66
	PD+Red	0.0002	63.68	0.0008	20.28	-0.0134	4.39	-0.422	0	1.485	97	-0.026	12.42	_	_	_	_	_	_
	EM+Green	0.0005	109.7	0.4532	31.55	-0.0121	4.48	-0.411	0	1.149	100	-0.0195	15.93	_	_	_	_	-1.114	2.31
	EM+Pink	0.0004	86.09	0.2381	24.54	-0.0037	4.34	-0.403	0	1.529	100	_	_	_	_	_	_	-0.0008	27.41
	EM+Red	0.0003	61.8	0.0008	22.01	-0.0007	4.41	-0.372	0	1.572	100	0.1912	23.9	_	_	_	_	-1.596	14.06
	ZZ+Green	0.0004	106.9	0.0007	34.09	-0.0008	4.55	-0.579	0	0.788	100	_	_	_	_	_	_	-0.467	3.2
	ZZ+Pink	0.0002	67.42	0.2505	24.26	-0.0002	4.61	-0.617	0	1.050	97.38	-0.0004	20.52	_	_	_	_	-1.205	6.58
	ZZ+Red	0.0001	53.86	0.1247	19.55	-0.0007	4.43	-0.506	0	1.154	95.63	-0.234	19.98	_	_	_	_	_	_

‡ quality data does not follow kinetic Law