# Moisture loss studies in Japanese plums (*Prunus salicina* Lindl.)

By

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# DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the authorship owner thereof and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

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# SUMMARY


## Moisture loss studies in Japanese plums (*Prunus salicina* Lindl.)

The export of Japanese plums from South Africa is challenging. Exporting late season plums require fruit to last as long as 8 weeks in cold-storage. Prolonged storage periods can cause some cultivars to develop a shrivelled appearance due to moisture loss. Moisture loss from perishable commodities manifests mainly as shrivelling due to a loss in the turgidity of the surface cells of the fruit, or weight loss.

'African Delight™' (highly susceptible to shrivel), 'Laetitia' (shrivel susceptible), 'Sapphire' (shrivel susceptible) and 'Songold' (not shrivel susceptible) plums were investigated by means of fluorescent microscopy for cracks and openings in the fruit peel. Only 'African Delight™' had open hairline cracks in its peel, and fruit with wider cracks were associated with higher water vapour permeabilities. Open lenticels were found in the peels of 'African Delight™', 'Laetitia' and 'Sapphire' plums. For 'Songold' no peel cracking or open lenticels were observed. The fact that the cuticle of this cultivar is mostly intact may be the reason why it is not susceptible to postharvest shrivel manifestation.

The water vapour permeance of the fruit peel determines how easily fruit lose moisture. In this study it was determined to what extent fruit, trees, orchards, harvest date and cultivar contribute to the total variation in plum peel water vapour permeability. The permeabilities of 'African Delight™', 'Laetitia', and 'Songold' were determined weekly from 4 weeks before harvest until post optimum maturity. Fruit to fruit variation made the largest contribution towards the total variation (> 45%), followed by harvest date (> 20%) and orchard (> 15%) effects. The permeability across all cultivars increased two-fold as fruit became over mature. The contribution of cultivar differences to fruit peel permeability varied greatly between seasons (42% in 2013/2014 and 5% in 2014/2015). Differences between cultivars may include cuticle thickness and composition, micro cracks in the peel and/or open lenticels.

Current handling protocols suggest that fruit should be cooled as soon as possible after harvest, but this is not always possible. 'African Delight™' plums were exposed to various handling scenarios in order to determine the handling protocol with the least

risk of moisture loss. The control consisted of packaging and cooling the fruit within 6 h of harvest. Fruit quality was comparable or even better than the control when the fruit were pre-cooled to 0 °C and 15 °C for up to 72 h. High vapour pressure deficits caused fruit to lose more moisture, especially when fruit were exposed to ambient temperatures for 48 h and 72 h. It is recommended that handling protocols for plums should be followed stringently in order to reduce mass loss and shrivel manifestation.

Since other studies found that silicate (Si) has positive effects on fruit quality, we applied potassium silicate preharvest to 'African Delight™' trees. However, we did not find significant differences between treatments regarding crack width or crack incidence in the fruit peel, shrivel, decay, internal browning, gel breakdown or aerated tissue levels. Currently preharvest potassium silicate applications are not recommended to improve plum quality.

# OPSOMMING


## Vogverlies studies in Japanese pruime (*Prunus salicina* Lindl.)

Die uitvoer van die Japanese pruime uit Suid-Afrika is 'n uitdaging, omrede daar verwag word dat laatseisoen kultivars tot 8 weke in koelopberging moet bly. Lang opbergingsperiodes veroorsaak dat sommige kultivars 'n verrimpelde voorkoms ontwikkel a.g.v. vogverlies. Vogverlies uit vars produkte manifesteer hoofsaaklik as verrimpeling a.g.v. 'n verlies in die turgiditeit van die selle in en onder die vrugskil, en as massaverlies.

'African Delight™' (hoogs vatbaar vir verrimpeling), 'Laetitia' (vatbaar vir verrimpeling), 'Sapphire' (vatbaar vir verrimpeling) en 'Songold' (nie vatbaar vir verrimpeling) pruime is ondersoek deur middel van fluoressensie mikroskopie vir krake en openinge in die vrugskil. Slegs 'African Delight™' het oop haarlyn krake in sy skil gehad en vrugte met wyer krake het 'n hoër waterdamp deurlaatbaarheid gehad. Oop lentiselle is gevind in die skille van 'African Delight™', 'Laetitia' en 'Sapphire' pruime. 'Songold' het geen krake of oop lentiselle getoon nie. Die feit dat 'Songold' se kutikula meestal ongeskonde was, mag die rede wees waarom hierdie kultivar nie vatbaar vir verrimpeling is nie.

Die waterdamp deurlaatbaarheid van 'n vrugskil bepaal hoe maklik vrugte vog verloor. In hierdie studie is bepaal tot watter mate vrugte, bome, boorde, oesdatum en kultivar bydra tot die totale variasie in die pruimskil se waterdamp deurlaatbaarheid. Die deurlaatbaarheid van 'African Delight™', 'Laetitia', en 'Songold' is weekliks bepaal vanaf 4 weke voor die verwagte oesdatum tot die vrugte oorryp was. Vrug tot vrug variasie het die grootste bydrae tot die totale variasie gemaak (> 45%), gevolg deur oesdatum (> 20%) en boord (> 15%). Die skildeurlaatbaarheid van al die kultivars het verdubbel in die tyd van net voor oes tot die vrugte oorryp was. Die kultivar se bydrae tot die deurlaatbaarheid van die vrugskil het baie gewissel tussen seisoene (42% in 2013/2014 en 5% in 2014/2015). Verskille in skil-deurlaatbaarheid tussen kultivars kan kutikula-dikte en -samestelling, mikro-krake in die skil en/of oop lentiselle insluit.

Huidige hanteringsprotokolle stel voor dat vrugte so spoedig moontlik afgekoel word na oes, maar dit is nie altyd moontlik nie. In hierdie studie is 'African Delight™' pruime

is blootgestel aan verskeie hantering scenario's om die hanteringsprotokol met die laagste risiko vir vogverlies te bepaal. Die kontrole vrugte is gepak en onder geforseerde verkoeling geplaas binne 6 ure na oes. Vrugkwaliteit was vergelykbaar of selfs beter in vergelyking met die kontrole wanneer die vrugte voorverkoel is tot 0 °C en 15 °C vir tot 72 uur. Hoë dampdrukverskille het veroorsaak dat vrugte meer vog verloor, veral wanneer vrugte aan kamertemperatuur blootgestel was vir 48 h en 72 h na oes. Dit word aanbeveel dat hanteringsprotokolle vir pruime streng gevolg moet word om massaverlies en verrimpeling te beperk.

Aangesien ander studies gevind het dat silikaat (Si) ‘n positiewe uitwerking op vrugkwaliteit het, het ons kaliumsilikaat vooroes aan ‘African Delight™’ bome toegedien. Daar was egter geen beduidende verskille tussen behandelings met betrekking tot kraakbreedte of kraakvoorkoms in die vrugskil of t.o.v. gehalte eienskappe soos die voorkoms van verrimpeling, bederf, interne verbruining, gelverval of deurlugte weefsel nie. Tans word voor-oes kaliumsilikaat spuite nie aanbeveel om pruimkwaliteit te verbeter nie.

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# TABLE OF CONTENTS

# NOTE

This thesis is a compilation of chapters, starting with a literature review, followed by four research papers. Each paper is prepared as a scientific paper for submission to *Postharvest Biology and Technology*. Repetition or duplication between papers might therefore be necessary.

# GENERAL INTRODUCTION AND OBJECTIVES

In South Africa Japanese plums are a valuable commodity. During the 2013/14 season 3% (2 038 ton) of the fruit were used for processing, 23% (16 823 ton) were sold on local markets and 74% (55 192 ton) of the fruit were shipped to overseas markets (HORTGRO, 2014). The total value of the plums exported during the 2013/14 season was R849.4 million.

Exporting plums to overseas markets can be very challenging as fruit should tolerate cold-storage at -0.5 °C for up to 8 weeks. Irrespective of the long storage period, the consumers expect fruit to look fresh when it arrives on supermarket shelves. For some cultivars this poses a real problem as they develop a shrivelled appearance during cold-storage due to moisture loss in the handling chain. Moisture loss from perishable commodities manifests mainly as shrivelling due to a loss in the turgidity of the surface cells of the fruit, or weight loss (Sastry, 1985; Banks et al., 2000). Ultimately, moisture loss leads to a decrease in the quality of the fruit, rendering the product worthless and resulting in economic losses to the industry (Sastry, 1985). Many authors reported that as little as a 5% loss in fresh weight can cause fruit to develop a shrivelled appearance (Ben-Yehoshua, 1987; Mitchell and Kader, 1989; Wills et al., 1989; Maguire et al., 2000).

Consequently, to gain a better understanding of moisture loss of Japanese plums, as well as how it is affected and reduced, numerous trials were conducted in this study. In Paper 1 we investigated, by means of fluorescence microscopy, if (1) openings or cracks in the fruit peel influenced moisture loss from shrivel susceptible cultivars, and (2) how the fruit peels differed between shrivel susceptible and non-susceptible cultivars. The cuticle of the fruit is a very effective barrier to water transport and acts as a protective layer between the product and its environment (Schönherr et al., 1979). The permeability of the peel determines the extent of gas exchange, including the exchange of water vapour, between the fruit and its surrounding environment (Kerstiens, 1996; Díaz-Pérez et al., 2007). Water vapour exits the fruit at various openings (natural or caused by injury) in the fruit peel (Mitchell and Kader, 1989). Generally there are four exit routes through which moisture can escape from the fruit peel, namely wounds, stomata or lenticels, through the cuticle and cracks in

the cuticle. Knoche and Peschel (2007) confirmed that cuticular cracks influence the permeability of the fruit peel when they found that micro cracks that develop in the cuticular membrane of European plums allowed moisture loss from the fruit.

Maguire et al. (2000) found that the peel permeability of apples varied between fruit, trees in the same orchard, orchards, harvest dates and cultivars, indicating that the permeability of the fruit peel is influenced by more than just cuticular openings or cracks. Fruit loses moisture in the form of water vapour which diffuses from the inside of the fruit through the cuticle into the surrounding environment (Maguire, 1998; Lara et al., 2014). Water vapour moves along a gradient; from a high to a lower concentration to establish equilibrium between the fruit and its environment. Hence, in fruit, water vapour moves from the intercellular airspaces and cell walls (where the water vapour pressure is usually close to saturation) into the surrounding atmosphere, where the concentration of water vapour is usually lower (Ben-Yehoshua, 1987). Moisture loss from horticultural products is governed by Fick's first law of gas diffusion (Ben-Yehoshua, 1987; Nobel, 1999). Consequently the rate of moisture loss from a product is determined by the effective permeance of the fruit surface to movement of water vapour, the difference in partial pressure of water vapour between the environment and inside the fruit, and the surface area of the fruit. Therefore, in Paper 2 we determined, by using Fick's first law of gas diffusion, the main preharvest factor/factors effecting plum peel permeability in order to develop or refine postharvest handling protocols to ensure that moisture loss, and hence postharvest shrivel manifestation, can be reduced to the minimum in Japanese plums.

Post-harvest handling can rarely restore lost moisture from fruit, but producers and exporters can strive to minimize moisture loss by reducing the difference in the partial pressure of water vapour, known as the vapour pressure deficit (VPD), between the fruit and its environment (Whitelock et al., 1994). Means to minimise fluctuations in VPD include maintaining small temperature differences between the product and its environment, limiting the air circulation inside the cooling room, or reducing the air pressure (Veraverbeke et al., 2003). It is important to cool fruit as soon as possible after harvest to reduce the VPD, and thus the driving force for moisture loss and subsequent shrivelling, between the fruit and its environment, but also to reduce the respiration rate of the fruit in order to ensure a prolonged shelf life (Paull, 1999). The

standard South African industry handling protocol is to remove field heat and to reduce the fruit pulp temperature to 15 °C within 3 h after harvest (HORTGRO, 2015). Subsequent to field heat removal it is recommended that fruit should be packed on the day it was received at the pack house and that it should be force air cooled to a pulp temperature of -0.5 °C within 24 to 36 h. However, due to labour and infrastructure constraints, it is not always possible for South African stone fruit producers to pack and cool fruit immediately after harvest. Hence, in Paper 3 we determined the VPD, moisture loss and shrivel manifestation of a number of simulated handling chains in order to establish an optimum handling protocol to reduce moisture loss, and hence, shrivel manifestation, to a minimum for plum fruit which cannot be packed and cooled to -0.5 °C on the day it was harvested.

Lastly, in Paper 4 we investigated if post-harvest shrivel could be reduced by pre-harvest potassium silicate ($K_2SiO_3$) applications. Some researchers have found that silicate (Si) is beneficial when supplied to various plants (Nasr et al., 2013). It have been found to enhance strength and rigidity of cell walls by being deposited as amorphous silica ($SiO_2.H_2O$) and opal phytoliths and/or by interacting with pectins and polyphenols in the cell walls (Epstein, 1999; Marchner, 2002; Stamatakis et al., 2003). Cell wall elasticity during extension growth is also increased by the application of silicon (Marchner, 2002). Si provides mechanical strength to plant cell walls, allowing them to be resistant to bacteria, fungi and insects (Menzies et al., 1991; Menzies et al., 1992; Epstein, 1999). It was also found that low concentrations of Si in post-harvest dips reduced chilling injury in lemon (Mditshwa et al., 2013). In a preliminary study done by Kritizinger and Jooste (2014) to determine if pre-harvest $K_2SiO_3$ applications could reduce the incidence of broken stones in ‘Laetitia’ plums, it was found that Si reduced postharvest shrivel manifestation. It was found that $K_2SiO_3$ applications also reduced moisture loss from lemons (Mditshwa et al., 2013) and avocados (Nasr et al., 2013). Reduced shrivel manifestation could be explained by an increase in strength or elasticity of the cell walls by silicate which could prevent the surface cells to display a loss in turgidity less easily. Alone, or in combination, these results can aid in the design of better postharvest protocols to avoid or reduce moisture loss from Japanese plums.

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# LITERATURE REVIEW:
# The effect of fruit characteristics and environmental factors on moisture loss from fresh produce

## 1. Introduction

Moisture loss from perishable commodities manifests mainly as shrivelling due to a loss in the turgidity of the surface cells of the fruit, or weight loss (Sastry, 1985a; Banks et al., 2000). In turn moisture loss and weight loss lead to a decrease in the quality of fruit. This decrease in quality can render a product worthless, which causes economic losses (Sastry, 1985a). As little as a 5% loss in weight can cause shrivelling (Ben-Yehoshua, 1987; Maguire et al., 2000; Mitchell and Kader, 1989; Wills et al., 1989). Moisture loss is driven by the diffusion of water vapour, hence factors that influence diffusion will have an effect on moisture loss (Nobel, 1999a). Furthermore, fruit peel permeability, the difference in the partial pressure of water vapour between the fruit and its environment, and the surface area of the fruit have an effect on the amount of moisture loss from the product (Ben-Yehoshua, 1987). These factors, as well as elements influencing them, will be reviewed in this paper.

## 2. Moisture loss

Fruit loses water in the form of water vapour which is transferred from the inside of the fruit to its surrounding environment (Maguire, 1998). This movement of water vapour happens against a gradient: usually from a high concentration inside the fruit to a lower concentration in the atmosphere surrounding the product. Moisture loss from horticultural products is governed by the steady state solution of Fick's first law of diffusion (Ben-Yehoshua, 1987; Nobel, 1999a). Consequently, the rate of water loss from a product can be calculated as follows:

$$r_{H_2O} = \Delta p_{H_2O} A P_{H_2O} \qquad \text{Eq. 1}$$

where:

$r_{H_2O}$ = rate of water loss from the product (mol $s^{-1}$)

$P_{H_2O}$ = difference in partial pressure of water vapour between the environment and the inside of the fruit (Pa)

$A$ = surface area of the fruit ($m^2$)

$P_{H_2O}$ = effective permeance of the fruit surface to movement of water vapour (mol $s^{-1}$ $m^{-2}$ $Pa^{-1}$)

According to Eq. 1 the rate of moisture loss depends on the water vapour permeance of the fruit peel ($P_{H_2O}$), the surface area of the fruit and the vapour pressure difference between the fruit and the surrounding atmosphere ($P_{H_2O}$). A change in any of these factors will result in an alteration in the rate of moisture loss from the product. Controlling these factors, therefore, can contribute to a management strategy to reduce moisture loss from fresh produce.

## 2.1. The water vapour permeance of the fruit peel

The epidermis (peel) of the fruit plays an important role in gas exchange between the product and its surrounding environment ( Kerstiens, 1996; Díaz-Pérez et al., 2007). Since water vapour is the gaseous phase of water, the peel also controls moisture loss from the fruit allowing it to maintain a high water content despite of being in an environment with a low relative humidity. Water vapour will exit the fruit at various openings in the peel which can be natural or caused by injury (Mitchell and Kader, 1989). Generally there are four exit routes through which moisture can escape from the fruit peel, namely wounds, stomata or lenticels, through the cuticle and cracks in the cuticle.

### *2.1.1. Wounds*

Wounds act as a direct pathway for water vapour to move from the intercellular airspaces to the fruit's surrounding environment (Sastry, 1985b). Hence, the presence of a wound in the fruit peel can dramatically increase the peel's permeability for water vapour. Wounding can occur at any time from before harvest until consumption (Mitchell and Kader, 1989). Insect damage, hail damage or wind marks are some of the injury possibilities whilst the fruit are still on the tree. From harvest to consumption there are a number of opportunities for fruit to be injured. Fruit transported from the

field to the packing shed can be injured by compression or bruising when pickers handle the fruit too roughly. Dropping fruit into a bin can inflict wounds, for instance when the cheek of one fruit is dropped onto the stem of another it can pierce through the peel of the fruit being dropped. Vibration during transportation can cause fruit to develop abrasion wounds which can also increase the fruit's peel water vapour permeance. Wounded fruit should only be considered for sale if it is intended for a market with standards allowing for a degree of wounding and if the transportation time is short. Such fruit also holds a higher risk for decay to develop.

### *2.1.2. Transpiration*

Transpiration occurs when plants transfer water vapour from the surface of the plant organ to the surrounding air (Ben-Yehoshua, 1987). This transfer aids in cooling the fruit. In order for transpiration to occur some sort of opening in the fruit peel is needed to allow gas diffusion across the peel. Gas exchange is usually facilitated by stomata (most common on leaves, but also present in the peel of stone fruit) and lenticels in the fruit peel (Burton, 1982; Ben-Yehoshua, 1987).

Generally stomata lose their functionality early in the fruit's development and lenticels form around the stomata (Burton, 1982). Lenticels can also form by means of cracks caused by peel expansion during fruit growth. Lenticels may remain open and still allow gas exchange, or may become cutinized and block gas exchange during fruit development (Ben-Yehoshua, 1987). Lenticels that remain open contribute to the water vapour permeance of the fruit peel by making it more permeable for water vapour.

### *2.1.3. Cuticle*

The above ground parts of terrestrial plants are covered by a cuticular membrane (CM) (Knoche and Peschel, 2007). The function of this membrane is to act as a protective barrier against moisture loss, pathogen infections and mechanical damage. For plants to be protected from these unwanted occurrences the CM needs to stay intact. This can be problematic for fruits that keep expanding towards maturity, because in some cases the deposition of the CM cannot keep up with fruit growth (Knoche et al., 2000).

When the fruit's surface expansion overtakes the deposition of the CM, cracks can develop in the CM. Cracking may also occur when maturation and harvest overlap with periods of high relative humidity. Such conditions cause water to be redeployed from branches and leaves to fruit on the same tree because of the big difference in their individual water potentials (Lara et al., 2014). Cracks not only assist the entry of rot pathogens, but also serve as an escape route for water vapour. Knoche and Peschel (2007) found that the cuticle deposition in European plums is not able to keep up with surface expansion, and that it lead to strain and cracking of the CM. They also found that micro cracking of the CM occurred more in the pedicel region, where there is a larger structural strain on the cuticle than on the cheek of the fruit. Shrivelling, which is strongly linked to moisture loss, are mostly found in the pedicel region on European plums. Hence, there may be a connection between micro crack incidence and an increase in transpiration which may lead to the shrivelling found at the pedicel end in European plums (Knoche and Peschel, 2007).

*2.1.3.1. Cuticle Composition*

Cuticles are characterized chemically by two groups of lipid substances according to their solubility in polar solvents, namely insoluble polymetric cutins (which establishes the framework of the membrane) and soluble cuticular lipids (which can appear on the surface as a epicuticular wax) (Holloway, 1982). The membrane structure can vary considerably according to species and developmental stage. Horrocks (1964) did a study where he removed the soluble cuticular lipids from apple peels and found that it caused the water vapour permeability for 'Golden Delicious' and 'Granny Smith' to increase 30 and 70-fold, respectively. Schönherr and Lendzian (1981) also found this when they removed the soluble cuticular lipids from the cuticle of tomato fruit and found the peel water vapour permeability increased 20-fold. This proves that soluble cuticular lipids have a significant effect on the barrier properties of the cuticle.

## 2.2. Surface area

Moisture loss from fruit is significantly influenced by its size (Ben-Yehoshua, 1987; Wills et al., 1989). Size has an effect on the total surface area and volume of a fruit. There is proportionally a larger loss in moisture from produce with a high surface

area to volume ratio, e.g. lettuce, compared to produce with a lower surface to volume ratio, e.g. a plum. Similarly, immature or small fruit has a larger surface to volume ratio than fruit that have reached the end of their fruit growth stage or large fruit that has a smaller surface to volume ratio. Larger fruit lose less moisture on a per unit weight basis than smaller and/or immature fruit.

## 2.3. Driving force behind moisture loss

Dry air is composed of 78% nitrogen, 21% oxygen, 0.034% carbon dioxide, 0.934% argon and other minor components which make out approx. 1% of the total gas mixture (Wills et al., 1989). Normal atmospheric air is moist and consists of a mixture of dry air and water vapour. If dry air comes into contact with water in an enclosed space, some of the water molecules will enter the vapour phase and become part of the air until the air is saturated with water vapour (Wills et al., 1989). Air may contain virtually zero amounts of water, but may also become saturated with water depending on the prevailing temperature and pressure (Thompson, 1992). The amount of water in the air can be described in many ways, but relative humidity (RH) is probably the most widely used in the postharvest fruit industry. RH is a ratio, expressed as a percentage in most cases, of partial pressure of water vapour in the air at a specific point in time ($P^{e}_{H_2O}$; Pa) to the saturation partial pressure at the environmental temperature ($P^{sat}_{H_2O}(T_e)$; Pa).

$$RH = \frac{P^{e}_{H_2O}}{P^{sat}_{H_2O}(T_e)} \times 100 \qquad \text{(Eq. 2)}$$

The driving force behind moisture loss from perishable commodities is primarily controlled by the difference in water vapour pressure between the air in the intercellular airspaces and the air surrounding the fruit (Thompson, 1992). When fruit are harvested they are removed from their source of water, and, hence, become subjected to the water vapour pressure of the air around them (Van den Berg, 1987). The partial pressure of water vapour of the air inside the intercellular air space of the fruit is assumed to be very close to saturation, with a RH of more than 99% (Ben-Yehoshua, 1987). The amount of water vapour of air under typical ambient and storage conditions is mostly lower than saturation, depending on temperature and the moisture content of the air (Wills et al., 1989). This variance creates a difference in

vapour pressure between the fruit and its environment, driving moisture loss from the fruit.

According to Fick's first law of diffusion water vapour will move from the fruit into the air surrounding it if the fruit remain warmer than the air surrounding it, i.e. from a high to a lower concentration. Given this, the driving force for moisture loss is, therefore, the difference in the partial pressures between the fruit and its environment ($\Delta p_{H_2O}$; Pa) (Ben-Yehoshua, 1987; Wills et al., 1989):

$$\Delta p_{H_2O} = p^f_{H_2O} - p^e_{H_2O} \qquad \text{Eq. 3}$$

Where:

$p^f_{H_2O}$ = Partial pressure of water vapour in the fruit (Pa)

$p^e_{H_2O}$ = Partial pressure of water vapour in the environment (Pa)

The following examples from Thompson (1992) illustrate the effect of the different water vapour pressures on the driving force behind moisture loss. The differences in water vapour pressure are listed in Table 1.

Example 1: a fruit with a pulp temperature at 20 ºC is placed in a refrigerated room (0 ºC and 100% RH). The vapour pressure (VP) of the fruit will be 2.34 kPa whereas that of the air will be 0.61 kPa according to psychrometric principles. Thus, the vapour pressure deficit (VPD) will be 1.73 kPa (2.34 kPa [Fruit] – 0.61 kPa [Air]), and will drive moisture loss from the fruit.

Example 2: the fruit is precooled to 0 ºC and placed in the same refrigerated room (0 °C and 100% RH). The VP of the fruit will be 0.61 kPa whereas that of the air will be 0.61 kPa. Thus, the VPD will be 0 kPa (0.61 kPa [Fruit] – 0.61 kPa [Air]), and there will be no drive for moisture loss from the fruit.

Example 3: when the fruit is precooled to 0 ºC and placed in a refrigerated room at 0 ºC and 70% RH the VP of the fruit will be 0.61 kPa whereas that of the air will be 0.43 kPa. Thus the VPD will be 0.18 kPa (0.61 kPa [Fruit] – 0.43 kPa [Air]), and will drive moisture loss from the fruit

In examples 1 and 3 there is a driving force for moisture loss, but the difference in water vapour pressure in example 3, where the fruit was precooled, was smaller (0.18 kPa) (Thompson, 1992). This means that there is a smaller driving force towards moisture loss than in the case of fruit not being precooled. This clearly illustrates the influence the difference in water vapour pressure between the fruit and its surrounding atmosphere has as the driving force behind moisture loss.

The VP values used were calculated using a psychrometric chart where the curved lines represents RH, the vertical lines represent temperature and the horizontal lines represent the water vapour pressure for that specific RH and temperature (Fig. 1). A given RH at different temperatures represents different vapour pressures in the air. It follows that different water vapour partial pressures represents different driving forces for moisture loss from fruit at any given temperature (Maguire, 1998). Tetens (1930) derived an equation that describes the curved saturation line on the psychrometric chart which is used to calculate the partial pressure of water vapour at the fruit's surface.

$$p_{H_2O}^{sat}(T) = 611\exp\left(17.27\left(\frac{T}{T+237.3}\right)\right) \qquad \text{Eq. 4}$$

Where:

$p_{H_2O}^{sat}(T)$ = Saturated water vapour pressure (Pa)

$T$ = Temperature (ºC) at the fruit surface.

The partial pressure of water vapour in air can be determined by using probes to measure RH and air temperature, or by using a psychrometer (wet and dry bulb thermometers). The psychrometer measures air and dew point temperatures, and together these measurements can be used to calculate the partial pressure of the water vapour in the air. Eq. 5 can be used to calculate the partial pressure of water vapour in the environment ($p_{H_2O}^{e}$) where $RH$ is expressed as a percentage and $T_e$ (ºC) as the environmental temperature.

$$p_{H_2O}^{e}(T) = 611\exp\left(17.27\left(\frac{T_e}{T_e+237.3}\right)\right) \times \frac{RH}{100} \qquad \text{Eq. 5}$$

It is clear from these relationships that fruit temperature, air temperature and relative humidity are the main factors contributing to the driving force of moisture loss.

## 3. Factors influencing fruit water vapour permeance

### 3.1. The effect of fruit developmental stage on peel permeance

Structural changes in the cuticle of fruit take place as the fruit grows towards maturity, and this has an effect on the permeance of the cuticle (Burton, 1982; Karbulková et al., 2008). Pieniazek (1943) sampled apple fruit at weekly intervals and determined their permeance over a 24 h period. He found that the permeance of immature apple fruit was initially high, but that it decreased as fruit development progressed, and reached a minimum just before the fruit became mature. Subsequently, as the fruit became overripe, the peel permeability increased again. Maguire et al. (2000) made the same observation when they studied water vapour permeance of apples from 2 weeks before harvest until 6 weeks after harvest.

### 3.2. Factors influencing peel permeance at harvest

#### *3.2.1. Time of harvest*

Pieniazek (1943) found an increase in the water vapour permeance of apples as fruit matured during the commercial harvesting period. He also found that the permeability of fruit increased when the harvest date was postponed. This result was confirmed by Maguire et al. (2000). They found that the permeance increased from 21.4 at first harvest to 46.4 $nmol \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$ at final harvest 10 weeks later for all cultivars (‘Braeburn’, ‘Pacific Rose’, ‘Cripps Pink’ and ‘Granny Smith’) they evaluated. Hence, Maguire et al. (2000) found that the permeance doubled from the beginning to the end of the harvesting window for the apple cultivars they evaluated. The increase in peel permeability as fruit matures can be ascribed to maturity differences between fruit, environmental effects because of a longer period on the tree, or to drying out of the fruit surface after picking (Maguire, 1998).

#### *3.2.2. Maturity*

As potatoes develop towards maturity the permeance of each of the maturity stages differs due to changes in the nature and structure of the outer layers

(Burton, 1982). Woods (1990) reported that the permeance of fruit lowers as fruit matured, while (Sastry, 1985a) stated that immature and over mature fruit transpired more rapidly than mature fruit. A possible reason for immature fruit to have a high water vapour permeability is more stomata in the fruit peel that is open and a larger surface to volume ratio. Over mature fruit may have a high permeability because of cracking or wounds due to continuous expansion of the fruit.

## 3.3. Postharvest factors influencing permeance

### *3.3.1. Mechanical damage*

Any cut or puncture in the fruit peel breaks the barrier between the surrounding air and the intercellular air spaces beneath the cuticle, allowing water vapour to escape from the fruit (Burton, 1982). These cuts and punctures incurred by fruit after harvest will increase the water vapour permeance and thus increase moisture loss (Sastry, 1985b). Bruising can damage the surface of the fruit as well, and it has been claimed to increase moisture loss (Wills et al., 1989).

Russeting, a peel disorder, can be identified by irregular, rough russeted spots anywhere on the fruit surface. It occurs on all plum and prune cultivars, in all production areas, and are caused by insects and mechanical injuries, e.g. twigs and branches rubbing against young, developing fruit (Rose et al., 1950). The degree of russeting can vary. More severe russeting has deeper cork formation and cracks, and causes an increase in moisture loss from fruit (Maguire, 1998). In a study on apples to understand how water moves through the fruit, Verner (1935) fed aqueous dye (acid fuchsin and methyl blue) into the cut ends of small branches. The dye penetration was observed in nearby fruit, and the movement of the dye indicated that it had moved into the tissues beneath regions of russeting, scab legions or cracks. It was also found that the rate of water passing through these openings was more rapid than elsewhere.

### *3.3.2. Relative humidity*

The structure of the fruit cuticle resembles a continuous hydrophobic polymer membrane (Maguire, 1998). Hydrophobic polymer films are known to increase their gas permeability when there is an increase in relative humidity (Barrie, 1968). In a study done by Sastry and Buffington (1983) on the transpiration rates of tomatoes, it

was suggested that the water vapour permeance of the fruit peel was independent of environmental changes. This, however, does not correspond to what other researchers found, namely an increase in water vapour permeance with an increase in relative humidity (Lentz and Rooke, 1964; Sastry et al., 1978). To accurately predict the moisture loss from fruit by using Eq. 1, one needs to understand the effect of $\Delta p_{H_2O}$ (difference in partial pressure of water vapour between the environment and the inside of the fruit) upon $P_{H_2O}$ (effective permeance of the fruit surface to movement of water vapour).

*3.3.3. Temperature*

The water vapour permeability of a cuticle increases with an increase in temperature (Schönherr et al., 1979). Schönherr et al. (1979) found that temperatures above 45 ºC changed the distribution of cuticular lipids in the cuticular membrane causing water vapour permeability to increase in an irreversible manner. In another study done by Eckl and Gruler (1980) it was found that an increase in temperature resulted in a phase transition and it led to the reorientation of the soluble cuticular lipids. This reorientation created hydrophilic holes in the barrier. When the soluble lipids were heated above 38 ºC it entered a fluid state, and above 45 ºC the molecular orientation of the soluble lipids and polymer matrix changed. Cooling resulted in the recrystallization of the soluble lipids in a structure different from the original, causing hydrophilic holes in the barrier. Schreiber and Schönherr (1990) suggested that the increase in water vapour permeability of the plant cuticles was caused by an increase in disorder at the interface of the polymer matrix and soluble lipids in the cuticle. They also found that the permeability of citrus leaves changed significantly with a 300% increase in temperatures between 10 ºC and 30 ºC (the physiological temperature range in which reactions occur within the plant). Furthermore, to calculate the permeability of a membrane one would need the difference in water vapour pressure (according to Eq. 1), and to calculate that, temperature and relative humidity of the surrounding air and the product are needed. Thus, it would be too complex to separate the effects of relative humidity and temperature on a product's peel permeability.

*3.3.4. Waxing*

Edible waxes are used as a surface coating for fruits and vegetables to either improve the cosmetic appearance of the crop (shine, perceived depth of colour), or to reduce deterioration by lowering moisture loss, or creating a modified atmosphere (MA) (Banks et al., 1997). Wax provides a partial physical barrier to water vapour transmission through the fruit surface, thus lowering the water vapour permeance of the fruit peel (Mitchell and Kader, 1989). Waxing is an excellent way of preventing moisture loss, but it can also inhibit gas exchange (Banks et al., 1997). Applied wax changes the peel's permeance to $O_2$ and $CO_2$ which can modify the internal atmosphere of the fruit, and in some cases lead anaerobic respiration (Mitchell and Kader, 1989).

## 4. Factors influencing the driving force behind moisture loss

4.1. Fruit temperature

Temperature is one of the main driving forces of moisture loss. Temperature is a form of energy, and can be transferred or removed by either sensible heat or latent heat (Nobel, 1999b).

*4.1.1. Sensible heat transfer*

Three mechanisms of sensible heat transfer are important in the fruit environment, namely conductance, convection and radiation (Monteith and Unsworth, 2008). Heat can be conducted from a warm body to a cooler one when they are in contact or by air when random thermal collisions of gas molecules transfer heat from one body to another.

Convective heat transfer occurs when turbulent air is in contact with a body and has the capability to remove heat from it (Monteith and Unsworth, 2008). There are two types of convective heat transfer, namely free and forced convection. Free convection happens when heat from a body is transferred to the air surrounding it. The heated body warms up the air around it, the air expands and decreases in density. Warm air is lighter and moves upward, causing heat to move away from the body. This will only happen when there is little to no air movement. Forced convection occurs

when the movement of the air is caused by wind, a fan or any other artificially induced convection current. As the speed of the air movement increases, the more heat will be removed by convection.

Infrared or thermal radiation is absorbed by plants from their environment. If an object has a temperature above absolute zero (0 K) it will emit thermal radiation (Nobel, 1999b). Thus, any part of a plant, including fruit, will emit and absorb thermal radiation.

*4.1.2. Evaporative cooling*

Evaporative cooling occurs when heat is dissipated by water vapour (Nobel, 1999b). Fruit contains water and it is possible for fruit to transfer its heat to water within itself. Due to an increase in its temperature, water in the liquid phase is then converted to the gas phase (water vapour), and is released by transpiration. The water vapour, consequently, moves into the air surrounding the fruit depending on the air's temperature and relative humidity. As the water vapour moves away from the fruit it takes the heat along with it. This causes a reduction in the temperature of the fruit surface and indirectly lowers the partial pressure of water vapour at the fruit surface, reducing the total driving force for moisture loss.

*4.1.3. Heat of respiration*

Fresh fruit is alive, meaning they will keep on respiring even if they are removed from the tree until they run out of fuel (carbohydrates). Respiration is a complex process which involves the conversion of carbohydrates and oxygen into water, carbon dioxide and heat (Taiz and Zeiger, 2010). The heat of respiration can cause a rise in fruit temperature (Sastry, 1985b). Heat generated from respiration should be removed, otherwise it will cause an increase of the fruit surface temperature which will increase the water vapour partial pressure at the fruit surface, and hence the driving force for moisture loss.

4.2. Packaging

Packaging has a profound effect on the air movement around fruit during storage, therefor it also has an effect on the $\Delta p_{H_2O}$ (Wills et al., 1989). The boundary

layer, which is a layer of air around the fruit where there is very little air movement, is affected by packaging (Sastry, 1985b). Packaging lowers the air velocity around the fruit and this has an effect on the thickness of the boundary layer. The thickness of the boundary layer is inversely related to the velocity of the air (Nobel, 1975):

$$\Delta x^{bt} = \frac{2.8\sqrt{\frac{d^f}{v}} + \frac{0.25}{v}}{1000} \qquad \text{Eq. 6}$$

Where:

$\Delta x^{bt}$ = boundary layer thickness (m)

$d^f$ = fruit diameter (m)

$v$ = air velocity (m $s^{-1}$)

The boundary layer is a microenvironment around fruit where the air tends to build up a higher relative humidity than the air in the surrounding atmosphere and acts an extra layer of resistance against moisture loss (Sastry, 1985b). Therefore, if the air velocity decreases, e.g. when the packaging surrounding the product is less permeable to air, the thickness of the boundary layer will increase, causing the rate of moisture loss to be lower (Nobel, 1975).

Packaging may also increase the relative humidity of the air around the fruit (Crouch, 1998). For instance, when the airflow is reduced, the product increases the humidity of the air inside the packaging, because the packaging prevents the moisture from the fruit to be released into the atmosphere. The moisture in the air accumulates in the packaging with time until it reaches a state close to saturation. In turn this will cause the water vapour partial pressure of the air inside the packaging to increase which will lower the $\Delta p_{H_2O}$, and will result in less moisture loss. In a study done by Crouch (1998) on 'Laetitia' plums, he found that plastic liners with a greater number of micro-perforations led to a higher shrivel incidence (which is caused by moisture loss), because the atmosphere inside the liner was closer to that of the air on the outside. This indicates that more ventilation within the packaging causes higher air velocities and creates a larger $\Delta p_{H_2O}$ value, which lead to more moisture loss.

Crouch (1998) also found that unperforated packaging, which does not allow any airflow around the product, will cause the air surrounding the product to reach a point close to saturation. This will cause the $\Delta p_{H_2O}$ inside the packaging to be very small. However, this will not stop moisture loss from happening completely, since the fruit will still be respiring and producing heat. The heat of respiration will always cause the temperature of the fruit and its environment to differ and, hence a small $\Delta p_{H_2O}$ will exist in packaging with an RH close to saturation. Therefore, moisture loss will not be stopped by a saturated environment, but it will be kept to a minimum (Wills et al., 1989). When packaging is developed it should be considered that a high relative humidity may reduce moisture loss, but it is also possible that there might be an increase in decay.

### 4.3. Relative humidity and temperature

Relative humidity cannot be discussed on its own, because it is depends on the temperature of the air of the environment, as stated in Eq. 2.2. The lowering of an environment's temperature will also reduce the temperature of the fruit contained in it. The partial pressure of water vapour at the surface of the fruit will also be lowered because the capacity of air to hold moisture will be smaller as a result of the lower temperature. The amount of moisture in an environment will stay the same if the temperature is lowered, but the capacity of the air to hold the moisture will become smaller and the air will be closer to saturation. This will lead to a smaller $\Delta p_{H_2O}$ and will thus reduce the driving force for moisture loss.

## 5. Other factors influencing moisture loss

### 5.1. Cultivar

Maguire et al. (2000) did a study to determine if harvest date, cultivar, orchard, and variation between trees had an effect on water vapour permeance of apples. She found that almost 30% of the variation in water vapour permeance was caused by differences between cultivars. This variation is presumably related to variation in the physical and chemical properties of the outer layers of the fruit. These properties include differences in the number of lenticels (Pieniazek, 1944), cuticle thickness (Kamp, 1930), microcracking (Peschel and Knoche, 2005) and the amount and type

of cuticular waxes (Riederer and Schneider, 1990). The same could be possible true for plums as some cultivars, such as Laetitia and African Delight™, are very susceptible to moisture loss, while other cultivars, such as Songold, are less susceptible (personal observation).

### 5.2. Orchard

Soil type, training systems and climate can vary between orchards, and in some cases even within the same orchard, and this can influence moisture loss from fruit (Maguire et al., 2000). Maguire et al. (2000) found that 4% of the variation in water vapour permeance from apples was caused by orchard effects and 7% by an interaction between harvest date and orchard effects. The reason for this was not explained, but it was speculated that the result was caused by the influence of a number of inherent growth and environmental factors on the increase in peel permeance to water vapour.

## 6. Conclusion

It is clear that there are many existing factors that affect moisture loss from fruit. Most of them are inter-linked with each other, therefore an integrated management strategy is needed to reduce moisture loss from fruit. From this review it is clear that the best possible way for producers to try and control moisture loss is to minimize the driving force behind moisture loss and manage the postharvest factors influencing water vapour permeability to the best of their capability. For breeders it should be important to avoid developing cultivars that have high peel permeabilities.

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## 8. Tables

### Table 1

Water vapour pressures from different storage air conditions and product temperatures (Thompson, 1992).

| Variables | | Water vapour pressure (kPa) |
|---|---|---|
| Room air: | 0ºC, 100% RH | 0.61 |
| | 0ºC, 70% RH | 0.43 |
| Fruit*: | 0ºC | 0.61 |
| | 20ºC | 2.34 |

*Assuming the air in the fruit is saturated with water vapour.

## 9. Figures

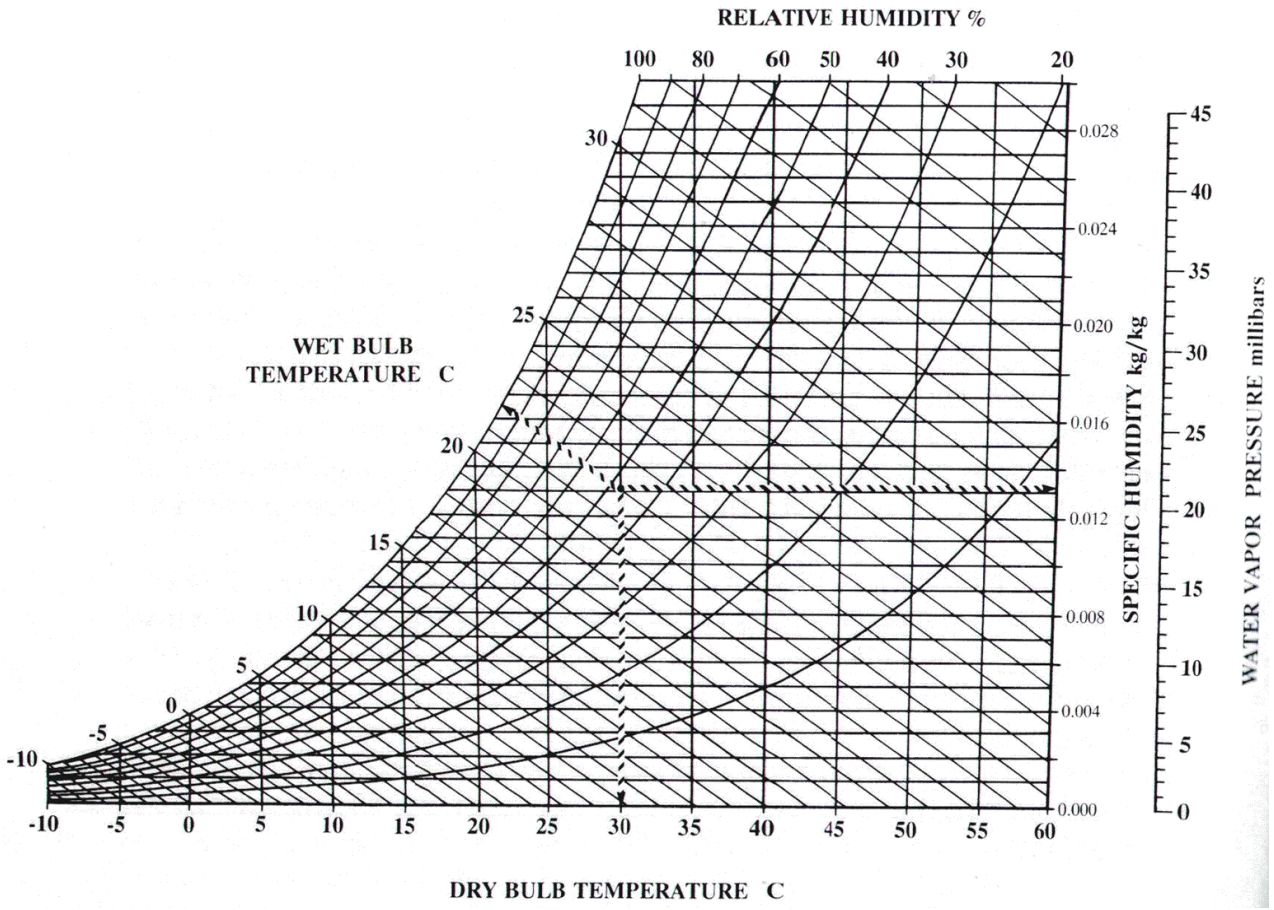


**Fig. 1.** A psychrometric chart where the curved lines represents relative humidity (RH), the vertical lines represent temperature and the horizontal lines represent the water vapour pressure for that specific RH and temperature (Ben-Yehoshua, 1987).

# PAPER 1:
# The contribution of hairline cracks towards moisture loss in Japanese plums (*Prunus salicina* Lindl.)


## Abstract

South African Japanese plums are mainly exported by sea and this entails a relatively long period in cold-storage. This causes fruit to lose moisture which can lead to fruit developing a shrivelled appearance. 'African Delight™' plums (which are highly susceptible to postharvest shrivel manifestation) are known for the concentric rings found at the pedicel end of the fruit. The aim of this study was to investigate, by means of fluorescent microscopy, if these concentric rings were open fruit cracks and if they influenced moisture loss. Furthermore, 'Laetitia' (shrivel susceptible), 'Sapphire' (shrivel susceptible) and 'Songold' (not susceptible to shrivel) plums were also investigated by means of fluorescent microscopy for openings or cracks in the fruit peel, and how the fruit peel differed between shrivel susceptible and non-susceptible cultivars. It was found that 'Sapphire' had the highest water vapour permeability, followed by 'African Delight™' and 'Songold', whilst 'Laetitia' had the lowest water vapour permeability on its optimum harvest date. The concentric rings of 'African Delight™' were found to be open hairline cracks and the wider cracks were associated with fruit with higher water vapour permeance. It was also observed that the lenticels in the peel of 'African Delight™', 'Sapphire' and 'Laetitia' plums were open, and probably caused these cultivars to be susceptible to postharvest moisture loss, and hence, shrivel. 'Songold' did not show any signs of peel cracking or open lenticels. The fact that the cuticle of this cultivar is mostly intact with very few or no openings contributing to moisture loss may be the reason why this cultivar is not susceptible to postharvest shrivel manifestation.


Keywords: Hairline cracks, Japanese plums, Peel, Water vapour permeability

## 1. Introduction

In South Africa Japanese plums are a very valuable commodity. Twenty three % (16 823 t) of the fruit are sold on local markets, 3% (2 038 t) are processed

and 74% (55 192 t) of the fruit are shipped to overseas markets (HORTGRO, 2014). South African plums are mainly exported by sea which entails a relatively long sea freight period (approx. 17 d). Early season plum cultivars usually have a total cold-storage period of approx. 35 d while some late season cultivars may be cold-stored for more than 8 weeks to allow for stock rolling overseas. The maximum cold-storage period is normally determined by the cultivar's susceptibility to chilling injury. Irrespective of the long storage period required by the South African plum industry of the highly perishable Japanese plums, the consumer expects the fruit to look fresh when it arrives on the supermarket shelves. This poses a real problem for some cultivars as they may develop a shrivelled appearance during cold-storage due to moisture loss occurring in the handling chain. Moisture loss from perishable commodities have mainly two outcomes, namely shrivelling (because of the loss in the turgidity of the surface cells of the fruit) or weight loss, which leads to a reduction in the quality of fruit (Sastry, 1985). This reduction in quality can render a product completely worthless, which causes financial losses.

Moisture loss from the fruit peel is governed by Fick's first law of diffusion (Nobel, 1999). This law states that the rate of moisture loss depends on the combination of three factors. The first factor is the contribution of the surface area of the fruit peel to moisture loss. Fruit size has a substantial effect on the total surface area of a fruit (Ben-Yehoshua, 1987). Smaller fruit have a larger surface to volume ratio compared to larger fruit. Larger fruit thus lose less moisture on a per unit weight basis. The second factor is the driving force behind moisture loss. Moisture loss from fresh commodities is primarily controlled by the difference in the water vapour pressure between the intercellular air spaces inside the fruit and of the air in the environment surrounding the fruit (Thompson, 1992). The partial pressure of water vapour of the air inside the intercellular air spaces of the fruit is assumed to be very close to saturation, with a RH of more than 99% (Ben-Yehoshua, 1987). The amount of water vapour of air under typical storage conditions is mostly lower than saturation, depending on temperature and the moisture content of the air (Wills et al., 1989), thus generating a difference in vapour pressure between the fruit and its environment, driving moisture loss from the fruit. The third factor is the water vapour permeability of the fruit peel. The fruit peel is the most important barrier to moisture loss and is a very

complex structure (Schönherr et al., 1979). The permeability of the fruit peel can be influenced by factors such as the composition and thickness of the cuticle or openings in the cuticle (Kamp, 1930; Riederer and Schneider, 1990). Driven by the water vapour deficit between the fruit and its environment, water vapour will exit the fruit at various openings in the fruit surface, which can be natural or caused by injury (Mitchell and Kader, 1989). Openings in the fruit peel which allow moisture loss include wounds inflicted by handling, transport or abrasion on the tree, stomata and/or lenticels used for transpiration, and cracks in the peel and cuticle.

Knoche and Peschel (2007) found that micro cracks develop in the cuticular membrane of European plums allowing moisture loss. Micro cracking was caused by a mismatch between expansion growth of the fruit and deposition of the cuticle, causing strain and subsequently micro-cracking of the cuticular membrane. These micro-cracks were openings in the peel that breached the protective barrier properties of the cuticle and allowed moisture loss and pathogen entry. The micro-cracks found by Knoche and Peschel (2007) were not visible to the naked eye. 'African Delight™' (cv. ARC PR00-29) (CULDEVCO, 2008) plums (which are highly susceptible to postharvest shrivel manifestation) are known for the concentric rings at the pedicel end of the fruit. These concentric rings are classified as being a cosmetic characteristic of the cultivar. Currently no literature is available on the development of these concentric rings and why this cultivar is more prone to shrivel. Hence, we hypothesized that the concentric rings, which develop as the fruit reach harvest maturity, might be open cracks in the fruit peel, allowing moisture loss. One of the aims of this study was, therefore, to investigate the concentric rings of 'African Delight™' plums by means of fluorescence microscopy to determine if they were indeed open fruit cracks on the fruit peel and if they influence moisture loss from the cultivar. Other cultivars, namely Sapphire (shrivel susceptible), Laetitia (shrivel susceptible) and Songold (not susceptible to shrivel) were also investigated by means of fluorescence microscopy to determine if (1) openings or cracks in the fruit peel influenced moisture loss from the shrivel susceptible cultivars, and (2) how the fruit peel differ between shrivel susceptible and non-susceptible cultivars.

## 2. Materials and methods

### 2.1. Plant material

The occurrence of hairline cracks and the contribution thereof towards moisture loss were monitored on four different cultivars of Japanese plums, namely 'Sapphire' (susceptible to shrivel), 'Songold' (not susceptible to shrivel), 'Laetitia' (susceptible to shrivel) and 'African Delight™' (susceptible to shrivel). For each cultivar 100 random fruit of uniform size and maturity and visually unblemished were sampled at their optimum harvest maturity. Fruit of each cultivar were sampled from a commercial orchard in the Franschhoek and Stellenbosch areas, South Africa. The farms were Bourgogne (33°55′33.26″S 19°07′03.02″E), Morgenzon (33°55′24.72″S 18°55′40.45″E) and Welgevallen experimental farm (33°56′50.68″S 18°52′14.98″E). 'African Delight™' was sampled in the 2013/14 season, while 'Sapphire', 'Songold' and 'Laetitia', were sampled in the 2014/15 season. Fruit were handled with care with minimal contact to the fruit surface and were transported to the laboratory within 1 h of harvest. At the laboratory the fruit was allowed to reach a pulp temperature of 21 °C (approx. 3 h) before the water vapour permeance ($P'_{H2O}$; mol $s^{-1}$ $m^{-2}$ $Pa^{-1}$) was determined for each fruit over a 16 h period. $P'_{H2O}$ was calculated in a constant environment (21 °C, 60% relative humidity and an air velocity of ~ 0.5 m $s^{-1}$) using the steady state solution of Fick's first law of diffusion (Taiz and Zeiger, 2010):

$$P'_{H20} = r'_{H20} / \Delta p_{H2O} A \qquad \text{(Eq. 1)}$$

$r'_{H2O}$ (the rate of water loss; mol $s^{-1}$) was calculated by weighing each fruit before and after the 16 h treatment without adjusting rates of mass loss for the contribution of respiration. $\Delta p_{H2O}$ (the difference in partial pressure of water vapour between the environment and inside the fruit; Pa) was calculated by means of psychrometric relationships (Kays and Paull, 2004) from average relative humidity and temperature data. The mean pulp and air temperature and relative humidity over the 16 h period were logged by using Thermocron® (inserted in the fruit) and Hygrochron™ (placed in the air surrounding the fruit) iButtons (CST electronics, Sandton). The surface area of the fruit; $m^2$ was calculated assuming the fruit shape to be that of a sphere.

After the permeability of each fruit was determined as described above, the fruit were sorted from the lowest to highest water vapour permeability. For all cultivars the four fruit with the highest permeability, intermediate permeability and the lowest permeability, respectively, were selected to be examined by means of fluorescent microscopy.

## 2.2. Fruit peel preparation and isolation

The 12 selected fruit per cultivar were incubated for 2 min at ambient temperature (~ 21 °C) in a 50 mM citric acid buffer (pH 6.5) containing 0.1% (w/v) acridine orange (fluorescent tracer; Sigma Aldrich, USA) and 0.025% (v/v) Silwet L-T (a silicone surfactant; Witco, Düsseldorf, Germany). Acridine orange interacts with DNA and RNA and lights up when viewed under fluorescent light, exposing openings in the fruit peel (Darzynkiewicz, 1990). Fruit were left to dry and thereafter five random peel segments (PS) (2 x 2 mm) were excised with a razor blade from inside the pedicel area from each fruit (60 PS per cultivar). PS contained the cuticular membrane, epidermis, hypodermis and some cell layers from the mesocarp tissue.

## 2.3. Monitoring of hairline cracks

PS were mounted on a slide along with a drop of distilled water and covered with a cover glass. The mounted PS were transferred to the stage of a fluorescence microscope (Axioskop, Zeiss, Germany) and viewed at 200 x magnification. Each segment was investigated for hairline cracks and photographed (688 x 513 $\mu m^2$). The average crack width of each photo was determined using image measurement software (KLONK Image measurement). Crack length could not be determined in this study, because the entire crack (when visible) could not be excised from the fruit peel and measured by microscope, because they were too long. In severe cases it was found that the hairline cracks formed concentric rings on the peel surface which was visible with the naked eye (Fig. 1).

## 2.4. Statistical analysis

A one-way analysis of variance was conducted on the mean crack width of the different water vapour permeance groupings per cultivar using SAS enterprise guide

version 5.1 (SAS Institute Inc., 2012). ANOVA-generated P-values and the significant differences between means were determined using Fisher's least significant differences (LSD) test with a 95% confidence interval.

## 3. Results

It was found that the concentric rings at the pedicle ends of 'African Delight™' plums' were hairline cracks, which can be defined as very fine cracks in the fruit peel just visible to the naked eye. Hairline cracks were found in the peel of 'African Delight™' plums on their optimum harvest date. These cracks were open, with no callus formation and exposed the endodermis and possibly the hypodermis of the fruit as well. The mean crack width differed significantly between the three permeance groupings selected (Table 1). Hairline cracks were found to be the widest on fruit with the highest water vapour permeance (Table 1 and Fig. 2), while fruit with a low water vapour permeance had the narrowest mean crack width (Table 1 and Fig. 3).

No hairline cracks were found in the peel of 'Laetitia', 'Sapphire' and 'Songold' plums. It was found that the lenticels, found mostly on the cheeks of 'African Delight™', 'Laetitia' and 'Sapphire' plums, were open (Fig. 4) and it is suggested that it could contribute to moisture loss. In this study the number of open lenticels could not be counted and could therefore, not be correlated with the water vapour permeance groupings. It is, therefore, suggested that this could be a topic for future research. No hairline cracks or open lenticels were found in the peel of 'Songold' plums.

'Sapphire' plums had the highest water vapour permeability, followed by 'African Delight™' (Table 2). The water vapour permeability of both these cultivars also varied much from the mean peel permeability determined. 'Songold' had approx. the same permeability as 'African Delight™', but with much less variation compared to 'African Delight™'. 'Laetitia' had the lowest water vapour permeability and the least variation from the mean of the four cultivars tested.

## 4. Discussion

The main aim of this study was to determine if hairline cracks contribute towards moisture loss from Japanese plums. It was found that the concentric rings at the

pedicel end of ‘African Delight™’ plums were indeed open hairline cracks. It was also found that ‘African Delight™’ fruit with wide hairline cracks had a higher water vapour permeance than fruit with narrow or no hairline cracks. This finding indicates that the water vapour permeance of the fruit peel of ‘African Delight™’ plums is linked to the width of the hairline cracks in the peel. It is, therefore, suggested that the high susceptibility of ‘African Delight™’ plums to postharvest shrivel manifestation is closely linked to the occurrence of the concentric hairline cracks at the pedicel end of the fruit. Similar to this study, Peschel and Knoche (2005) also found a positive correlation between the number of micro cracks in the cuticular membrane and the permeability of the excised peel segments of European plums (*Prunus domestica* Lindl.).

The exact reason why ‘African Delight™’ develops hairline cracks is not clear. It is suggested that cuticular cracks develop from an imbalance between wax production, growth of the fruit pulp and the cuticle (Roy et al., 1994; Keren-Keiserman et al., 2004). Rapid fruit growth of fleshy fruit can also cause cuticular cracks to occur (Christensen, 1973; Ohta et al., 1997; Peschel and Knoche, 2005). It is interesting to note that the development of hairline cracks started at the stem-end of the fruit and, in severe cases, spread over the shoulder towards the cheek of the plum (Fig. 1). The reason for this may be that the curvature over the shoulder area is the largest for the whole fruit and the stress, theoretically, should be the largest in that area (Considine and Brown, 1981). The development of hairline cracks in ‘African Delight™’ may also be linked to environmental conditions such as temperature or relative humidity (Martin and Rose, 2014).

It is known in the South African plum industry that ‘African Delight™’ is highly susceptible to shrivel. It is also known that ‘Laetitia’ and ‘Sapphire’ are susceptible to shrivel, but to a lesser extent than ‘African Delight™’, and that ‘Songold’ is not susceptible to shrivel. It was found that ‘Sapphire’ had the highest permeability of the cultivars investigated in this study. This finding was not expected as ‘African Delight™’ had hairline cracks in the peel, allowing the water vapour permeance of the peel to increase as the width of the cracks increase. Furthermore, it was found that ‘African Delight™’ also had open lenticels, which should, in conjunction with the hairline cracks, result in this cultivar having the highest water vapour permeability of all the cultivars. It may be possible that ‘Sapphire’ plums has more open lenticels than

‘African Delight™’ plums, but in this study the number of open lenticels present in the peel of each cultivar could not be quantified. Another possibility is that the permeability of the fruit from the specific orchard used were very high (‘Sapphire’) or very low (African Delight™’). Orchards may have a significant effect on fruit peel permeability as was found in Paper 2 and by Maguire et al. (2000) in apple orchards. To test the effect of orchard on peel permeability more orchards, the role of crop load and the age of the trees need to be studied. It was not expected that ‘Laetitia’ would have the lowest water vapour permeability compared to the other cultivars, since the cultivar is highly susceptible to postharvest shrivel and since open lenticels are present in its peel. This is an indication that peel permeability is affected by more than just openings in the fruit peel. It is possible that the thickness of the cuticle (Kamp, 1930) or the amount and type of cuticular waxes (Riederer and Schneider, 1990) may influence the permeability as well. It is, therefore, recommended that fruit must be sampled from more than one orchard in future studies. It would be beneficial if the amount, type and composition of the cuticular waxes could also be determined in future studies.

The three shrivel susceptible cultivars investigated in this study, namely ‘African Delight™’, ‘Laetitia’ and ‘Sapphire’, had open lenticels in their peel. Brown and Considine (1982) found that lenticels and other rigid bodies in the fruit peel could lead to rupturing of the cuticular membrane, allowing moisture loss and pathogen entry. Hairline cracks and open lenticels serve as pathways for moisture loss from the fruit by allowing water to bypass the relative impermeable barrier of the cuticle and escaping into the atmosphere (Mitchell and Kader, 1989). This route of moisture loss is more rapid than the diffusion route through cell membranes and an intact cuticular membrane (Maguire et al., 1999). It is also possible for permeability to increase during storage, because of these water vapour escape routes, even if the peel permeability is low at harvest, as was the case with ‘Laetitia’. It is recommended that future research investigate how the water vapour permeability changes during cold-storage. In this study no open lenticels or any form of skin cracks were found in the peel of ‘Songold’ plums. The lack of open lenticels or cracks in this cultivar’s peel is probably the reason why it is not susceptible to the manifestation of postharvest shrivel.

## 5. Conclusion

This study provides four important and new observations to the South African stone fruit industry regarding the cultivars that were evaluated. The first finding is that the concentric rings found in the peel at the pedicel area of 'African Delight™' plums are open hairline cracks. The second finding is that the hairline cracks, which are of differing widths in fruit from the same orchard and of the same maturity, contribute towards moisture loss from 'African Delight™' plums. This is an important finding, since 'African Delight™' plums are highly susceptible to shrivel. The third important finding was that the lenticels in the peel of 'African Delight™', 'Laetitia' and 'Sapphire' are open and could possibly be contributing towards postharvest moisture loss. The fourth important finding was that 'Songold', a cultivar not susceptible to shrivel, did not show any signs of hairline cracking, nor lenticels that were open. The fact that the cuticle of this cultivar is mostly intact with very few or no openings contributing to moisture loss probably explains why this cultivar is not susceptible to shrivel.

Excessive moisture loss in plums can lead to postharvest shrivelling of the fruit which is not accepted by international markets and consumers, causing financial losses. Therefore, it is suggested that fruit should be harvested during the cooler time of day, kept in the shade after harvesting, and full picking bins are covered with wet blankets prior to packing. Packaging such as perforated bags or perforated shrivel sheets, depending on the cultivar, and recommended cold-storage temperature, in order to decrease the water vapour deficit between the fruit and the surrounding atmosphere can also be used to lower moisture loss. Fruit with excessive hairline cracks at the stem (pedicel) -end should not be packed and field heat removal and/or forced air cooling should commence as soon as possible after harvest. Furthermore it is suggested that the South African plum breeding program should eliminate cultivars with open hairline concentric rings at the pedicel. It is also suggested that further studies must be conducted to determine the effect of open lenticels as well as the number of open lenticels in the peel of the fruit to moisture loss.

## 6. Acknowledgements

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## 8. Tables

**Table 1.**

The effect of crack width in the fruit peel on the water vapour permeance of the fruit peel of ‘African Delight™’ plums from the Stellenbosch region on the optimum harvest date of the cultivar (11 February 2014).

| Grouping according to water vapour permeance | Mean crack width (µm) |
|---|---|
| High | 100.94 a |
| Medium | 33.43 b |
| Low | 6.60 c |
| P-value | <0.0001 |
| LSD (P≤0.05) | 23.70 |

**Table 2.**

The average water vapour permeability of the fruit peel of ‘African Delight™’, ‘Laetitia’, ‘Songold’ and ‘Sapphire’ plums on their respective optimum harvest dates.

| Cultivar | Water vapour permeance (mol $s^{-1}$ $m^{-2}$ $Pa^{-1}$) | |
|---|---|---|
| | Average | Standard deviation |
| ‘African Delight™’ | 66.40 | 23.43 |
| ‘Laetitia’ | 43.82 | 8.91 |
| ‘Songold’ | 60.44 | 16.80 |
| ‘Sapphire’ | 97.71 | 34.01 |

## 9. Figures

**Fig. 1**. An ‘African Delight™’ plum with concentric hairline cracks extending over the shoulders of the fruit.

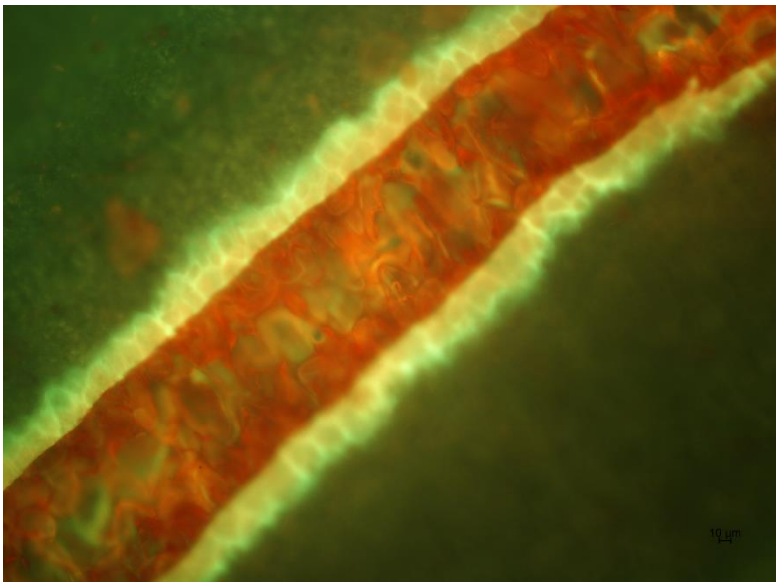

**Fig. 2.** Fluorescence microscope image taken at 200 x magnification of a hairline crack in the pedicel area of an ‘African Delight™’ plum, from the ‘high’ water vapour permeance grouping.

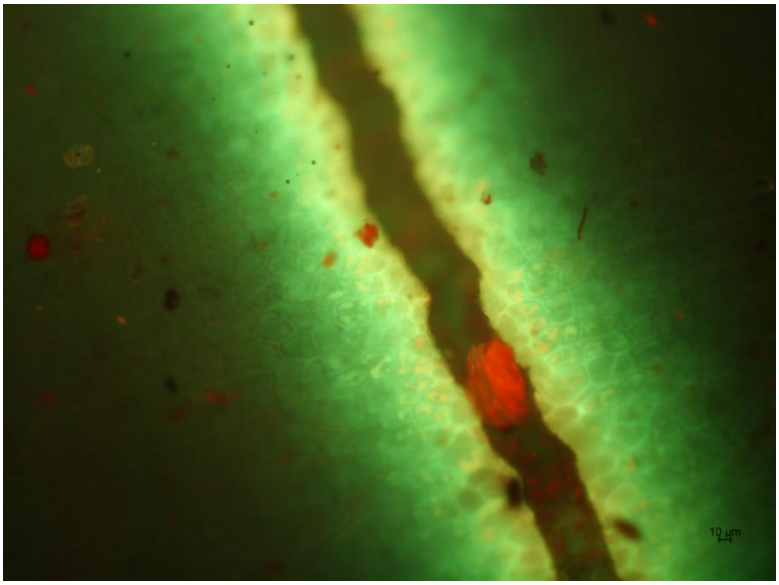

**Fig. 3.** Fluorescence microscope image taken at 200 x magnification of a hairline crack in the pedicel area of an 'African Delight™' plum, from the 'low' water vapour permeance grouping.

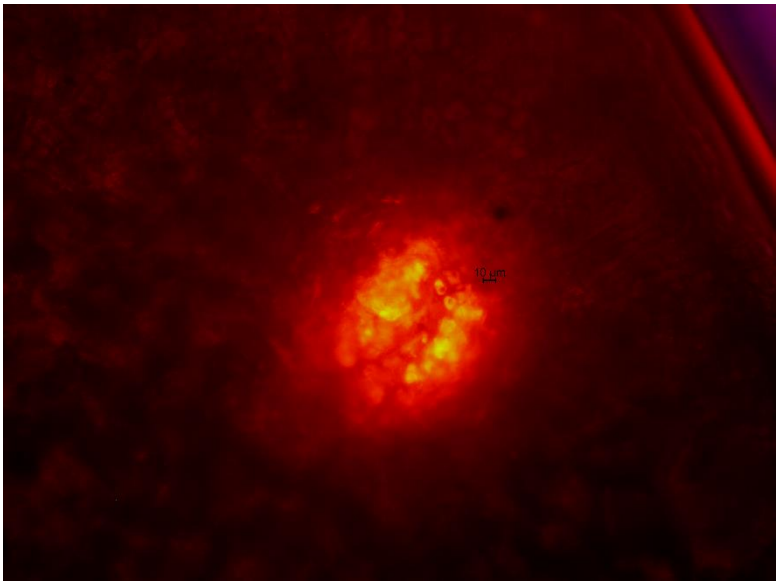

**Fig. 4.** Fluorescence microscope image taken at 200 x magnification of an open lenticel in the pedicel area of a 'Sapphire' plum.

# PAPER 2:

# The effect of fruit to fruit variation, harvest date, tree and orchard effects as well as cultivar differences on water vapour permeance of Japanese plums (*Prunus salicina* Lindl.)


## Abstract

Japanese plums from South Africa are mostly exported (74%). Exporting late season plums require fruit to last up to 8 weeks in cold storage. Prolonged storage periods can cause some cultivars to develop a shrivelled appearance due to moisture loss. The water vapour permeance of the fruit peel is one of the factors influencing the rate of moisture loss in horticultural products. Other studies found that the water vapour permeance of apples differed between cultivars, farms, orchards, trees in the same orchard, fruit on the same tree and harvest date. In this study the water vapour permeance of 'African Delight™' (shrivel susceptible), 'Laetitia' (shrivel susceptible) and 'Songold' (not susceptible to shrivel) plums was determined weekly from 4 weeks before the optimum harvest maturity of each cultivar until the fruit reached post-optimum maturity. It was found that fruit to fruit variance made the largest contribution (> 45%) to the total variation of the water vapour permeance of each cultivar. Orchard (> 15%) and harvest date (> 20%) also made large contributions to the total variance in water vapour permeance of the three cultivars. It was found that the permeance of all the cultivars reached a minimum at approx. 2 weeks before their respective optimum harvest dates after which it increased two-fold until the fruit were overripe. The contribution made by cultivar differences to fruit peel permeability varied greatly between seasons (42% in 2013/2014 and 5% in 2014/2015). Differences in fruit peel permeability between cultivars may be caused by dissimilarities in cuticle thickness and composition, micro cracks in the peel and open lenticels. To prevent postharvest moisture loss and shrivel manifestation, producers should not compromise when following postharvest handling protocols since it is now known that the permeability of plum fruit increases when the fruit reaches their optimum harvest maturity.


Keywords: Japanese plums, Shrivel, Water vapour permeability, Moisture loss

## 1. Introduction

The South African plum industry ships 74% of its produce to overseas markets (HORTGRO, 2014). The long sea freight period (approx. 17 d) and stock rolling overseas may add up to 8 weeks of cold storage for some late season cultivars. Some cultivars develop a shrivelled appearance due to moisture loss during this long handling chain. This is a real challenge for exporters and producers, since consumers expect fruit to look fresh upon arrival at markets and supermarkets. Moisture loss from perishable commodities manifests mainly as shrivelling due to a loss in the turgidity of the surface cells of the fruit, or weight loss (Sastry, 1985a; Banks et al., 2000). Ultimately, moisture loss leads to a decrease in the quality of the fruit, rendering the product completely worthless resulting in economic losses to the industry (Sastry, 1985b). It was found that as little as a 5% loss in fresh weight can cause shrivelling in fresh produce (Ben-Yehoshua, 1987; Mitchell and Kader, 1989; Wills et al., 1989; Maguire et al., 2000). Weight loss is the result of two physiological processes in the fruit, namely moisture loss and respiration (Maguire et al., 2000).

Fruit lose water in the form of water vapour which diffuses from the inside of the fruit through the cuticle into the surrounding environment (Maguire, 1998; Lara et al., 2014). Water vapour moves along a gradient; from a high to a lower concentration, to establish equilibrium between the fruit and its environment. Hence, in fruit, water vapour moves from the intercellular airspaces and cell walls, where the water vapour pressure is usually close to saturation, into the surrounding atmosphere, where the concentration of water vapour is usually lower (Ben-Yehoshua, 1987). Moisture loss from horticultural products is governed by Fick's first law of gas diffusion (Ben-Yehoshua, 1987; Nobel, 1999). Consequently, the rate of water loss from a product can be calculated as follows:

$$r_{H2O} = \Delta p_{H2O} \; A \; P'_{H2O} \qquad \text{(Eq. 1)}$$

Where:

$r_{H2O}$ = rate of water loss from the product (mol $s^{-1}$)

$\Delta p_{H2O}$ = difference in partial pressure of water vapour between the environment and inside the fruit (Pa)

A = surface area of the fruit ($m^2$)

$P'_{H2O}$ = effective permeance of the fruit surface to movement of water vapour (mol $s^{-1}$ $m^{-2}$ $Pa^{-1}$)

Water vapour permeance ($P'_{H2O}$) indicates the ease with which water vapour can escape from the fruit and can be affected by openings in the fruit peel such as wounds, the presence of lenticels (allowing transpiration), and differences in the composition of the cuticles between different cultivars (Maguire et al., 2000). Furthermore, Maguire et al. (2000) found that factors such as differences between farms, orchards on the same farm, trees in the same orchard, fruit on the same tree as well as harvest date can play an important role in the fruit peel permeability. The water vapour permeance of plum fruit produced in South Africa is currently unknown. Hence, in this study the water vapour permeance of 'African Delight™' (shrivel susceptible), 'Laetitia' (shrivel susceptible) and 'Songold' (not susceptible to shrivel) plums was determined to establish if cultivar differences, variation between farms, orchards on the same farm, trees in the same orchard, between fruit on the same tree and/or harvest date contribute to fruit peel permeability. Our objective was to determine the main preharvest factor/factors responsible for moisture loss in order to develop or refine postharvest handling protocols to ensure that moisture loss, and hence postharvest shrivel manifestation, can be reduced to the minimum in Japanese plums.

## 2. Materials and methods

Two separate trials were conducted. For Trial 1, orchards of the same cultivar were compared to establish the main preharvest factor/ factors affecting the peel permeability of the specific cultivar. For Trial 2, different cultivars were compared to

establish how the peel permeabilities of the different cultivars differed, and if there was a relationship between shrivel propensity of a cultivar and its peel permeability compared to other cultivars.

## 2.1. Trial sites

During the 2013/14 season five farms in Franschhoek region, South Africa, were selected. The farms were La Dauphine (33°56′06.43″S 19°06′28.84″E), Bourgogne (33°55′33.26″S 19°07′03.02″E), Cabriere (33°54′58.42″S 19°07′08.17″E), Terra de Luc 3 (33°53′40.92″S 19°06′53.66″E) and Terra de Luc 1 (33°53′54.51″S 19°07′08.17″E).

During the 2014/15 season La Dauphine and Terra de Luc 1 were excluded (due to fruit quality constraints experienced in the previous season) from the original five selected farms and two new farms in the Franschhoek region, namely Keerweder (33°55′40.41″S 19°07′50.37″E) and Môrelig (33°50′59.09″S 19°02′15.15″E), were selected in their place.

## 2.2. Experimental layout and sampling

A randomised complete block design with five trees per orchard per cultivar was used for both Trial 1 and Trial 2. In the 2013/14 season Trial 1 was conducted only on ‘African Delight™’ plums, and the fruit were sampled from one orchard on each of the five farms. During the same season Trial 2 was conducted on three cultivars, namely ‘African Delight™’. ‘Laetitia’ and ‘Sunbreeze™’ (cv. ARC Sun 2, a mutation of ‘Songold’), and the fruit was sampled from only one farm, namely Terra de Luc 1. For the 2014/15 season Trial 1 was expanded to include three plum cultivars, namely ‘African Delight™’, ‘Laetitia’ and ‘Songold’. The fruit were sampled from one orchard from each of the five farms. Trial 2 was also expanded, and ‘Laetitia’, ‘Songold’ and ‘African Delight™’ plums were sampled from one orchard each from each of the five farms compared to one farm used in the previous season.

For both trials, and in both seasons, fruit sampling was done on a weekly basis from approx. 4 weeks before the anticipated optimum harvest date until the fruit reached optimum maturity. On each sampling date five visually unblemished fruit of

the same size and ground colour were picked from each of the five trees per orchard per cultivar. Fruit from each tree were carefully harvested into plastic bags and transported to the laboratory at the Department of Horticultural Science, Stellenbosch University. Care was taken to handle the fruit as little as possible to not injure or disturb the bloom or fruit peel. The fruit reached the laboratory within approx. 3 h after it was harvested. On arrival at the laboratory each fruit was numbered according to the tree and orchard it was picked from and its diameter was recorded with a digital calliper (Mitutyo, Japan) to calculate the surface area of the fruit, assuming the fruit shape to be that of a sphere. Subsequently, each fruit was weighed using a balance accurate to 0.001 g (XB 320M, Precisa Instruments Ltd., Switzerland), placed in pulp fruit trays and were allowed to reach a pulp temperature of 20 °C (approx. 5 h) in a temperature conditioned room. The fruit was then placed in a plastic container and subjected to an airflow of ≈ 0.5 m $s^{-1}$ at 20 °C and an average relative humidity (RH) of 60% for a 16 h period (Fig. 1). Air RH and temperature was recorded using a Hygrochron™ iButton (CST electronics, Sandton), and pulp temperature was recorded using a Thermocron® iButton. The Hygrochron™ iButton was placed underneath the lid of the container to record the RH and air temperature while the Thermocron® iButton was inserted into a fruit, which was not part of the trial, to record pulp temperature at 5 min intervals during the 16 h period. Afterwards the individual fruit were weighed again and the difference in weight was used to calculate the rate of moisture loss, assuming that respiration did not have a significant effect on mass loss due to the relatively short duration over which the test was performed.

2.3. Determination of the water vapour permeance of the fruit peel ($P'_{H20}$) of each fruit

$P'_{H20}$ was calculated for each fruit according to Fick's first law of gas diffusion (Eq. 1). Eq. 1 was rearranged to designate $P'_{H20}$ the subject of the equation:

$P'_{H2O} = r'_{H2O} / (\Delta p_{H20} \times A)$ (Eq. 2)

Where:

$r'_{H20}$ = rate of moisture loss (mol $s^{-1}$)

$\Delta p_{H20}$ = difference in the water vapour pressure inside and outside the fruit (Pa)

A = area of the fruit surface ($m^2$)

2.4. Statistical analyses

Contributions of different sources of variation was analysed using components of variance analysis using Dell Inc. (2015). STATISTICA (data analysis software system), version 12.

## 3. Results

Values for $P'_{H20}$ from all cultivar samples were highly variable. Fruit to fruit variation explained most (> 45%) of the total variance in peel permeability of 'African Delight™' (Fig. 2A and B), 'Laetitia' (Fig. 3) and 'Songold' (Fig. 4) plums. Orchard effects explained > 15% of the total variance in the peel permeability of 'African Delight™' (Fig 2A and B), 'Laetitia' (Fig. 3) and 'Songold' (Fig. 4). The effect of harvest date varied substantially between the two seasons in this study for 'African Delight™' – it explained a mere 2% of the total variation in the peel permeability in the 2013/2014 season (Fig. 2A), but 30% of the variation in the 2014/2015 season (Fig. 2B). For the 2014/2015 season, harvest date explained 39% and 21% of the total variation for 'Laetitia' and 'Songold,' respectively, (Fig. 3 and 4). The effect of differences between trees in the same orchard was only significant for 'African Delight™' during the 2013/2014 season, where it made a contribution of 8% to the total variation (Fig. 2A). In the 2014/2015 season variation between trees in the same orchard made no contribution to the total variation in peel permeability.

During the 2013/2014 season fruit sampling started much earlier, with some orchards being sampled 7 weeks before their optimum harvest dates. From Fig. 5A it is clear that there was a decrease in the water vapour permeability of 'African

Delight™' plums between approx. 4 to 2 weeks prior to the optimum harvest date (except for Farm 5). Subsequently the peel permeability started to increase and followed the increasing trend until after the optimum harvest date. The 2013/2014 finding was confirmed in 2014/2015 where it was again found that the water vapour permeability of 'African Delight™' plums started to increase 1 to 2 weeks prior to the optimum harvest date (Fig. 5B). On average the peel permeability of 'African Delight™' plums displayed a two-fold increase from 3 weeks before harvest (≈ 50 $mol.s^{-1}m^{-2}.Pa^{-1}$) until 2 weeks after the optimum harvest date (≈ 100 $mol.s^{-1}.m^{-2}.Pa^{-1}$).

Compared to 'African Delight™', 'Laetitia' had a relatively stable peel permeability for the 3 weeks prior to its optimum harvest date (Fig. 6A and B). However, the peel permeability of 'Laetitia' increased after its optimum harvest date. The extent of the increase seems to be dependent on the season and the farm, as the effect was much more pronounced in the 2014/2015 season (Fig. 6B) compared to the 2013/2014 season (Fig. 6A).

Similar to 'African Delight™', 'Songold' plums generally had decreasing peel permeability until approx. 2 weeks prior to the optimum harvest date where after it generally increased until post-optimum maturity (Fig. 7A and B). This effect, however, was dependent on the season and/or farm, as it was much more pronounced in the 2014/2015 season compared to the 2013/2014 season. 'Laetitia' and 'Songold' also generally showed a two-fold increase in peel water vapour permeability between pre-optimum to post-optimum maturity (Fig. 6A and B and Fig. 7A and B).

When cultivars were compared with each other it was found that fruit to fruit variation again explained > 50% of the total variation in fruit peel permeability (Fig. 8). The effect of cultivar differences varied between the two seasons – it explained 42% of the total variation in the fruit peel permeability in the 2013/2014 season, but only 5% in the 2014/2015 season. Similar to cultivar differences, the effect of the harvest date on the total variation in the fruit peel permeability also varied greatly between the seasons. It explained only 2% of the total variation in the 2013/2014 season, but 24% in the 2014/2015 season. Tree effects made a small contribution to the total variation in the peel permeability - 1% in the 2013/2014 season, and 10% in the 2014/2015 season. Since more farms were used in the 2014/2015 season, differences between

farms had to be brought into the analysis, and it was found that it explained 10% of the total variation of the peel permeability.

The three cultivars followed more or less the same pattern in peel permeability during the sampling period in both seasons. In the 2013/2014 season, when the three cultivars were sampled from the same farm, the peel permeability was relatively low at the optimum harvest date, but increased at later harvests (Fig. 9A). The peel permeability of 'African Delight™' started to increase just after the optimum harvest date, while that of 'Laetitia' and 'Songold' only started to increase 2 weeks after the optimum harvest date in the 2013/2014 season. In the 2014/2015 season, when the cultivars were sampled from five farms, it was clear that the peel permeability of all the cultivars started to increase from approx. 2 weeks prior to the optimum harvest date and this increasing trend was followed until after the harvest date for all three cultivars (Fig. 9B). 'African Delight™' had the highest water vapour permeability of the three cultivars, whilst 'Laetitia' and 'Songold' followed more of less the same pattern and levels of water vapour permeability.

## 4. Discussion

There was an increase in water vapour permeance of 'African Delight™', 'Laetitia' and 'Songold' plums with later sampling dates in both seasons. Pieniazek (1943) and Maguire et al. (2000) also found that the water vapour permeability of apples increased as fruit matured past their optimum maturity and this could possibly be explained by changes in cuticular waxes and the thickness of the cuticle.

For all three cultivars it was found that the fruit to fruit variation was the largest contributor (> 45%) to the total variation in water vapour permeance of the cultivars included in this study. Since the variation between trees in the same orchard was small, the result indicates that the water vapour permeance of the cultivars included in this study was due to fruit characteristics, and that the influence of the physiology of the whole tree and genetic variation were minimal. Maguire et al. (2000) found that fruit to fruit variation contributed 22% to the permeance of apple fruit. It is unlikely that the large fruit to fruit variation in this study could have been caused by fruit not being

of the same maturity, because care was taken to sample fruit that were visually of the same size and peel colour. Factors such as position of the fruit on the tree, exposure to sunlight, split pit and shape of the fruit could possibly contribute to the fruit to fruit variation. Therefore, better sampling methods would not have been the answer to reduce this variation between fruit. Commercial harvesting is done by hand and fruit are picked according to visual appearance. Fruit maturity is also not determined on the packing line, but fruit is sorted by their visual appearance (colour) and size. This leads to large fruit to fruit variation in packed cartons, and could be a contributing factor why some fruit in the same carton develop shrivel and others not.

Harvest date also played a significant role in the total variation of the three cultivars. It was found that the water vapour permeance started to increase from about two weeks before the optimum harvest date until fruit were well past their optimum maturity. Pieniazek (1943) and Maguire et al. (2000) also found that apple fruit harvested later in the season had a higher permeability to water vapour which could be caused by changes in the cuticle thickness and composition over time.

Orchards differences explained 15% and more of the total variation of the cultivars included in this study. It was found that none of the orchards used stood out from the rest with regards to permeability, except for Farm 5 of ‘African Delight™ in the 2013/14 season. It was found that fruit from Farm 5 (Terra de Luc 1) started to mature much earlier than the other farms used in the study. It is possible that the development of the cuticular waxes were not at the same stage as fruit from other farms at the same maturity. The fruit quality of this specific orchard was also much lower due to insect damage compared to the other orchards used. In the 2014/15 season Farm 2 (Bourgogne) had the highest permeance for ‘African Delight™’ compared to the other farms. Fruit from this farm was very susceptible to the development of hairline cracks at the pedicel end of the fruit while fewer concentric rings were found on fruit from the other farms (personal observation). The higher incidence of hairline cracks in the fruit peel could have caused fruit form this farm to have higher water vapour permeabilities compared to the fruit sampled form the other farms. Generally the water vapour permeability did not differ much between farms for ‘Laetitia’ and ‘Songold’ in the 2014/2015 season. Therefore, no specific growing conditions could be identified to minimize the permeance of the fruit peel for these

cultivars. Crisosto et al. (1994) found that when fruit received excessive irrigation the fruit's cuticle was thinner and more susceptible to shrivel compared to fruit which received optimal or deficit irrigation. Hence, it is suggested that producers should make sure that they are using optimal irrigation regimes for their plum orchards. It also stands to reason that excessive rain prior to harvest may cause more shrivel.

For the second part of the study where the peel permeability of different cultivars were compared, fruit to fruit variation also made the biggest contribution to the total variation in the water vapour permeance of the fruit. In the 2013/2014 season it was found that cultivar also made a large contribution (> 40%) towards the total variation, but this was probably due to the relatively small sample size (only one orchard of each cultivar was selected on a single farm). The much bigger sample size used in the 2014/2015 season (5 orchards per cultivar) resulted in cultivar not having such a big contribution (5%) of the total variation in peel permeability. Maguire et al. (2000) found that cultivar differences explained 30% of the total variation in apple peel permeability, but this could only be proven in plums in one season (2013/14). Cultivar still had an influence on the total permeability variance in the 2014/15 season, just not as big as in the 2013/14 season. Variance in permeance caused by cultivar differences may be related to variance in physical and chemical properties of the outer layers of the fruit. These properties may include the presence of open lenticels (Pieniazek, 1944), cuticle thickness (Kamp, 1930), the presence of micro cracks (Peschel and Knoche, 2005), and the amount and type of cuticular waxes (Riederer and Schneider, 1990). The increase in permeance observed when fruit were allowed to pass their optimum maturity may be the result of changes in the above mentioned factors or a combination of changes in these factors. Since these parameters were not measured in this study it is not possible to make exact suggestions as to why the permeance increased with an increase in fruit maturity. It would be interesting if the causes for these increases could be explored by further studies. It was found that 'African Delight™' plums had slightly higher water vapour permeability than Laetitia' and 'Songold' (Fig. 9B). This could be explained by the concentric hairline cracks found at the pedicle end of 'African Delight™' plums. In Paper 1 it was found that concentric hairline cracks had an effect on the water vapour permeability of the fruit peel. It is not known when and how these cracks develop during fruit development. Open lenticels

were found in the peel of ‘African Delight™’ and ‘Laetitia’ (Paper 1), but the effect thereof on moisture loss could not be determined. Pieniazek, (1944) found that lenticels in apple peel contributed to the moisture loss of the fruit and that the removal of the cuticular waxes increased moisture loss. Unfortunately the composition and thickness of the cuticular waxes are not known for cultivars examined in this study, and it is suggested that it should be investigated in further studies.

Although the permeability of the fruit peel was lower in less mature fruit, and will cause less postharvest moisture loss and lead to lower levels of shrivel it cannot be recommended. Other fruit maturity factors such as susceptibility to internal disorders during cold storage and the development of an acceptable eating quality after cold storage are the main drivers when optimum maturity for plum cultivars are determined. However, it can be recommended to harvest fruit less mature but within the current harvest maturity window. Since it is known that the water vapour permeance of the cultivars increase with an increase in fruit maturity, it is important that fruit should be handled carefully after harvest to prevent moisture loss. It is recommended that fruit should be harvested during the cooler time of day, kept in the shade after harvest and plums in bins should be covered with wet blankets prior to packing. Packaging such as perforated bags or perforated shrivel sheets, depending on the cultivar, and recommended cold-storage temperature, in order to decrease the water vapour deficit between the fruit and the surrounding atmosphere can also be used to lower moisture loss. After harvest fruit should be cooled as soon as possible in order to reduce moisture loss and minimize the risk for shrivel manifestation.

## 5. Conclusion

This study indicated that the peel of ‘African Delight™’ plums was more permeable to water vapour than the peel of ‘Laetitia’ and ‘Songold plums. If was found that the water vapour permeance increased as fruit maturity increased. It is, therefore, recommended that fruit should be harvested during the cooler time of day, kept in the shade after harvesting and covered with wet blankets. Fruit should also be packed in perforated bags or perforated shrivel sheets, depending on the cultivar, and recommended cold-storage temperature, in order to decrease the water vapour deficit between the fruit and the surrounding atmosphere. After harvest fruit should be packed

and cooled as soon as possible in order to reduce moisture loss and minimize the risk for shrivel manifestation. ‘Laetitia’ and ‘Songold’ plums were found to have more or less the same permeabilities, but despite this, ‘Laetitia’ is still susceptible to shrivel and ‘Songold’ not. This might have to do with the fact that ‘Laetitia’ has open lenticels (Paper 1), whilst the peel of ‘Songold’ plums is free of openings or cracks. It may be possible that the permeance of ‘Laetitia’ increases during cold storage leading to moisture loss and shrivel. A future study investigating changes in water vapour permeability of these plums during cold storage should shed some light on this matter.

The method used in this study to determine fruit peel permeability can be recommended to plant breeders to detect high water vapour permeability in new cultivars. If high permeability can be detected at an early stage in the breeding program of a cultivar, it could be removed from the program. This could greatly aid the management of postharvest moisture loss from plum cultivars exported from South Africa.

## 6. Acknowledgements

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## 8. Figures

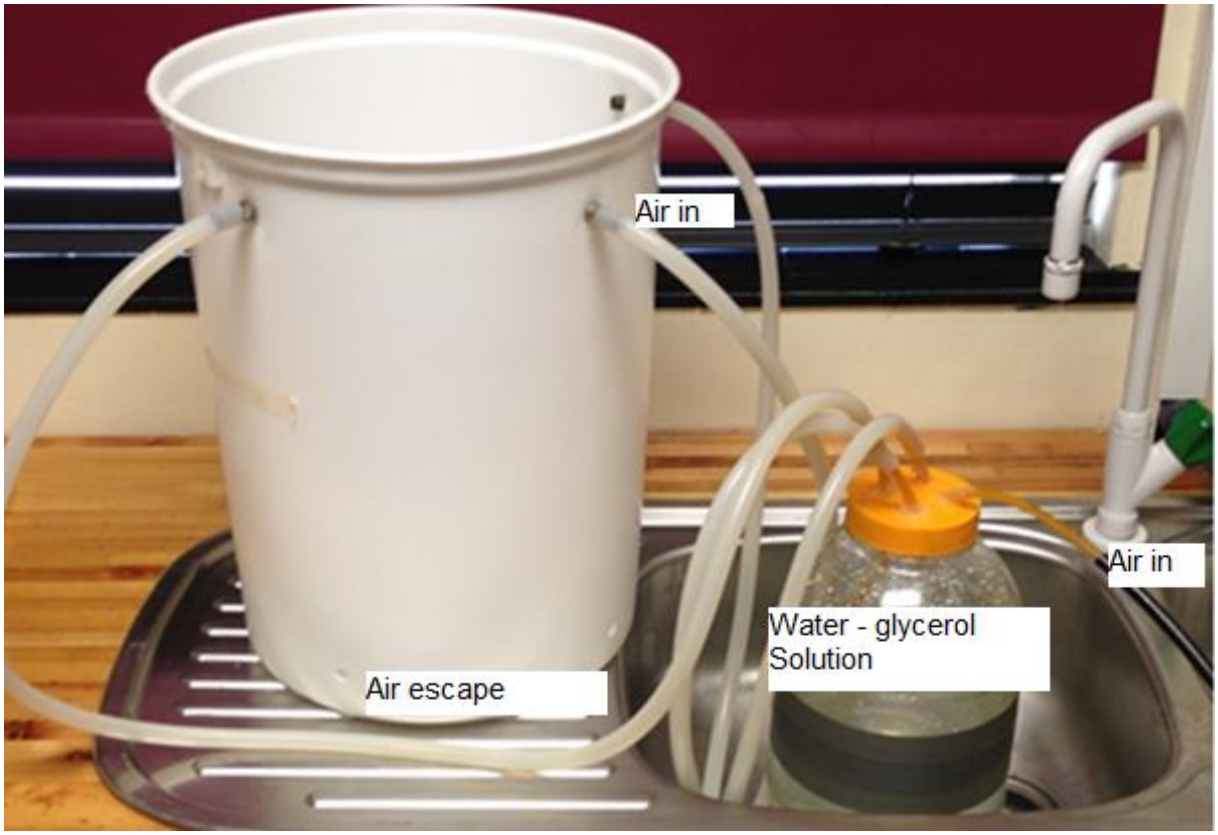


**Fig. 1.** Image illustrating the system used in the study to determine the $P_{H2O}$ of the fruit peels. Air from a compressor was bubbled through a glycerol and water solution to adjust the RH of the air to 60%. The air was subsequently forced at ~ 0.5 m $s^{-1}$ over the fruit in the container and escaped through the holes in the bottom of the container.

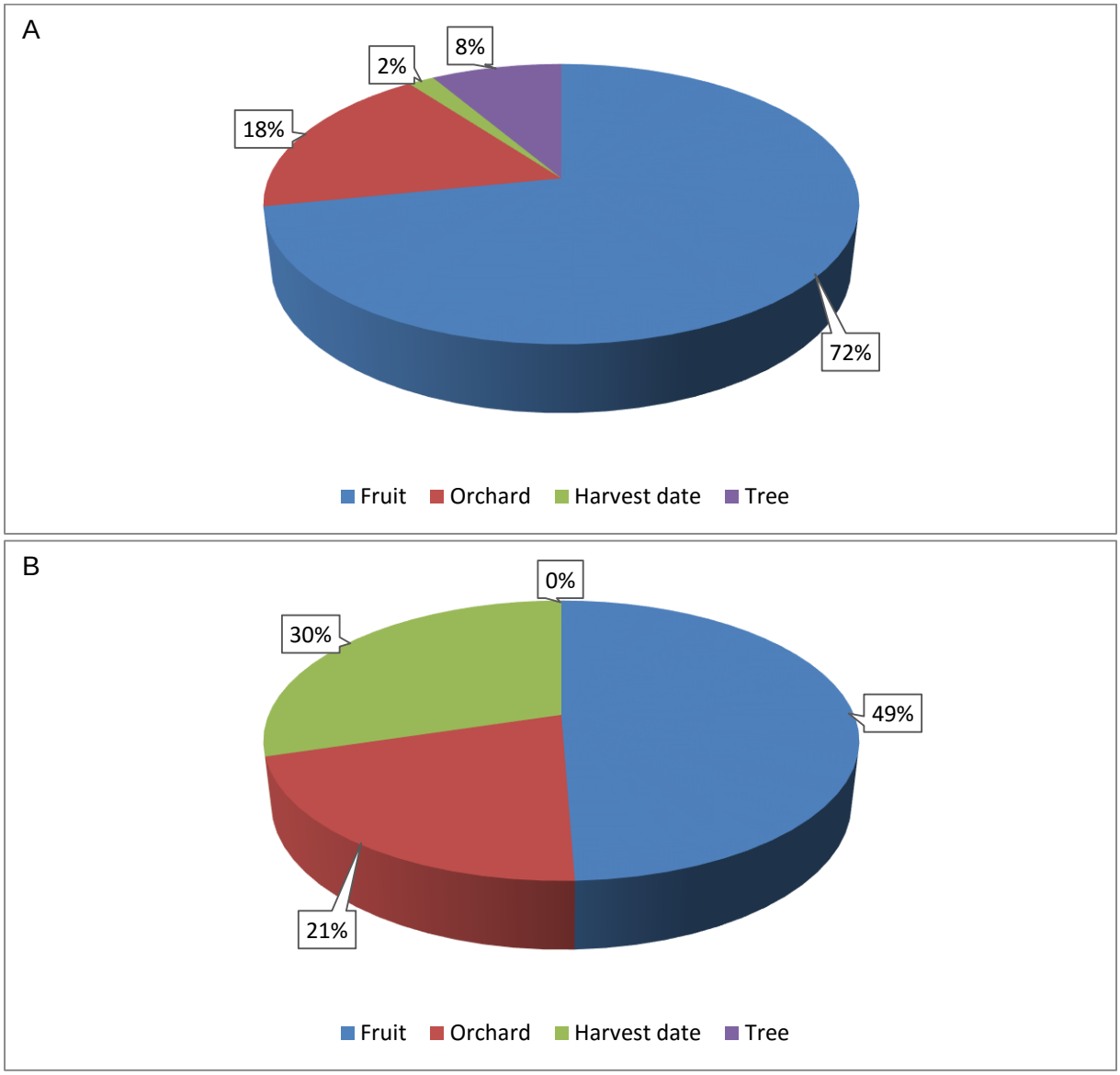


**Fig. 2.** Relative components of variance contributed by fruit to fruit variation, orchards differences, harvest date and tree to tree differences to the total variation of the water vapour permeance of 'African Delight™' plums. The fruit were sampled from five different orchards in the Franschhoek area from 4 weeks prior to the optimum harvest date until approximately 1 week after the optimum harvest date. Figure A represents data from the 2013/14 season and Figure B the data from the 2014/15 season.

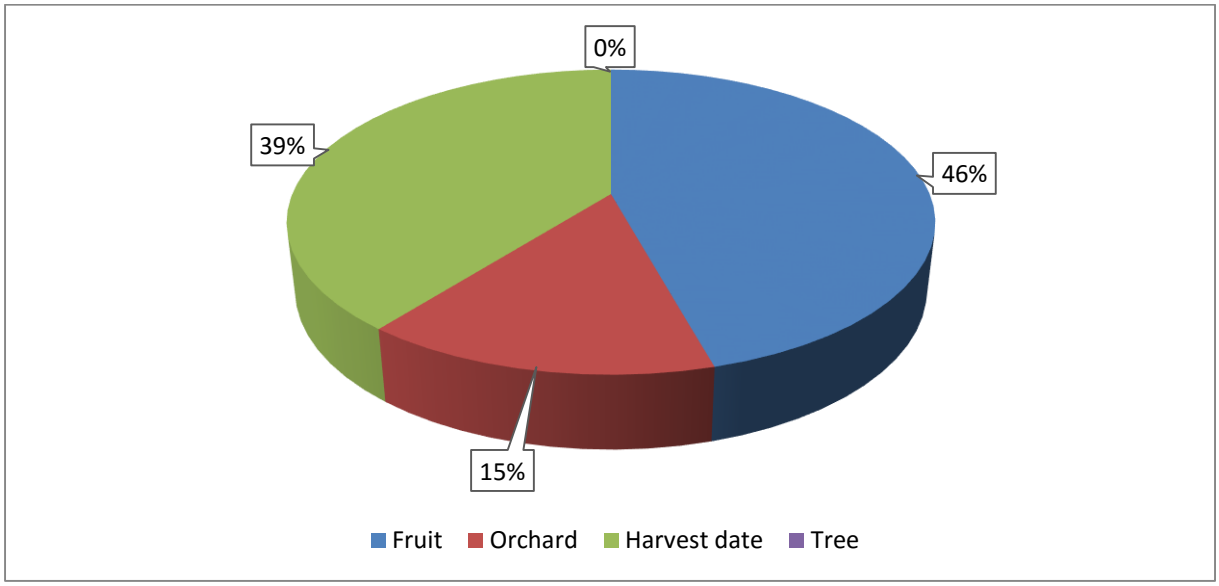


**Fig. 3.** Relative components of variance contributed by fruit to fruit variation, orchards differences, harvest dates and tree to tree differences to the total variation of the water vapour permeance of ‘Laetitia’ plums in the 2014/2015 season.

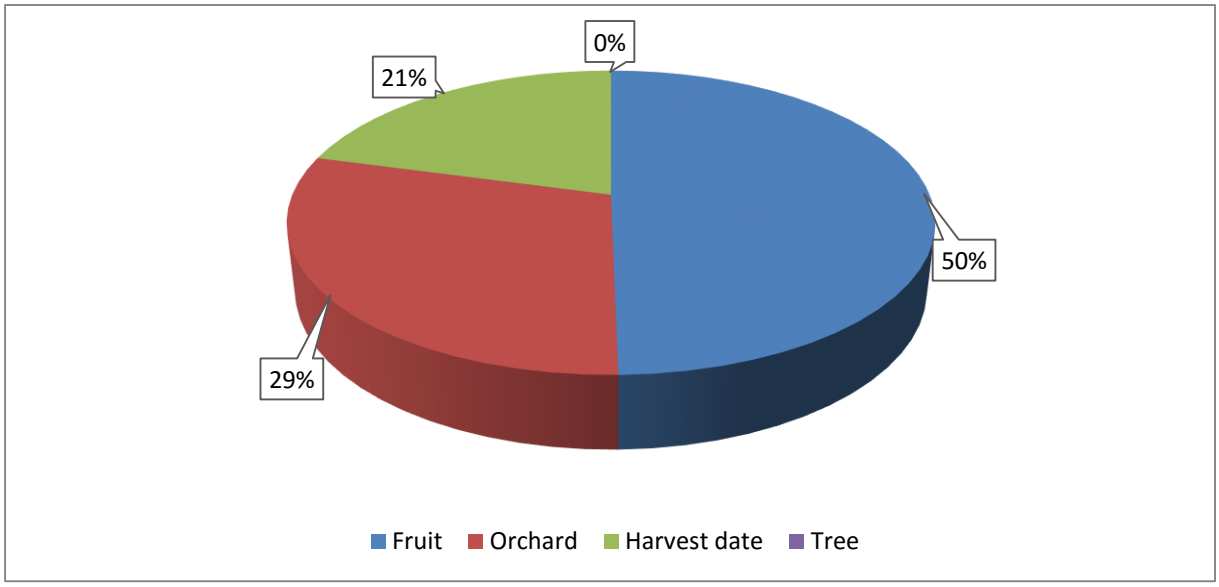


**Fig. 4**. Relative components of variance contributed by fruit to fruit variation, orchards differences, harvest dates and tree to tree differences to the total variation of the water vapour permeance of ‘Songold’ plums in the 2014/2015 season.

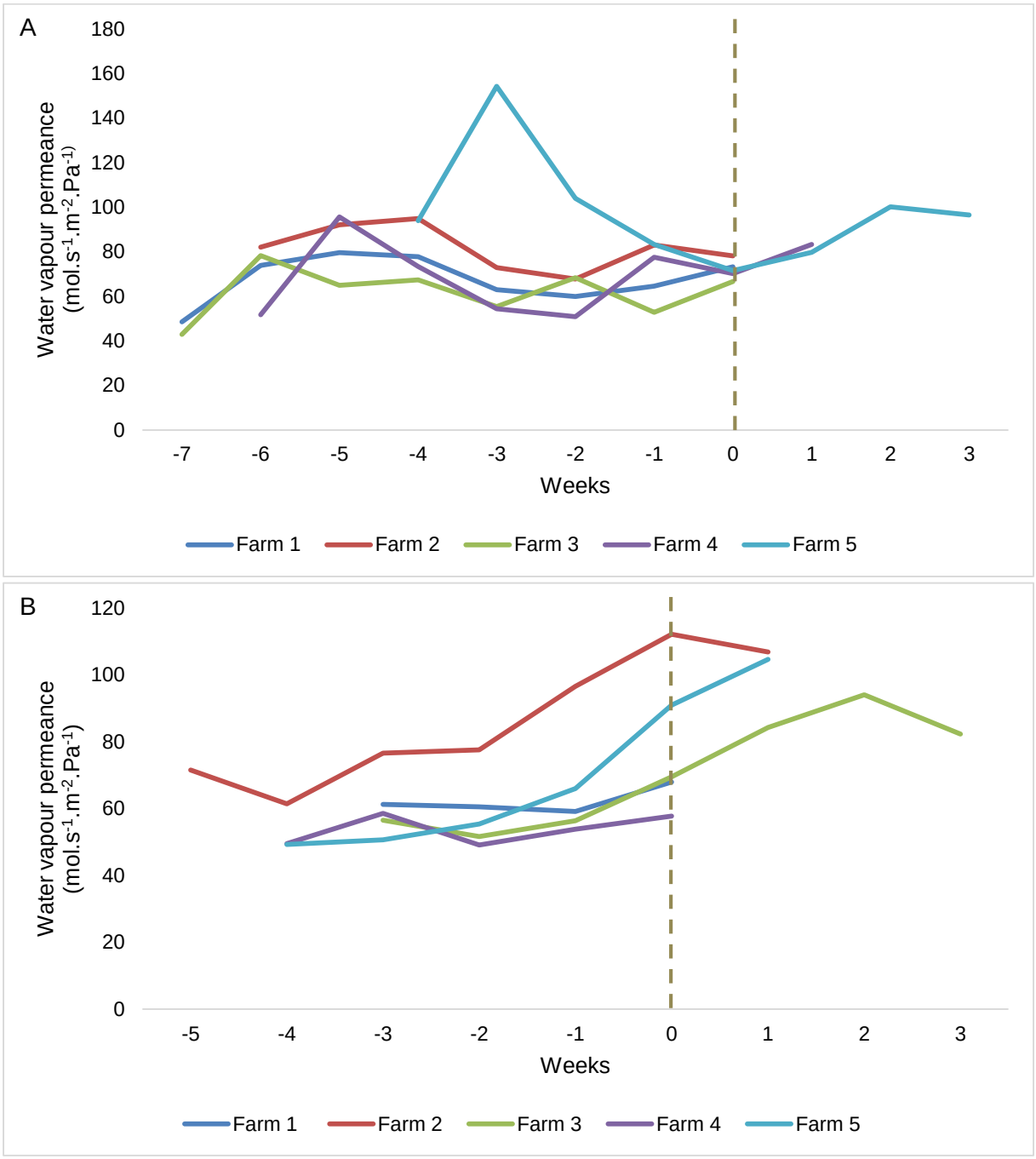


**Fig. 5.** Water vapour permeance of fruit from five 'African Delight™' orchards harvested at different times relative to the commercial harvest maturity (0 Weeks). Figure A represents the 2013/14 season and Figure B the 2014/15 season.

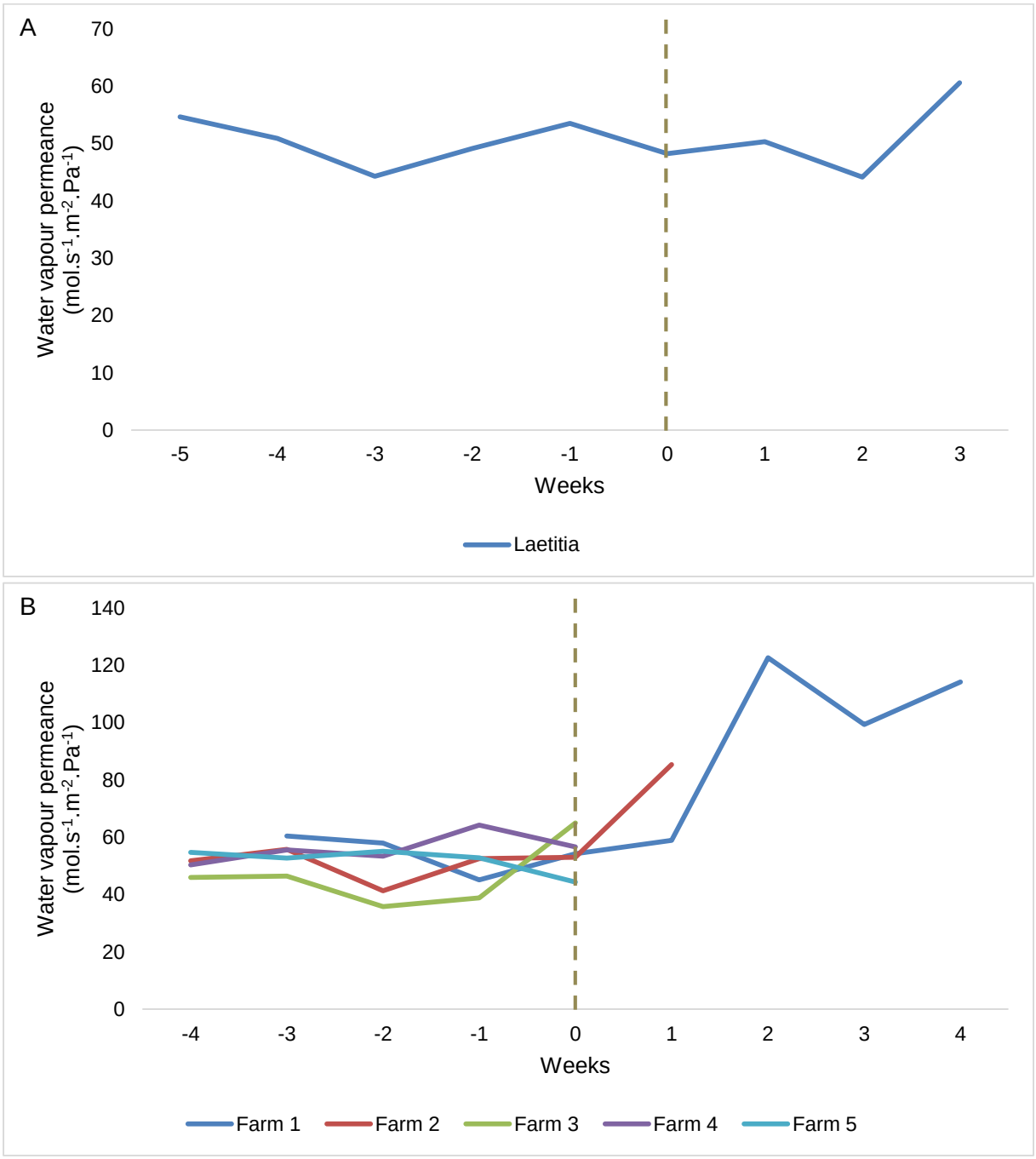


**Fig. 6.** Water vapour permeance of fruit from 'Laetitia' orchards harvested at different times relative to the commercial harvest maturity (0 Weeks). Figure A represents the 2013/14 season and Figure B the 2014/15 season.

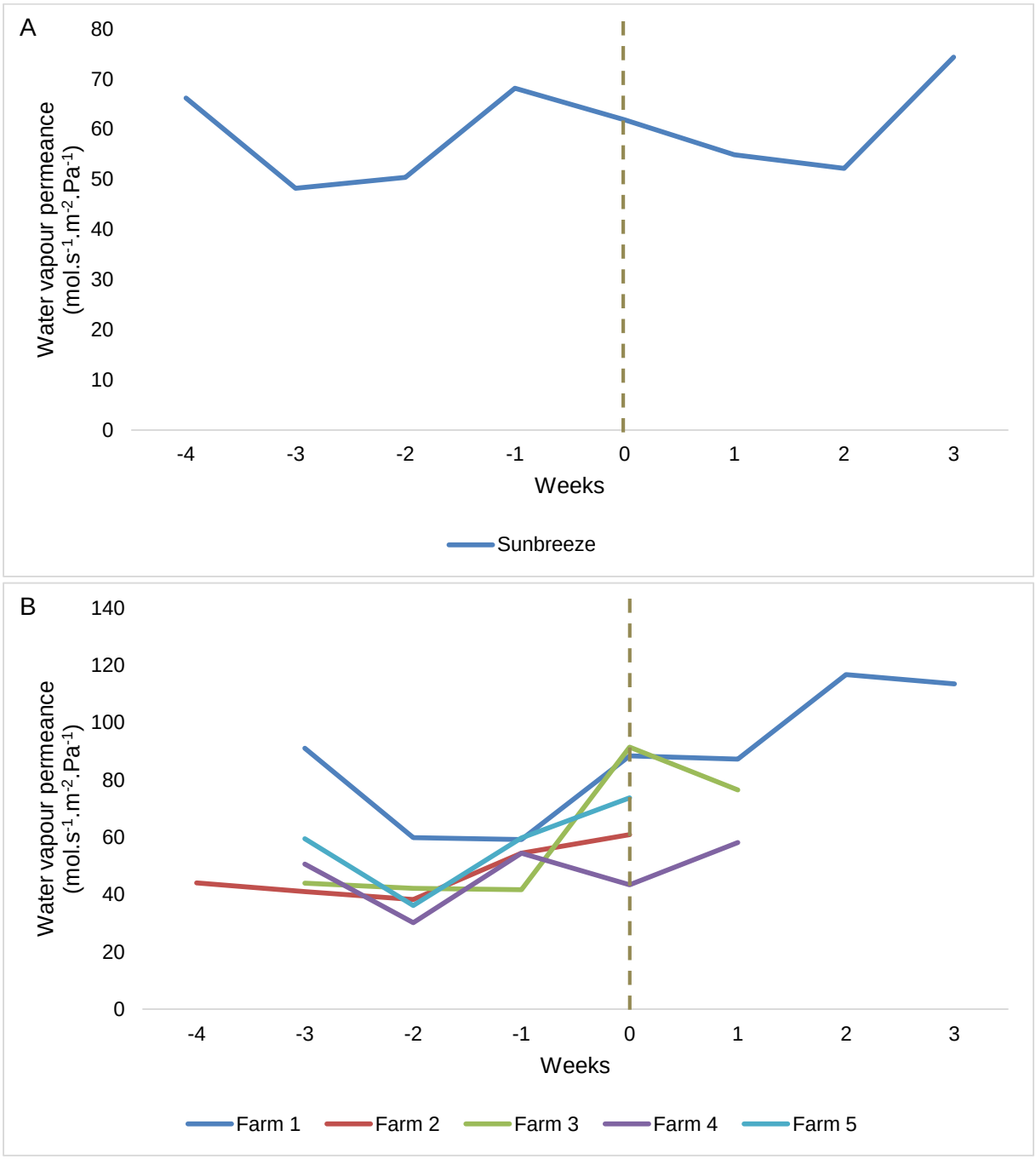


**Fig. 7.** Water vapour permeance of fruit from 'Songold' ('Sunbreeze™') orchards harvested at different times relative to the commercial harvest maturity (0 Weeks). Figure A represents the 2013/14 season and Figure B the 2014/15 season.

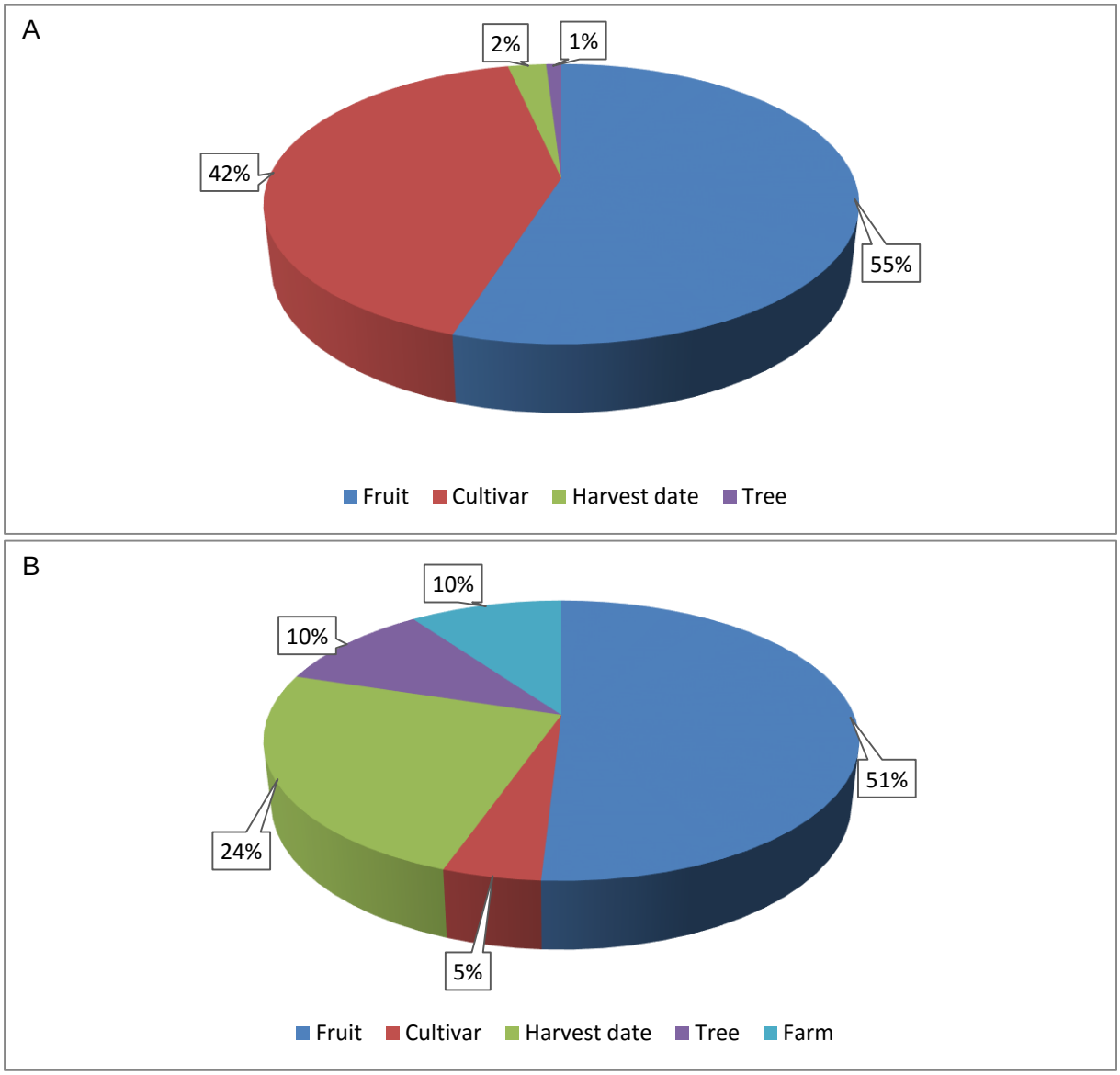


**Fig. 8.** Relative components of variance contributed by fruit to fruit variation, cultivar differences, harvest dates, tree to tree differences and farm differences to the total variation of the water vapour permeance of 'African Delight™', 'Laetitia' and 'Songold' plums. Figure A represents the 2013/14 season and Figure B the 2014/15 season.

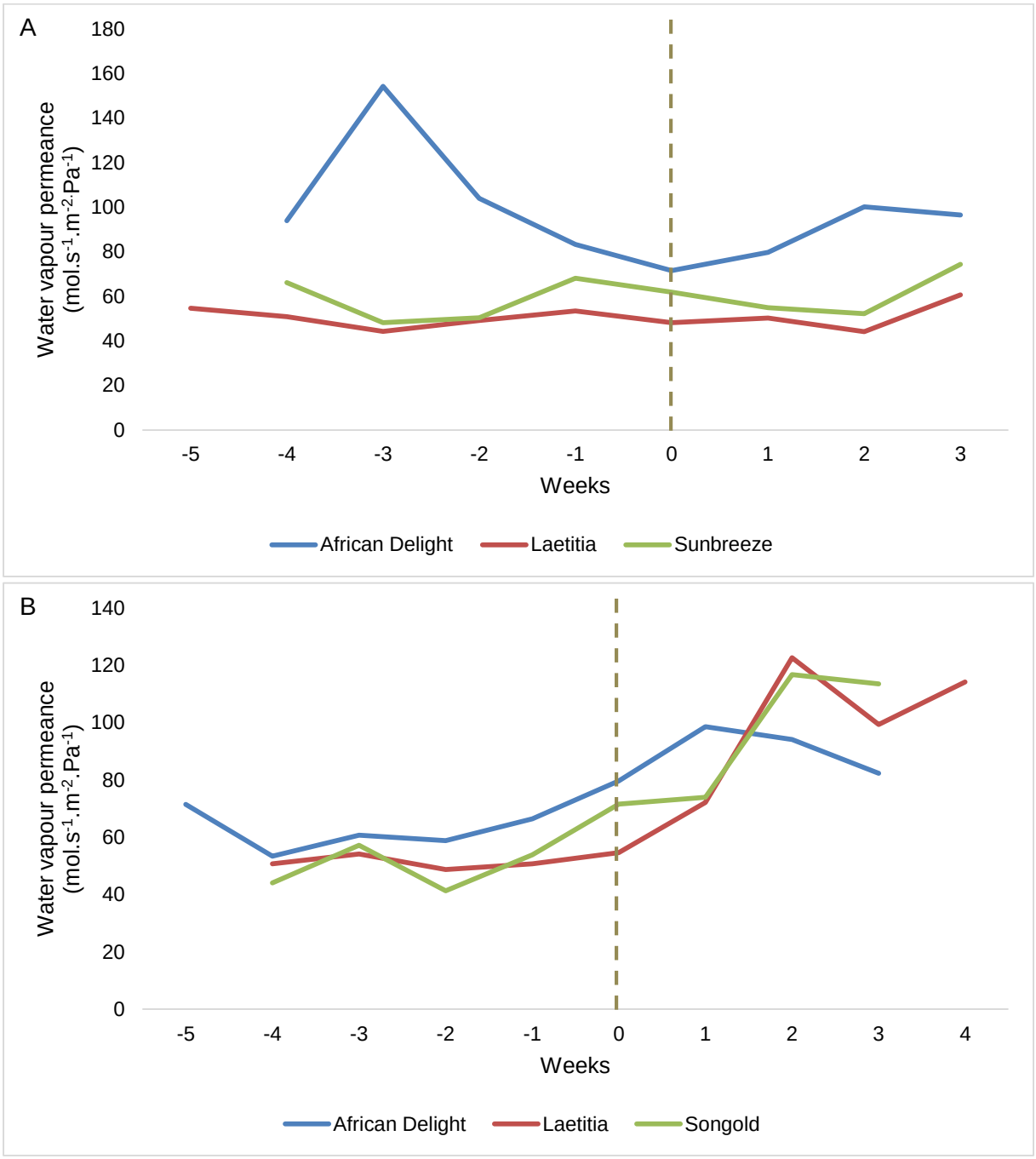


**Fig. 9.** Water vapour permeance of fruit from 'African Delight™', 'Laetitia' and 'Songold' trees harvested at different times relative to the commercial harvest maturity (0 Weeks) for each cultivar. Figure A represents the 2013/14 season and Figure B the 2014/15 season.

# PAPER 3:

# The contribution of the pre-storage and storage vapour pressure deficit between the fruit and its environment to post-storage shrivel manifestation in Japanese plums (*Prunus salicina* Lindl.)


## Abstract

Annually approximately three quarters of the plums produced in South Africa are exported. Exporting plums entails relatively long sea freight and cold storage during which moisture loss occurs resulting in a high incidence of shrivelled fruit. Current handling protocols suggest that fruit should be cooled as soon as possible after harvest, but this, however, is not always possible due to infrastructure and labour constraints. The aim of this study, therefore, was to determine an optimum handling protocol to reduce moisture loss and shrivel manifestation for plum fruit which cannot be packed and cooled to -0.5 °C on the day it was harvested. This study was done by exposing 'African Delight™' plums, which are highly susceptible to shrivel, to various simulated handling scenarios which are commonly used by industry in order to determine the handling protocol with the least risk of moisture loss. Fruit was exposed to three different pre-cooling durations, namely 24, 28 and 72 h, at three different temperatures, namely 0 °C, 15 °C and ambient (approx. 25 °C). The control consisted of packaging and cooling the fruit within 6 h of harvest (recommended industry handling protocol). Fruit maturity and quality was evaluated at harvest, after cold-storage and after shelf-life. Mass loss was determined on arrival at the pack house, after forced air cooling (FAC), after cold-storage and after shelf-life. It was found that fruit quality was comparable or even better compared to the control when the fruit were pre-cooled to 0 °C and 15 °C for up to 72 h. When fruit were left at ambient temperature the vapour pressure deficit (VPD) between the fruit and surrounding air was larger compared to the other treatments. This caused fruit to lose more moisture, especially when fruit were exposed to ambient temperatures for 48 h and 72 h. It was also observed that moisture loss was the highest between arrival at the pack house and the end of FAC. It was also found that a mass loss of 2% caused shrivel in 'African Delight™' plums. The results of this study indicated that post-harvest handling

protocols for plums should be followed stringently in order to reduce mass loss and shrivel development.

Keywords: Japanese plums, Moisture loss, Vapour pressure deficit, Field heat

## 1. Introduction

Approximately 74% of the plums produced in South Africa are exported to overseas markets (HORTGRO, 2014). The relatively long sea freight period (approx. 17 d) plus stock rolling overseas require that some late season plum cultivars must be cold-stored for up to 8 weeks. One of the main expectations of consumers is that the fruit must look fresh when they buy them. Some cultivars, especially 'African Delight™', develop a shrivelled appearance due to moisture loss during this long handling chain. Shrivelling occurs when the surface cells of the fruit lose their turgidity (Sastry, 1985a; Banks et al., 2000). Moisture loss usually results in shrivel and weight loss (in conjunction with respiration). Ultimately, moisture loss leads to a decrease in the quality of the fruit, rendering the product worthless, and results in economic losses to the industry (Sastry, 1985b). Many researchers reported that as little as a 5% loss in fresh weight can cause shrivelling in fresh produce (Ben-Yehoshua, 1987; Mitchell and Kader, 1989; Wills et al., 1989; Maguire et al., 2000). Weight loss is the result of two physiological processes in the fruit, namely moisture loss and respiration (Maguire et al., 2000).

Moisture loss from fruit occurs when water vapour diffuses from the inside of the fruit through the cuticle into the surrounding environment (Maguire, 1998; Lara et al., 2014). Water vapour moves from a high to a lower concentration to establish equilibrium between the fruit and its environment. Hence, in fruit, water vapour moves from the intercellular airspaces and cell walls (where the water vapour pressure is usually close to saturation) into the surrounding atmosphere, where the concentration of water vapour is usually lower (Ben-Yehoshua, 1987). Moisture loss from horticultural products is governed by Fick's first law of gas diffusion (Ben-Yehoshua, 1987; Nobel, 1999). Consequently, the rate of water loss from a product can be calculated as follows:

$r_{H2O} = \Delta p_{H2O} A P'_{H2O}$ (Eq. 1)

Where:

$r_{H2O}$ = rate of water loss from the product (mol $s^{-1}$)

$\Delta p_{H2O}$ = difference in partial pressure of water vapour between the environment and inside the fruit (Pa)

A = surface area of the fruit ($m^2$)

$P'_{H2O}$ = effective permeance of the fruit surface to movement of water vapour (mol $s^{-1}$ $m^{-2}$ $Pa^{-1}$)

Since the fruit is removed from its source of water at harvest, moisture loss, and hence a loss in fruit quality, can occur rapidly after harvest if the product is handled in environments with high temperature and low relative humidity. Postharvest handling can rarely restore lost moisture from the product, but producers and exporters can strive to minimize moisture loss by reducing the difference in the partial pressure of water vapour between the fruit and its environment, known as the vapour pressure deficit (VPD) (Whitelock et al., 1994). Means to minimise fluctuations in VPD include maintaining small temperature differences between the product and its environment, limiting the air circulation inside the cold room, or reducing the air pressure (Veraverbeke et al., 2003). It is important to cool fruit as soon as possible after harvest to reduce the VPD, and thus the driving force for moisture loss and subsequent shrivelling, between the fruit and its environment, but also to reduce the respiration rate of the fruit in order to ensure a prolonged shelf life (Paull, 1999). Currently the recommended handling protocol for plums is to remove field heat from fruit as soon as possible after harvest by means of forced air cooling in order for the fruit to reach a pulp temperature of 15 °C within 3 h after commencement of cooling (HORTGRO, 2015). Subsequent to field heat removal it is recommended that fruit should be packed on the day it was received at the pack house and that is should be force air cooled to a pulp temperature of -0.5 °C within 24 to 36 h. However, due to labour and infrastructure constraints, it is not always possible for South African stone fruit producers to pack and cool fruit immediately after harvest. The aim of this study,

therefore, was to determine an optimum handling protocol to reduce moisture loss, and, hence, shrivel, for plum fruit which cannot be packed and cooled to -0.5 °C on the day it was harvested. The VPD was determined for various simulated handling scenarios of African Delight™ plum, a cultivar highly susceptible to shrivel in order to determine the handling protocol with the least risk of moisture loss. The obtained VPD data was substantiated with the determination of moisture loss and shrivel manifestation at different points in the various simulated handling chains to establish which handling chain/chains would be most optimal under South African conditions.

## 2. Materials and methods

### 2.1. Fruit sampling and experimental layout

The trial was conducted in the 2013/14 and 2014/15 seasons on 'African Delight™' plums. For both seasons a complete randomised design with six replicates per treatment were used. Fruit were sampled from commercial farms. In the 2013/14 season the fruit were sampled from Morgenzon (33°55′24.72″S 18°55′40.45″E), Stellenbosch, South Africa, while in the 2014/15 season fruit were sampled from Franschhoek Fruit Packers (33°54′25.82″S 19°06′45.34″E), Franschhoek, South Africa. Sampling was conducted under field conditions to simulate harvesting. Visually unblemished fruit of the same maturity (by means of foreground colour and size) were sampled from the picking bins in the orchard on the optimum harvest date. In the 2013/14 season a total of 40 fruit were selected per replicate, and in the 2014/15 season a total of 50 fruit were sampled per replicate per treatment. Fruit was of similar size and ground colour according to export standard (DAFF, 2014). The fruit of each replicate were jumbled in a plastic lug which was highly ventilated to simulate the harvesting and transport of fruit in bins from the orchard to the pack house. Ten extra fruit per replicate per treatment (total of 600 fruit) were sampled to determine fruit maturity on the harvest date.

Ten handling chains (treatments) were simulated (Table 1). A Thermocron® iButton (CST electronics, Sandton) recording fruit pulp temperature was inserted into one fruit (an extra fruit that was not used for any other measurements) per replicate (lug) at harvest. A Hygrochron™ iButton, which recorded ambient temperature and

RH, was placed on the inside of each lug. The iButtons, which were numbered according to their treatment and replicate, accompanied the fruit in their respective replicates throughout the different simulated handling chains to facilitate the calculation of the vapour pressure deficits of each replicate and, hence, treatment. Data recording was done every 45 min in the 2013/14 season and every hour in the 2014/15 season from harvest until the end of shelf-life.

After sampling in the field was completed, the lugs were transported to the laboratory in Stellenbosch (approx. 1 h) in an uncooled vehicle to simulate transport of fruit from the orchard to the pack house. Following the different delay periods after arrival at the laboratory as depicted in Table 1, fruit from each lug were packed according to export standards into a 4.5 kg carton lined with a perforated (54 x 2 mm) high density polyethylene (HDPE) bag with a thickness of 16 µm, containing two pulp trays (two layers of 20 fruit each in the 2013/2014 season and two layers of 25 fruit each in the 2014/2015 season) before the commencement of FAC. Packing of the fruit took approx. 0.5 h. After the 8 week cold-storage period the HDPE bags were removed from the cartons and the fruit were placed at 10 °C for 7 d to simulate shelf-life conditions.

2.2. Fruit evaluations

The weight of the same 40 fruit (2013/2014 season) or 25 fruit (2014/2015 season) in each replicate was determined using a balance, accurate to 0.001 kg (Mettler PC24, Mettler Instrument corporation, USA), immediately after sampling in the field, immediately after arrival at the laboratory (to simulate arrival at the pack house), after forced air cooling (FAC), after cold-storage and after shelf-life. In the 2013/2014 season all the fruit of each replicate was weighed at the different stages in the handling chain. However, since all the fruit had to be used to determine fruit weight after cold-storage and after the shelf-life period, it did not allow for destructive fruit quality determinations after cold-storage. Hence, in the 2014/2015 season only the 25 fruit in the bottom layer of each carton was weighed to allow for destructive fruit quality measurements in the 25 fruit in the top layer of each carton after cold-storage.

On the sampling date 10 extra fruit per replicate per treatment were used to determine the maturity of the fruit. Hue angle was determined on both cheeks of 10 fruit per replicate using a calibrated colorimeter (Minolta colour recorder DR-10, Japan). Flesh firmness (kg) was determined on both peeled cheeks of 10 fruit per replicate using a FTA (Fruit Texture analyser, Güss Instruments) fitted with an 11 mm tip. Total soluble solids (TSS, %Brix) was determined on a pooled juice sample of 5 fruit per replicate using a temperature controlled, digital refractometer (Palette, PR-32 ATAGO, Bellevue, USA). Total titratable acidity (TA, %) was determined on a pooled juice sample of 5 fruit per replicate. TA was determined by titrating a 10 g aliquot of the juice sample with 0.1 M NaOH to a pH end-point of 8.2 using an automated titrator (Metrohm AG 760, Herisau, Switzerland).

Fruit quality was again determined after cold-storage and after shelf-life. In the 2013/2014 season all the fruit in each carton (approx. 40 fruit) were inspected for shrivel (%) and decay (%) after cold-storage and after shelf-life. In the 2014/2015 season, shrivel and decay was determined in the top layer of fruit in each carton after cold-storage (25 fruit) and in the bottom layer of fruit after shelf-life (25 fruit). Shrivel was deemed present when the shrivelled peel extended over the shoulder of the fruit.

In the 2013/2014 season the hue angle of both cheeks of five fruit from the top layer and five fruit from the bottom layer in each carton was determined after cold-storage and after shelf-life. In the 2014/2015 season hue angle was determined on one cheek of 10 fruit in the top layer of fruit in each carton after cold-storage and on one cheek of 10 fruit in the bottom layer of each carton of fruit after shelf-life.

In the 2013/2014 season flesh firmness was only determined after shelf-life on one peeled cheek of five fruit each from the top and bottom layer of each respective replicate. In the 2014/15 season flesh firmness was determined on one peeled cheek of 10 fruit in the top layer of each carton after cold-storage and 10 fruit of the bottom layer of each carton after shelf-life. Internal defects were determined by cutting 15 fruit per replicate around the equatorial axis separating the fruit into two halves. In the 2013/2014 season internal defects were only recorded after shelf-life, while it was recorded after cold-storage (in 15 fruit from the top layer of each replicate) and after shelf-life (in 15 fruit from the bottom layer of each carton) in the 2014/2015 season.

Internal defects were recorded as a percentage of the total number of fruit examined. A gelatinous breakdown of the inner mesocarp tissue surrounding the stone, while the outer mesocarp tissue has a healthy appearance, was classified as gel breakdown (GB). A brown discolouration of the mesocarp tissue, associated with a loss in juiciness, was classified as internal browning (IB). Whitish, dry, firm mesocarp tissue was classified as aerated tissue (AT).

### 2.3. Statistical analyses

Mixed model repeated measures ANOVA was used to investigate the effects of treatment and season on weight loss over time (mass loss (%) and accumulated mass loss (g per fruit). Total mass loss (%) was analysed using a two-factorial ANOVA with season and treatment as the two factors. Other data was analysed with a repeated measures analysis of variance. ANOVA-generated P-values and the significant differences between means was determined using Fisher's least significant differences (LSD) test with a 95% confidence interval. All the above mentioned analyses were done using Dell Inc. (2015) STATISTICA (data analysis software system), version 12.

## 3. Results

At harvest it was found that fruit were within prescribed export standards as required by DAFF (2014) (Table 2).

### 3.1. Fruit mass loss

A significant interaction was found between treatments and the evaluation times for fruit mass loss (Fig. 1) and accumulated fruit mass loss (Fig. 2). Although the differences were not always significant, the mass loss from the control, 0 °C and 15 °C treatments generally increased from harvest until the end of cold-storage, where after it decreased during the shelf-life period (Fig. 1). This trend was not observed for the ambient treatments (approx. 25 °C). Mass loss increased significantly from harvest to the end of FAC for the ambient treatments where after it decreased significantly between the end of FAC and the end of cold-storage. Mass loss also decreased between the end of cold-storage and the end of the shelf-life period in the ambient

treatments, but this difference was not always significant. This trend was especially prominent in the 48 h and 72 h ambient treatments.

For all treatments mass loss was the lowest in the period between harvest and arrival at the pack house (Time 1) (Fig. 1). Average mass loss for Time 1 was 0.32% with a standard deviation of 0.14% for all the treatments. Time 2 (the period between arrival at the pack house and the end of FAC) was found to be the period with the most variation in mass loss between treatments. Average mass loss for Time 2 varied from 0.24% (0 °C for 24 h) to 2.36% (ambient for 72 h) and averaged at 0.83% with a standard deviation of 0.7%. Mass loss for Time 3 (the cold-storage period), did not differ significantly between treatments. Average mass loss for Time 3 was 0.86% with a standard deviation of 0.08%. For Time 4, the shelf life period, mass loss also did not differ significantly between treatments. Average mass loss for Time 4 was 0.67% with a standard deviation of 0.04%.

There was a significant interaction between accumulated mass loss (kg) and evaluation times (Fig. 2). Mass loss from Time 2 differed most between treatments (Fig. 1). The control did not differ from where fruit were kept at 0 °C for 24 h for Time 2. The accumulated mass loss did not differ between the rest of the 0 °C and 15 °C treatments for this period. It was found that the ambient treatments had significantly higher mass loss compared to the other treatments and it increased with the increase in precooling time. In the end the total accumulated mass loss (Time 4) of the control did not differ from fruit kept at 0 °C for 24 h. Fruit kept at 0 °C for 24 h did not differ from the rest of the 0 °C treatments and where fruit were kept at 15 °C for 24 h and 48 h. The total accumulated mass loss from the ambient treatments all differed from each other, showing an increase in mass loss as the precooling time increased. The ambient treatments also differed from the control, and all 0 °C and 15 °C treatments.

Total mass loss (%) in the control did not differ significantly from the treatments where fruit were precooled at 0 °C for 24 and 72h (Fig. 3). The 15 °C treatments differed significantly from the control, but not from fruit precooled at 0 °C for 48 and 72h. Treatments stored at ambient had the highest total mass loss, ranging from 3 to 4%. Therefore, mass loss generally increased with an increase in precooling

temperature with the control and fruit precooled at 0 °C having the least moisture loss at the end of shelf-life.

### 3.2. Vapour pressure deficit (VPD)

The VPD's from the 10 treatments differed the most from one another and were the highest during Time 1 (the period between harvest and arrival at the pack house) (~ 0.14 kPa with a standard deviation of 0.16 kPa) and Time 2 (the period between arrival at the pack house and the end of FAC) (~ 0.02 kPa – average for all the treatments - with a standard deviation of 0.17 kPa). The VPD's of all treatments were low for Time 3 (~ 0.007 kPa – average for all the treatments - with a standard deviation of 0.006 kPa) and Time 4 (~ 0.01 kPa – average for all the treatments - with a standard deviation of 0.014 kPa) and did not differ much between treatments.

Roughly the same trend was observed for the total VPD of the different treatments for the two seasons (Fig. 4A and B). However, the total VPD for each treatment was much higher (in most cases more than twice as high) in the 2013/2014 season compared to the 2014/2015 season. This was caused by more condensation on the loggers in the 2014/15 season resulting in lower VPDs to be achieved. In the 2013/14 season the control did not differ significantly from the fruit precooled to 0 °C for 24 h and 48 h and 15 °C for 24 h, 48 h and 72 h. In the 2014/15 season the control did not differ significantly from fruit precooled to 0 °C and 15 °C for 24 h and 72 h. Fruit kept at ambient temperature before FAC tended to have the highest total VPD.

### 3.3. Fruit quality parameters

In the 2013/2014 season flesh firmness was measured at harvest and after the shelf-life period (Table 3). The treatments did not differ significantly, but fruit was significantly softer after shelf-life compared to the harvest date. In the 2014/2015 season flesh firmness was measured at harvest, after cold-storage and after shelf-life and a significant interaction was found between treatment and evaluation time (Fig. 5). Generally flesh firmness decreased from harvest until the end of cold-storage in all the treatments, and where fruit was precooled to 0 °C for 48 and 72 h, at 15 °C and kept at ambient for 72 h, the decrease in firmness was statistically significant. Flesh firmness did not change much between the end of cold-storage and after the shelf-life

period in the different treatments, except for fruit precooled to 0 °C and 15 °C for 48 h where a significant increase in flesh firmness was observed.

In the 2013/2014 season when hue angle was determined at harvest, after cold-storage and after shelf-life, treatment did not have an effect on the fruit peel colour, but the fruit were significantly redder after cold-storage and after the shelf-life period compared to the harvest date (Table 3). There was not a significant difference in the fruit colour between the end of cold-storage and the end of the shelf-life period in the 2013/14 season. In the 2014/2015 season there was a significant interaction between treatment and evaluation time (Fig. 6). Except for fruit precooled to 0 °C for 48 and 72 h, to 15 °C for 48 h and kept at ambient for 48 h, fruit became significantly redder during cold-storage and shelf-life compared to the harvest date. Interestingly, fruit precooled to 0 °C and 15 °C for 24 h was significantly less red after the shelf-life period compared to after cold-storage.

There was a significant interaction between treatment and evaluation time for both seasons for shrivel manifestation (Fig. 7A and B). In the 2013/2014 season shrivel levels were generally higher (although not always statistically significant) after cold-storage compared to after the shelf-life period. An opposite trend was observed in the 2014/2015 season, namely that shrivel levels were generally higher after the shelf-life period compared to after cold-storage. In the 2013/2014 season all the fruit in each carton was examined for shrivel after cold-storage and after shelf-life with no destructive measurements being made after the cold-storage period. In the 2013/14 season (Fig. 7A) fruit precooled to 0 and 15 °C for 48 h had significantly lower shrivel levels after cold-storage compared to the control, while fruit kept at ambient for 72 h had the highest (although not significantly more than fruit kept at ambient for 24 h) shrivel levels after cold-storage. After shelf-life control fruit and fruit held at ambient had the highest shrivel levels. In the 2014/2015 season fruit kept at ambient for 48 h and longer had significantly higher shrivel levels, while fruit precooled to 0 °C and 15 °C had significantly lower shrivel levels after cold-storage compared to the control (Fig. 7B). After shelf-life shrivel levels generally decreased in fruit precooled to 0 °C and 15 °C with an increase in precooling time, however, this decrease was not always significant. In fruit held at ambient, shrivel levels increased significantly with an increase in time at ambient before fruit was force air cooled.

For the 2013/14 season fruit precooled to 0 °C for 24 h and at 15 °C for 24 h and 48 h had no decay while all the other treatments developed decay (Table 3). The differences between treatments, however, were not statistically significant. For the 2014/15 season there was a statistically significant interaction between treatment and evaluation time for decay (Table 3). Decay levels were low in all the treatments after cold-storage and shelf-life, except for fruit kept at ambient for 24 h between harvest and packing which had significantly higher decay levels after shelf-life compared to the other treatments. Similar to the 2013/2014 season, fruit precooled to 0 °C for 24 h and at 15 °C for 24 h had lower decay levels compared to the other treatments, but the differences were not statistically significant.

In the 2013/14 season, when internal defects were only determined after the shelf-life period, it was found that gel breakdown (GB) levels were the highest in fruit precooled to 0 °C for 48 h compared to the other treatments (Table 3). In the 2014/2015 season, when GB was determined after cold storage and after shelf life, there was a significant interaction between treatment and evaluation time (Table 3). While low or even no GB was observed in most treatments, fruit kept at ambient for 24 h had the highest levels of GB.

Aerated tissue was only evaluated after the shelf-life period in the 2013/14 season, and it was the highest in fruit precooled to 0 °C for 72 h and at ambient for 48 and 72 h between harvest and packing of fruit for (Table 3). In the 2014/15 season aerated tissue was evaluated after cold-storage and after shelf life, and it was found that treatments did not differ from each other, but that there was an increase in the incidence of aerated tissue from after the cold-storage evaluation until the end of shelf life (Table 3).

No internal browning (IB) was found in the 2013/14 season (data not shown), but in the 2014/15 season there was a significant interaction between evaluation time and treatment for IB manifestation (Table 3). Fruit kept at ambient for 24 h between harvest and packing of the fruit had significantly higher levels of IB after shelf life compared to the other treatments.

## 4. Discussion

The differences that existed between treatments between harvest and arrival at the pack house (Time 1) are ascribed to natural fruit variation as all the treatments were treated the same during Time 1. Research by Maguire et al. (2000) on apples and the results from Paper 2 also indicated fruit to fruit variation as the biggest contributor to peel permeability during fruit maturation. The variation between treatments were less for Times 3 and 4, probably because fruit and air temperature was the same, resulting in a lower VPD, lowering the driving force for moisture loss. Fruit were also placed in the same cold room where conditions were the same for all treatments which caused mass loss to be approximately the same for all the treatments. The only period in the simulated handling chains where conditions between treatments really differed, was during Time 2, the period from arrival at the pack house until after FAC. Generally it was found that Time 2 had more mass loss (average of 0.83% for all the treatments) than Time 1 (average of 0.32% for all the treatments). It was found that as much as 2.36% of fruit mass could be lost in 72 h during Time 2, which is a significant amount of moisture loss compared to Time 3 (8 weeks at -0.5 °C; 0.86%) and Time 4 (1 week at 10 °C; 0.7%).

Generally mass loss increased with an increase in pre-cooling time for treatments kept at 0 °C, 15 °C and ambient for Time 2. This was not the case for fruit precooled to 0°C for 72 h before FAC. This treatment did not show an increase in mass loss with an increase in precooling time compared to the 24 h and 48 h treatments of the same precooling temperature. This could be explained by a smaller VPD between the fruit and the air surrounding it after 72 h of precooling. After harvest field heat was removed from this treatment and the fruit reached the temperature of the cold room air. When FAC commenced the fruit were already on temperature, which led to a smaller initial VPD during FAC, causing fruit to lose less moisture during the FAC period. This is supported by the total VPD results for this treatment compared to the other treatments (Fig. 4). Ambient treatments showed significant increases in mass loss as precooling time increased for Time 2. This can be explained by the large VPD between the fruit and the environment. Fruit that were kept at ambient for 72 h had the highest total mass loss because of exposure to high VPD’s for an extended period

compared to fruit kept at ambient for only 24 h. This high VPD caused moisture to be lost from the fruit.

Large VPD's are one of the driving forces behind moisture loss and may be linked to the potential risk for shrivelling (Kays, 1991; Thompson, 1992). When fruit are harvested they are removed from their source of water which causes the fruit to be more susceptible to moisture loss due to a large VPD between the fruit and the surrounding ambient air (Van den Berg, 1987). Shrivel occurs under circumstances where dehydration occurs as water lost from the surface of the fruit is not replaced and the tissue contracts (Burdon et al., 2014). It was found that Time 2, 3 and 4 made considerable contributions towards the total mass loss, namely 0.83, 0.86 and 0.67%, respectively. However, Time 2 was a relatively short period (max. 72 h) compared to Time 3 (8 weeks) and Time 4 (1 week), indicating that the large VPD's experienced during Time 2 must have made a significant contribution to moisture loss and shrivel development. The total VPD of fruit precooled to 0 °C for 24, 48 and 72 h and to 15 °C for 24 and 72 h did not differ significantly from the control (Fig. 4). This was a surprising finding as the control was cooled to -0.5°C in a much shorter time than the other treatments. The reason for this is probably because the control fruit was warm when FAC commenced, and the cold air forced over it resulted in a large initial VPD. In the 2013/14 season it was found that fruit precooled to 0 °C for 72 h had a significantly lower VPD than the control. This is probably because this fruit was already at 0 °C when FAC commenced, causing a smaller VPD during the initial FAC time compared to the control (Kays and Paull, 2004). Ambient treatments did not differ significantly from each other in the 2013/14 season, but total VPD increased significantly with pre-cooling time in the 2014/15 season. The VPD's for the ambient treatments were higher than the other treatments because the relative humidity (RH) of the surrounding air of the room where fruit was kept was much lower than the air in the cold rooms where the other treatments were placed, which was closer to saturation (although an initial high VPD would have been experienced in the fruit precooled to 0 °C and 15 °C due to the temperature difference between the fruit and the pre-cooling room). Since the air in the intercellular spaces of the fruit is almost saturated with water vapour (Ben-Yehoshua, 1987) and, therefore, at a higher RH than the surrounding ambient air, the VPD between the fruit kept at ambient and the air surrounding them

was high for the full duration of the pre-cooling period, while it decreased for the fruit precooled to 0 °C and 15 °C as the pulp temperatures reached the room temperature. This high VPD between fruit kept at ambient and the holding room will drive moisture loss. This was clearly demonstrated by the accumulated mass loss of the fruit kept at ambient being significantly higher compared to fruit from other treatments (Fig. 1 and 2).

They main fruit quality parameter measured in this study was shrivelling. In the 2013/14 season shrivel was determined on the same fruit after cold-storage and after shelf-life, and a decrease in shrivel levels was observed between the two evaluation times in almost all treatments. It is suggested that the decrease in shrivel levels during the shelf-life period is probably due to cell wall disassembly in conjunction with a loss in the turgidity of the mesocarp cells during fruit ripening at the higher storage temperature (10 °C) (Jooste, 2012). This was not observed in the 2014/15 season. The reason for this is probably because all the fruit in the carton was examined for shrivel after cold-storage, but only the fruit in the bottom tray after the shelf-life period, because the fruit in the top layer in each carton was evaluated for internal defects after cold-storage, which is a destructive evaluation. In both seasons the fruit kept at ambient for 48 and 72 h had high shrivel levels. This is explained by the long period the fruit was exposed to a high VPD between themselves and the surrounding atmosphere. This result is further supported by the mass loss data, where it was found that fruit kept at ambient had more moisture loss than fruit precooled to 0 °C and 15 °C. It cannot be explained why the fruit from the control had relatively high levels of shrivel whilst showing low fruit mass loss compared to other treatments. Hruschka (1977) did a study to determine how shrivel severity correlated with the average percentage weight loss (weight loss was measured instead of the actual moisture loss, since respired substrates usually make up a minor part of the total weight loss) of different crop types. It was found that zero shrivel to extremely severe shrivel occurred with a weight loss percentage between 14.2% to 24.8% for nectarines, and 9.0% to 20.4% for peaches. In this study it was found that fruit developed a shrivelled appearance with has little as 2% mass loss. Hence, the weight loss that was experienced in this study was too high and resulted in high levels (more than 10%) of shrivel in most of the treatments. The VPD measurements also did not predict shrivel

manifestation accurately for all treatments. Burdon et al., (2014) report that moisture loss is necessary for fruit to shrivel, but it is not the only factor that determines when shrivelling occurs. This indicates that there might be other reasons except for moisture loss, such as differences between cultivars or seasons, why fruit from all the treatments shrivelled.

In the 2013/14 season no significant differences were found in decay, but in the 2014/15 season it was found that fruit kept at ambient for 24 h had significantly higher decay levels after shelf-life than other treatments. Higher levels of decay after shelf-life was expected, because if decay causing pathogens were present, they would grow and infect at a higher rate at shelf life temperatures (10 °C) compared to cold-storage temperatures (-0.5 °C). The reason for the significantly higher decay levels observed in only the 24 h ambient treatment cannot be explained, and it is suggested that it should be considered as a sampling error. This treatment was also the only one to differ from the other treatments after shelf life with regards to gel breakdown and internal browning for the 2014/15 season. This result strengthens the suggestion that the differences between this treatment and the other treatments regarding quality parameters were not a treatment effect, but rather a sampling error. The higher gel breakdown levels observed in fruit kept at 0 °C for 24 h in the 2013/14 season could also not be explained by treatment effect. Aerated tissue was measured after shelf life during the 2013/14 season and it was found to be higher in fruit precooled to 0 °C for 72 h and kept at ambient for 48 h and 72 h. In the 2014/15 season it was found that treatments did not differ regarding the incidence of aerated tissue, but levels did differ significantly between evaluation times. Lima et al. (2001) found that aerated tissue in mango was related to lower carbohydrate metabolism during fruit ripening in the affected fruit. If this is also the reason for the manifestation of aerated tissue in plums, is not clear and further research is needed to investigate this defect.

Flesh firmness and hue angle decreased during storage indicating that the ripening process continued throughout storage. The decrease in flesh firmness is caused by the biosynthesis of ethylene (produced during ripening) which activates cell wall degrading enzymes which, in turn, cause changes in the primary cell wall components leading to decreased flesh firmness (Taiz and Zeiger, 2010). It was found that fruit kept at 15 °C, especially for 48 h, had much lower flesh firmness than the

other treatments. While it is known that higher temperatures stimulate ethylene production, and hence, fruit softening, it is not clear why fruit precooled to 15 °C for 72 h and fruit kept at ambient did not show the same trend in fruit softening. Ethylene production during fruit ripening also lead to changes in chlorophyll, carotenoid and flavonoid concentrations allowing colour pigments to be more exposed, giving fruit a redder appearance (Taiz and Zeiger, 2010).

## 5. Conclusion

The aim of this study was to determine to what extent producers can postpone packing and cooling of 'African Delight™' plums after harvest. We found that only a 2% mass loss causes shrivel development in 'African Delight™' plums. A tenth of the total mass loss occurred in the period between harvest and arrival at the pack house. It is, therefore, strongly recommended that harvesting protocols, such as harvesting during cooler times of the day, covering fruit in bins with wet blankets and keeping fruit in the shade, must be followed stringently for this plum cultivar. Regarding the period between arrival of the fruit at the pack house and the end of FAC, it was found that fruit should be packed and be under FAC within 6 h after harvest, or being precooled to 0 °C to have the least moisture loss. It was also found that, if fruit are precooled to -0.5 °C, it is better to keep the fruit at -0.5 °C for 72 h and not for a shorter duration. By doing this, the relatively large VPD created at the onset of FAC and the fruit that has a temperature higher than the delivery air will be eliminated.

The results also showed that less shrivel will develop if fruit are precooled prior to FAC compared to not receiving precooling – even when fruit is packed as soon as possible after harvest and force air cooled. However, it should be kept in mind that mass loss will increase with an increase in keeping time at 0 or 15 °C. Keeping fruit at ambient temperatures, especially for longer than 24 h, is not advisable as it could lead to higher moisture loss, generating a bigger risk for moisture loss and shrivel development. Although it was found that precooling fruit can reduce moisture loss and shrivel, it was found that there is a tendency for flesh firmness to decrease more during storage in fruit precooled to 0 °C or just above the dew point of the pack house compared to fruit packed and put under FAC within 6 h after harvest. It was also found that, regardless of treatment and although fruit was packed in perforated bags, fruit

lost ~ 1% in mass during cold-storage. It is, therefore, recommended that future studies should focus on packaging and other ways to minimize mass loss during cold-storage.

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## 8. Tables

### Table 1.

Treatments used to simulate handling of Japanese plums in the South African industry.

| Treatment | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Trt 1 (Control)** | **Trt 2** | **Trt 3** | **Trt 4** | **Trt 5** | **Trt 6** | **Trt 7** | **Trt 8** | **Trt 9** | **Trt 10** |
| Harvest ↓ 6 h delay at ambient (approx. 25 °C) to simulate packaging process ↓ Pack (within 1 h) ↓ Forced air cooling for 24 h to pulp temperature of -0.5 °C ↓ Cold-storage at -0.5 °C for 8 weeks ↓ Shelf-life for 7 days at 10 °C | Harvest ↓ 24 h delay at -0.5 °C ↓ Pack (within 1 h) ↓ Forced air cooling for 24 h to pulp temperature of -0.5 °C ↓ Cold-storage at -0.5 °C for 8 weeks ↓ Shelf-life for 7 days at 10 °C | Harvest ↓ 48 h delay at -0.5 °C ↓ Pack (within 1 h) ↓ Forced air cooling for 24 h to pulp temperature of -0.5 °C ↓ Cold-storage at -0.5 °C for 8 weeks ↓ Shelf-life for 7 days at 10 °C | Harvest ↓ 72 h delay at -0.5 °C ↓ Pack (within 1 h) ↓ Forced air cooling for 24 h to pulp temperature of -0.5 °C ↓ Cold-storage at -0.5 °C for 8 weeks ↓ Shelf-life for 7 days at 10 °C | Harvest ↓ 24 h delay at 15 °C (to simulate field heat removal just above dew point of the packhouse) ↓ Pack (within 1 h) ↓ Forced air cooling for 24 h to pulp temperature of -0.5 °C ↓ Cold-storage at -0.5 °C for 8 weeks ↓ Shelf-life for 7 days at 10 °C | Harvest ↓ 48 h delay at 15 °C (to simulate field heat removal just above dew point of the packhouse) ↓ Pack (within 1 h) ↓ Forced air cooling for 24 h to pulp temperature of -0.5 °C ↓ Cold-storage at -0.5 °C for 8 weeks ↓ Shelf-life for 7 days at 10 °C | Harvest ↓ 72 h delay at 15 °C (to simulate field heat removal just above dew point of the packhouse) ↓ Pack (within 1 h) ↓ Forced air cooling for 24 h to pulp temperature of -0.5 °C ↓ Cold-storage at -0.5 °C for 8 weeks ↓ Shelf-life for 7 days at 10 °C | Harvest ↓ 24 h delay at ambient (approx. 25 °C) ↓ Pack (within 1 h) ↓ Forced air cooling for 24 h to pulp temperature of -0.5 °C ↓ Cold-storage at -0.5 °C for 8 weeks ↓ Shelf-life for 7 days at 10 °C | Harvest ↓ 48 h delay at ambient (approx. 25 °C) ↓ Pack (within 1 h) ↓ Forced air cooling for 24 h to pulp temperature of -0.5 °C ↓ Cold-storage at -0.5 °C for 8 weeks ↓ Shelf-life for 7 days at 10 °C | Harvest ↓ 72 h delay at ambient (approx. 25 °C) ↓ Pack (within 1 h) ↓ Forced air cooling for 24 h to pulp temperature of -0.5 °C ↓ Cold-storage at -0.5 °C for 8 weeks ↓ Shelf-life for 7 days at 10 °C |

**Table 2.**

Maturity of ‘African Delight™’ plums at harvest (standard deviations are presented in brackets).

| Parameter | Season | |
|---|---|---|
| | 2013/14 | 2014/15 |
| Flesh firmness (kg) | 5.78 (0.81) | 7.27 (0.75) |
| Hue angle | 17.14 (4.23) | 22.97 (7.12) |
| Total soluble solids (%) | 15.30 (0.90) | 14.11 (0.96) |
| Total titratable malic acid (%) | 1.22 (0.10) | 1.09 (0.09) |

**Table 3.**

The effect of temperature break treatment and evaluation time on quality of 'African Delight™' plums during the 2013/14 season.

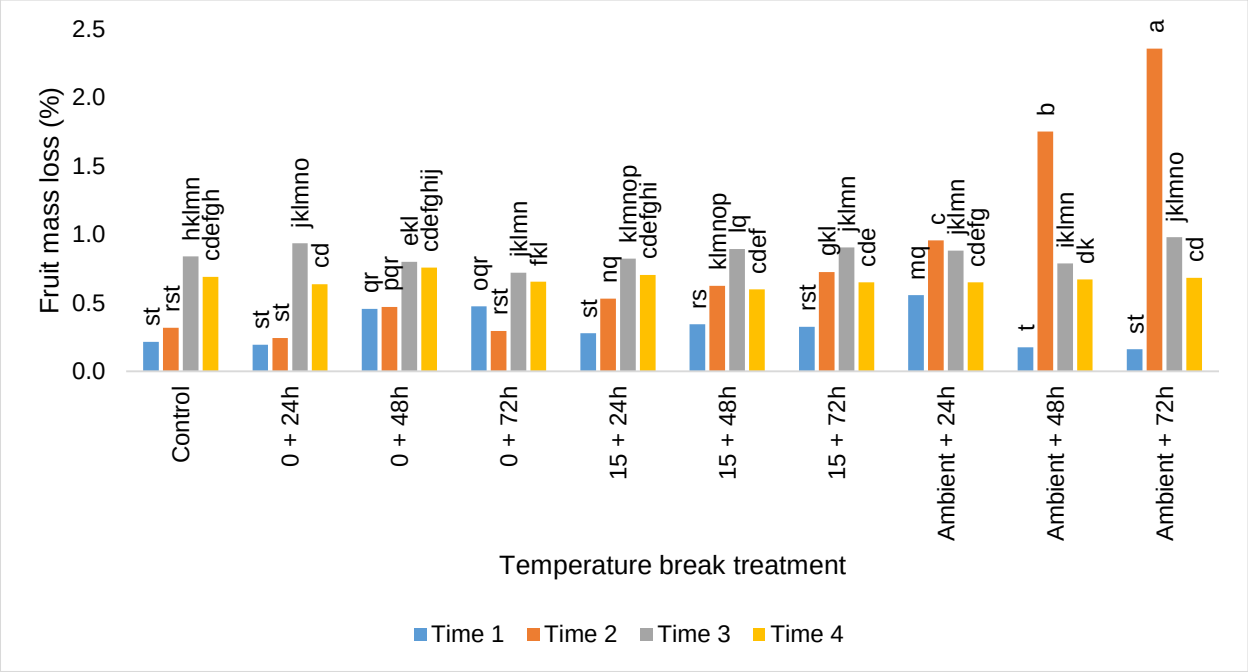
| Examination parameter[1] | Evaluation time[2] | Treatments[3] (A) | | | | | | | | | | Evaluation time (B)[2] | | | | Prob. > F | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 1 | 2 | 3 | 4 | A | B | A x B |
| 2013/14: | | | | | | | | | | | | | | | | | | |
| Firmness (kg) | 1+4 | 8.4 | 8.1 | 7.4 | 7.2 | 7.8 | 7.6 | 7.7 | 7.9 | 7.0 | 7.8 | 9.7a | | | 5.8b | 0.4800 | <0.0001 | 0.8341 |
| Hue angle | 1+3+4 | 13.1 | 14.5 | 18.6 | 15.7 | 14.1 | 11.4 | 11.9 | 15.4 | 14.2 | 13.1 | 17.1a | | 12.8b | 12.7b | 0.7238 | <0.0001 | 0.7068 |
| Decay (%) | 3+4 | 1.3 | 0.0 | 1.3 | 1.3 | 0.0 | 0.0 | 1.3 | 2.5 | 2.5 | 1.3 | | | 1.3 | 1.8 | 0.0807 | 0.2630 | 0.5949 |
| Gel Breakdown (%) | 4 | 0.2b | 0.2b | 3.2a | 0.5b | 0.5b | 0.2b | 0.2b | 0.8b | 0.8b | 0.5b | | | | | <0.0115 | | |
| Aerated tissue (%) | 4 | 0.5c | 0.2c | 0.7c | 3a | 0.2c | 0.5c | 0.5c | 1.0c | 2.3ab | 3.2a | | | | | <0.0001 | | |
| 2014/15: | | | | | | | | | | | | | | | | | | |
| Decay (%) | 3 | 1.3a | 0.7a | 0.0a | 1.3a | 0.0a | 1.3a | 0.0a | 0.7a | 0.7a | 1.3a | | | | | 0.0300 | 0.0590 | 0.0200 |
| | 4 | 0.7a | 0.0a | 2.7a | 0.0a | 0.0a | 1.3a | 1.3a | 10.0b | 1.3a | 2.0a | | | | | | | |
| Gel Breakdown (%) | 3 | 0.0a | 0.0a | 0.0a | 0.0a | 1.1a | 0.0a | 0.0a | 0.0a | 0.0a | 0.0a | | | | | 0.0220 | 0.1490 | 0.0189 |
| | 4 | 0.0a | 0.0a | 0.0a | 0.0a | 0.0a | 0.0a | 0.0a | 16.7b | 0.0a | 0.0a | | | | | | | |
| Internal Browning (%) | 3 | 0.0a | 1.1a | 0.0a | 0.0a | 0.0a | 1.1a | 0.0a | 0.0a | 0.0a | 0.0a | | | | | 0.2330 | 0.1670 | 0.0180 |
| | 4 | 0.0a | 0.0a | 0.0a | 0.0a | 0.0a | 0.0a | 0.0a | 21.1b | 0.0a | 0.0a | | | | | | | |
| Aerated tissue (%) | 3+4 | 6.7 | 5.0 | 6.1 | 11.7 | 6.7 | 3.3 | 3.9 | 9.4 | 7.2 | 8.3 | | | 4.0b | 9.67a | 0.3170 | <.0001 | 0.5833 |

[1] Data pooled across evaluation time and temperature break treatments for non-significant interactions.

[2] Evaluation time 1 = At harvest, Evaluation time 2 = After FAC, Evaluation time 3 = After cold storage, Evaluation time 4 = After shelf-life.

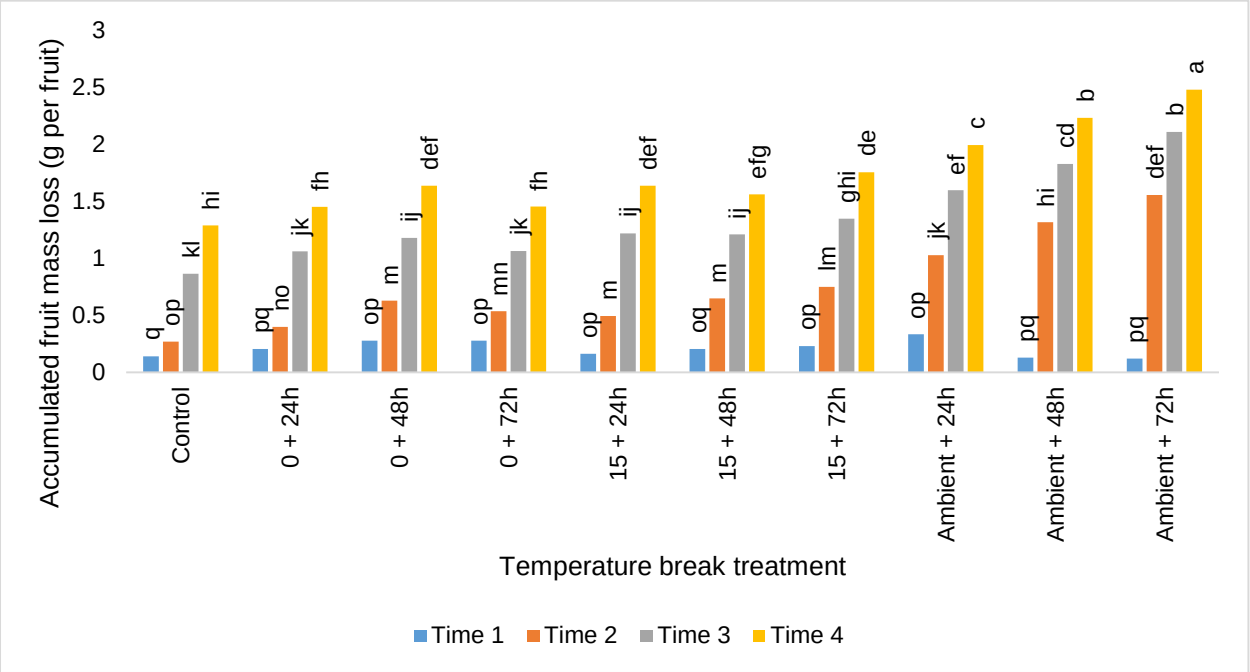
[3] For an explanation of what different treatments entailed, see Table 1.

## 9. Figures



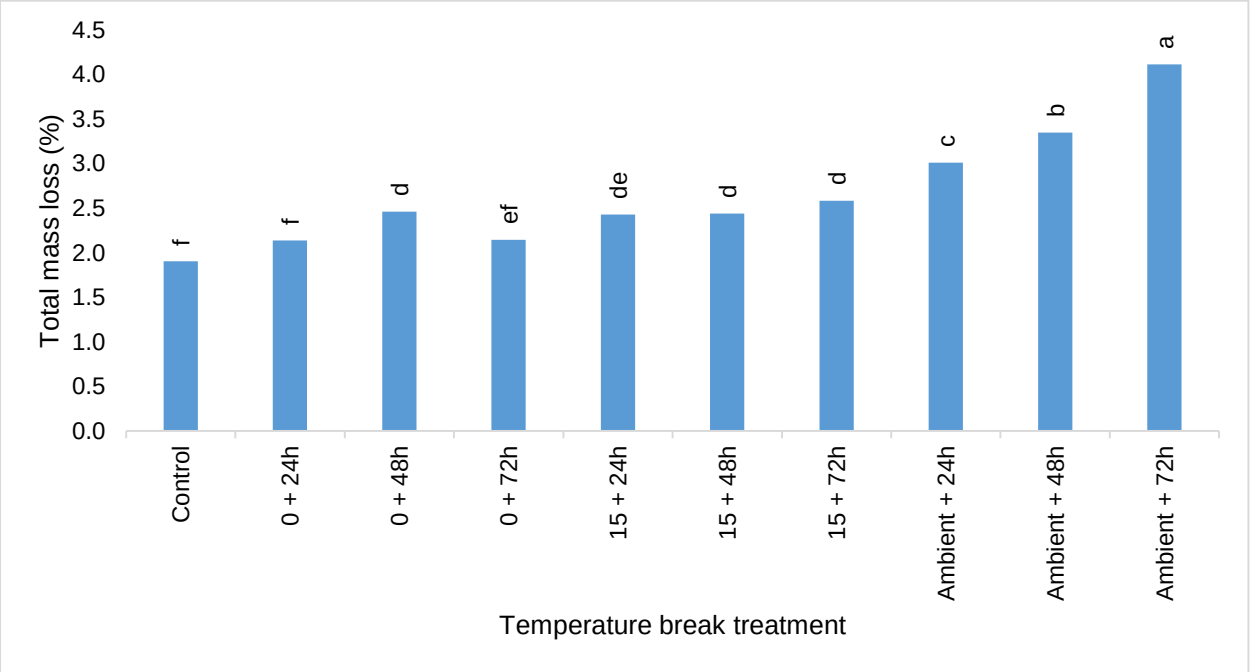

| Effect | F | p |
|---|---|---|
| Treatment | 27.94 | 0.0000 |
| Time | 167.19 | 0.0000 |
| Treatment x Time | **32.94** | **0.0000** |

**Fig. 1**. Fruit mass loss, expressed as a percentage, measured at different intervals in the postharvest handling chain. The data of the two seasons were pooled to remove the variation contributed by season in order to determine the effect of treatment only on fruit mass loss. Time 1 = time between harvest and arrival at the pack shed, Time 2 = time between field heat removal and the end of forced air cooling, Time 3 = time between end of forced air cooling and end of cold-storage (8 weeks at -0.5 °C), Time 4 = time between end of cold-storage and end of shelf-life (7 days at 10 °C). For an explanation of what different treatments entailed, see Table 1.




| Effect | F | p |
|---|---|---|
| Treatment | 16.84 | 0.0000 |
| Time | 6568.59 | 0.0000 |
| Treatment x Time | **61.70** | **0.0000** |

**Fig. 2.** Accumulated fruit mass loss (g per fruit) measured at different intervals in the postharvest handling chain. The data of the two seasons were pooled to remove the variation contributed by season in order to determine the effect of treatment only on fruit mass loss. Time 1 = time between harvest and arrival at the pack shed, Time 2 = time between field heat removal and the end of forced air cooling, Time 3 = time between end of forced air cooling and end of cold-storage (8 weeks at -0.5 °C), Time 4 = time between end of cold-storage and end of shelf-life (7 days at 10 °C). For an explanation of what different treatments entailed, see Table 1.




| Effect | F | p |
|---|---|---|
| Treatment | 31.96 | **0.0000** |

**Fig. 3.** Total fruit mass loss expressed as a percentage for each treatment from harvest until the end of shelf-life. The data of the two seasons were pooled to remove the variation contributed by season in order to determine the effect of treatment only on fruit mass loss. For an explanation of what different treatments entailed, see Table 1.

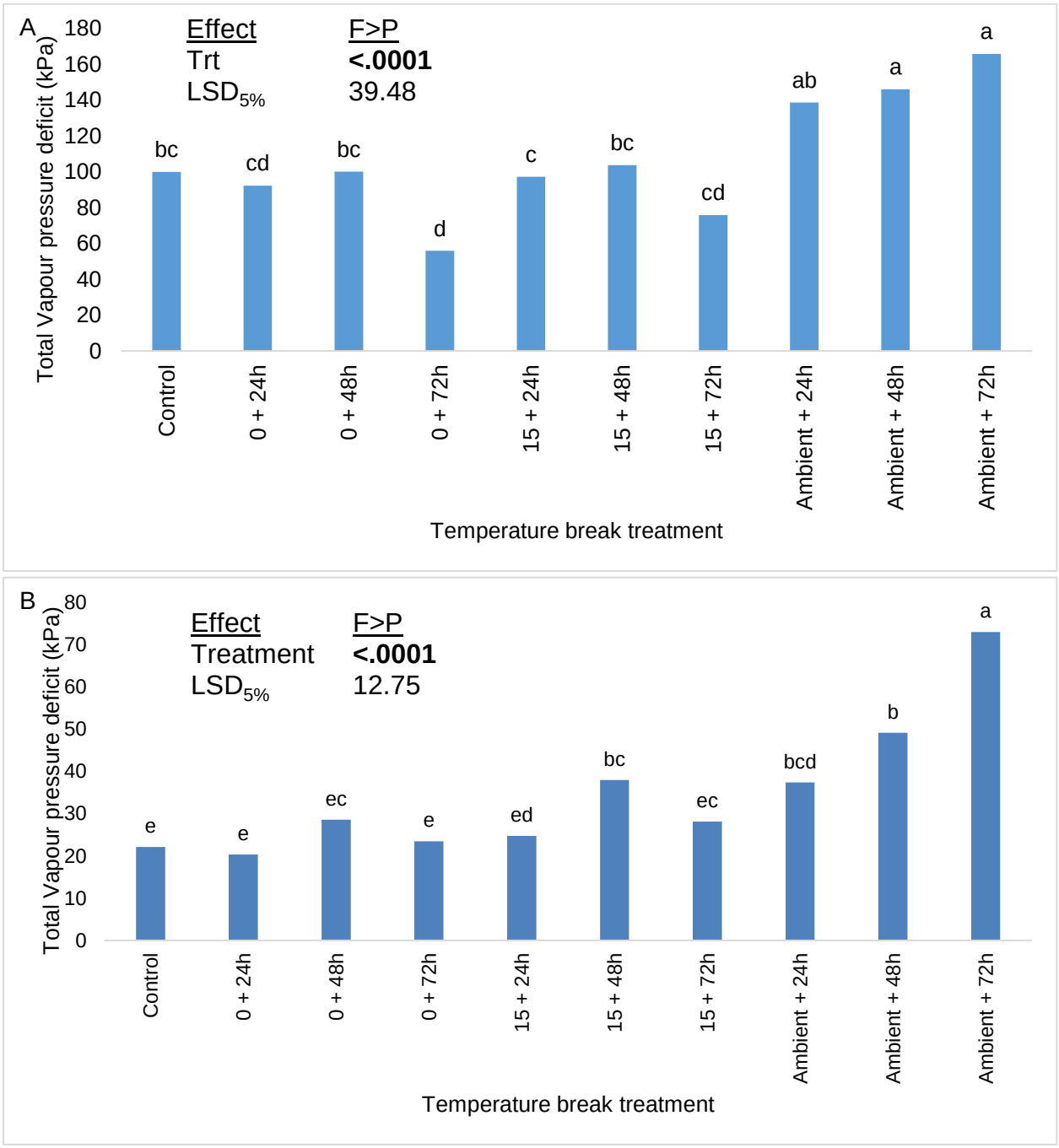
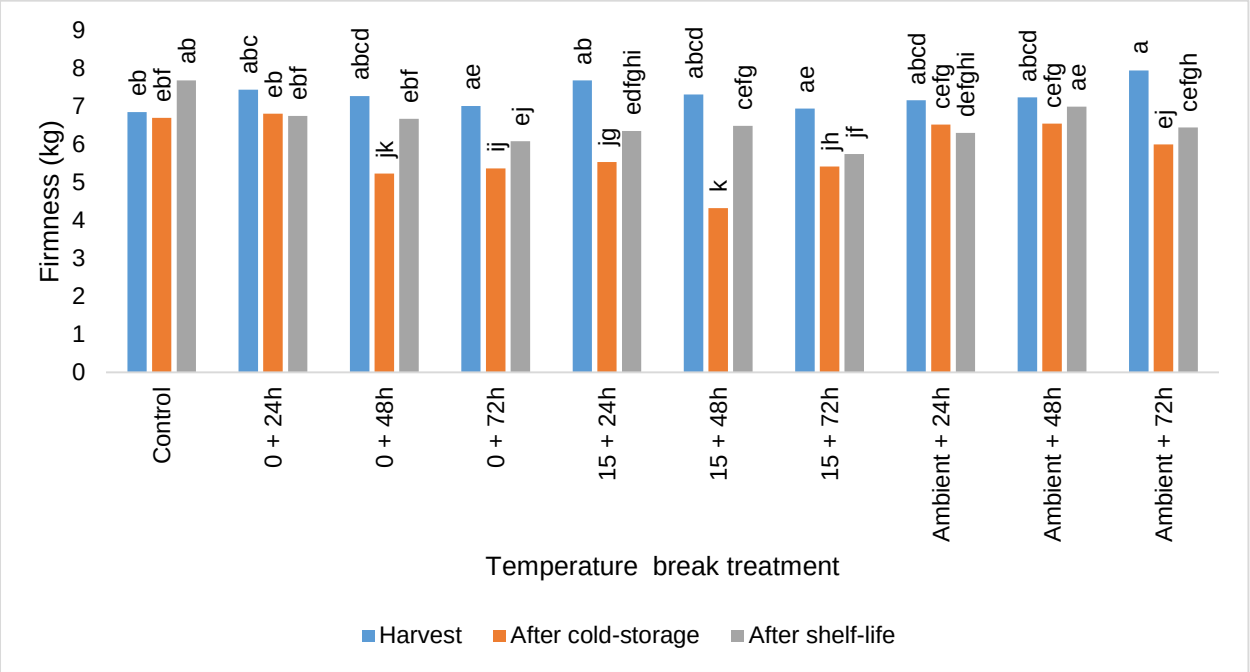
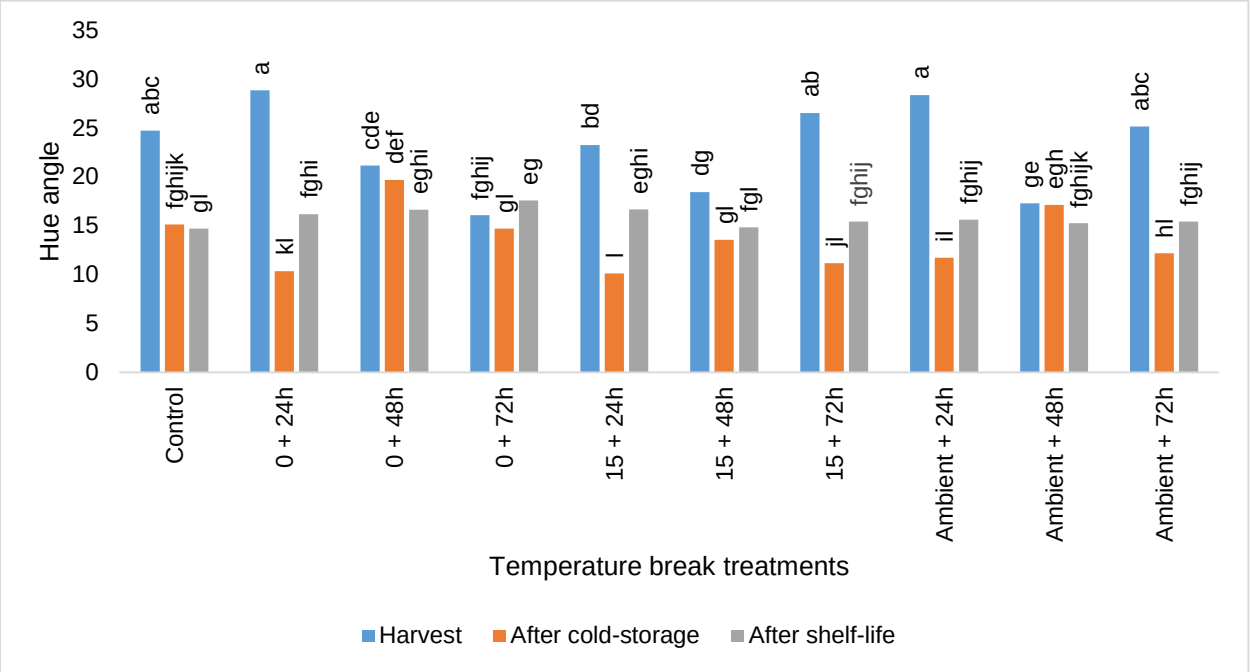



**Fig. 4**. Total vapour pressure deficit measured for each treatment from harvest until the end of shelf-life. Figure A represents the 2013/14 season and Figure B represents the 2014/15 season. For an explanation of what different treatments entailed, see Table 1.



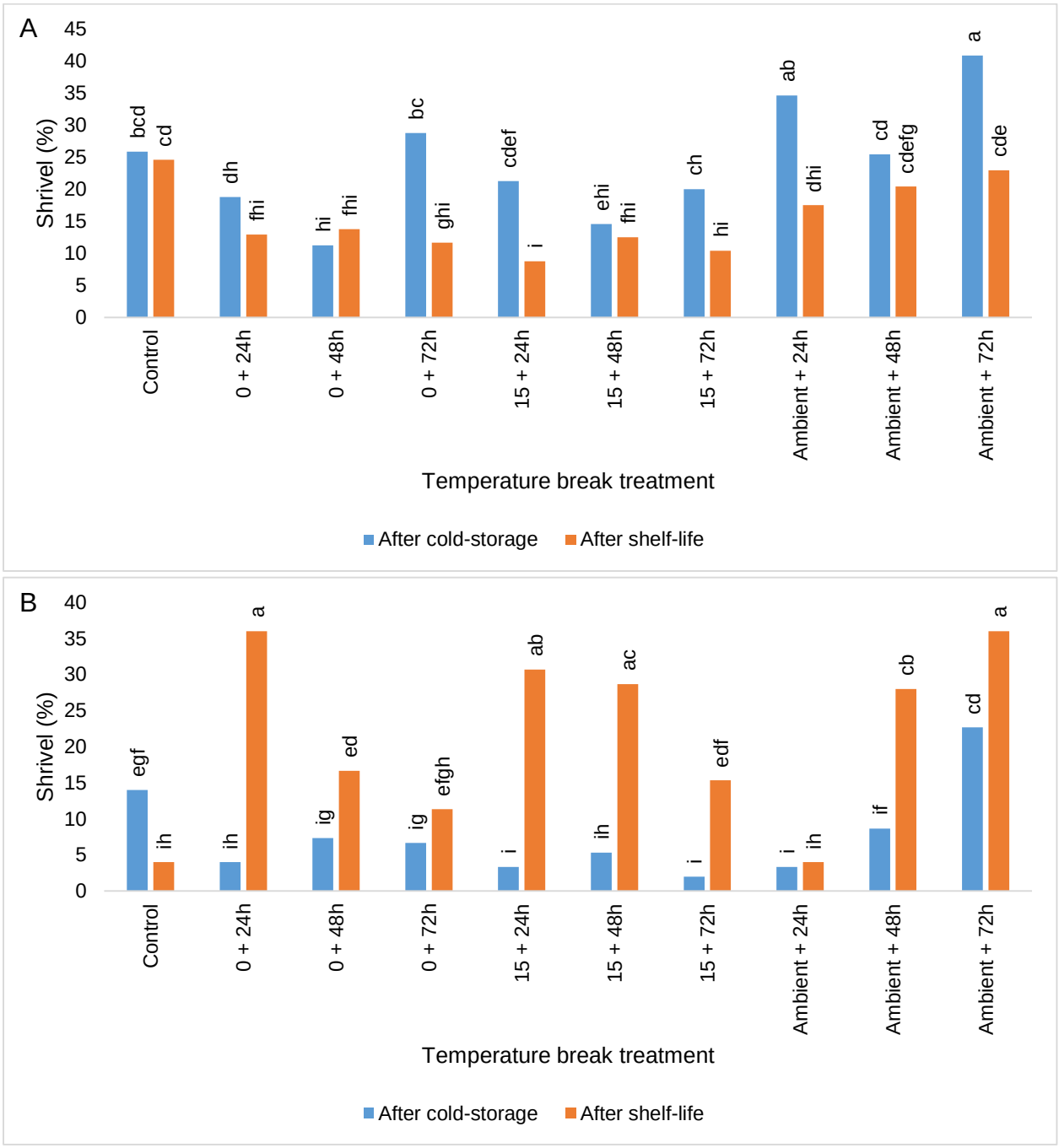

| Effect | F | p |
|---|---|---|
| Treatment | 3.57 | 0.002 |
| Evaluation | 36.12 | 0.0000 |
| Treatment x Evaluation | 2.01 | **0.0160** |

**Fig. 5.** The effect of precooling temperature on flesh firmness (kg) measured at harvest, after cold-storage (8 weeks at -0.5 °C) and after shelf-life (cold-storage plus 7 days at 10 °C), for the 2014/15 season. For an explanation of what the different treatments entailed, see Table 1.




| Effect | F | p |
|---|---|---|
| Treatment | 1.39 | 0.2100 |
| Evaluation | 75.09 | 0.0000 |
| Treatment x Evaluation | 4.24 | **0.0000** |

**Fig. 6.** The effect of pre-storage temperature breaks on hue angle measured at harvest, after cold-storage (8 weeks at -0.5 °C) and after shelf-life (cold-storage plus 7 days at 10 °C), for the 2014/15 season. For an explanation of what the different treatments entailed, see Table 1.




| Effect | F | | p | |
|---|---|---|---|---|
| | A | B | A | B |
| Treatment | 8.7 | 11.92 | 0.0000 | 0.0000 |
| Evaluation | 31.77 | 130.38 | 0.0000 | 0.0000 |
| Treatment x evaluation | 2.33 | 12.03 | **0.0277** | **0.0000** |

**Fig. 7.** The effect of precooling temperature on shrivel (%) manifestation measured after cold-storage (8 weeks at -0.5 °C) and shelf-life (cold-storage plus 7 days at 10

°C). Figure A represents the 2013/14 season and Figure B represents the 2014/15 season. For an explanation of what the different treatments entailed, see Table 1.

# PAPER 4:

# The effect of preharvest potassium silicate ($K_2SiO_3$) applications on the manifestation of hairline cracks in the peel of 'African Delight™' plum (*Prunus salicina* Lindl.)


## Abstract

'African Delight™' is a mid- to late season South African bred plum cultivar. The cultivar is characterized by large fruit and relatively high total soluble solids of 16 to 20 °Brix. Due to these characteristics the cultivar is extremely popular and is currently the fifth most planted cultivar in South Africa. Unfortunately the cultivar is prone to sunburn and postharvest shrivel. The cultivar develops concentric rings at the pedicel-end of the fruit, which was found to be open cracks in the fruit peel, allowing moisture loss. When and how these hairline cracks develop is still unknown and practices to reduce the incidence have not been developed. Silicate (Si) has been found to have a number of positive effects on fruit quality, inter alia that it could reduce shrivel incidence in 'Laetitia' plums. Hence, it was hypothesized that pre-harvest potassium silicate ($K_2SiO_3$) applications could reduce post-harvest moisture loss and consequent shrivelling in 'African Delight™' plums by strengthening and adding elasticity to the cell walls of the surface cells of the fruit to prevent hairline cracks from developing. Three treatments were evaluated in the study, namely a control where no Si was applied, a foliar Si spray and a root Si spray application. Fruit quality was determined at harvest, after cold-storage and after shelf life. No significant differences were found between the treatments at any of the evaluations indicating that $K_2SiO_3$ had no effect on crack width or incidence or other fruit quality characteristics. Although not significant, it was found that fruit treated with $K_2SiO_3$ had slightly lower levels of internal browning (a type of chilling injury). It is recommended that higher concentrations and more frequent applications of $K_2SiO_3$ should be evaluated in future studies to determine if it could reduce hairline cracks and postharvest shrivel manifestation in 'African Delight™' plums. Currently preharvest $K_2SiO_3$ applications are not recommended to improve plum fruit quality.


Keywords: Japanese plums, Moisture loss, Shrivel, Potassium silicate, $K_2SiO_3$

## 1. Introduction

'African Delight™', a mid- to late season South African bred Japanese plum cultivar, was released for commercial production in 2008 (Erasmus, 2012). The cultivar has characteristic large fruit and total soluble solids of 16 to 20 °Brix (CULDEVCO, 2008). Due to these favourable characteristics the cultivar is currently the fifth most planted cultivar in South Africa (>330 ha) and more than 600 000 cartons (5.25 kg equivalents) were exported in the 2013/2014 season (HORTGRO, 2014). Unfortunately the cultivar is prone to sunburn and postharvest shrivel (Erasmus, 2012). One of the characteristics of the cultivar is that it develops concentric rings at the pedicel-end of the fruit during fruit development (Fig. 1). It was found that these concentric rings are actually open, hairline cracks (Paper 1). It is suspected that these hairline cracks are responsible for the significantly higher peel permeability to water vapour of the cultivar compared to other South African bred Japanese plum cultivars (Paper 2). When and how these hairline cracks develop is still unknown and practices to reduce the incidence have not been developed, yet.

Moisture loss from perishable commodities manifests mainly as shrivelling, due to a loss in the turgidity of the surface cells of the fruit, or weight loss (Banks et al., 2000). Ultimately, moisture loss leads to a decrease in the quality of the fruit, rendering the product completely worthless resulting in economic losses to the industry (Sastry, 1985b). Researchers have reported that as little as a 5% loss in fresh weight can cause shrivelling in fresh produce (Ben-Yehoshua, 1987; Mitchell and Kader, 1989; Wills et al., 1989; Maguire et al., 2000). Weight loss is the result of two physiological processes in the fruit, namely moisture loss and respiration (Maguire et al., 2000). Moisture loss is driven by the diffusion of water vapour from the fruit and factors influencing diffusion can have an effect on moisture loss (Nobel, 1999). Fruit peel permeability, the difference in partial pressure of water vapour between the fruit and its environment and the surface area of a fruit have an effect on the extent of moisture loss through diffusion (Ben-Yehoshua, 1987).

The cuticle of the fruit is a very effective barrier to diffusion of water from the fruit and acts a protective layer between the product and its environment (Schönherr et al., 1979). The permeability of the peel determines the extent of gas exchange, as well

as the exchange of water vapour, between the fruit and its surrounding environment (Kerstiens, 1996; Díaz-Pérez et al., 2007). Water vapour exits the fruit at various openings (natural or caused by injury) in the fruit peel (Mitchell and Kader, 1989). Generally there are four exit routes through which moisture can escape from the fruit peel, namely wounds, stomata or lenticels, through the cuticle and cracks in the cuticle. Silicon (Si) is the second most abundant element in the earth's crust, but not essential for plants (Epstein, 1999; Etebarian et al., 2013). Si is mostly applied in the form of potassium silicate ($K_2SiO_3$), but other forms such as calcium ($CaSiO_3$) and nitrate silicate ($Na_2SiO_3$) are also used. Calcium and nitrate silicate are not as popular as $K_2SiO_3$ because they are less soluble (Kaluwa et al., 2010). Some researchers have found that Si can be beneficial when supplied to various plants (Nasr et al., 2013). It has been found to enhance strength and rigidity of cell walls by being deposited as amorphous silica ($SiO_2.H_2O$) and opal phytoliths and/or by interacting with pectins and polyphenols in the cell walls (Epstein, 1999; Marchner, 2002; Stamatakis et al., 2003). Cell wall elasticity during extension growth is also increased by the application of Si (Marchner, 2002). Si provides mechanical strength to plant cell walls, allowing them to be resistant to bacteria, fungi and insects (Menzies et al., 1991; Menzies et al., 1992; Epstein, 1999). Si can also associate with cell wall proteins and it is suggested that these associations may trigger the production of natural defence compounds such as chitinases, peroxidases, polyphenol oxidases and flavonoid phytoalexins that protect the plant against pathogen attacks (Chérif et al., 1994; Currie and Perry, 2007). It was also found that low concentrations of Si in post-harvest dips reduced chilling injury in lemon (Mditshwa et al., 2013). In a preliminary study done by Kritizinger and Jooste (2014) to determine if pre-harvest $K_2SiO_3$ applications could reduce the incidence of broken stones in 'Laetitia' plums, it was found that Si reduced postharvest shrivel. It was found that $K_2SiO_3$ applications also reduced moisture loss from lemons (Mditshwa et al., 2013) and avocados (Nasr et al., 2013). Reduced shrivel manifestation could be explained by an increase in strength or elasticity of the cell walls by silicate which could prevent the surface cells to display a loss in turgidity. Consequently, it was hypothesized that pre-harvest $K_2SiO_3$ sprays could reduce post-harvest moisture loss and consequent shrivelling in 'African Delight™' plums by strengthening and adding elasticity to the surface cell walls to prevent hairline cracks

from developing. The aim of this paper was, therefore, to determine if post-harvest shrivel could be reduced by pre-harvest $K_2SiO_3$ applications.

## 2. Materials and methods

### 2.1. Plant material

The trial was conducted on 'African Delight™' plums (*Prunus salicina* Lindl.) in the 2014/15 season on a commercial farm, Bourgogne, in the Franschhoek area, South Africa (33°55′33.26″ S 19°07′03.02″ E). Trees on 'Marianna' rootstock were planted in 2009 at a planting distance of 4 x 1 m and trained to a Tatura trellis system.

### 2.2. Experimental layout

A randomized complete block design with eight two-tree plots per treatment was used (8 x 3 = 24 plots). Two buffer trees were left between plots as well as rows where necessary to prevent drift from foliar applications.

### 2.3. Treatments

Treatments consisted of a control, where the normal orchard spray programme was followed, and two $K_2SiO_3$ treatments, namely a foliar and root application. Apart from the $K_2SiO_3$ applications, standard cultivation practices and spraying programme were followed in the orchard. Root applications started at full bloom and were applied every 4 weeks until harvest. In total there were 6 root applications. Foliar applications started 3 weeks after full bloom and were applied every 2 weeks when the wind speed was less than 4 m $s^{-1}$ until the harvest date. In total 11 foliar applications were applied. AgriSil™ K50 (PQ Corporation, Wolseley), containing 33 g $kg^{-1}$ potassium (K) and 96 g $kg^{-1}$ silica (Si), was applied at a rate of 5 kg $ha^{-1}$ for both the foliar and root treatments. For each $K_2SiO_3$ application both sides of the tree was sprayed for 30 s with a motorised rucksack sprayer (Stihl, Waiblingen, Germany), delivering 2 L of solution per tree at a concentration of 100 mL 100 $L^{-1}$ of water or 5 kg $ha^{-1}$. No surfactant was used for the $K_2SiO_3$ treatments. The foliar application was done by spraying the full canopy of the trees, while the root application was done by spraying the full area under the drip line of the tree.

Fruit were harvested on the commercial harvest date. A sample of 70 fruit was harvested per block per treatment. Forty fruit per treatment per block were packed, according to commercial export standards, into two count 20 pulp trays which were placed in a 5.25 kg export carton lined with a perforated (54 x 2 mm) high density polyethylene (HDPE) bag with a thickness of 16 µm. Thirty fruit per treatment per block were placed in plastic bags and used to determine fruit quality and maturity on the harvest date.

## 2.4. Fruit evaluation

Upon arrival at the laboratory at the Department of Horticultural Science, Stellenbosch University, the thirty bagged fruit per block were visually inspected for concentric, hairline cracks at the pedicel-ends of the fruit. Fruit were grouped according to three classes of concentric rings, namely (1) no concentric rings, (2) concentric rings limited to the pedicel cavity area, and (3) concentric rings extending over the shoulder at the pedicel-end of the fruit (Fig. 1). Crack width was determined on one peel sample per fruit of five fruit per block per treatment (five peel samples per block per treatment, or 40 peel samples per treatment) to determine severity of hairline cracks per treatment. The same method was followed as described in Paper 1.

## 2.5. Harvest maturity

Hue angle was determined on both cheeks of five fruit per block per treatment using a calibrated colorimeter (Minolta chroma meter CR-400, Japan). Flesh firmness was determined on both peeled cheeks of 25 fruit per block per treatment using a FTA (Fruit Texture analyser, Güss Instruments) fitted with an 11 mm tip. Total soluble solids (TSS, %Brix) was determined on a pooled juice sample of 25 fruit per block per treatment using a temperature controlled, digital refractometer (Palette, PR-32 ATAGO, Bellevue, USA). Total titratable acidity (TA, %) was determined on a pooled juice sample of 25 fruit per block per treatment. TA was determined by titrating a 10g aliquot of the juice sample with 0.1 M NaOH to a pH end-point of 8.2 using an automated titrator (Metrohm AG 760, Herisau, Switzerland).

### 2.6. Cold storage

One carton of fruit per treatment per block was stored at -0.5 °C for 56 d.

### 2.7. Fruit quality evaluation

After cold-storage 20 fruit in the top layer as well as the perforated bag of each carton were removed and the remaining fruit in each carton was placed at 10 °C for 7 d to simulate shelf-life conditions. After cold-storage and after shelf-life 20 fruit per treatment per block were evaluated for shrivel (%) as well as decay (%).Shrivel was recorded when the shrivelled peel reached over the shoulder of the fruit. Hue angle and flesh firmness were determined as described for harvest maturity. Hue angle was determined on both cheeks of five fruit per block per treatment. Flesh firmness was determined on both peeled cheeks of 8 fruit per block per treatment. Internal disorders were determined by cutting 12 fruit per block per treatment around the equatorial axis separating the fruit into two halves. Disorders were recorded as a percentage. A gelatinous breakdown of the inner mesocarp tissue surrounding the stone, while the outer mesocarp tissue has a healthy appearance, was classified as gel breakdown (GB). A brown discolouration of the mesocarp tissue, associated with a loss in juiciness, was classified as internal browning (IB). A dry, firm, whitish mesocarp tissue was classified as aerated tissue (AT).

### 2.8. Statistical analyses

Data was analysed with a mixed model repeated measures analysis of variance using SAS enterprise guide version 5.1 (SAS Institute Inc., 2012). ANOVA-generated P-values and the significant differences between means were determined using Fisher's least significant differences (LSD) test with a 95% confidence interval.

## 3. Results

### 3.1. Crack width and concentric hairline crack incidence

Open cracks in the peel were found in most of the fruit (Table 1). There were no significant differences in crack width between treatments. Similarly, no significant differences were found between treatments in the number of plums without concentric

cracks, plums with concentric cracks within the pedicel area and plums with concentric cracks extending over the shoulder of the fruit.

3.2. Maturity indexing at harvest

Maturity indexing was done at harvest by means of measuring fruit firmness, TSS, hue angle and TA. It was found that the treatments did not differ regarding their maturity at harvest (Table 1).

3.3. Evaluation after cold storage

The treatments did not differ significantly regarding flesh firmness, hue angle, shrivel (%), decay (%) or internal disorders (%) after cold storage of 8 weeks (56 d) at -0.5 °C (Table 2). Although differences were not significant, Si treatments tended to have higher shrivel levels compared to the control.

3.4. Evaluation after simulated shelf-life

The treatments did not differ significantly regarding flesh firmness, hue angle, shrivel (%), decay (%) or internal disorders (%) after the simulated shelf-life of 7 d at 10 °C (Table 3). Although differences were not significant, Si treatments tended to have higher shrivel levels and lower internal browning levels (a type of chilling injury) compared to the control.

**4. Discussion**

Fruit firmness, hue angle, TA and TSS did not differ significantly between the three treatments (root Si application, foliar Si application and control) at harvest, after cold storage and after shelf life. Flesh firmness and hue angle decreased during storage indicating that the ripening process continued throughout storage. The decrease in flesh firmness is caused by the biosynthesis of ethylene (produced during ripening) which activates enzymes involved in fruit softening. Enzymes cause changes in the primary cell wall components leading to decreased flesh firmness (Taiz and Zeiger, 2010). Ethylene production during fruit ripening also lead to changes in chlorophyll, carotenoid and flavonoid concentrations allowing colour pigments to be more exposed, giving fruit a redder appearance (Taiz and Zeiger, 2010).

The occurrence of concentric hairline cracks was not influenced by the two Si treatments. Not only did the Si applications not have an effect on the concentric hairline crack incidence, it also failed to reduce the width of the concentric hairline cracks. This indicates that the Si did not enhance the mechanical strength and elasticity of the cell walls in the plum fruit peel as was found in other studies (Menzies et al., 1991; Menzies et al., 1992; Epstein, 1999; Marchner, 2002).

A number of studies found that $K_2SiO_3$ has the ability to reduce moisture loss through the cuticle (Marchner, 2002; LiQun et al., 2006; Ma and Yamaji, 2006; Mditshwa et al., 2013; Nasr et al., 2013). Kritizinger and Jooste (2014) also observed that plums treated with $K_2SiO_3$ had slightly lower levels of shrivel than plums that were not treated. The same effect could not be achieved in this study. It may be that not only the fruit type, but also the specific cultivar reacted differently to the $K_2SiO_3$ applications compared to what was found in the other studies. It was found that the treated fruit had slightly higher shrivel levels compared to the control. The reason for this is not clear. Although the concentration and application frequency was according to the supplier of the product, it is possible that the concentration that was used was too low or that applications must be made more frequently. It is, hence, suggested that this should be evaluated in further studies.

Internal browning (a type of chilling injury) did not differ significantly between treatments, but it was found that the Si treatments, especially the foliar application, tended to reduce the incidence of this defect after cold-storage and after the simulated shelf-life period. Mditshwa et al. (2013) also found that post-harvest Si dips reduced chilling injury in lemons. In this study the incidence of internal browning was very low, and it is recommended to verify this result in further studies in order to determine if Si treatments are able to reduce chilling injury in plums. This finding also supports the finding that Si can protect crops against abiotic stresses to some extent (Currie and Perry, 2009). Other quality parameters which were determined, such as decay incidence, and the manifestation of gel breakdown and aerated tissue, did not differ significantly between treatments, at both fruit evaluations, and levels were generally very low.

## 5. Conclusion

The aim of this study was to determine if pre-harvest use of Si by means of root or foliar applications could reduce postharvest shrivel manifestation in 'African Delight™' plums. It was expected that $K_2SiO_3$ would lower the permeability of the fruit peel cuticle and strengthen cell walls whilst improving elasticity. It was also expected that $K_2SiO_3$ would reduce the width of the concentric hairline cracks, or prevent crack formation at the pedicel end of the fruit. However, we found that fruit treated with $K_2SiO_3$ did not differ from the control regarding the formation of the hairline cracks, the width of the cracks or postharvest shrivel manifestation. For future studies it is recommended to use higher concentrations of $K_2SiO_3$ and more frequent applications to determine if it could reduce hairline cracks and postharvest shrivel manifestation in 'African Delight™' plums. Currently preharvest $K_2SiO_3$ applications are not recommended to improve plum fruit quality.

## 6. Acknowledgements

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## 8. Tables

### Table 1.

Quality of 'African Delight™' plums **at harvest**. Fruit were treated with and without $K_2SiO_3$ applications. Foliar $K_2SiO_3$ was applied every 2 weeks from 4 weeks after full bloom until harvest and a $K_2SiO_3$ root drench was applied every 4 weeks from 3 weeks after full bloom until harvest.

| Variables | Treatment | | | *LSD (P ≤ 0.05)* | *Prob. > F* |
|---|---|---|---|---|---|
| | Control | $K_2SiO_3$ foliar application | $K_2SiO_3$ root application | | |
| Crack width (nm) | 83.95 | 78.24 | 83.95 | *9.00* | *0.0928* |
| No rings (Class 1)[1] | 0.12 | 2.25 | 2.00 | *2.15* | *0.1036* |
| Rings inside (Class 2)[1] | 8.12 | 8.87 | 8.87 | *3.32* | *0.8568* |
| Rings over shoulder (Class 3)[1] | 21.75 | 18.87 | 19.12 | *4.10* | *0.2831* |
| Rings (Total)[1] | 29.87 | 27.75 | 28.00 | *2.15* | *0.1036* |
| Flesh firmness (kg) | 7.93 | 7.89 | 7.54 | *0.37* | 0.0806 |
| Hue angle | 19.35 | 19.96 | 20.70 | *3.31* | *0.69* |
| Total soluble solids (%) | 16.55 | 16.01 | 16.03 | *0.61* | *0.1425* |
| Titratable malic acid (%) | 1.18 | 1.16 | 1.16 | *0.05* | *0.6551* |

[1] Fruit were classified according to a self-developed classification system (Fig. 1) where fruit with no concentric rings were classified as Class 1, fruit with concentric rings in the stem (pedicel) cavity as Class 2 and fruit with concentric rings spreading over the shoulder of the fruit were classified as Class 3.

**Table 2.**

Quality of 'African Delight™' plums **after cold storage of 8 weeks at -0.5 °C**. Fruit received preharvest $K_2SiO_3$ applications. Foliar $K_2SiO_3$ was applied every 2 weeks from 4 weeks after full bloom until harvest and a $K_2SiO_3$ root drench was applied every 4 weeks from 3 weeks after full bloom until harvest.

| Variables | Treatment | | | *LSD (P ≤ 0.05)* | *Prob. > F* |
|---|---|---|---|---|---|
| | Control | $K_2SiO_3$ foliar application | $K_2SiO_3$ root application | | |
| Flesh firmness (kg) | 5.73 | 5.58 | 5.88 | *0.76* | *0.6958* |
| Hue angle | 13.22 | 12.51 | 14.74 | *2.38* | *0.1597* |
| Shrivel % | 14.37 | 20.00 | 16.25 | *9.79* | *0.4747* |
| Decay (%) | 0.00 | 0.62 | 0.00 | *1.04* | *0.3927* |
| Internal Browning (%) | 0.00 | 0.00 | 1.04 | *1.82* | *0.3927* |
| Gel Breakdown (%) | 1.04 | 0.00 | 0.00 | *1.82* | *0.3927* |
| Aerated Tissue (%) | 1.04 | 2.08 | 4.16 | *5.55* | *0.4887* |

**Table 3.**

Quality of 'African Delight™' plums after cold storage of 8 weeks at -0.5 °C **plus a simulated shelf-life of 7 days at 10 °C**. Fruit received preharvest $K_2SiO_3$ applications. Foliar $K_2SiO_3$ was applied every 2 weeks from 4 weeks after full bloom until harvest and a $K_2SiO_3$ root drench was applied every 4 weeks from 3 weeks after full bloom until harvest.

| Variables | Treatment | | | *LSD (P ≤ 0.05)* | *Prob. > F* |
|---|---|---|---|---|---|
| | Control | $K_2SiO_3$ foliar application | $K_2SiO_3$ root application | | |
| Flesh firmness (kg) | 5.89 | 5.90 | 6.08 | *0.72* | *0.8277* |
| Hue angle | 17.83 | 17.08 | 18.38 | *1.82* | *0.3366* |
| Shrivel (%) | 16.87 | 19.37 | 25.00 | *15.67* | *0.5377* |
| Decay (%) | 0.62 | 1.25 | 0.00 | *1.49* | *0.2338* |
| Internal Browning (%) | 2.08 | 0.00 | 0.00 | *3.64* | *0.3927* |
| Gel Breakdown (%) | 1.04 | 1.04 | 1.04 | *3.37* | *1.0000* |
| Aerated Tissue (%) | 2.08 | 2.08 | 3.12 | *5.47* | *0.8956* |

## 9. Figures

Class 1 Class 2 Class 3

**Fig. 1**. The colour chart that was developed to classify fruit with concentric rings into three classes, namely Class 1 (no concentric rings), Class 2 (concentric rings limited to the pedicel cavity area) and Class 3 (concentric rings extending over the shoulders at the pedicel end of the fruit).

# GENERAL DISCUSSION AND CONCLUSION

Some of South Africa's popular exporting plum cultivars are susceptible to shrivel. This poses a real problem as customers expect fruit to look fresh. Moisture loss from perishable commodities manifests mainly as shrivelling due to a loss in the turgidity of the surface cells of fruit, or as weight loss (Sastry, 1985; Banks et al., 2000). Ultimately, moisture loss leads to a decrease in the quality of the fruit, rendering the product worthless, and resulting in economic losses to the industry (Sastry, 1985). Many authors reported that as little as a 5% loss in fresh weight can cause fruit to develop a shrivelled appearance (Ben-Yehoshua, 1987; Mitchell and Kader, 1989; Wills et al., 1989; Maguire et al., 2000).

The aim of Paper 1 was to determine if hairline cracks contribute towards moisture loss from Japanese plums. Fluorescent microscopy was done on 'African Delight™' (very susceptible to shrivel), 'Sapphire' (susceptible to shrivel), 'Laetitia' (susceptible to shrivel) and 'Songold' (not susceptible to shrivel) plums to determine if there were any cracks or openings in their peels. It was found that the concentric rings at the pedicel end of 'African Delight™' plums were indeed open hairline cracks. It was also found that 'African Delight™' fruit with wide hairline cracks had a higher water vapour permeance than fruit with narrow or no hairline cracks. This finding indicates that the water vapour permeance of the fruit peel of 'African Delight™' plums is linked to the width of the hairline cracks in the peel. Similar to this study, Peschel and Knoche (2005) also found a positive correlation between the number of micro cracks in the cuticular membrane and the permeability of the excised peel segments of European plums (*Prunus domestica* Lindl.).

The exact reason why 'African Delight™' develops hairline cracks is not clear. It is suggested that cuticular cracks develop from an imbalance between wax production, growth of the fruit pulp and cuticle (Roy et al., 1994; Keren-Keiserman et al., 2004). Rapid fruit growth of fleshy fruit can also cause cuticular cracks to occur (Christensen, 1973; Ohta et al., 1997; Peschel and Knoche, 2005). It is interesting to note that the development of hairline cracks started at the stem end of the fruit and, in severe cases, spread over the shoulder towards the cheek of the plum. The reason for this may be that the curvature over the shoulder area is the largest for the whole

fruit and the stress, theoretically, should be the largest in that area (Considine and Brown, 1981). The development of hairline cracks in 'African Delight™' may also be linked to environmental conditions such as temperature or relative humidity (Martin and Rose, 2014).

The three shrivel susceptible cultivars investigated in this study, namely African Delight™, Laetitia and Sapphire, had open lenticels in their peel. Brown and Considine (1982) found that lenticels and other rigid bodies in the fruit peel could lead to rupturing of the cuticular membrane, allowing moisture loss and pathogen entry. Hairline cracks and open lenticels serve as pathways for moisture loss from the fruit by allowing water to bypass the relative impermeable barrier of the cuticle and escaping into the atmosphere (Mitchell and Kader, 1989). This route of moisture loss is more rapid than the diffusion route through cell membranes and an intact cuticular membrane (Maguire et al., 1999). In this study no open lenticels or any form of skin cracks were found in the peel of 'Songold' plums. The lack of open lenticels or cracks in this cultivar's peel is probably the reason why it is not susceptible to the manifestation of postharvest shrivel.

The aim in Paper 2 was determine the main preharvest factor/factors responsible for moisture loss in order to develop or refine postharvest handling protocols to ensure that moisture loss, and hence postharvest shrivel manifestation, can be reduced to the minimum in Japanese plums. The water vapour permeance of 'African Delight™', 'Laetitia' and 'Songold' was determined weekly from 4 weeks before the optimum harvest date until post-optimum maturity. There was an increase in water vapour permeance of 'African Delight™', 'Laetitia' and 'Songold' plums with later sampling dates in both seasons. Pieniazek (1943) and Maguire et al. (2000) also found that the water vapour permeability of apples increased as fruit matured past their optimum maturity and could possibly be explained by changes in cuticular waxes and the thickness of the cuticle.

For all three cultivars it was found that the fruit to fruit variation was the largest contributor (>45%) to the total variation in water vapour permeance of the cultivars included in this study. Since the variation between trees in the same orchard was small, the result indicates that the water vapour permeance of the cultivars included in

this study was due to fruit characteristics, and that the influence of the physiology of the whole tree and genetic variation were minimal. Maguire et al. (2000) found that fruit to fruit variation contributed 22% to the permeance of apple fruit. The large fruit to fruit variation in this study could have been caused by fruit not being of the same maturity, although care was taken to sample fruit that were visually the same size and having the same peel colour. Fruit maturity is also not determined on the packing line, but fruit is sorted by their visual appearance (colour) and size. This leads to large fruit to fruit variation in packed cartons, explaining why some fruit in a carton develop a shrivelled appearance and others not.

Orchard differences explained ≥ 15% of the total variation of the cultivars included in this study. It was found that none of the orchards used stood out from the rest with regards to permeability, except for Farm 5 (Terra de Luc 1) of 'African Delight™' in the 2013/14 season and Farm 2 (Bourgogne) of 'African Delight™' in the 2014/15 season. The reason for these farms having higher permeances could be caused by high levels of insect damage (Farm 5) or crack incidence (Farm 2) (personal observation). Generally the water vapour permeability did not differ much between farms for 'Laetitia' and 'Songold' in the 2014/2015 season. Therefore, no specific growing conditions could be identified to minimize the permeance of the fruit peel for these cultivars. Crisosto et al. (1994) found that when fruit received excessive amounts of irrigation the fruit's cuticle was thinner and more susceptible to shrivel compared to fruit which received optimal or deficit irrigation. Hence, it is suggested that producers should make sure that they are using optimal irrigation regimes for their plum orchards.

Harvest date also played a significant role in the total variation in peel permeability of the three cultivars. It was found that the water vapour permeance started to increase from about 2 weeks before the optimum harvest date until fruit were well past their optimum maturity. Pieniazek (1943) and Maguire et al. (2000) also found that apple fruit harvested later in the season had a higher permeability to water vapour which could be caused by changes in the cuticle thickness and composition over time.

For the second part of the study where the peel permeability of different cultivars were compared, fruit to fruit variation also made the biggest contribution to the total variation in the water vapour permeance of the fruit. In the 2013/2014 season

it was found that cultivar also made a large contribution (> 40%) towards the total variation, but this was probably due to the relatively small sample size (only one orchard of each cultivar was selected on a single farm). The much bigger sample size used in the 2014/2015 season (5 orchards per cultivar) resulted in cultivar not having such a big influence (5%) of the total variation in peel permeability. Maguire et al. (2000) found that cultivar differences explained 30% of the total variation in apple peel permeability, but this could not be proven in plums. Variance in permeance caused by cultivar differences may be related to variance in physical and chemical properties of the outer layers of the fruit. These properties may include the presence of open lenticels (Pieniazek, 1944), cuticle thickness (Kamp, 1930), the presence of micro cracks (Peschel and Knoche, 2005), and the amount and type of cuticular waxes (Riederer and Schneider, 1990).

The increase in permeance observed when fruit were allowed to pass their optimum maturity may be the result of changes in the above mentioned factors or of a combination of changes in these factors. Since these parameters were not measured in this study it is not possible to make exact suggestions as to why the permeance increased with an increase in fruit maturity. It is suggested that the causes for these increases in peel permeability must be explored by further studies. It was found that ‘African Delight™’ plums had slightly higher water vapour permeability than Laetitia’ and ‘Songold’. This could be explained by the concentric hairline cracks found at the pedicle end of ‘African Delight™’ plums (Paper1). Open lenticels was found in the peel of ‘African Delight™’ and ‘Laetitia’ in Paper 1, but the effect thereof on moisture loss could not be determined. Pieniazek, (1944) found that lenticels in apple peel contributed to the moisture loss of the fruit and that the removal of the cuticular waxes increased moisture loss. Unfortunately the composition and thickness of the cuticular waxes are not known for cultivars examined in this study.

In Paper 3 the aim was to determine to what extent producers can postpone packing and cooling of ‘African Delight™’ plums after harvest. Generally mass loss increased with an increase in pre-cooling time for fruit precooled to 0°C, 15°C and ambient (approx. 25 °C) for Time 2 (period between arrival at the pack house and the end forced air cooling (FAC)). Fruit kept at ambient before they were packed and force air cooled showed significant increases in mass loss as precooling time increased.

This can be explained by the large VPD between the fruit and the environment. Fruit that were kept at ambient for 72 h had the highest total mass loss because of exposure to high VPD's for an extended period compared to fruit kept at ambient for only 24 h. This high VPD caused moisture to be lost from the fruit.

Large VPD's are one of the driving forces behind moisture loss and may be linked to the potential risk for shrivelling to occur (Kays, 1991; Thompson, 1992). When fruit are harvested they are removed from their source of water which causes the fruit to be more susceptible to moisture loss due to a large VPD between the fruit and the surrounding ambient air (Van den Berg, 1987). Shrivel occurs under circumstances where dehydration occurs as water lost from the surface of the fruit is not replaced and the tissue contracts (Burdon et al., 2014). It was found that Time 2, 3 (cold-storage period) and 4 (shelf-life period) made considerable contributions towards the total mass loss, namely 0.83, 0.86 and 0.67%, respectively. However, Time 2 was a relatively short period (max. 72 h) compared to Time 3 (8 weeks at -0.5 °C) and Time 4 (1 week at 10 °C), indicating that the large VPD's experienced during Time 2 must have made a significant contribution to moisture loss and shrivel manifestation. The total VPD of fruit precooled to 0 °C for 24, 48 and 72 h and to 15 °C for 24 and 72 h did not differ significantly from the control. This was a surprising finding as the control was cooled to -0.5°C in a much shorter time than the other treatments. The reason for this is probably because the control fruit was warm when FAC commenced, and the cold air forced over it resulted in a large initial VPD. In the 2013/14 season it was found that fruit kept for 72 h at 0 °C had a significantly lower VPD than the control. This is because this fruit was already at 0 °C when FAC commenced, causing a smaller VPD during the initial FAC time compared to the control (Kays and Paull, 2004). Ambient treatments did not differ significantly from each other in the 2013/14 season, but total VPD increased significantly with pre-cooling time in the 2014/15 season. The VPD's for these three treatments were higher than the other treatments because the relative humidity (RH) of the surrounding air of the room where fruit was kept was much lower than the air in the cold rooms where the other treatments were placed, which was closer to saturation. Since the air in the intercellular spaces of the fruit is almost saturated with water vapour (Ben-Yehoshua, 1987) and, therefore, at a higher RH than the surrounding ambient air, the VPD between the fruit kept at ambient and the air

surrounding them will be high. This high VPD between fruit kept at ambient and the holding room will drive moisture loss.

They main fruit quality parameter measured in this study was shrivelling. During the 2013/14 season shrivel was determined on the same fruit after cold-storage and after shelf-life, and a decrease in shrivel levels was observed between the two evaluation times in almost all treatments. It is suggested that the decrease in shrivel levels during the shelf-life period is probably due to cell wall disassembly in conjunction with a loss in the turgidity of the mesocarp cells during fruit ripening at the higher storage temperature (10 °C) (Jooste, 2012). In both seasons the fruit kept at ambient for 48 and 72h had high levels of shrivel. This is explained by the long period the fruit were exposed to a high VPD between themselves and the surrounding atmosphere. This result is further supported by the mass loss data, where it was found that fruit kept at ambient had more moisture loss than fruit kept at lower temperatures. It cannot be explained why the fruit from the control had relatively high levels of shrivel whilst showing low fruit mass loss compared to other treatments. Hruschka (1977) did a study to determine how shrivel severity correlated with the average percentage weight loss (weight loss was measured instead of the actual moisture loss, since respired substrates usually make up a minor part of the total weight loss) of different crop types. It was found that zero to extremely severe shrivel levels occurred with a weight loss percentage between 14.2% to 24.8% for nectarines, and 9.0% to 20.4% for peaches (Hruschka, 1977). In this study it was found that fruit developed a shrivelled appearance with has little as 2% mass loss. Hence, the weight loss that was experienced in this study was too much and resulted in high levels (more than 10%) of shrivel in most of the treatments. The VPD measurements also did not predict shrivel manifestation accurately for all treatments. Burdon et al., (2014) report that moisture loss is necessary for fruit to shrivel, but it is not the only factor that determines when shrivelling occurs. This indicates that there might be other reasons except for moisture loss, such as differences between cultivars or seasons, why fruit from all the treatments shrivelled.

In Paper 4 our aim was to investigate if pre-harvest potassium silicate sprays could reduce post-harvest moisture loss and consequent shrivelling in ‘African Delight™’ plums by strengthening and adding elasticity to the surface cell walls to

prevent hairline cracks from developing. Three treatments were applied to the trees namely, a foliar potassium silicate spray application, a root potassium silicate spray application and a control, where trees were left untreated. Fruit were harvested, packaged in commercial packaging and cold-stored for 8 weeks followed by shelf-life simulation of a week. No significant differences were found between fruit treated with Si (root and foliar applications) and untreated fruit (control) with regards to maturity parameters. Fruit firmness, hue angle, titratable acidity and total soluble solids did not differ between the three treatments (root Si application, foliar Si application and control) at harvest, after cold storage and after shelf life. The occurrence of concentric hairline cracks was not influenced by any of the two Si treatments. Not only did the Si applications not have an effect on the concentric hairline crack incidence, it also failed to reduce the width of the concentric hairline cracks. This indicates that the Si did not enhance the mechanical strength and elasticity of the cell walls in the plum fruit peel as was found by other studies (Menzies et al., 1991; Menzies et al., 1992; Epstein, 1999; Marchner, 2002).

A number of studies found that $K_2SiO_3$ has the ability to reduce moisture loss through the cuticle (Marchner, 2002; LiQun et al., 2006; Ma and Yamaji, 2006; Mditshwa et al., 2013; Nasr et al., 2013). Kritizinger and Jooste (2014) also observed that plums treated with $K_2SiO_3$ had slightly lower levels of shrivel than plums that were not treated. The same effect could not be achieved in this study. It may be that not only the fruit type, but also the specific cultivar reacted differently to the Si applications compared to what was found in the other studies. It was found that the treated fruit had slightly higher shrivel levels compared to the control. The reason for this is not clear. It is possible that the concentration of product that was used was too low or that applications must be made more frequently.

Internal browning (a type of chilling injury) did not differ significantly between treatments, but it was found that the Si treatments, especially the foliar application, reduced the incidence of this defect after cold-storage and after the simulated shelf-life period. Mditshwa et al. (2013) also found that post-harvest Si dips reduced chilling injury in lemons. In this study the incidence of internal browning was very low, and it is recommended to verify this result in further studies in order to determine if Si treatments are able to reduce chilling injury in plums. This finding also supports the

finding that Si can protect crops against abiotic stresses to some extent (Currie and Perry, 2009)

In conclusion, this study provides a number of important and new observations to the South African stone fruit industry regarding the cultivars that were tested. The first finding is that the concentric rings found in the peel in the pedicel area of 'African Delight™' plums are open hairline cracks and that wider cracks contribute more towards moisture loss than narrower cracks. The second important finding was that the lenticels in the peel of 'African Delight™', 'Laetitia' and 'Sapphire' are open and could possibly be contributing towards postharvest moisture loss. The third finding was that 'Songold', a cultivar not susceptible to shrivel, did not show any signs of hairline cracking, nor lenticels that were open. The fact that the cuticle of this cultivar is mostly intact with very few or no openings contributing to moisture loss probably explains why this cultivar is not susceptible to shrivel. The fourth finding was that the peel of 'African Delight™' plums are more permeable to water vapour than the peels of 'Laetitia' and 'Songold' plums. This is probably the result of the hairline cracks in the pedicel area of the cultivar and/or the fact that its peel contains open lenticels. The fifth important finding was that variation between fruit, orchards and harvest date made the largest contribution towards the total variation in water vapour permeance. The method used in Paper 2 can also be used by plant breeders to detect high water vapour permeabilities at an early stage in the breeding program. The sixth important finding was that only a 2% mass loss causes shrivel manifestation in 'African Delight™' plums. The seventh finding was that if fruit cannot be packed and cooled within 6 h of harvest, the best practice would be to precool fruit to -0.5 °C for 72 h, and not shorter, in order to eliminate the relatively large VPD created at the onset of FAC and the fruit having a temperature higher than the delivery air. The eighth important finding was that keeping fruit at ambient temperatures, especially for longer than 24 h, is not advisable as it could lead to higher moisture loss, and shrivel manifestation. The ninth finding was that, regardless of treatment, and although fruit was packed in perforated bags, fruit lost ~ 1% in mass during cold-storage, indicating that future studies should focus on packaging and other ways to minimize mass loss during cold-storage. The tenth and final finding was that pre-harvest applied potassium silicate did not decrease post-harvest shrivel manifestation, but did reduce internal browning to some extent.

Overall this study found that great care should be taken in following the correct postharvest handling protocols for plums. It is strongly suggested that fruit should be harvested in the cooler time of day, kept in the shade after harvesting and covered with wet blankets. Field heat removal and/or forced air cooling should commence as soon as possible after harvest. It was also found that plum fruit can be stored at 0 °C or 15 °C for up to 72 h before it is packed and force air cooled. Fruit should never be left at ambient for extended periods after harvest. Fruit should be packed in perforated bags or perforated shrivel sheets, depending on the cultivar at hand, in order to decrease the water vapour deficit between the fruit and the surrounding atmosphere. Fruit with excessive hairline cracks at the stem (pedicel) end should not be packed. Furthermore it is suggested that the South African plum breeding program should test cultivars with concentric rings at the pedicel end to make sure that the rings are not open hairline cracks. If it is found that the concentric rings are open hairline cracks, these cultivars should be excluded from the breeding program as it was shown that it contributes to moisture loss from the fruit.

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