DEVELOPMENT AND OPTIMIZATION OF AN INTEGRATED POSTHARVEST MANAGEMENT SYSTEM FOR STORAGE AND HANDLING OF FRESH MARKET TOMATOES IN SOUTH AFRICAN SUPPLY CHAINS

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ABSTRACT

The South African tomato industry is an important source of fresh food and valuable industrial raw material, contributing approximately 20% of the gross fresh fruit and vegetable production. In South Africa, commercial producers supply approximately 95% of tomato produce to various domestic and export markets. The industry has been growing steadily over the last decade, but challenges associated with the physiological nature of the crop have stagnated its progress. To date, the crop is mainly produced to satisfy domestic demand, yet the potential for export exists.

The global tomato production has been increasing for the past 30 years due to investment in breeding and scientific breakthrough in genetic engineering. Although research in postharvest handling of tomato have improved its quality and shelf-life through a better understanding of molecular and genetic processes that occur after harvest, it is still estimated that the global postharvest losses of tomato are as high as 30-40%. In South Africa, conservative estimates put these losses at 13.5%. The tomato supply system and to a large extent, the majority of fresh fruits and vegetables, are complex systems with various production and supply strategies applied by different actors in the supply chain.

Post-harvest losses of tomato constitute qualitative and quantitative aspects of the product. Every fresh fruit and vegetable supply chain, including tomato, is unique as each has peculiar characteristics. The identification and apportionment of these losses to the different phases of the harvest to consumption continuum is important in order to formulate sound strategies to mitigate them. It is estimated that in developing countries, postharvest losses of up to 20% occur during transportation.

The effect of transportation coupled with various handling conditions along different supply chains on fresh tomato has not been studied and well understood from a quality perspective. Understanding quality degradation kinetics, and integrating it in the overall management strategy of the tomato supply chain is important in ensuring consumer satisfaction and improving the returns to producers. The control of microbial contamination by surface disinfection using various decontaminants is important to prevent postharvest spoilage as well as meet legal microbial quality requirements. The existing industry standard disinfectants such as chlorine have perceived environmental and health concerns and therefore, there is need to develop disinfectants that are both eco-friendly, and have properties that can improve the quality and shelf-life of tomato products. Integrated-surface treatments have the potential of filling this gap.
This study centres on establishing the effect of transporting fresh tomato along various supply chains on its quality. Integrated post-harvest treatments will be developed and evaluated in order to establish treatment combinations that effectively extend the product shelf-life under different transportation conditions. Infield post-harvest handling, transport and storage practices will also be evaluated to establish their role in contributing to the post-harvest losses downstream the supply chain, in order to develop industry best practices for tomato supply in typical commercial set-ups. The study will culminate in the development of quality deterioration models from empirical data where a modelling approach that integrates the effect of transportation conditions, costs and consumer acceptability will be used to establish the optimum supply chain parameters that suit various supply constraints and modelling scenarios. This model could be used by the industry as a management and decision making tool for their operations.
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1. INTRODUCTION

Tomato (*Lycopersicon esculentum*) is a herbaceous plant of the *Solanaceae* family that is grown for its edible fruit Moneruzzaman *et al.* (2009). It is a valuable industrial raw material and fresh produce crop, as well as the second most important vegetable in the world after potato (Dorais *et al.*, 2008). In fresh forms, it is eaten as fruit salads, sandwiches and salsa or processed into pastes, preserves, juices and soups (Beckles, 2012; Mujtaba and Masud, 2014; Pinheiro *et al.*, 2014). Many dishes are also prepared using tomato and therefore, its consumption in this way is interwoven into the culture of different communities, hence explaining its global appeal to meal preparation (Beckles, 2012). 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 566,180 metric tons (FAOSTAT, 2015) and contributed 24% of the total vegetable production, from an area of 6,000 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 abundant in nutritional 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 gives it its 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 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 is affected by pre-harvest factors, as well as the handling and storage conditions after harvesting. It is estimated that 30-40% of harvested tomato in developing nations is lost due to postharvest spoilage (Moneruzzaman *et al.*, 2009). Recent studies have reported postharvest losses of tomato in tropical countries to be 20-50% due to handling and transportation (Mujtaba and Masud, 2014). These losses may constitute a loss in physical quality or losses in essential nutrients, vitamins and minerals (Nasrin *et al.*, 2008).
Storage and packaging conditions are important factors that determine the quality and shelf-life of tomato. For instance, changes in the phytochemical and nutrient attributes of tomato 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 are some of the strategies that have been implemented in industrial and commercial applications to improve the quality and shelf-life of harvested tomato by regulating metabolic processes that lead to deterioration in quality (Ali et al., 2004; Sandhya, 2010). There is still need to further understand how environmental conditions in the field affect quality and shelf-life of tomato as this influences their quality downstream the supply chain.

Surface treatments are important in managing microbial contamination of tomato and thereby protecting against decay, 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 tomato. 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 have health benefits (Mahfoudhi et al., 2013; Guerreiro et al., 2015). The increased need for eco-friendly processing technologies on fresh foods has also made surface decontamination of tomato using chlorine unpopular (Pinheiro et al., 2014), hence the need for an alternative by the tomato industry. The use of biocontrol agents in extending the shelf life of tomato 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 (Moneruzzaman et al., 2009). Moneruzzaman et al. (2009) reported that all tomato cultivars have the longest shelf-life when harvested at the mature green stage. Different postharvest 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, chemical and physiological treatments can be managed, coupled with the storage and handling conditions to maximize the shelf-life of tomatoes with 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 postharvest 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 tomato without negatively affecting its bioactive compounds. Workneh et al. (2009) also used MAP, evaporative cooling and ComCat® treatments to maintain the keeping quality and marketability of tomato 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 has not been assessed under commercial conditions.

The globalization of FFV supply chains have necessitated the transport of products such as tomatoes over long distances from the point of production. Food supply chains are complex and require orchestration of activities in order to meet supply criteria (Trienekens, 2010) and integrating quality to be among the core factors in management of the supply of tomato is important. The effect of long distance transportation of tomato in commercial South African set-ups has not been investigated, particularly from a quality perspective. Presently, consumers are health conscious, with an increased demand for food products that not only meet their basic quality requirements, but are also nutritionally rich and present no risk to human health.

The careful application of various postharvest management strategies to fresh tomato throughout its supply chain will ensure that products supplied meet the required quality and cost criteria sustainably. The understanding of the changes in tomato quality 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 postharvest management of tomato can help reduce postharvest losses and result in products that meet a complex mix of quality and supply chain criteria.

The purpose of the proposed study is to analyse, model and optimize various storage, handling and transportation conditions of tomato fruit of three maturity stages produced under commercial set-ups in South Africa.
2. LITERATURE REVIEW

2.1 Introduction

In this chapter, a detailed review of the post-harvest physiology, handling practices and current preservation technologies that are applied to extend the shelf-life and maintain the quality of fresh tomato is presented. The tomato supply chain under South African conditions is also reviewed with the view of highlighting the existing gaps and challenges in mitigating post-harvest losses and the management of quality throughout the supply chain. A brief summary of the findings of the review is given at the end of the chapter, and these form the basis of the development of the research proposal.

2.2 Fresh Market Tomato Supply Chain in South Africa

Tomato is cultivated in South Africa by both commercial and emerging farmers and contributed 18% of the total gross value of vegetable production in 2012 (DAFF, 2013). It is the second most important vegetable in terms of economic importance in South Africa, just second after potato (DAFF, 2013). The South African tomato industry has shown steady growth over the last two decades, and by the end of 2014, the industry was valued at approximately ZAR 2.1 billion (DAFF, 2015) with a gross production of 566,180 million tons.

The production of tomato in South Africa is done in almost all provinces, but Limpopo province (3,590 ha) is the major producer contributing approximately 75% of the total area covered by the crop (DAFF, 2013). 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)

<table>
<thead>
<tr>
<th>Province</th>
<th>Area planted as a % of the national total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limpopo</td>
<td>55</td>
</tr>
<tr>
<td>Mpumalanga</td>
<td>14</td>
</tr>
<tr>
<td>Eastern Cape</td>
<td>12</td>
</tr>
<tr>
<td>KwaZulu-Natal</td>
<td>10</td>
</tr>
<tr>
<td>North West</td>
<td>5</td>
</tr>
<tr>
<td>Western Cape</td>
<td>3</td>
</tr>
<tr>
<td>North West/Free state</td>
<td>1</td>
</tr>
</tbody>
</table>
Commercial scale tomato production is carried out in all provinces except Gauteng (Michael and Gundidza, 2012), with the commercial sector contributing 95% of the total production and emerging growers contributing the remaining 5% (DAFF, 2013). South Africa is not a major tomato exporter, and therefore, nearly most 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 as the preferred marketing avenue (DAFF, 2015). In South Africa, the main players in tomato supply chain 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.

Transport of tomato is typically from the growers and packing houses by road using trucks to feed local retail outlets, processing plants or export points. Throughout transport, cold chain management is enforced by use of refrigerated container trucks for products sold to high end supermarkets e.g. Woolworths. In addition to transport, these markets have stringent cold temperature control requirements by suppliers, while their products are in the cold storage facilities, in distribution centres as well as retail outlets that sell the products to consumers (DAFF, 2013). This is, however, not entirely the case for products supplied to FPMs. A detailed description of the South African tomato supply and distribution channels is given by Sibomana et al. (2016) and DAFF (2013).

The foregoing statistics clearly underscore the importance of the Limpopo province as the major producer of fresh tomato in South Africa. It is also evident that there is a latent capacity for the expansion of production to target regional and international markets. Exploration of these markets would effectively imply the expansion of the market size of South African tomato industry. Exporting to regional and international markets would have transport as the dominant activity. An in-depth understanding of the effect of long distance transportation on the quality and shelf-life of tomato in South African conditions is, therefore, required in order to effectively export to these markets without incurring appreciable loss in quality. An emerging trend of higher profitability of exported fresh tomato products than products sold in domestic markets (DAFF, 2015) further makes this markets appealing to commercial producers.

The challenges in South African commercial tomato industry centres primarily on the perishable nature of tomato fruit. Its fragile nature during freight further exacerbates the problem. The commercial entities have long distribution chains that increase the transit time of
products and introduces multiple handling that result in deterioration of quality and damage to the products. The problem is further worsened in cases where refrigerated transport is not used. Emerging farmers have capacity problems due to their inability to invest in costly infrastructural installations such as cooling units. The variability of constraints affecting both sets of producers demand for targeted solutions to meet their specific needs. Efficiency of movement of products through logistical orchestration could be one of the approaches. The effect of this approach could be analysed and understood at a deeper level through modelling of the supply chain.

2.3 Physiological and Qualitative Attributes of Tomato

2.3.1 Development phases and postharvest physiology of tomato fruit

Tomato is a climacteric fruit that is grown globally for its edible fruit. The fruit gradually ripens even after harvest, when it has reached a certain maturity point (Rančić et al., 2010). It is a vegetable crop, which, in strict terms, is a fruit (ISU, 2015) classified as a berry (Rančić et al., 2010; ISU, 2015). Tomato fruits develop and grow from the fertilized ovary after flowering, and four developmental phases during its production are well known (Tanksley, 2004; Heuvelink, 2005; ISU, 2015). These phases are the fruit-set, the phase of rapid cell division, cell expansion phase and ripening. A summary of these developmental stages is illustrated in Figure 2.1.

![Developmental Phases of Tomato and Physiological Changes](image)

Figure 2.1 A schematic representation of developmental phases of tomato and the concomitant physiological and biochemical changes (Atwell et al., 1999).
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 tomato with concentrations ranging from 1-1.4%, and 0.93-1.2% of its fresh weight, respectively (Suárez et al., 2008). Sucrose is also present in tomato albeit at much lower concentrations (Pangaribuan, 2005). Citric and malic acid are the most abundant organic acids in tomato with both organic acids contributing about 12% of the dry matter (Pangaribuan, 2005). The compositional nature of tomato makes it susceptible to water loss, decay and microbial attack and this necessitates post-harvest treatments to mitigate these vulnerabilities.

At the end of ripening, tomatoes reach their end of their physiological life and undergo senescence where the product becomes unmarketable. The short cycle of development, and even shorter post-harvest life of tomato makes it a perishable crop that requires strategies to maintain its quality to be put in place immediately after harvest and throughout the product’s supply to distant markets (Seymour et al., 2013).

### 2.3.2 Postharvest microbiological quality issues of tomato

The consumption of contaminated fresh fruits and vegetables has been recently recognized as a means through which food-borne pathogens are transmitted (Bartz et al., 2015; Pagadala et al., 2015). It is no surprise that from 1998-2008, 46% of all foodborne illnesses have been linked to fresh produce, and for all the cases, 7.1% was related to the consumption of contaminated tomato (Pagadala et al., 2015).

Fresh tomato has been specifically implicated in sporadic outbreaks of foodborne illnesses in the USA between 2008 and 2010 (CDC, 2013; Pagadala et al., 2015). Between 1997 and 2007, majority of these outbreaks have been traced back to California and the Eastern shores of Virginia (Pagadala et al., 2015). Other major outbreaks of foodborne illnesses due to contaminated tomatoes have been reported by Lynch et al. (2009) and Pagadala et al. (2015). These outbreaks 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). They also result in loss of consumer confidence in the products supplied (Yun et al., 2015). There has been an upward trend in the frequency of the occurrence of these incidences in the world. In the USA for instance, it increased from 1% in 1970 to 6% by 1990 and had doubled this by 2009 (Lynch et al., 2009). 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). The vast distribution of fresh produce due to global demand in places far from their production zones further aggravates the problem (Brackett, 1999; Hedberg et al., 1999; Lynch et al., 2009).

A broad range of microbial pathogens have been isolated as the culprits responsible for the outbreak of human illnesses associated with tomato consumption in different parts of the world. 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). Table 2.1 shows a summary of various microbial pathogens that have been linked to human illnesses in fresh tomato between 1990 and 2006.

Shi et al. (2009) reported that salmonella outbreaks in 2009 implicated the farms and packaging plants used for its production, and observed that bacterial contamination in tomato cause human illness mainly through the oral-faecal route. Consumption of tomatoes without heat treatment further aggravates these microbial quality problems (Dugassa et al., 2015).

Table 2.2 A summary of microbial pathogens associated with contaminated tomatoes that have caused illnesses between 1990 and 2006

<table>
<thead>
<tr>
<th>Pathogen</th>
<th>Year of occurrence</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Escherichia Coli</em> 0157:H7</td>
<td>1997</td>
<td>Dugassa et al. (2015)</td>
</tr>
<tr>
<td>Botrytis Cinerea</td>
<td>1999</td>
<td>Wang et al. (2010)</td>
</tr>
<tr>
<td>Penicillium Expansum</td>
<td>2007</td>
<td>Liu et al. (2007)</td>
</tr>
<tr>
<td>Salmonella Javiana</td>
<td>1990</td>
<td>Hedberg et al. (1999)</td>
</tr>
<tr>
<td>Salmonella Montevideo</td>
<td>1993</td>
<td>Hedberg et al. (1999)</td>
</tr>
<tr>
<td>Salmonella Thompson</td>
<td>2000</td>
<td>Shi et al. (2009)</td>
</tr>
<tr>
<td>Salmonella Newport</td>
<td>2002</td>
<td>Greene et al. (2008)</td>
</tr>
<tr>
<td>Salmonella Javiana</td>
<td>2002</td>
<td>Toth et al. (2002)</td>
</tr>
<tr>
<td>Multiple</td>
<td>2004</td>
<td>CDC (2005)</td>
</tr>
<tr>
<td>Salmonella Braenderup</td>
<td>2004</td>
<td>CDC (2005)</td>
</tr>
<tr>
<td>Salmonella Newport</td>
<td>2005</td>
<td>Greene et al. (2008)</td>
</tr>
<tr>
<td>Salmonella Braenderup</td>
<td>2005</td>
<td>Greene et al. (2008)</td>
</tr>
<tr>
<td>Salmonella Braenderup</td>
<td>2006</td>
<td>CDC (2007)</td>
</tr>
<tr>
<td>Salmonella Typhimurium</td>
<td>2006</td>
<td>CDC (2007)</td>
</tr>
</tbody>
</table>

Hedberg et al. (1999) in an epidemiological surveillance study between 1990 and 1993 reported that in three households that unknowingly consumed contaminated, refrigerated raw tomatoes that were washed and cored, seven people out of 11 (64%) in one household fell ill. In the same study, it was reported that eight out of 13 members (62%) in another family exhibited diarrheal illness within seven days after consumption. Other studies have also shown that there is an emergence of bacterial colonies in tomatoes and other vegetables that are resistant to antibiotics
with others having resistance to combinations of antibiotics; suggesting abuse of antibiotics in Africa (Dugassa et al., 2015).

Fungal contamination in tomato has been reported by Seo et al. (2010) to cause health problems that are linked to the mycotoxins they produce, while others may elicit allergies when they contaminate fresh tomatoes. *Rhizopus Nigricans, Botrytis 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 mode of tomato pathogen infection is a complex process that has elicited divergent views from scientists due to the complex nature of interactions between the different biological and environmental systems involved (Shi et al., 2009). Pagadala et al. (2015) asserted that the determination of the source of pathogens and understanding the mechanisms causing contamination remains a challenge.

Cross-contamination during handling of tomatoes and leakage of nutrients from cellular materials are a potential mechanism of microbial contamination (Dugassa et al., 2015). The wash water used during the cleaning process of tomato in the pack-house is also another potential means of contamination, and may trigger cross-contamination between bruised tomatoes during tomato handling, especially when the chlorine content in the water is not continually monitored. It has been widely reported that when fresh produce including tomato is contaminated, particularly after internalization, by foodborne pathogens, washing before consumption has an insignificant effect in decontaminating such products (Lynch et al., 2009). Bartz et al. (2015) defined internalization as the migration of microbial contaminants from the plant surfaces and the environment into the internal apoplast of the plant tissue. A classical mechanism for the occurrence of this phenomena is when hot fruit is put in water during cleaning, causing a pressure deferential in the internal tissues that results in water with microbes to be drawn internally through the surface apertures. Fruit bruising has also been reported in the literature as one of the mechanisms through which microbes are internalized in tomato (Bartz et al., 2015). Other mechanisms that cause microbial internalization in tomato have been discussed in (Pagadala et al., 2015; Shenge et al., 2015).

The postharvest microbial contamination of tomato may also occur when the application of irrigation water and organic manures are not closely monitored and strategies to limit transfer of microbial contaminants to the products are not implemented. Pagadala et al. (2015) investigated the source of irrigation water (surface or groundwater), and the mode of fertilizer
application (organic, compost or inorganic) as possible vehicles of microbial contamination in tomato. The study reported shiga contamination in two irrigation water samples and one tomato sample. Field soil samples were positive for *Escherichia coli* (80%) and of the 259 tomato samples that were analysed, 5.4% showed the presence of generic E. coli. Tomatoes that touched the ground/mulch reported the highest total coliform (TC) count. It was further observed that, groundwater had lower APC, TC counts and generic *E. coli* than surface water. The use of breached drip systems to irrigate tomato is a further possible risk factor that may be a crucial vehicle of foodborne pathogen contamination. The study by Pagadala *et al.* (2015) showed the APC and TC counts at the end of the drip line to be higher than counts at the water intake point, suggesting that sections of breached drip lines might be a potential source of contamination. Water management practices should, therefore, be integrated into good agricultural practices (GAP) to ensure that this source of contamination is controlled. One of the GAP recommended by the FDA lays down guidelines prohibiting produce that touch the ground from entering the market. The study by Pagadala *et al.* (2015) also recommended tomatoes that are attached to the plant but touching the ground, to be barred from entering the market. These are, but a few GAP, aiming at controlling microbial contamination on fresh produce originating from soil and surface water sources. The practicality of implementing such guidelines is questionable. Postharvest treatments using surface disinfectants are, however, easier to implement and less cumbersome to manage and monitor. Some of these treatments can not only disinfect the product but also improve the shelf-life of the product enabling long transportation with minimal loss of quality. The importance of developing food safety solutions for the tomato supply chain can therefore, not be overemphasised.

2.3.3 Postharvest quality changes in fresh tomato

Quality is a loosely defined term that is often defined differently depending on the perspective of who is looking at the product and the purpose for which it is used (Shewfelt, 1999). In general, quality is seen as the absence of a defect or the degree of excellence of a commodity (Cardello, 1995). The quality of fresh produce can be either product-oriented or consumer-oriented. Consumer-oriented product qualities mainly focus on the attributes that drive consumer acceptability and buying decisions of fresh produce (Zeithaml, 1988). Post-harvest research primarily focuses on product-oriented qualities of fresh commodities, which are often measurable using objective tests (Shewfelt, 1999).
The quality of fresh market tomato encompasses physical, nutritive, chemical and safety attributes (Shewfelt, 1999; 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 content, minerals (Nasrin et al., 2008) and bioactive compounds that comprise of antioxidants (lycopene, β- and α-carotene), phenolic compounds and oxidized metabolites (Gierson and Kader, 1986; Anju-kumari and Bhardwaj, 1993; Gil et al., 2002; Moneruzzaman et al., 2009). These attributes holistically influence the postharvest shelf-life and sensory attributes of fresh tomato.

All these quality parameters are affected by genetic characteristics of the respective tomato cultivar, agronomic practices, and postharvest handling and storage practices (Gierson and Kader, 1986; Anju-kumari and Bhardwaj, 1993; Maul et al., 2000b; Nasrin et al., 2008; Wang et al., 2008; Moneruzzaman et al., 2009; Tigist et al., 2013). The postharvest quality of fresh tomato can be maintained by manipulating the postharvest storage and handling practices.

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 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 changes 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 °C and below 30 °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 cherry type cultivars, round shaped, pear shaped, plump type, pear oval, pear-elongated, small or large sized tomatoes. The shape and size of tomatoes is, therefore, a widely variable attribute as shown by Díez and Nuez (2008). Table 2.3 depicts a typical classification of tomato fruits according to their size, shape and texture.

Table 2.3  A summary of the size, texture and shape of various fresh tomato varieties (After Díez and Nuez, 2008)

<table>
<thead>
<tr>
<th>Fruit size</th>
<th>Fruit ribbing</th>
<th>Growth habit</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large fruits calibre G and GG &gt; 67 mm</td>
<td>Smooth or slight Medium or strong</td>
<td>Indeterminate or determinate Determinate or indeterminate</td>
<td>Beefsteak Marmande</td>
</tr>
<tr>
<td>Medium sized fruits calibre M 57-67 mm</td>
<td>Smooth or slight</td>
<td>Indeterminate or determinate Indeterminate</td>
<td>Vemone (round or slightly flattened) Papper-Shaped</td>
</tr>
<tr>
<td>Small fruits calibre MM 47-57 mm</td>
<td>Smooth</td>
<td>Indeterminate</td>
<td>Moneymaker and Canary Hanging Basket Tomato</td>
</tr>
<tr>
<td>Small fruits calibre MMM</td>
<td>Smooth</td>
<td>Indeterminate</td>
<td>Cocktail (round and pear-shaped)</td>
</tr>
<tr>
<td>Very small fruits &lt; 30 g</td>
<td>Smooth</td>
<td>Indeterminate</td>
<td>Cherry (edible and ornamental)</td>
</tr>
</tbody>
</table>

During ripening and maturation, fresh tomato is characterized by changes in its shape and size albeit modest. Shrivelling of tomato fruit occurs as it approaches senescence, and is accompanied by loss of weight due to respiration and water loss (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 (Tucker et al., 2007; Tigist et al., 2013).

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

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).
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 8 tomato varieties during storage to range from 0.25% at the end of storage, to 0.89% at harvest.

Ascorbic acid (AA) is one of the most important quality attributes in fresh fruits and vegetables. AA content of fresh tomato has been reported to range from 14.6 to 21.7 mg per 100g (Tigist et al., 2013). Toor and Savage (2006) reported AA content of 9.29 to 15.08 per 100g in their study, where they observed a slight increase in AA mid-storage time, followed by a decrease as the fruit approached senescence. In general, AA is reported to give varied trends under normal storage (Tigist et al., 2013). 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 (Betancourt et al., 1977; Beckles, 2012). The storage temperature is a significant factor affecting the accumulation of sugars in tomato (Beckles, 2012), with low temperature favouring the accumulation of soluble sugars than higher temperatures (Beckles, 2012). Maul et al. (2000b) reported glucose levels to be significantly higher in tomato samples stored at 5°C compared to those stored at 12 °C and 20 °C, while fructose levels and sucrose equivalents were considerably higher in tomato samples stored at 5 °C and 10 °C compared to those stored at higher temperatures (Betancourt et al., 1977; Beckles, 2012). 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 tomato (Heuvelink, 2005).

Tomato is rich in lycopene, a bioactive compound that is known to have numerous disease prevention and immune boosting benefits on human health (Alexander and Grierson, 2002; Brandt et al., 2006). Lycopene biosynthesis and accumulation is a genetically controlled process with its accumulation increasing under normal storage conditions with storage time, and peaks before senescence. 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. Lycopene accumulates following increased expression of \( hp \) and \( og^c \) genes (Brandt et al., 2006) and therefore, is produced through genetically controlled biosynthetic pathways. Lycopene is synthesized from phytoene, and through the central isoprenoid pathway, four desaturation steps to generate lycopene (Liu et al., 2012). 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, just like lycopene, have important antioxidant properties in tomato. 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 other 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 are discussed in detail by Antunes et al. (2013). The development of postharvest handling and storage strategies that enhance and maintain the abundance of these health promoting compounds cannot be, therefore, overemphasized.

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 (Yilmaz, 2001; Díaz de León-Sánchez et al., 2009). Commercial harvesting conditions and postharvest handling practices have a significant effect on the taste of fresh market tomato (Maul et al., 2000b), since these conditions often cause injuries that induce early ripening resulting in qualitative and quantitative changes that alter the product’s aroma profile and flavour (Moretti et al., 2002). Maul et al. (2000b) reported that tomato aroma and flavour is significantly affected by low temperatures and short storage durations, with such products exhibiting low tomato flavour and ripe aroma. The study concluded that the recommended postharvest storage temperature of 10 to 12.5 °C may induce unfavourable flavour and aroma in fresh tomato. This, therefore, implies that refrigeration of tomato at typical refrigerator temperatures induces inferior tomato flavour. Poor tomato flavour has been one of the prevalent consumer complaints especially in tomato 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 related to its ripening process. Due to the perishable nature of tomato fruit, postharvest handling practices that slow down the deteriorative processes that start postharvest without adversely affecting its quality, are invaluable in ensuring that products are transported to distant market without appreciable loss in quality.
2.3.4 Postharvest quality assessment of tomato

The analysis of the quality attributes of tomato fruit is essential in order for the appropriate quality control steps to be mated out where there is deviation from the required standards. The quality components of fresh tomato include: physical, chemical, biochemical, organoleptic, nutritional and safety attributes. A summary of some of the methods of assessment of some of these parameters is shown in Table 2.4.

Table 2.4 A summary of various methods used to assess the quality of tomato

<table>
<thead>
<tr>
<th>Quality component</th>
<th>Parameters</th>
<th>Methods</th>
<th>Destructive/Non-destructive</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical</td>
<td>Colour</td>
<td>Colorimetric</td>
<td>Non-destructive</td>
<td>Žnidarčič and Požrl (2006)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Computer vision</td>
<td>Non-destructive</td>
<td>Pathare et al. (2013)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sensory</td>
<td>Non-destructive</td>
<td>Pathare et al. (2013)</td>
</tr>
<tr>
<td></td>
<td>Texture /Firmness</td>
<td>Firmness testers</td>
<td>Destructive</td>
<td>Batu (2004)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Durometers</td>
<td>Destructive</td>
<td>Edan et al. (1997)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Firmness sensors</td>
<td>Non-destructive</td>
<td>Lesage and Destain (1996)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Laser scattering</td>
<td>Non-destructive</td>
<td>Tu et al. (2000)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Computer vision</td>
<td>Non-destructive</td>
<td>Gonzalo et al. (2009)</td>
</tr>
<tr>
<td>Size and Shape</td>
<td>Mechanical damage</td>
<td>Visual</td>
<td>Non-destructive</td>
<td>Li and Thomas (2014)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hyperspectral imaging</td>
<td>Non-destructive</td>
<td>Cho et al. (2013)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIRS &amp; MRI</td>
<td>Non-destructive</td>
<td>Milczarek et al. (2009)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Visual</td>
<td>Non-destructive</td>
<td>Artes and Escriche (1994)</td>
</tr>
<tr>
<td>Decay</td>
<td></td>
<td>Titrimetric</td>
<td>Destructive</td>
<td>Duma et al. (2015)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Potentiometric</td>
<td>Destructive</td>
<td>Kowalczyk et al. (2011)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chromatographic</td>
<td>Destructive</td>
<td>Sayajon et al. (2012)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Refractometric</td>
<td>Destructive</td>
<td>Aoun et al. (2013)</td>
</tr>
<tr>
<td>Chemical</td>
<td>Titratable acidity</td>
<td>Spectrophotometric</td>
<td>Destructive</td>
<td>Ceballos Aguirre and Vallejo Cabrera (2012)</td>
</tr>
<tr>
<td></td>
<td>Sugars</td>
<td>Spectrophotometric</td>
<td>Destructive</td>
<td>Arias et al. (2000)</td>
</tr>
<tr>
<td></td>
<td>Total soluble solids</td>
<td>Spectrophotometric</td>
<td>Destructive</td>
<td>Duma et al. (2015)</td>
</tr>
<tr>
<td>Biochemical</td>
<td>Lycopene</td>
<td>Spectrophotometric</td>
<td>Destructive</td>
<td>Szuvandzsiév et al. (2014)</td>
</tr>
<tr>
<td></td>
<td>Total carotenoids</td>
<td>Chromatographic</td>
<td>Destructive</td>
<td>Re et al. (2002)</td>
</tr>
<tr>
<td></td>
<td>Total polyphenols</td>
<td>Spectrophotometric</td>
<td>Destructive</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flavonoids</td>
<td>Chromatographic</td>
<td>Destructive</td>
<td></td>
</tr>
<tr>
<td>Safety</td>
<td>Microbial load</td>
<td>Plating methods</td>
<td>Destructive</td>
<td>Lopez-Galvez et al. (2014)</td>
</tr>
<tr>
<td></td>
<td>Toxicants</td>
<td>Chromatographic</td>
<td>Destructive</td>
<td>Kozukue et al. (2004)</td>
</tr>
<tr>
<td>Nutritional</td>
<td>Vitamin C &amp; A</td>
<td>Spectrophotometric</td>
<td>Destructive</td>
<td>Duma et al. (2015)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chromatographic</td>
<td>Destructive</td>
<td>Aoun et al. (2013)</td>
</tr>
<tr>
<td>Organoleptic</td>
<td>Flavour and aroma</td>
<td>Sensory</td>
<td>Destructive</td>
<td>Maul et al. (2000a)</td>
</tr>
<tr>
<td></td>
<td>Taste</td>
<td>E-nose</td>
<td>Non-destructive</td>
<td>Gómez et al. (2008)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sensory</td>
<td>Destructive</td>
<td>Beullens et al. (2008)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E-tongue</td>
<td>Destructive</td>
<td>Beullens et al. (2008)</td>
</tr>
</tbody>
</table>
Modelling techniques for assessing the quality of fresh market tomato have also been reported in the literature. Some of these models have been used to predict the variation of the total volatile compounds and total sugar with time during storage of fresh tomato Azodanlou et al. (2003a). (Azodanlou et al., 2003b). Other attempts by Jahns et al. (2001) that used fuzzy models to assess the overall quality and consumer acceptability of fresh tomato showed a good correlation between the total quality and the product's optical properties. There has been, however, minimal use of these models as analytical tools under commercial conditions.

The limiting nature of techniques for quality assessment in remote production and supply nodes necessitates the development and improvement of non-destructive, rapid assessment tools and techniques that can be used to assess the quality of tomato rapidly and accurately. These tools would be particularly useful in remote pack-houses and fields that are far from the laboratory. Traditional analytical techniques for quality assessment would, therefore, be used for calibration and product development as they are time-consuming and costly. Modelling approaches predicting quality changes in a supply chain would also be useful under field conditions.

2.3.5 Post-harvest losses in tomato supply chain

Post-harvest losses are a significant constraint in South African and global tomato supply chains. Data from the last four decades show that 40-50% of fresh fruits and vegetables (FFV) produced in developing nations are lost due to poor storage and post-harvest handling conditions (Kitinoja and AlHassan, 2010), resulting in decreased nutritional quality and market value.

Currently, an emphasis has been put on expanding the production of FFV in many developing nations, with a corresponding decline in resources and efforts invested in mitigating post-harvest losses (PHL) (Kitinoja and AlHassan, 2010). It has been noted, however, that the reduction in PHL of FFV including tomato, is an important avenue towards ensuring their sustainable production (Kitinoja and AlHassan, 2010; Etebu et al., 2013).

It is reported by Genova II et al. (2006) that higher postharvest losses in global tomato supply chain are incurred by retailers and wholesalers compared to those recorded by farmers. They also reported that postharvest losses are lower in tomato during the dry season compared to wet seasons, with the average losses between farm and retail level being 17.5%. A summary of the leading causes of postharvest losses in tomato is presented in Table 2.3. It is noticeable that some of the triggers occasioning PHL at the farm level are carried through and compounded
downstream the supply chain. It is therefore crucial for strategies to mitigate them to be applied at all levels for desirable, affordable and sustainable outcomes to be realised in managing them.

Table 2.5 An overview of the causes of postharvest losses of fresh tomato at different supply chain levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Cause of loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farm level</td>
<td>Harvesting at high humidity, harvesting in hot weather</td>
</tr>
<tr>
<td></td>
<td>Disease attack at harvest</td>
</tr>
<tr>
<td></td>
<td>Damage during harvesting, damage during transport</td>
</tr>
<tr>
<td>Wholesalers - consumers</td>
<td>Harvesting at high humidity, harvesting in hot weather</td>
</tr>
<tr>
<td></td>
<td>Disease attack at harvest</td>
</tr>
<tr>
<td></td>
<td>Damage during transport</td>
</tr>
<tr>
<td></td>
<td>Poor packaging</td>
</tr>
<tr>
<td></td>
<td>Poor infrastructural facilities</td>
</tr>
<tr>
<td></td>
<td>High temperature in storage facility</td>
</tr>
<tr>
<td></td>
<td>High supply that exceeds the market demand</td>
</tr>
<tr>
<td></td>
<td>Poor quality of product</td>
</tr>
</tbody>
</table>

Strict cold chain management is one of the most important approaches to maintaining the quality of fresh tomato as discussed by Kitinoja and AlHassan (2010) since high temperature is known to accelerate respiration and water loss resulting in products with low quality and market value. Arah (2015), in a recent review, presented some of the major issues that trigger PHL affecting tomato in Africa and other developing nations. Logistical issues, improper packaging and handling conditions are some of the key challenges that negatively affect the quality and market value of fresh tomato in African supply chains. A recent study by Etebu et al. (2013) also reported that 20% of tomato in Nigeria is lost due to poor storage, transport, field diseases and market mismatch. The global amount of PHL of tomato is estimated to be 30-40% and is attributed to the inherent nature of tomato fruit being a food product with a high moisture content and nutrients, making it susceptible to microbial attack, water loss and a host of spoilage reactions (Etebu et al., 2013).

There is scarce information that quantify the level of PHL of fresh market tomato in South African supply chains. Although rough estimates have been presented by Sibomana et al. (2016) as 10.2%, the actual level might even be higher in South Africa and other developing nations of the African continent, especially where investment in mitigation of PHL in FFV is still lacking (Arah et al., 2015). Studies have so far not been reported that quantify the exact level of PHL in South Africa. There have been, however, some research efforts aimed at
improving the quality and shelf-life of fresh tomato in South Africa (Workneh et al., 2011; Tigist et al., 2013).

2.3.6 Emerging issues in tomato supply chain in Africa

In many African tomato supply chains, there is fragmentation of the market at producer and retailer ends of the supply chain. Other attributes of these supply chains include: direct payment of supplier, little or no quality control, few quality standards, minimal or no product innovation and vested market power in the hands of wholesale players (Neven and Reardon, 2004). Quality and safety standards are a challenge since most countries lack proper regulatory and enforcement mechanisms, especially at the low tier markets such as the informal markets (Lee et al., 2012). Of huge concern are products that are contaminated with pathogenic microorganisms and persistent synthetic pesticides that exceed the allowed maximum residue limits (MRLs).

The FFV industry in Africa has been growing rapidly as evidenced by penetration of retail and supermarket (Neven and Reardon, 2004; Lee et al., 2012) chains specializing in fresh produce and other fresh market and consumer goods (FMCG). This growth has affected the supply systems of FFV, including tomato, in various ways. Transnational FFV supply chains have gradually integrated small growers in developing nations into global sourcing networks (Lee et al., 2012). This volume driven business requires high coordination among the various players in the supply chain, coupled with stringent safety and quality requirements, that often lock out small farmers and suppliers from selling their products to large retail and supermarkets outlets (Lee et al., 2012), as penetrating these networks demand considerable financial, network and informational resources. Mycotoxins are also an emerging issue in tomato supply chains that pose a new food safety risk to consumers often overlooked by the business community (Van Boxstael et al. (2013).

Some of the solutions suggested to the challenges facing FFV in African supply chains require investment in physical, infrastructural and capacity building (Arah, 2015), as well as the development of low-cost and innovative solutions through research. This is because some of the investment requirements are beyond the reach of most small and medium scale farmers, and other supply chain players in Africa and developing nations. Transportation occurs in virtually all supply chains in South Africa and other developing nations and is an important contributor of postharvest losses in the supply chain. The understanding of how transportation
conditions along various supply chains in South Africa affect tomato quality is important in
developing strategies to mitigate losses occurring during carriage.

2.4 Postharvest Shelf-life Management Strategies of Fresh Market Tomato

The extension of shelf-life of fresh tomato has been intensively researched in a bid to maximize
and maintain a constant supply of products of the right quality to markets. Advances in the
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 techniques that are currently in use.

2.4.1 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 (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 tomato and a myriad of regulatory hurdles
(Redenbaugh et al., 1993; Falk et al., 2002) further complicates its adoption. Direct methods
of managing, for instance, the effect of exogenous ethylene during transport of tomato 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 is still at its infancy, 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).
2.4.2 Surface disinfection

Surface decontamination using different sanitizing agents, thermal and radiative 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 shelf-life of fresh tomato (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 tomato (Sapers and Jones, 2006; Chaidez et al., 2007). In general, surface sanitizers are regarded as effective if they can reduce the microbial load on the fruit surface of tomato by at least 2 log CFU/g (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). 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 2.5-3 log CFU/g 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 fruits 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 from tomato to levels of <1 log CFU/g. Other recently assessed chemical sanitizers include chlorine dioxide, bromine, iodine, acids and quaternary ammonium compounds (Goodburn and Wallace, 2013).

The use of pulsed light (Aguiló-Aguayo et al., 2013), ultrasound Brilhante São José and Dantas Vanetti (2012) 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. The use of biocontrol agents as a surface treatment has been tested on citrus and is currently a commercially acceptable product in the citrus industry (Sangwanich et al., 2013). Application of biocontrol agents to tomato have been investigated to a limited extent (Wang et al., 2010).
2.4.3 Edible coatings

Edible coatings play the dual role of improving the shelf-life of tomato and other fruits by modifying the atmosphere around the products hence reducing respiration, water loss, as well as preserving texture (Dávila-Aviña et al., 2014). In some cases, edible coatings exert antimicrobial effects (Dávila-Aviña et al., 2014). This area has recently received considerable attention due to the environmental friendliness of the technology and accrued health benefits it passes on 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.

2.4.4 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). Extension of tomato shelf-life can be achieved through ripening retardation, whereby they are sealed in packaging films that alter the gas composition around them with time, and 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). 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 until 50 days of 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 (Kantola and Helén, 2001; 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 with cold storage can significantly increase the shelf-life of tomato 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).

### 2.4.5 Temperature and humidity control

Humidity and temperature control are the most common approaches used to extend the shelf-life of fresh fruits and vegetables. Low-temperature storage is widely used since higher temperatures increase fruit respiration and shortens their shelf-life (Pinheiro et al., 2013; Biswas et al., 2014; Pinheiro et al., 2014). Storage temperature of fresh tomato depends on the maturity stage and cultivar (Pinheiro et al., 2013; Pinheiro et al., 2014). It has been, however, shown that temperatures lower than 13 °C induce chilling injury in tomato (McDonald et al., 1999).

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

### 2.4.6 Integrated postharvest management approaches

Integrated postharvest technology harnesses 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 (Abd-Alla et al., 2009; Workneh and Osthoff, 2010; Workneh et al., 2012; Mukhopadhyay et al., 2013; Mukhopadhyay et al., 2015) may be used as a set of integrated post-harvest treatments.

Integrated postharvest treatments have shown remarkable success (Ali et al., 2004) in their application to retard quality loss in tomato. For instance, 1-Methylcyclopropene (1-MCP) and MAP compared to either treatment alone were 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 rate of ripening of stored tomato resulting in a significant improvement of its marketability. This emerging research niche still has potential, especially in cases where novel treatments are environmentally friendly and confer health benefits on consumers (Stevens et al., 1997).

2.5 Modelling Approaches for Quality Management in Tomato Supply Chain Network

The estimation of quality changes during storage, transport and handling operations of fresh produce is important (Sloof et al., 1996). Product quality determines the value and acceptability of FFV to consumers and is a major determinant of the market price (Sloof et al., 1996). Models that holistically capture the dynamics of quality and supply chain parameters under various conditions during supply of FFV, are powerful tools that allow the accurate description and estimation of the supply chain under any set of conditions (Tijskens and Schouten, 2014). Such models could be valuable to the South African tomato industry.

2.5.1 Approaches to modelling tomato quality

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 their use to predict 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). Simplification can be done at the process level, depending on the degree of complexity required, but not at the mathematical or statistical level. All 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 involving three systems; product behaviour (dynamic model) coupled to 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 produce 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). Firmness and colour of tomato are the most important quality attributes for 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; Schouten et al., 2007b). Equations (2.1) and (2.2) are typical colour and firmness models of tomato developed by Schouten et al. (2007a), respectively.

\[
Red(t) = Red_{max} + k_{pre} \cdot \Delta t_C \cdot \frac{\text{factor 1} \cdot \text{factor 2}}{\text{factor 2} + (Red_{ref} - Red_{min})e^{\text{factor 1}(k_{Rpre} \cdot \Delta t_C - k_{Rpost} \cdot t)}}
\]  

\[
F(t) = (F_{ref} - F_{fix})e^{-k_{Fpost} \cdot t - k_{Fpre} \cdot \Delta t_F} + F_{fix}
\]  

Where \(Red(t)\) is the development of red pigment at a given time \(t\) after harvest, \(Red_{max}\) in 1000/G is the asymptotic colour value at \(+\infty\), \(Red_{min}\) in 1000/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, \(\Delta t_C\) is the colour biological age in days needed to change the colour from \(Red_{ref}\) to \(Red_0\) and \(k_{pre}\) is the rate of formation of red colour precursor compounds. factor 1 = \(Red_{max} + k_{pre} \cdot \Delta t_C - Red_{min}\), factor 2 = \(Red_{max} + k_{pre} \cdot \Delta t - Red_{ref}\) and \(R_0\) 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 \(\Delta t_F\) 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.

\[
K = K_{ref} \cdot e^{\frac{E_a}{R} \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)}
\]  

Where \(T\), \(T_{ref}\), \(E_a\) and \(R\) are the absolute temperature (K), arbitrarily chosen reference temperature, activation energy (J.mol\(^{-1}\)) and universal gas constant (8.314J.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.
2.5.2 An overview of the application of FFV models on globalised supply chains

Numerous research has been carried out to incorporate variation in quality of batches of FFV in order to accurately predict the quality of such products in globalized supply chains. 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 in 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; Schouten et al., 2007b). The modelling procedure for estimating biological age has been discussed in detail by Hertog et al. (2004) and Schouten et al. (2007b). Batch models that combine firmness and colour with consumer limits in fresh tomato supply chain have been used by Schouten et al. (2007b) to provide purchase periods between which batches change from acceptable (unripe-ripe) and ends when a batch becomes unacceptable (ripe-overripe). There is need to integrate the relevant behaviour of fresh fruits and vegetables in pre- and post-harvest domains, as well as the introduction of biological variability in models to understand the processes that contribute to the observed phenomena (Tijskens and Schouten, 2014). This cannot be realized through traditional modelling techniques, but requires a systems approach (Tijskens and Schouten, 2014).

Incorporation of biological variability in FFV that originate from different parts of the world provides a means of developing models that are useful in globalized supply chains. An example of these is the model developed by Tijskens and Schouten (2014) that integrates temperature fluctuations and biological variation using differential equations to predict the effect of temperature shifts on the propagation and distribution of biological age within each fruit batch. Rong et al. (2011), Munhoz and Morabito (2014) also attempted to model and optimize FFV supply system, where they used supply chain model functions that incorporate production levels, customer acceptance, logistical costs, quality compliance and non-compliance related costs to arrive at parameters that meet various production and supply chain scenarios.

Transportation of fresh tomato is one of the costly, logistically complex and delicate operation especially due to the perishable nature of the product. This is even critical when large volumes of product are transported to either domestic or international destinations. Transport conditions, over different supply chains vary and this aspect has to be accounted for in order to formulate sound strategies for maintaining product quality. Development of quality deterioration models...
in tomato supply chains is one of the effective means of predicting supply chain parameters in order to forestall quality and economic losses downstream. Quality loss is the dominant parameter that has been modelled in tomato supply chain with firmness loss and colour change being the common parameters that are modelled. With the increasing importance of nutrient composition of food products, degradation kinetics of bioactive compounds and vitamins should be incorporated into such models to enhance their effectiveness and usefulness and increase the value of information output by such models. Integrating quality, demand, cost and other consumer constraints into such models would make them powerful tools that can be used to improve the strategic and operational efficiency of tomato supply chains and, in the long run, the entire industry.

2.6 Prospects for Future Research

Tomato fruit production is an important part of the agricultural and industrial sectors of the South African economy that provides employment and contributes to the national gross domestic product (GDP) growth. The South African tomato industry has grown steadily over the past decade in terms of its monetary value (2.1 billion ZAR by 2014) and the absolute quantities of yield. The Limpopo province is the leading producer of tomato in South Africa accounting for over 75% of the total planted area in 2013 compared to 55% in 2007, a 20% increase over a 6-year period.

The South African tomato industry is structured in such a way that most of its output is supplied to the domestic markets, with limited supply to regional markets and virtually none to international markets. There is, however, a latent capacity for the industry to produce for international markets. A recent report highlighting the lucrative nature of tomato exported to international markets further underscores the importance of expanding to these markets. The perishability of the tomato fruit is, however, the limiting factor coupled with other technical factors that also affect domestic supply chains. The industry currently records high postharvest losses of tomato synonymous to other developing nations. The nature, occurrence and specific quantities of these losses especially in industrial setups is still, at best, given as estimates.

Research both locally and internationally has yielded strategies and technologies for maintenance of tomato quality. However, limited attempts have been made to adapt them to the practicalities of industrial scale production making their adoption a challenge. The effect of long distance transportation on tomato quality and shelf-life especially under commercial conditions in south Africa has not been investigated, yet it significantly contributes to
postharvest losses. This is especially important given the spoke and wheel distribution configuration of tomato supply in South Africa, with the Limpopo province being the hub from which tomato fruit is transported over long distances.

The complexity of FFV supply chains due to the variable nature of the markets and long transit routes requires logistical orchestration with quality and costs in mind. Understanding of the supply chain dynamics through the development of a post-harvest model of tomato fruit in South African conditions can allow valuable information of how quality varies during transportation, hence allowing for prediction and analysis of various supply scenarios.

The increased demand for fresh tomato without hazardous residues by both consumers and regulatory agencies has put producers under pressure to develop and adopt surface disinfectants that are eco-friendly, beneficial in improving tomato shelf-life and confer health benefits to consumers. For instance, the use of anolyte water in disinfection of tomato has given promising results yet it has not been tested and adopted under commercial settings. Similarly, biocontrol agents and biocontrol treatments as part of integrated agro-treatments have also not been evaluated in tomato products, yet some biocontrol agents have shown remarkable success in controlling post-harvest disorders in other fruit. The effect of packaging and handling conditions on the postharvest quality of tomato before and during long distance transport has also not been adequately researched. The proposed study is a practical attempt to address some of these gaps.
3. RESEARCH PROPOSAL

3.1 Introduction

The quality and shelf-life of fresh tomato depends on a complex set of dynamic factors, including environmental conditions, handling practices and supply chain decisions. At present, there is an increased demand for high quality tomato products that are nutritionally rich and have excellent sensory quality and shelf-life. Tomato fruits are, however, highly perishable and in order to deliver them to consumers situated long distances from the production sites without incurring appreciable loss in quality, strategies to maintain their quality have to be put in place immediately after harvest. Each FFV supply chain, including tomato, is unique and therefore targeted solutions for the maintenance of product quality should be implemented in order to deliver value to consumers, minimize losses and improve returns to producers and suppliers.

This research proposal presents a roadmap for the development of an integrated postharvest management system targeting commercial and small-holder tomato producers in South Africa.

3.2 Problem Statement

Long distance transportation of fresh produce affects the rate of deterioration in its quality. Fresh market tomatoes are produced in localized zones mainly located in the northern parts of South Africa, and transported to distant markets countrywide. This research proposal seeks to establish the effect of road quality and handling conditions during long distance transport, on the quality of fresh tomato supplied through various supply routes from Limpopo to Pietermaritzburg.

3.3 Rationale

Tomato fruit is an important fresh food product and a valuable source of healthy and immune-boosting nutrients. The production and trade in tomato is a key contributor of the GDP growth of South Africa and a source of livelihood to its people. Commercial growers produce and supply over 95% of the gross tomato production in South Africa and are concentrated mainly in Limpopo province, situated in the northern part of the country. It is therefore necessary to transport the products through various road networks to markets as far as Cape Town under various handling and road conditions. The perishable nature of the crop is a huge constraint that limits long freight and often causes economic losses to producers, supply chain players and leaves consumers dissatisfied.
Understanding the effect of transport conditions on the quality of tomato along various supply chains is not currently well known, although it is an important factor in developing appropriate solutions to maintain its quality. There have been numerous research efforts in postharvest preservation of tomato both locally and internationally yet the South African tomato industry still records high postharvest losses due to lack of targeted solutions specifically applicable to commercial producers. These solutions would potentially benefit the South African tomato industry through a deeper understanding of the link between quality degradation of fresh tomato and transportation conditions under various production and supply chain scenarios.

### 3.4 Research Questions

To address the objectives, the study will seek to answer the following research questions:

(a) What are the effects of storage conditions on the shelf-life and quality of fresh tomatoes of different maturity stages and harvesting seasons?

(b) What is the impact of route conditions on the shelf-life and the quality of fresh tomato of various maturity stages in South African under commercial supply chain conditions?

(c) What effect do integrated treatments have on the quality and consumer acceptability of fresh tomato in South African supply chains?

(d) What aspects of handling significantly contribute the greatest to postharvest losses in tomato supply chain between the post-harvest and consumption continuum in South African supply chains?

(e) Can fresh tomato supply chain parameters be modelled with quality, handling costs, logistical costs and environmental conditions in mind to in order to predict their acceptability under different modelling scenarios?

### 3.5 Research Hypotheses

The following research hypotheses have been formulated for this study:

(a) Integrated treatments will significantly improve the shelf-life of fresh tomato.

(b) There is an optimal mix of handling practices, environmental and storage conditions that are best suited for handling fresh tomato in South African supply chain.

(c) An integrated approach combining critical parameters in tomato supply chain can be modelled and optimized to satisfy a complex mix of cost, product quality and environmental sustainability criteria.
3.6 Research Objectives

The aim of this study is to investigate the effect of different handling and transportation conditions on the quality and acceptability of fresh tomato using empirical and modelling approaches. The specific objectives are:

(a) to investigate the effect of post-harvest maturity stage and storage conditions on the quality of fresh tomato in three South African supply chain routes,

(b) to evaluate the effect of three supply chain routes and handling conditions on the shelf-life and consumer acceptability of fresh tomato in South African supply conditions,

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

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

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

3.7 Materials and Methods

3.7.1 Tomato samples

Tomato fruit (Solanum lycopersicum) will be sourced from three farms in Limpopo province. Two farms located in Musina and Pont drift will be fruit of Nemo Nettaa variety, while the farm in Mooketsi will be the Topacio variety. The fruit will be harvested at three maturity stages, red, pink and green during the winter (June) and summer (September) season.

The harvested tomato will be 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. The fruit will then be transported in non-refrigerated trucks through three supply routes with varying road conditions to Pietermaritzburg fresh produce market, where they will be taken to the Bioresources laboratory for treatment and analysis. While transporting the products, the time, temperature and RH conditions in the trucks will be measured at suitable intervals using iButton loggers (Maxim Integrated, California, USA) placed in three locations (top, middle and bottom) inside the truck. The location of the farms namely, Musina, Mookotsi and Pont drift
are 1061, 905 and 1098 km, respectively from the laboratory. The trucks will be driven at a speed of 80 km/h on the highways and 60 km/h on rough roads.

### 3.7.2 Experimental design

Figure 3.1 A schematic representation of the completely randomized block experimental design (CRBD) for objective one, two and four with three routes (PD-PMB, MO-PMB and MU-PMB) and fruit of three maturity stages (red, pink and green). Each experimental unit (rectangular blocks) represents seven treatments (Control, HWT, Bio, Chlorine, Chl+Bio, Ano+Bio, HWT+Bio) replicated thrice. Each replicate consists of a box of 25 fruit. Blocking will be done along each supply chain route and maturity stage. The fruit will be tested under Ambient conditions (C) and cold storage at 11 °C (D) during summer (A) and winter (B). The response factors will be the quality factors: Total soluble solids (TSS), pH, colour, texture (firmness), sugar, lycopene and ascorbic acid (AA) content. Consumer acceptability as either (A-F), (A-S) or (N-A) will be established based on the fruit firmness.

Figure 3.2 A schematic representation of the completely randomized block experimental design (CRBD) for objective three, to be carried out using pink tomato in two pack houses in cold or ambient storage conditions after harvesting in the morning or afternoon and handling using bins or lugs (LM, LA, BM and BA). A designates samples precooled within two hours and B after six hours. All treatments in experimental units are replicated thrice. Each replicate will consist of a box of 20 fruit and blocking will be done along each harvesting site supplying fruit to the respective pack house. The response factors will be texture (firmness), marketability, pH, colour, weight loss and visual appearance.
3.7.3 Data collection

Physical and Engineering properties

Diameter and volume

Tomato fruit diameter will be measured using a Vernier calliper (Jahns et al., 2001) on its shorter and longer axis, its weight measured using a digital balance (Adam Core CQT 202, UK) and its volume measured by the Archimedes method (Gautier et al., 2005).

Moisture content measurement

The moisture content will be determined according to Kerkhofs et al. (2005), where a fresh tomato fruit will be cut into four quarters placed in aluminium moisture dishes and put in an oven set at 105 °C overnight until it attains a constant weight. For each of these properties, measurements of six randomly selected fruits per sample will be carried out and readings recorded. These measurements will be carried out immediately after the samples reach the laboratory (day 0 of storage).

Colour

Colour will be measured using a Minolta Chroma meter (Model CR-400, Narachi Pty, South Africa). Readings will be made at an observer angle of 2° after standardizing with a white tile (Y=93.8, X= 0.3030, y=0.3191). Illuminant C will be used to measure the L*a*b* values where six readings will be done from three fruits per sample, for each treatment. L* indicates the lightness (0 =black and white=100), a* represents a change from greenness to redness (-60 to +60) and b* represents a change from blueness to yellowness (-60 to +60) (Kerkhofs et al., 2005; Pinheiro et al., 2015). Sampling was done immediately after harvest and on days 0, 8, 16, 24 and 30 of storage.

Subjective quality evaluation

Subjective tests will also be performed to ascertain the proportion of the sample under shelf-life studies that will be marketable. The overall visual appearance will be the primary criterion used to judge if samples were still marketable after 0, 8, 16, 24 and 30 days of storage. Samples perceived to have shrivelled excessively, decayed or be physiologically damaged in any way, and that could not be sold at local markets will be considered unmarketable and will be removed from the test samples during sampling. This procedure will follow the method used by Tadesse et al. (2012).
Fruit firmness

The firmness of tomatoes will be tested using Instron universal testing machine (model 3345, Advanced Laboratory Solutions, South Africa). The samples will be tested using a 6.1 mm flat end stainless steel probe at a cross-head speed of 20 mm/min and the force-deformation curves automatically recorded by the Bluhill® software (Batu, 2004). The maximum force required to puncture the tomato skin, and the average slope of the curve to the bio-yield point will also be recorded by this software. This slope (secant modulus) will be used to assess the consumer acceptability of the samples at selected storage intervals, based on the criteria developed by Adegorye et al. (1989), where samples with a firmness >1.48 N/mm are acceptable for sale in supermarkets, those >1.28 and <1.48 N/mm are acceptable for home use for making salads and those below 1.28 N/mm unacceptable for commercial and home use. Six fruits will be tested per treatment, and the results reported as maximum puncture force (N) and secant modulus (N/mm) (Batu, 2004).

pH Value

Product pH will be 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 will first be standardized using 4.01, 10.00 and 7.00 pH buffers. Two tomato samples will be 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 will then be determined using the pH meter. Readings will be repeated thrice per treatment for the selected sampling days.

Total soluble solids (TSS)

The TSS will be established from clear drops of juice (2-3 drops) previously extracted through a cheese cloth during pH determination, using a pocket refractometer (Model Atago PAL-3, Selectech Pty, South Africa). The refractometer has a range of 0-93% brix and a resolution of 0.1% brix. The readings will be done thrice per treatment for sampling day 0, 8, 16, 24 and 30. Each reading will be made after rinsing and standardizing the refractometer with distilled water and drying the glass prism with a paper towel.

Physiological mass loss

Mass loss will be monitored at selected intervals of storage using the method proposed by (Pinheiro et al., 2013). Three batches of 3 tomatoes per treatment will be marked and weighed at day 0 and the mass loss reported at day 8, 16, 24 and 30 relative to day 0, using equation 3.1.
% Mass loss = \left(\frac{W_0 - W_t}{W_0}\right) \times 100 \tag{3.1}

Where $W_0$ is the mass on day 0 and $W_t$ is the mass on day $t$.

**Chemical and biochemical characteristics**

**Sugar analysis**

The analysis of sugars will follow the method suggested by Baldwin et al. (1991) with modification. In summary, three quarters of three frozen tomato samples per treatment will be 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 will then be sonicated using ultraturrax mixer (model IKA T25D, Cole-Parmer, South Africa) at 8600 rpm for one minute. The homogenate will then be incubated in a water bath at 80 °C for an hour, removed and left to stand overnight at 4 °C. This homogenate will be 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 °C for 6 hours. Two ml Ultra-pure water will thereafter be added to the dried extract and filtered through a 0.45 μm nylon syringe filter (Merck pty, Durban, South Africa). 20 μL of the filtrate will finally be injected into a HPLC column set at 85 °C, with double distilled water as the mobile phase flowing at 0.6 mL/min. The sugars will be detected by differential refraction using a RID detector (RID-10A, Shimadzu, South Africa). Standards will be run and their retention times ascertained. All analyses of selected treatments will be carried out in triplicate.

**Ascorbic acid**

Ascorbic acid (AA) content of the tomato samples will be analysed spectrophotometrically using the method suggested by Chang et al. (2006). In summary, 0.5 g of a freeze-dried sample will be extracted in 50 ml metaphosphoric acid (1% v/v) for 1 hour. The extract will then be centrifuged at 3000g at room temperature for 15 min. One ml of the supernatant will subsequently be added to 9 ml 0.05 mM DPIP and mixed for 5 sec, and the absorbance of this solution measured at 515 nm against a blank made by one ml 1% metaphosphoric acid (v/v) added to nine ml 0.05 mM DIP and mixed for 15 sec. The results will be computed in AA per mL from the standard curve prepared between 0-500 μg AA per mL.
Lycopene estimation

Lycopene will be determined using the method reported by Davis et al. (2003). In brief, approximately 25 g of tomato will be added to distilled water (W/V) and blended for 30 sec using a stick blender. 0.6 g of the puree will then be 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 will then be shaken in ice at 180 RPM for 15 min and thereafter, 3 ml of deionized water added and shaken in ice for an additional 5 min. The mixture will finally be left for 5 min to allow phase separation, then the absorbance of the upper hexane layer measured at 503 nm in a 1 cm path glass cuvette against hexane as the blank. Lycopene content will be calculated using equation 3.2.

\[
\text{Lycopene (mg kg of tissue)} = \frac{A_{503} \times 31.2}{g \text{ of tissue used}}
\]  

Where \( A_{503} \) is the absorbance at 503 nm.

All determinations for AA and lycopene will be replicated thrice for each of the selected treatments.

3.7.4 Data analysis

A general analysis of variance (ANOVA) will be used to analyse the effect of the supply chain conditions on various quality parameters, and a weighted criterion used to assess the overall effect. The weighing will be related to the relative importance attached by consumers to these factors. The main effects and interactions will also be reported. Fisher's least significant difference (LSD) method will be used to separate means.

Multiple analysis of variance (MANOVA) will also be used to evaluate the effect of handling and transport conditions on the shelf-life and consumer acceptability of fresh tomatoes in South Africa. A general ANOVA will be used to analyse the effect of handling conditions on the shelf-life of tomato under in field conditions and recommend handling practices that best extend the shelf-life of harvested produce. MANOVA will be used to assess the effect of various integrated post-harvest treatments, storage, transportation and handling conditions on the shelf-life and quality of fresh tomato in South African supply conditions.

SPSS (SPSS 23, IBM, USA) will be used for all statistical analyses, where results will be reported at 0.05 significance level. Principal component analysis (PCA) will also be used to
analyse the set of production and supply chain conditions that yield the best shelf-life and product quality.

3.8 Modelling and Optimizing the Tomato Supply Chain Network (SCN)

Modelling fresh produce supply chain in most instances, serves to satisfy two reasons:

a) To assimilate all the knowledge on processes occurring in a supply chain network (SCN), in order to gain insight into the effect of various supply variables on the performance of the entire supply system.

b) To investigate and predict future occurrences in order to manage a FFV supply system to meet some desirable criteria.

In this study, we propose a model that seeks to achieve these objectives.

3.8.1 Modelling approach in the development of the tomato supply chain model

Systems approach will be used to model the SCN in this manner:

i. Understanding all the operations within the supply network, from harvesting, cooling, transport to pack-house, storage, packing, transport to distribution centres (DC), storage, and transport to either retailers, supermarket chains or export.

ii. A breakdown of these processes into sub-processes to ease the modelling process.

iii. From the previous laboratory shelf-life studies, isolate the quality factors that contribute to the overall quality index (KQI), and develop a system of weighing their contribution to this index. This will also be related to the R1 function that relate to the deterioration of quality of different batches of tomato harvested at a given maturity stage.

iv. Develop the quality deterioration models for the following factors: a) firmness, b) colour and c) AA concentration.

v. Link these factors to the controlling parameters – time and temperature. As such, these models must obey physical laws and laws of chemical kinetics.

vi. Develop quality constraints (minimum KQI from the consumers’ side and acceptability criteria from users on a ‘best to use’ basis).

vii. Create a demand function specific for every end user. The demand function may be dynamic.

viii. Develop responses from the model on what issues it should answer such as; recommended temperature profile at different levels of the supply system, whether to
do cooling at different nodes of the supply system and if this will be value for money, and a mix of supply routes that will meet a set of supply criteria.

ix. Formulate the objective functions which ought to minimize costs, minimize transport distance (sustainability - often correlates to product freshness).

3.8.2 Fruit quality loss equations

Quality degradation of fresh food follows reaction kinetics of the general form;

\[
\frac{dq}{dt} = kq^n
\]  
(3.3)

q is the product quality, k the rate of degradation, n the power factor and t the degradation time. In fresh fruits and vegetables, often n=0 (Labuza, 1982).

Quality degradation processes in most food products are mostly time-temperature controlled, and follow the Arrhenius equation described as,

\[
k = k_0e^{\frac{E_a}{R} \left(\frac{1}{T} - \frac{1}{T_0}\right)}
\]  
(3.4)

\(k_0\) is the kinetic rate at \(T_0(K)\), \(E_a\) Arrhenius activation energy (J.mol\(^{-1}\)) and \(R\) the universal gas constant (J.mol\(^{-1}\) K\(^{-1}\)) (Martins et al., 2008).

The degradation of AA follows fractional kinetics as described by Martins et al. (2008) as

\[
\frac{C - C_{eq}}{C_0 - C_{eq}} = e^{kt}
\]  
(3.5)

\(C_0\) is the initial AA quality; \(C\) is the AA quality concentration (g l\(^{-1}\)) at time t and \(C_{eq}\) is the final AA quality at chemical equilibrium.

The firmness of tomato will be modelled using a simplified form of firmness decay function,

\[
F = F_0e^{-kt} + F_{fix}
\]  
(3.6)

\(F_0\) is the initial firmness, \(F\) the firmness at time t, \(k_f\) the reaction constant of firmness reduction and \(F_{fix}\) the invariable firmness (Tijskens, 2001).

Colour change from green will follow the equation that obeys the Arrhenius equation given by;

\[
\frac{dG}{dt} = -k_r, G.R
\]  
(3.7)

Which analytically yields a normalized solution (\(R_0+G_0=1\)) under constant temperature conditions of;
\[ G = \frac{1}{\left( \frac{1}{G_0} - 1 \right) e^{(K_r t)} + 1} \]  

(3.8)

G is the amount of green colour at time t, \( k_r \) the reaction rate constant and \( G_0 \) the initial quantity of the green colour (Tijskens, 2001).

### 3.8.3 Model scenarios

The following scenarios of interest will be modelled in order to gain insight into their feasibility and their long-term sustainability.

a) Simple retail (no cooling)
b) Supermarket chain (cooling)
c) Export

### 3.8.4 Flow of model development

![Diagram of tomato supply chain model development process](image)

Figure 3.3 A schematic representation of the tomato supply chain model development process
3.9 Novelty and Contribution of the Study

The novelty of this PhD study lies in the model that would be developed, which would be broadly used in similar fruit and vegetable supply chain networks in predicting changes in key quality attributes along various supply chains. Quality changes would be the key robust attribute that would be built into this model. The research would also give insight as to the nature and the level of real nutritional losses occurring under various transportation and handling conditions in tomato supply chains in South Africa.

The main contribution of this research will be; further insight into the effect of different handling and transportation conditions on the quality of tomato in commercial supply chains in South Africa. It is anticipated that the proposed work will produce at least a conference paper and two publications.
### 3.10 Project Plan

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