International Food Research Journal 26(3): 979-989 (June 2019)

Journal homepage: http://www.ifrj.upm.edu.my

Application of logistic statistical modelling in the evaluation of suitable conditions for the supply of fresh tomatoes in selected South African supply chains

[1,3*]Cherono, K., [1]Workneh, T. S. and [2]Melesse, S. F.

[1]*Department of Bioresources Engineering, School of Engineering, University of KwaZulu-Natal, Private bag X01, 3209 Scottsville, Pietermaritzburg, South Africa*
[2]*School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, Private bag X01, 3209 Scottsville, Pietermaritzburg, South Africa*
[3]*School of Biosystems and Environmental Engineering, Jomo Kenyatta University of Agriculture and Technology, P. O Box 62000-00200, Nairobi, Kenya*

Article history

Received: 25 September, 2017
Received in revised form: 6 January, 2019
Accepted: 20 February, 2019

Keywords

Anolyte water
Binary variable
IRI
Probability of marketability
Transportation effect

Abstract

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

Introduction

Tomato (*Solanum lycopersicum* L.) is grown globally for its edible fruit. It is one of the most important fresh fruits and vegetables (FFVs), whose popularity globally is only second to potatoes (Dorais *et al*., 2008). In South Africa, the tomato industry is an important contributor to the country's GDP growth. In 2014, the value of the industry was in excess of 150 million USD (DAFF, 2015). The key attribute of the South African tomato industry is that commercial producers dominate the pool of tomato suppliers, with the country being home to the largest commercial tomato producers in the southern hemisphere (Munyeka, 2014). The production zones are predominantly situated in the northern parts of the country, and this necessitates the transportation of tomatoes over long distances to markets that are as far away as Cape Town (DAFF, 2012).

The physiological nature of the tomato makes it susceptible to mechanical damage during transportation, distribution and storage (Kays, 1999). It is also a high moisture content food that is rich in nutrients and sugars, making it a conducive substrate for microbial contamination (Dugassa *et al*., 2014). For these reasons, postharvest losses of tomato globally are among the highest of all FFVs supplied in different regions of the world. It is estimated

*Corresponding author.
Email: kip.cherono@gmail.com

that tomato losses in some regions in Africa are as high as 40%, while conservative estimates peg postharvest tomato losses in South Africa at 10.2% (Moneruzzaman *et al*., 2009; Sibomana *et al*., 2016).

The use of sub-optimal transportation, storage and handling conditions in tomato supply chains could be a further source of postharvest losses, which are often manifested by the tomatoes being either damaged or overripe, resulting in low marketable quality. Spoilage microorganisms can further problems downstream of the supply chain, if a rigorous disinfection regime is not implemented. Chlorinated water is one of the most commonly used surface disinfectants in the tomato industry (Guo *et al*., 2014). The FFV industry is, however, currently facing challenges in replacing chlorinated water, as a surface disinfectant, as it has been shown to have a harmful effect on the environment (Venta *et al*., 2010).

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

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

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

Materials and methods

Tomato production

Tomatoes of the Nemo Netta variety were produced from three farms in the Limpopo Province, South Africa. The farms were located in Esme Four (22°19’48.7” S 30°28’21.3” E), Pont Drift (22°11’52.7” S 29°11’30.7” E) and Mooketsi (23°26’05.2” S 30°26’47.5” E). The crop was trained during the growing season. Drip irrigation was also implemented to meet crop water requirement throughout the growing season. For the entire growing season, the crop was grown under sustainable soil and water management practices (compost use, crop rotation, minimum tillage), as well as soft pest control practices. This production system is known as Natuurboerdey® system (Taurayi, 2011). Through this system, inorganic fertilisers are replaced by carbon loaded fertilisers with additional foliar spray, bio-stimulants and nutrient supplements depending on the growing stage of the crop. The tomatoes were harvested at three maturity stages, namely, red, pink and green, during the winter (June) and summer (September) seasons.

Transportation conditions

The tomatoes were harvested in the morning, transported in bulk bins to the respective pack house located near each of the farms, where they were precooled to remove field heat using forced air coolers for 3-4 h. The tomatoes were then transported overnight during the cooler period of the day. from each pack houses to Pietermaritzburg using non-refrigerated trucks to mimic normal supply operations. Each route [(Esme Four-Pietermaritzburg (ZZ), Mooketsi-Pietermaritzburg (EM) and Point Drift-Pietermaritzburg (PD)] had varying road conditions. The three routes that were selected typify long distance transportation operations of tomatoes in South Africa, where they are transported over long distances on roads of varying road surface profile and distances. The routes chosen were some of the supply routes commonly used by the largest tomato producers in South Africa. The samples were then taken to the Food Engineering laboratory of the University of KwaZulu-Natal for the application of pre-storage treatments. Each route had varying proportions of both rough and asphalt roads. The road quality, which signified the quality of ride induced on the tomatoes, was measured using a road surface laser profilometer (PaveProf V2.0, Pavetesting, UK). The trucks were driven at a speed of 80 km.h^{-1} on the highways and 60 km.h^{-1} on the rough roads.

Experimental design

The experimental design consisted of three transportation routes with varying road quality (PD, EM and ZZ), tomatoes of three maturity stages at harvest (red, pink and green) and two storage environments (ambient and refrigerated at 11°C). The seven pre-storage treatments were randomly assigned to each experimental unit and all observations replicated thrice in a full factorial experiment. Chl designates chlorinated water, Bio biocontrol treatment, HWT hot water treatment and Ano designates anolyte water.

Each treatment was replicated thrice. The experiment was carried out in the summer and winter to account for seasonal effects.

Application of pre-storage treatments

Upon arrival at the laboratory, the damaged and defective tomatoes were discarded and seven pre-storage treatments were applied. These included dipping in chlorinated water (100 ppm, 20 min), hot water (42.5°C, 30 min), biocontrol (1 g of B-13 yeast.L^{-1} tap water, 30 s), control (dipping in tap water, 1 min), hot water (42.5°C, 30 min) in combination with biocontrol, chlorinated water in combination with biocontrol and biocontrol in combination with anolyte water (5 min) (Workneh *et al.*, 2012). The treated tomatoes were then stored in ambient or cold storage conditions (11°C). Hobo loggers (U12-012, C.W. Price & Co., Midrand, South Africa) were used to monitor the temperature and relative humidity (RH) conditions of the ambient and cold storage rooms during the storage period.

Data collection

The quality parameters of stored tomatoes were assessed over a 30-day storage period. Colour, pH, firmness, marketability and mass loss were assessed from each treatment on day 0 and after storage for 8, 16, 24 and 30 days. These quality attributes were briefly analysed as follows.

Colour

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

Subjective quality analysis

Subjective quality tests were performed to ascertain the proportion of the sample that was marketable. Assessing the marketability of FFVs typically mimics the procedure an average buyer of fresh agricultural foods uses when making buying decisions. The buyer typically relies on visual and tactile ques when the product is on display in the market, to select products perceived to be of acceptable quality. In the present work, the overall visual appearance was the primary criterion used to judge if samples were still marketable during sampling. Tomato fruit perceived to have shrivelled excessively, to have decayed or be physiologically damaged in any way, and that could not be sold at local markets, was considered unmarketable and was therefore removed from the test sample during sampling. This procedure followed the method used by Tadesse *et al*. (2012).

Firmness

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

pH

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

Mass loss

The mass loss was determined at selected storage intervals, following the method proposed by Pinheiro *et al*. (2013). Three batches of three tomatoes per treatment were marked and weighed on day 0 and the percentage mass loss reported on days 8, 16, 24 and 30, relative to day 0.

Logistic modelling of tomatoes quality data

A logistic model was built, based on the binary variable related to tomato fruit marketability. This variable can be expressed using Eq. 1:

$$y_i = \begin{cases} 1 \text{ if } y^* > \tau \\ 0 \text{ if } y^* \leq \tau \end{cases} \qquad \text{(Eq. 1)}$$

where y_i = latent binary variable, based on product marketability and returns a marketable or unmarketable result, based on selected threshold τ.

The logistic regression is a member of the generalised linear models (Nelder and Wedderburn, 1972) used to model binary data. It is mainly used to study the relationship between the probability of an event and the predictor variables. This relationship is usually nonlinear. The S-shaped curve called logistic function is often the realistic shape for the relationship (Agresti, 1996).

The simple logistic function is based on a linear relationship between the natural logarithm (ln) of the chance of an event and a single predictor variable. For instance, in our case the probability of marketability was expressed using Eq. 2:

$$logit(\pi(x)) = \ln\left(\frac{\pi(x)}{1 - \pi(x)}\right) = \alpha + \beta x \qquad \text{(Eq.2)}$$

where $\pi(x)$ = probability of marketability when the predictor variable (X) has a value equal to x, α = Y intercept, β = slope parameter and X is either categorical or continuous variable.

The alternative formula for the simple logistic function (2) which can directly give us the probability of marketability is given by Eq. 3:

$$\pi(x) = p(Y \text{ is outcome of interest} \mid X = x) = \frac{1}{1 + e^{-\alpha - \beta x}} \qquad \text{Eq.3)}$$

Eq. 2 shows that the relationship between the natural logarithm of the chance and the predictor variable is linear, but Eq. 3 shows nonlinear relationship between the predictor variable and the probability of marketability. The simple logistic function (2) can be extended to multiple logistic regression function. This relates a single binary outcome to two or more predictor variables. The multiple logistic functions are given by Eq. 4 and Eq. 5:

$$\log it\,(\pi(x)) = \left(\frac{\pi(x)}{1-\pi(x)}\right) = \alpha + \sum_{i=1}^{k} \beta_i x_i \qquad \text{(Eq. 4)}$$

$$\pi(x) = \frac{1}{1 + e^{-\left(\alpha + \sum_{i=1}^{k} \beta_i x_i\right)}} \qquad \text{(Eq. 5)}$$

where $\pi(x)$ = probability of tomatoes marketability, a is the intercept, βs the slope parameters and Xs = set of predictor variables. The logistic regression was fitted using the maximum likelihood (ML) estimation approach. By using ML estimation method, the parameters of model (4) can be estimated. The maximum likelihood estimation identifies the values of the parameters for which the probability of the observed data is maximum. ML computations for fitting logistic regression models are complex, but are easy to perform using statistical software (Agresti, 1996; Melesse *et al*., 2016).

Eq. 1 was used to convert tomato fruit marketability data into a binary variable, which was used as a surrogate that holistically represented the quality of tomato fruit at a given time period x. The probability of marketability of tomatoes was modelled as a function of the storage period. The quality data were modelled as predictors of the tomato fruit marketability and the best predictors were chosen. A comparison of the combinations of various storage, disinfection and transportation conditions that gave the best quality was also assessed and selected, by comparing the odds ratio between each group of treatments.

Results and discussion

Transportation conditions

The EM route was a distance of 934.12 km, taking a total time of 10.43 h to complete. The route had 70 and 91% of its road length having maximum IRI values of 2.5 and 5 m.km^{-1}, respectively. The PD route was a distance of 894.49 km, taking a drive time of 9.33 h to complete. The PD route also had 58 and 93% of its road length having maximum IRI values of 2.5 and 5 m.km^{-1}, respectively. The ZZ route was the furthest with a distance of 1157.93 km that took 12.76 h to complete. This route had 63 and 95% of its road length having maximum IRI values of 2.5 and 5 m.km^{-1}, respectively. The drive time was related to the distance and the road quality. In sections with rough roads, the trucks were driven at 60 km.h^{-1}, compared to speeds of 80 km.h^{-1} on highways. The PD route had a larger proportion of its road length comprising rough roads. Similarly, the EM route had a higher proportion of its road length comprising smoother road surface, compared to both the PD and ZZ routes.

Based on international road classification, using IRI values, the thresholds of 2.7 m.km^{-1} and 1.5 m.km^{-1} have been set for acceptable and good quality roads, respectively (Arhin *et al*., 2015). These values, however, relate to human comfort and are not related to the level of damage subjected to agricultural commodities during transportation. Although the IRI values in the present work gave an indication of the relationship between road roughness and its effect on tomato quality, road surface classification and guidance threshold values should be developed for fragile and high value fresh agricultural commodities, such as strawberries, blueberries, tomatoes and cut fresh flowers.

Storage conditions

Figure 1 shows the variation in temperature and the RH conditions with storage duration in ambient and cold storage environments. Cold storage conditions were generally within a close range of values for both RH and temperature across the summer and winter seasons. On the other hand, ambient temperature

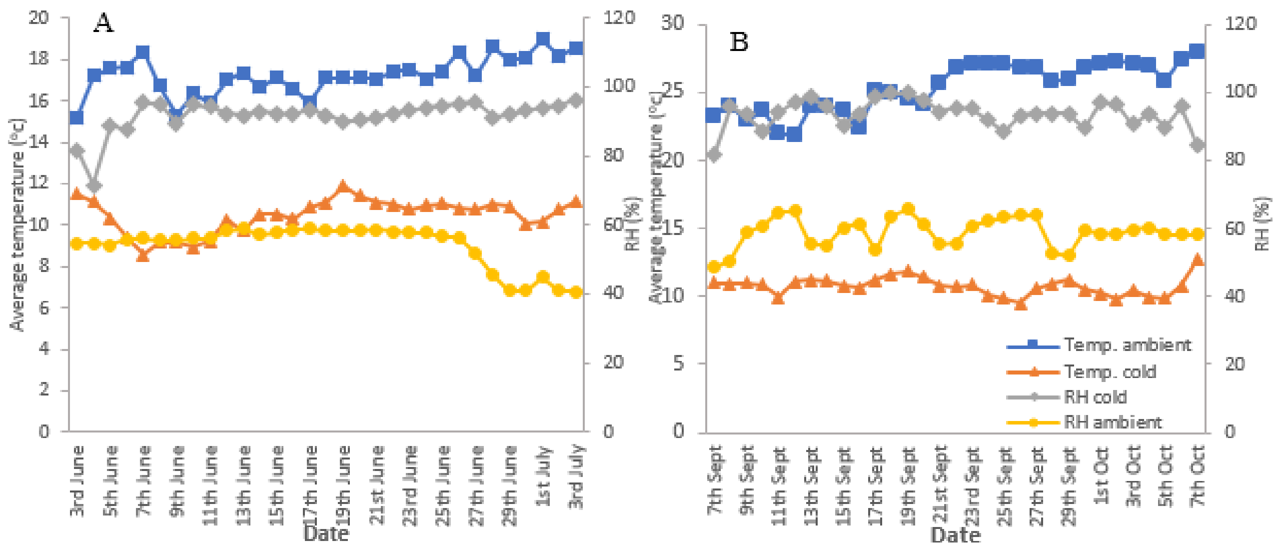

Figure 1. Comparison of the variation in temperature and relative humidity in ambient and controlled temperature storage rooms during storage of tomatoes in winter (A) and summer (B).

conditions were generally higher in the summer, as compared to the winter season. The ambient RH conditions during the summer season were also higher than RH conditions in the winter season, for the entire storage period. The optimum storage temperature and RH conditions for tomatoes and other horticultural produce have been widely reported in the literature. For instance, tomatoes require an optimal RH of 90-95% and temperatures of 13-22°C, depending on their maturity at harvest (Kitinoja and Kader, 2002). It has, however, been reported by Nunes *et al*. (2009) that fluctuating storage temperatures, in combination with low RH conditions, leads to significant water loss in FFVs within the first few days of storage. The control of ambient RH conditions is therefore becoming increasingly important, from a postharvest quality perspective of horticultural produce. The control of RH in storage units, however, is a difficult feat that requires precise instrumentation, which makes it an endeavour with prohibitive cost implications (Paull, 1999).

Changes in tomatoes marketability with storage period

The probability of tomato fruit marketability decreased with storage over the 30-day period, with a noticeable drop in the chances of marketability between day 8 and 16 when equation 6 was plotted. This was a drop of over 50% for this storage interval and a further 40% drop between days 16 and 24.

The variation in the probability of marketability ($\hat{p}$) with storage period, designated as days of storage (dos), was estimated using Eq. 6:

$$\hat{p} = \frac{1}{(1+e^{-(4.595-0.274dos)})} \quad \text{(Eq. 6)}$$

Effect of categorical variables on the probability of tomato fruit marketability

Changes in the probability of marketability with days of storage (dos), as a function of categorical variables, are shown in Table 1. Tomatoes supplied in the summer showed a better chance of marketability than those supplied in winter. This may be attributed to fluctuations in ambient temperature conditions, accompanied by lower ambient RH during the beginning of storage in the winter season, as compared to the summer season (Figure 1). This has been shown by Nunes *et al*. (2009) to cause rapid moisture loss during the first few days of storage, leading to a lower chance of marketability. This renders cooler ambient temperatures during the winter not to be beneficial to tomatoes, hence the importance of controlling the ambient RH during the winter season. Although tomatoes were generally kept longer in winter, the bulk marketable threshold of tomatoes declined more rapidly in winter, as compared to in summer.

Tomatoes harvested at the green maturity stage had a higher probability of being marketable, as compared to those harvested at the pink or red maturity stages. This is expected from a tomato physiological changes perspective, since, as the biological age of tomatoes increases, the cumulative physiological changes that will have occurred, such as mass loss, respiration and transpiration, are comparatively larger in quantity at a later time than at an earlier time. It has also been established that, as tomatoes ripen, their susceptibility to mechanical damage increases (Mohammadi-Aylar *et al*., 2010). These aspects, therefore, resulted in a decreased probability of tomato fruit marketability. The transportation conditions, especially the road quality, had a clear effect on the probability of tomatoes marketability. Tomatoes harvested and transported along the EM route had a higher chance of marketability, as compared to those supplied through the PD and ZZ routes. Similarly, tomatoes harvested and transported along the ZZ route had the lowest probability of marketability of all the routes. These observations can be corroborated by the road quality conditions measured. The EM route had a smoother road profile, as compared to the PD and ZZ route, which translated to better ride quality, where minimal vibrations were transmitted to the tomatoes through the road-vehicle

Table 1. Variation of the probability of marketability of tomatoes of various maturity stages with days of storage across different seasons, transportation conditions and storage environment.

Day of storage (dos)	Probability of marketability ($\hat{p}$)									
	Season		Maturity at harvest			Transportation			Storage environment	
	summer	winter	green	pink	red	PD	EM	ZZ	Cold	Ambient
0	0.9970	0.9869	0.9970	0.9936	0.9826	0.9948	0.9957	0.9815	0.9990	0.9874
8	0.9689	0.9138	0.9689	0.9356	0.8414	0.9490	0.9575	0.8373	0.9817	0.8086
16	0.7451	0.5991	0.7451	0.5766	0.3320	0.6431	0.6854	0.3324	0.7421	0.1843
24	0.2150	0.1739	0.2150	0.1131	0.0444	0.1484	0.1740	0.0459	0.1334	0.0119
30	0.0443	0.0288	0.0443	0.0211	0.0078	0.0293	0.0352	0.0082	0.0168	0.0013

system, resulting in lower mechanical damage. Mechanical damage on tomato fruit has been shown to trigger an increase in ethylene production, leading to increased fruit ripening rates (Mutari and Debbie, 2011; Aba *et al*., 2012). Although the ZZ route had a relatively smoother road profile than PD, it was much further than EM and PD. Studies have also shown that longer transportation distances, under moderately rough road conditions, caused far more serious mechanical damage to tomatoes than shorter transportation distances, under much poorer roads (Linke and Geyer, 2002; Linden *et al*., 2006; Aba *et al*., 2012). Ambient storage also had lower chance of yielding marketable tomatoes, as compared to cold storage conditions (odds ratio of 0.458). Higher storage temperature of tomatoes resulted in a higher rate of metabolic processes, leading to a rapid decline in tomato quality. Temperature control is one of the principal means of maintaining the postharvest quality of FFVs (Mutari and Debbie, 2011). Maintaining the cold chain during the transportation, distribution and storage of tomatoes is therefore one of the single most important practices necessary for the maintenance of tomato quality (Castro *et al*., 2005).

The effect of the pre-storage treatments on the probability of tomatoes marketability is shown in Figure 2. Tomatoes treated with HWT and HWT+Bio had the lowest probability of marketability, with tomatoes treated with chlorinated water and anolyte water, combined with biocontrol (Ano+Bio), having the highest probability of marketability (Figure 2). Although chlorinated water showed the best performance in maintaining the probability of marketability of the tomatoes, it was marginally better than Ano+Bio, and other results have shown that the performance of the pre-storage treatments in maintaining the quality of tomatoes was dependent on their maturity at harvest. For instance, tomatoes treated with Ano+Bio had the highest probability of tomatoes marketability harvested at the red maturity stage. The oxidative reactions that chlorinated water relies on in inactivating microorganisms could play a role in exacerbating degradative processes in ripe tomatoes due to their already degraded pericarp tissues as a result of the advanced ripening processes. Chlorinated water also takes time to form free radicals as compared to anolyte water which has them readily available for microbial inactivation (Workneh *et al*., 2012). The free radicals in anolyte water are fairly active within a short period.

Modelling probability of marketability of tomatoes from quality parameters

The measured tomato quality parameters that included hue angle, pH, mass loss and firmness, were entered together as predictors of the probability of tomatoes marketability. The result yielded a model with an 82.9% accuracy of correctly classifying tomatoes marketability, based on these quality parameters. The model showed the tomato hue angle and firmness as being the most important quality parameters that contributed more to the chance of them being marketable. Each of these quality parameters were significant ($p \leq 0.05$) in the overall model, hence these parameters could be good predictors of the chances of marketability of tomatoes. A unit reduction in the hue angle resulted in a 1.109 times reduction in the chance of tomatoes being marketable

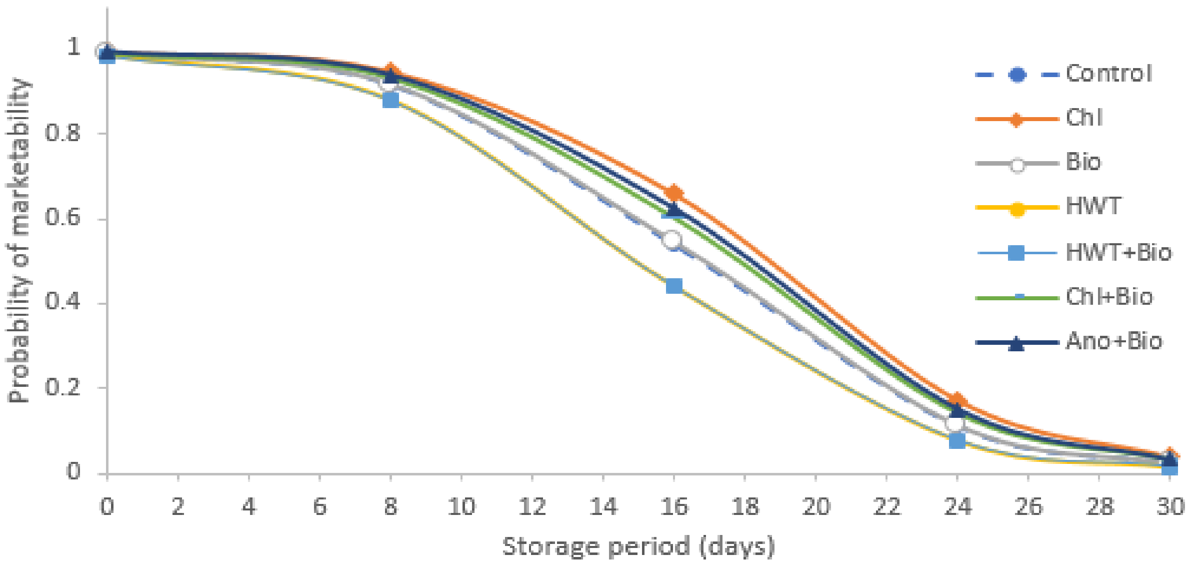

Figure 2. Effect of pre-storage treatments on the probability of marketability of tomatoes.

(odds ratio = 1.109). A unit reduction in firmness also led to a 1.071 times reduction in the probability of marketability (odds ratio = 1.071). Similarly, a unit increase in mass loss and pH resulted in a 0.741 and 0.522 reduction in the chances of tomato fruit marketability, respectively (odds ratio = 0.741 and 0.522, respectively).

Changes in tomato quality are related to enzymatic breakdown of structural compounds that contribute to cell structure integrity in its pericarp (Batu, 2004). In addition to enzymatic reactions, respiration and transpiration further lead to its mass loss and shrinkage, contributing to the loss of firmness (Tigist *et al*., 2013). Tomato colour changes encompasses chemical and biochemical reactions that occur through genetically controlled biosynthetic pathways (Brandt *et al*., 2006). It is generally manifested by changes in tomato colour from green to pink due to the breakdown of chlorophylls and the concomitant accumulation of lycopene and other carotenoids (López Camelo and Gómez, 2004). For these reasons, the hue angle, that signifies changes in tomato colour, is one of the key quality attributes that is linked to changes in numerous biological and chemical systems in tomatoes. It is no surprise that tomato fruit firmness and colour are cited as the key quality attributes that can be used as predictors of the overall quality changes in tomatoes (Schouten *et al*., 2007). Variations in the pH and weight loss of tomatoes could be captured by changes in their firmness and colour.

Combination of factors in the model

The selection of suitable transportation conditions, storage environment and pre-storage treatments for tomatoes harvested at various maturity stages was carried out by building a logistic model that combined these factors. The basis of selection was a combination of factors that yielded tomatoes with the highest probability of marketability. Table 2 shows the statistical parameters of the model that combined independent variables. When these factors were entered into the model, the dos, storage conditions, transportation conditions and maturity at harvest were all statistically significant ($p \leq 0.05$) predictors of the probability of marketability of tomat oes. Some of the pre-storage disinfection treatments (biocontrol treatment and Chl+Bio) were found not to be significant ($p > 0.05$) predictors of tomato fruit marketability in the model. Tomatoes treated with the biocontrol agent had the lowest probability of marketability amongst all treatments. This may be due to the aesthetical issues exhibited by tomatoes treated with biocontrol as the yeast attempted to competitively control other microorganisms on the tomatoes by covering the entire surface, giving it a white, dull appearance. This implied that tomatoes treated with biocontrol gave low marketability scores. This could explain why biocontrol treatment was not significant in the model. Chl+Bio was marginally insignificant in the overall model partly due to the overriding effect of the biocontrol treatment.

Tomatoes harvested at the green maturity stage, transported through the EM route to Pietermaritzburg,

Table 2. Model parameters when all categorical factors were used as predictors of the probability of tomatoes marketability.

Experimental factor	Model coefficient	Wald $\chi2$	Significance	odds ratio	95% CI	
					Lower	Upper
Constant	7.619	563.608	0.000	2036.5		
dos	-0.452	939.339	0.000	0.637	0.618	0.655
Green		249.610	0.000			
Pink	-1.126	58.759	0.000	0.324	0.243	0.432
Red	-2.675	249.021	0.000	0.069	0.049	0.096
PD route		219.110	0.000			
EM route	0.287	4.003	0.045	1.333	1.006	1.766
ZZ route	-1.978	154.630	0.000	0.138	0.101	0.189
Control		71.714	0.000			
Chlorine	0.800	13.025	0.000	2.226	1.441	3.438
Biocontrol	0.049	0.049	0.825	1.050	0.681	1.619
HWT	-0.636	8.201	0.004	0.529	0.342	0.818
HWT+Bio	-0.636	8.201	0.004	0.529	0.342	0.818
Chl+Bio	0.414	3.503	0.061	1.512	0.981	2.332
Ano+Bio	0.560	6.405	0.011	1.750	1.135	2.700

stored in the cold storage and treated with chlorinated water or Ano+Bio, had the highest chance of marketability. Tomatoes treated with chlorinated water had only a slightly better chance of marketability than those treated using Ano+Bio. Ano+Bio can therefore be considered as a potential replacement of chlorinated water when the environmental and health concerns of using chlorinated water to disinfect FFVs are considered.

A multi-factor model that combined all the variables, including dependent variables resulted in a multiple logistic model that had maturity at harvest, season, pH, hue angle, firmness, mass loss, transportation and storage conditions, as factors that significantly ($p \leq 0.05$) contributed to the model's prediction of the probability of marketability of the tomatoes. Some of the pre-storage treatments in the model, were, however, not significant ($p > 0.05$) in terms of predicting the chance of tomato fruit marketability. These were chlorinated water, biocontrol, Chl+Bio and Ano+Bio. Similarly, pH was also not a significant ($p > 0.05$) factor in the overall model as a predictor of the probability of marketability of the fruit. The multi-logistic model essentially depicts the key factors that influence the changes in tomato fruit, as well as the measured quality parameters that can be used as surrogates for predicting the holistic quality changes in tomatoes. (Melesse *et al*., 2016).

Validation of the overall model

Table 3 shows a summary of the statistical parameters of the validated model. In terms of the overall significance, the likelihood ratio was 4863.5 with $p < 0.0001$. This, therefore, implies that the model adequately predicted the probability of marketability of the tomatoes, based on the storage, transportation and pre-storage treatment conditions, and the associated quality parameters.

The Hosmer and Lemeshow test also gave a statistically non-significant ($p > 0.05$) result, which strengthens the validity of the model in predicting the probability of tomato fruit marketability. The model correctly classified 86.9% of the marketable tomatoes (specificity) and 86.3% of unmarketable ones (sensitivity). This implies that the model gave good predictions and only gave 13.1% as false positives and 13.7% as false negatives.

Other measures of the model's validity (Sommers's D, Goodman Kruskal Gamma and c-statistic) also gave values close to 1, implying a close association between the observed responses and the predicted probabilities. A comparison of these parameters with those reported in study by Melesse *et al*. (2016) show good similarities, although the measures of model specificity and sensitivity were slightly lower in the present work. In another study by Lammertyn *et al*. (2000), the pre- and post-harvest parameters that affected the onset of core breakdown of conference pears were built into a logistic model that correctly classified 86% of the pears. The model's specificity in their study was similar to that reported in the present work (86.9%). In general, the model was good in predicting changes in the probability of marketability of the tomatoes across various disinfection treatments, storage and transportation conditions.

Table 3. Summary of statistical parameters for validation of the overall model.

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

Conclusion

In the present work, a novel statistical modelling procedure was applied to assess and recommend a combination of tomato supply chain parameters that are most suitable for maintaining the quality of tomatoes of different maturity stages at harvest. Transportation conditions were shown to affect the probability of tomatoes marketability, with the route that had a high proportion of rough road surface profile having tomatoes with the lowest probability of marketability. All the measured tomato quality parameters were good predictors of their probability of marketability. The model that combined categorical variables showed that Ano+Bio gave comparable probabilities of tomato fruit marketability with chlorinated water. It was also found that a combination of harvesting tomatoes at the green maturity stage, transportation through the EM supply route, storing in cold storage conditions and treatment with chlorinated water maximised the chance of tomatoes marketability. Ano+Bio can potentially be used as a replacement for chlorinated water, when the negative effects exerted by chlorinated water to the environment and human health are considered. With the developed models, the probability of marketability of the tomatoes can be adequately predicted depending on the road conditions, storage environment, pre-storage treatment tomatoes were subjected to, as well as their maturity at harvest. The utilisation of information given by these models will be beneficial to farmers and fresh tomato suppliers at various levels from the a perspective of minimisation of tomato postharvest losses, improving profitability and quality of tomatoes delivered to the markets.

Acknowledgement

The authors thank the Tomato Producer Organisation (TPO) and Postharvest Innovation Programme (PHI) for financially supporting this strudy (grant no. 7/2014).

References

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

Agresti, A. 1996. An Introduction to Categorical Data Analysis (2nd ed). USA: John Wiley & Sons, Inc.

Ali, M. S., Nakano, K. and Maezawa, S. 2004. Combined effect of heat treatment and modified atmosphere packaging on the color development of cherry tomato. Postharvest Biology and Technology 34(1): 113-116.

Arhin, S. A., Noel, E. C. and Ribbiso, A. 2015. Acceptable international roughness index thresholds based on present serviceability rating. Journal of Civil Engineering Research 5(4): 90-96.

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

Brandt, S., Pék, Z., Barna, É., Lugasi, A. and Helyes, L. 2006. Lycopene content and colour of ripening tomatoes as affected by environmental conditions. Journal of the Science of Food and Agriculture 86(4): 568-572.

Castro, L. R., Vigneault, C., Charles, M. T. and Cortez, L. A. B. 2005. Effect of cooling delay and cold-chain breakage on 'Santa Clara' tomato. Journal of Food, Agriculture and Environment 3(1): 49-54.

Department of Agriculture, Forestry and Fisheries (DAFF). 2012. A profile of the South African tomato market value chain. Retrieved from DAFF website: https://www.nda.agric.za/doaDev/sideMenu/Marketing/Annual%20Publications/Commodity%20Profiles/field%20crops/Tomato%20Value%20Chain%20Profile%20%202012.pdf

Department of Agriculture, Forestry and Fisheries (DAFF). 2015. Market analysis report no 1 of 2015: Tomato. Retrieved from DAFF website: https://www.nda.agric.za/doaDev/sideMenu/Marketing/Quartely%20Bulletins%20Uploaded/Tomato%20Market%20Analysis%20Report%20No%201%202015.pdf

Dorais, M., Ehret, D. L. and Papadopoulos, A. P. 2008. Tomato (Solanum lycopersicum) health components: from the seed to the consumer. Phytochemistry Reviews 7: 231-250.

Dugassa, A., Bacha, K. and Ketama, T. 2014. Microbiological quality and safety of some selected vegetables sold in Jimma town, Southwestern Ethiopia. African Journal of Environmental Science and Technology 8(11): 633-653.

Favati, F., Lovelli, S., Galgano, F., Miccolis, V., Tommaso, T. D. and Candido, V. 2009. Processing tomato quality as affected by irrigation scheduling. Scientia Horticulturae 122(4): 562-571.

Getinet, H., Seyoum, T. and Woldetsadik, K. 2008. The effect of cultivar, maturity stage and storage environment on quality of tomatoes. Journal of Food Engineering 87(4): 467-478.

Guo, Q., Wu, B., Peng, X., Wang, J., Li, Q., Jin, J. and Ha, Y. 2014. Effects of chlorine dioxide treatment on respiration rate and ethylene synthesis of postharvest tomato fruit. Postharvest Biology and Technology 93: 9-14.

Kays, S. J. 1999. Preharvest factors affecting appearance. Postharvest Biology and Technology 15(3): 233-247.

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

Kitinoja, L. and Kader, A. A. 2002. Small-scale Postharvest Handling Practices: a Manual for Horticultural Crops (4th ed). California: University of California.

Lammertyn, J., Aerts, M., Verlinden, B. E., Schotsmans, W. and Nicolaï, B. M. 2000. Logistic regression analysis of factors influencing core breakdown in 'Conference' pears. Postharvest Biology and Technology 20(1): 25-37.

Linden, V. V., Scheerlinck, N., Desmet, M. and Baerdemaeker, J. D. 2006. Factors that affect tomato bruise development as a result of mechanical impact. Postharvest Biology and Technology 42(3): 260-270.

Linke, M. and Geyer, M. 2002. Postharvest behaviour of tomatoes in different transport packaging units. In Verlinden, B. E., Nicolaï, B. M. and De Baerdemaeke, J. (Eds). Proceedings of the International Conference Postharvest Unlimited (Vol. 599), p. 115-122. Belgium: International Society for Horticultural Science.

López Camelo, A. F. and Gómez, P. A. 2004. Comparison of color indexes for tomato ripening. Horticultura Brasileira 22(3): 534-537.

McHugh, M. L. 2011. Multiple comparison analysis testing in ANOVA. Biochemia Medica 21(3): 203-209.

Melesse, S., Sobratee, N. and Workneh, T. 2016. Application of logistic regression statistical technique to evaluate tomato quality subjected to different pre- and post-harvest treatments. Biological Agriculture and Horticulture 32(4): 277-287.

Mohammadi-Aylar, S., Jamaati-e-Somarin, S. and Azimi, J. 2010. Effect of stage of ripening on mechanical damage in tomato fruits. American-Eurasian Journal of Agricultural and Environmental Science 9(3): 297-302.

Moneruzzaman, K. M., Hossain, A. B. M. S., Sani, W. and Saifuddin, M. 2008. Effect of stages of maturity and ripening conditions on the biochemical characteristics of tomato. American Journal of Biochemistry and Biotechnology 4(4): 329-335.

Moneruzzaman, K. M., Hossain, A. B. M. S., Sani, W., Saifuddin, M. and Alenazi, M. 2009. Effect of harvesting and storage conditions on the post harvest quality of tomato (Lycopersicon esculentum Mill) cv. Roma VF. Australian Journal of Crop Science 3(2): 113-121.

Munyeka, W. 2014. Price mediation in tomato commerce of Limpopo Province of the Republic of South Africa. Mediterranean Journal of Social Sciences 5(20): 778-791.

Mutari, A. and Debbie, R. 2011. The effects of postharvest handling and storage temperature on the quality and shelf of tomato. African Journal of Food Science 5(7): 446-452.

Nelder, J. A. and Wedderburn, R. W. M. 1972. Generalized linear models. Journal of the Royal Statistical Society: Series A 135(3): 370-384.

Nunes, M. C. N., Emond, J. P., Rauth, M., Dea, S. and Chau, K. V. 2009. Environmental conditions encountered during typical consumer retail display affect fruit and vegetable quality and waste. Postharvest Biology and Technology 51(2): 232-241.

Ortega, D. L., Wang, H. H., Wu, L. and Olynk, N. J. 2011. Modeling heterogeneity in consumer preferences for select food safety attributes in China. Food Policy 36(2): 318-324.

Paull, R. E. 1999. Effect of temperature and relative humidity on fresh commodity quality. Postharvest Biology and Technology 15(3): 263-277.

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

Pinheiro, J., Alegria, C., Abreu, M., Gonçalves, E. M. and Silva, C. L. M. 2015. Influence of postharvest ultrasounds treatments on tomato (Solanum lycopersicum, cv. Zinac) quality and microbial load during storage. Ultrasonics Sonochemistry 27: 552-559.

Sangwanich, S., Sangchote, S. and Leelasuphakul, W. 2013. Biocontrol of citrus green mould and postharvest quality parameters. International Food Research Journal 20(6): 3381-3386.

Schouten, R. E., Huijben, T. P. M., Tijskens, L. M. M. and van Kooten, O. 2007. Modelling quality attributes of truss tomatoes: linking colour and firmness maturity. Postharvest Biology and Technology 45(3): 298-306.

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

Tadesse, T., Workneh, T. S. and Woldetsadik, K. 2012. Effect of varieties on changes in sugar content and marketability of tomato stored under ambient conditions. African Journal of Agricultural Research 7(14): 2124-2130.

Taurayi, S. 2011. An investigation of natuurboerdery (natural farming) approach: a ZZ2 case study. South Africa: University of Stellenbosch, Master Thesis.

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

Venta, M. B., Broche, S. S. C., Torres, I. F., Pérez, M. G., Lorenzo, E. V., Rodriguez, Y. R. and Cepero, S. M. 2010. Ozone application for postharvest disinfection of tomatoes. Ozone: Science and Engineering 32(5): 361-371.

Wang, Y., Bao, Y., Shen, D., Feng, W., Yu, T., Zhang, J. and Zheng, X. D. 2008. Biocontrol of Alternaria alternata on cherry tomato fruit by use of marine yeast Rhodosporidium paludigenum Fell & Tallman. International Journal of Food Microbiology 123(3): 234-239.

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

Workneh, T. S., Osthoff, G. and Steyn, M. S. 2009. Integrated agrotechnology with preharvest ComCat® treatment, modified atmosphere packaging and forced ventilation evaporative cooling of tomatoes. African Journal of Biotechnology 8(5): 860-872.

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