Unpacking the Influence of Internal Packaging on Cooling Characteristics and Postharvest Quality of Pomegranate Fruit

By

By ROBERT LUFU

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Supervisor: Prof. Umezuruike Linus Opara

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Declaration

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Abstract

Plastic films (liners) are commonly used inside packages of pomegranates. Liners can create modified atmosphere around fruit (MAP) and minimize fruit moisture loss. However, the barrier nature of liners affects cooling characteristics by increasing resistance to airflow (RTA), delaying cooling and promoting condensation, leading to fruit spoilage. During this research the impact of liners on the characteristics and postharvest quality of pomegranate fruit during cold storage and subsequent shelf life was investigated. The role and impact of liner perforations was highlighted. The effect on RTA by non-perforated 'Decco', micro-perforated Xtend®, macro-perforated 'Decco' liners (2 mm × 70 and 4 mm × 18) and macro-perforated high density polyethylene (HDPE) liners (2 mm × 54 and 4 mm × 36), was studied in a wind tunnel. Generally, fruit stack packed with non-perforated 'Decco' and micro-perforated Xtend® liners increased the RTA of the no-liner packed fruit by 175.7 and 238.4 %, respectively. However, using macro-perforated 2 and 4 mm 'Decco' liners increased the RTA of the no-liner packed fruit by only 69.2 and 113.6 %, respectively.

The impact of non-perforated 'Decco' and micro-perforated Xtend® liners on cooling characteristics was carried using a forced-air cooling (FAC) setup. The 7/8 cooling time of fruit stack packed with no-liner was 3.5 ± 0.2 h, compared to 8.1 ± 0.1 h with non-perforated 'Decco' and 8.5 ± 0.1 h with micro-perforated Xtend® liners. As a result, more energy was consumed in pre-cooling fruit packed in liners than with no-liners. However a higher stack cooling uniformity (81.6 ± 1.7 and 78.7 ± 1.5 %) was obtained for fruit packed with non-perforated 'Decco' and micro-perforated Xtend® liners, respectively, compared to fruit packed with no-lines (64.2 ± 0.2 %).

The effect of non-perforated ('Decco' and 'Zoe'), micro-perforated (Xtend®), macro-perforated 2 and 4 mm HDPE liners on fruit quality during storage at 5 °C and 90 ± 5 % relative humidity (RH) for 12 weeks and subsequently 5 days at 20 ° C, was evaluated. At the end of 12 weeks of cold storage, the no-liner fruit lost 15.6 ± 0.3 % of its initial weight. Non-perforated ('Decco' and 'Zoe') liners minimized weight loss by 95.0 % compared to Xtend® micro-perforated (73.2 %), 2 mm macro-perforated HDPE (84.3 %) and 4 mm macro-perforated HDPE (62.5 %) liners, respectively. Fruit packed in perforated and non-perforated liners maintained a lower respiration rate and retained better peel colour than fruit with no-liners. Micro- and macro-perforation of liners increased diffusion of moisture lost from the fruit across film to the room atmosphere. This minimized moisture condensation inside the liners leading to a reduced fruit decay, with acceptable shrivel severity. The type of liner and perforation quality (size and number) did not have a significant impact on total soluble solids (TSS), titratable acidity (TA), juice colour, total phenolic concentration and antioxidant activity. Overall, the use of perforated liners reduced RTA, energy consumption and moisture condensation associated with non-perforated liners, and yet retained fruit texture, colour, weight and chemical quality attributes during and after prolonged cold storage.

Key words: *Pomegranate, Packaging, Perforation, Cooling rate, Energy consumption, Storage quality.*

Opsomming

Plastiek voerings (“liners”) word algemeen gebruik in die verpakking van granate. Voerings skep `n gemodifiseerde atmosfeer rondom vrugte (MAP), wat vogverlies verminder. Voerings is uiteraard `n beskermingslaag, en beïnvloed dus die verkoelingseienskappe deur weerstand teen lugvloei (RTA) te verhoog, verkoeling te vertraag en kondensasie te bevorder, wat lei tot vrug bederf. Tydens hierdie navorsing is die impak van voerings op die verkoelingseienskappe en die na-oes kwaliteit van granate tydens koelstoring en die daaropvolgende raklewe geëvalueer. Die rol en impak van perforasie in die voerings is beklemtoon. Die effek op RTA van nie-geperforeerde ‘Decco’, mikro-geperforeerde Xtend®, makro-geperforeerde ‘Decco’ voerings (2 mm × 70 en 4 mm × 18) en makro- geperforeerde hoë druk HDPE voerings (2 mm × 54 en 4 mm × 36), is in 'n windtonnel bestudeer Oor die algemeen het vrugte wat met nie-geperforeerde ‘Decco’ en mikro-geperforeerde Xtend® voerings in stapels gepak is, die RTA van voeringlose gepakte vrugte met 175.7 en 238.4%, onderskeidelik vermeerder. Maar, met behulp van makro-geperforeerde 2 en 4 mm 'Decco' voerings, het die RTA van die voeringlose gepakte vrugte met slegs 69.2 en 113.6%, onderskeidelik toegeneem

Die impak van nie-geperforeerde ‘Decco’ en mikro-geperforeerde Xtend® voerings op verkoelingseienskappe is tydens geforseerde lugverkoeling (FAC) getoets Die 7/8 verkoelingstyd van vrugte wat voeringloos in stapels gepak is, was 3.5 ± 0.2 h in vergelyking met 8.1 ± 0.1 h in nie-geperforeerde ‘Decco’, en 8.5 ± 0.1 h met mikro-geperforeerde Xtend® voerings. Die gevolg was meer energie verbruik tydens die voor-verkoeling van vrugte verpak in voerings, teenoor voeringlose verpakking. `n Hoër stapel verkoelings-eenvormigheid van onderskeidelik 81.6 ± 1.7 en 78.7 ± 1.5 % is verkry vir vrugte wat met nie-geperforeerde ‘Decco’ en mikro-geperforeerde Xtend® voerings voorsien is. Dit is in vergelyking met voeringlose verpakkings (64.2 ± 0.2 %).

Die effek van nie-geperforeerde (‘Decco’en ‘Zoe’), mikro-geperforeerde (Xtend®), en makro-geperforeerde 2 en 4 mm HDPE voerings op vrugkwaliteit tydens stoor by 5 °C en 90 ± 5% RH vir 12 weke en daaropvolgend 5 dae by 20 ° C, is geëvalueer. Na 12 weke van die koue-stoor het voeringlose vrugte 15.6 ± 0.3% van die aanvanklike gewig verloor. Nie-geperforeerde (‘Decco’ en ‘Zoe’) voerings het gewigsverlies tot 95.0% beperk in vergelyking met Xtend® mikro-geperforeerde (73.2%), 2 mm makro-geperforeerde HDPE (84.3%) en 4 mm makro-geperforeerde HDPE (62.5 %) voerings, onderskeidelik. Daarbenewens het vrugte verpak in geperforeerde en nie-geperforeerde voerings ‘n laer respirasietempo gehandhaaf, en beter skil kleur behou as vrugte sonder voering. Mikro- en makro-perforasie van voerings het die diffusie van vrugte se vogverlies oor die voering na die kameratmosfeer verminder. Dus is vog kondensasie verminder binne verpakking, wat gelei het tot verlaagde vrugte verval binne gevoerde sakke, met ’ n aanvaarbare verkrimpingskoers. Voering tipe en perforasie kwaliteit (grootte en aantal) het nie `n beduidende impak op totale oplosbare stowwe (TSS), titreerbare suur (TA), sap kleur, totale fenoliese konsentrasie en antioksidant aktiwiteit gehad nie. In die geheel het die gebruik van geperforeerde voerings weerstand teen lugvloei, energieverbruik en vog kondensasie wat verband hou met nie-geperforeerde voerings verminder, terwyl dit nog steeds vrugtekstuur, kleur, gewig en chemiese kwaliteit eienskappe tydens en na 'n lang koue stoor behou het.

Sleutel woorde: *Granate, Verpakking, Perforasie, Verkoelings tempo, Energieverbruik, Stoor gehalte.*

List of conferences

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Table of contents

This thesis is a compilation of manuscripts where each chapter is an individual entity and some repetition between chapters has, therefore, been unavoidable. Language and styles used in this thesis are in accordance with the requirements of the International Journal of Food Science and Technology.

SECTION I

Chapter 1. General introduction

Chapter 2. Internal packaging and its impact on fruit cooling & postharvest quality – an interpretative review

1 General Introduction

1.1 Background

Pomegranate (*Punica granatum* L.) fruit from the family Punicaceae, is botanically classified as a berry with about 55-60 % of the whole fruit mass as edible portion (Al-Said *et al*., 2009; Fawole & Opara, 2013). The fruit can be eaten fresh or processed into juice, wine and jam (Kader, 2006; Opara *et al*., 2009; Wetzstein *et al*., 2011). Pomegranate grows well in sub-tropical, tropical and moderate Mediterranean climate regions of Asia, Africa and Europe (Morton, 1987; Nanda *et al*., 2001). Historically, pomegranate has been commercially grown in the Northern Hemisphere with India being the leading global producer followed by Iran. Southern Hemisphere countries like Chile, Peru and South Africa have found great economic importance in developing the pomegranate industry (Kader & Chordas, 1984; Teixeira da Silva *et al*., 2013; Fawole & Opara, 2013). Area of commercial production in South Africa is about 4500 ha (Pomegranate Association of South Africa, 2015), exporting about 62% of total production in 2014 to European markets, Middle East and Asia (Pomegranate Association of South Africa, 2014). Currently, increase in production, promotion and consumption of pomegranate is associated with consumer demand for its nutritional and health values, and increasing public health awareness (Holland & Bar-Ya'akov, 2008; Holland *et al*., 2009; Viuda-Martos *et al*., 2010).

Like other fruit grown in same region, pomegranate fruit industry suffers both quantitative and qualitative postharvest losses. At pack house level, it was recently reported that 12 % of pomegranate produced in South Africa was wasted, while 25 % was of lower grade (Pomegranate Association of South Africa, 2014). Weight loss and fruit decay are common postharvest handling physiological disorders among others like chilling injury and husk scald, contributing to fruit loss (Elyatem & Kader, 1984; Caleb *et al*., 2012). Pomegranates are highly prone to moisture loss owing to the relatively high water permeability across the skin through minute openings, despite having a thick rind (Elyatem & Kader, 1984; Nanda *et al*., 2001). Fruit moisture loss, if not well controlled, results into shrinkage, shrivel, wilt, quantitative loss in weight, taste, reduce visual appearance and overall fruit acceptability (Maguire *et al*., 2001; Vigneault *et al*., 2009). Temperature and relative humidity are the major storage conditions influencing moisture loss across the fruit skin surface. A combination of cold chain and packaging postharvest technique is important in minimizing quality losses in fresh fruit. An immediate lowering of temperature and maintaining cold chain with relatively high humidity will lower respiration rate, ethylene production, enzymatic spoilage, microbial decay and minimize moisture loss (Kitinoja & Thompson, 2010; Mukama, 2015). In addition, packaging protects fresh fruit against mechanical damage and contamination, minimizes weight loss, as well as aiding fruit marketing and distribution (Opara & Mditshwa, 2013; Pathare & Opara, 2014).

A number of techniques have been applied in the fresh fruit industry to minimize moisture loss. Surface coating and waxing have been applied on apples, oranges and pomegranate to minimize moisture loss (Nisperos-Carriedo *et al*., 1990; Park *et al*., 1994; Nanda *et al*., 2001). Heat shrinkable wrapping has been applied on individual pomegranate fruit, before packaging in cartons (Artés *et al*., 2000; Nanda *et al*., 2001; D'Aquino *et al*., 2010). On the other hand, shrink wrapping, surface coating or waxing can lead to anaerobic respiration by creating an oxygen deficit and high CO_2 atmosphere around the fruit. This results in production of off-flavours and undesirable changes in fruit taste (Truter *et al*., 1994; Taylor *et al*., 1995; Gil *et al*., 1996; Cantı´n *et al*., 2008).

Plastic liners are commonly applied internal packaging (IP) to minimize moisture loss for pomegranate and other fruit packaged in ventilated cartons (external packaging). However, the use of liners may give rise to moisture condensation within the bags and around the fruit especially due to temperature fluctuations. Moisture condensation can initiate and or accelerate fruit decay (Wiley *et al*., 1999). Furthermore, liners influence resistance to airflow (RTA), cooling rate and energy consumption during forced-air cooling (FAC) of apples, table grapes, straw berries and pomegranate (Wiley *et al*., 1999; Ngcobo *et al*., 2012a; Berry, 2013; Ngcobo *et al*., 2013; Mukama, 2015). It is therefore important that these liners be comprehensively assessed for suitability of use. Liners can be improved through use of perforations so as to minimize challenge of moisture condensation within the bags, improve fruit cooling rate and minimize energy consumption during FAC of fruit (Ben-Yehoshua *et al*., 1988; Ngcobo *et al*., 2012a; Ngcobo *et al*., 2012b; Wiley *et al*., 1999). Both micro and macro-perforations of varying number and sizes have been applied in the fresh fruit industry.

Plastic liners are often applied in the multi-scale packaging (MSP) of horticultural produce. Ventilated MSP is currently being applied in the cold chain of pomegranate as well as other fresh fruit like apples, table grapes, pears, strawberries and plums. In MSP, ventilated fibreboard carton is the most commonly used external packaging (EP), in which trays, polyliners, thrift bags, bunch carry bags, punnets, shrink wraps and riffle sheets are applied as internal packages (IPs). The type of IPs used depends on market destination and legal requirements (Berry, 2013; Delele *et al*., 2013; Ngcobo *et al*., 2013;). Some research has assessed MSP of apples and table grapes on cooling patterns and quality of produce (Berry, 2013; Ngcobo, 2013; Ngcobo *et al*., 2013). The impact of plastic liners and other IPs like trays and punnets on fruit quality (Aharoni *et al*., 2008; Thompson *et al*., 2008; Selcuk & Erkan, 2014), RTA and cooling patterns has been reported in MSP of apples and table grapes, (Ngcobo *et al*., 2012a; Berry, 2013; Delele *et al*., 2013; Ngcobo *et al*., 2013). Liners are a common IP for pomegranate, where they are applied in modified atmosphere packaging (MAP) and minimizing moisture loss. Quite a number of studies have been done on MAP ability of liners and their impact on quality of whole pomegranate fresh fruit (Artés *et al*., 2000; Cantı´n *et al*., 2008; Bayram *et al*., 2009; Porat *et al*., 2009; D'Aquino *et al*., 2010; Caleb *et al*., 2012; Selcuk & Erkan, 2014). So far, less information has been found on how these liners affect the cooling characteristics and postharvest quality of fresh whole pomegranate fruit. This research study can be used as a science based tool aiding packaging of pomegranate, through resourceful knowledge on the effect of internal packaging on cooling characteristics and postharvest quality.

1.2 Aim and objectives

1.2.1 Aim

The overall aim of this research study was to investigate the effect of internal packaging (liners) on cooling characteristics and postharvest quality of pomegranate (cv. Wonderful) during cold storage and shelf life.

1.2.2 Objectives

The research aim was accomplished by achieving the following specific objectives;

a) Assess the effects of non-perforated and perforated liners on resistance to airflow and cooling characteristics of pomegranate.
b) Evaluate the effect of non-perforated and perforated liners on postharvest quality of pomegranate fruit during cold storage and ambient shelf life storage.

1.3 Thesis structure

This dissertation is structured into four Sections (I - IV), with each section addressing a particular research theme.

Section I: provides a brief general background and presents the research aim and specific objectives (Chapter 1). Furthermore, provides an interpretative review on the different types of internal packaging and how they impact on pre-cooling and storage quality characteristics of fresh fruit (Chapter 2).

Section II: focuses on impact of perforated and non-perforated plastic liners on resistance to airflow and cooling characteristics of pomegranate fruit (Chapter 3).

Section III: reports the studies on the effect of perforated and non-perforated plastic liners on the postharvest quality of pomegranate fruit during prolonged cold storage and subsequent shelf life conditions (Chapter 4 & 5).

Section IV: summaries and integrates the results from all the above sections and highlights practical contribution of the studies to the postharvest pomegranate industry (Chapter 6).

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2 Internal Packaging and its Impact on Cooling and Postharvest Quality of Fruit – An Interpretative Review

Abstract

Fresh fruit attract increasing production and research due to their contribution to nutritional, medicinal and pharmaceutical properties. After harvest, fruit are susceptible to mechanical damage, moisture loss and microbial contamination, suggesting need for good packaging practices and cold chain maintenance. Plastic liners have been applied as internal packaging (IP) in ventilated multi-scale packaging of fruit to modify atmosphere around the fruit and offer protection against mechanical damage and moisture loss. However, internal packaging has been found to delay pre-cooling processes and promote decay of fruit. A comprehensive scientific understanding of the influence of IP on fruit quality is needed. This review describes the use and types of different internal packaging materials, and also highlights their impact on cooling characteristics and postharvest quality as applied in horticultural fresh produce industry.

Key words: *Postharvest, Fruit quality, Internal packaging, Perforations*

2.1 Introduction

Temperature and humidity are important factors that regulate spoilage and physiological damage during postharvest handling of fruit. Freshly harvested fruit contain heat from the field that should be removed immediately before storage at lowest allowable temperature to preserve quality and increase shelf life (Brosnan & Sun, 2001; Ravindra & Goswami 2008). However, fresh produce is susceptible to mechanical damage, moisture loss and contamination, thereby requiring combination of good packaging practices and cold chain maintenance.

Packaging as a postharvest handling technique contributes greatly to the containment, protection, preservation, communication, distribution and marketing of fresh fruit as agricultural produce (Robertson, 2013). Different types of packaging materials and package designs have been adopted in postharvest handling of fresh produce depending on type of fruit, storage requirements, distribution and marketing conditions. In some cases fruit has been bulk packed in plastic and wooden crates (Kaur *et al.*, 2013), while in other cases multi-scale packaging is applied to effectively preserve fruit quality, convenient distribution and marketing

(Ngcobo *et al*., 2012a; Ngcobo *et al*., 2013b). In multi-scale packaging, beside the most common corrugated paperboard cartons (Kader, 2002), internal packages like thrift bags, polyethylene liner bags, wraps, trays, punnets are being used depending on market destination (Robertson, 2006) and type of fruit, such as table grapes, apples, pears, pomegranates, stone fruit and straw berries.

Internal packages have been found to maintain a high relative humidity around fresh produce during cooling thereby minimizing weight loss in fresh produce (Suparlan & Itoh, 2003; Ngcobo *et al*., 2012d). Internal packages minimize mechanical damage and promote easy marketing of fruit. They have also been applied in modified atmosphere packaging of fruit to lower respiration rate (Drake *et al*., 2004; Selcuk & Erkan, 2014; Wang & Long, 2014). However, internal packages increase airflow resistance and reduces the rate of heat removal during pre-cooling of fresh fruit, hence, having profound effect on quality and pre-cooling energy consumption, besides contributing to product price and municipal waste (Wiley *et al*., 1999; Ngcobo *et al*., 2012a; Ngcobo *et al*., 2012d; Ngcobo *et al*., 2013b). To achieve rapid, uniform and efficient cooling, vent-holes on packaging boxes should be properly designed and internal packages should be as minim as possible (de Castro *et al*., 2005b; Thompson *et al*., 2010).

The increasing application of internal packaging and associated challenges has attracted research globally. Researchers have investigated the impact of carton design (Vigneault and Goyette, 2002; de Castro *et al*., 2004; Pathare *et al*., 2012; Mukama, 2015; Berry *et al*., 2016; Fadiji *et al*., 2016a; Fadiji *et al*., 2016b; Fadiji *et al*., 2016c) and internal packaging materials (Ngcobo *et al*., 2012d; Selcuk & Erkan, 2014; Wang & Long, 2014) on mechanical damage and keeping quality of fresh horticultural produce. However, the effects of internal packages on postharvest handling of fresh fruit has not been clearly understood. This review articulates applications and effects of different types of internal packaging on cooling characteristics and quality as applied in horticultural fresh produce industry.

2.2 Multi-scale packaging

Multi-scale packaging in horticulture is a system applying successive layers or components of packaging to contain a produce (Ngcobo *et al*., 2012b; Ngcobo *et al*., 2012c; Berry, 2013) to cater for the different physical and environmental conditions along the value chain. This technique usually consists of outermost external packaging and one or more internal packaging components, each component serving a specific function. Examples of multi-scale packaging in table grapes are presented in Ngcobo *et al*. (2013b) where the following internal packaging was used inside fibreboard cartons: (1) perforated box liner, riffled sheet, bunch-carry bags, moisture absorption sheet and sulphur dioxide pad. Here, fruit was primarily inside and in contact with the bunch carry bag; (2) perforated liner, clamshell punnets, moisture absorption sheet and sulphur dioxide pad; (3) open-top punnets primarily containing the grapes replacing clamshell punnets of the second combination.

Multi-scale packaging system facilitates integrated preservation of fruit quality. However, a packaging system should promote good airflow during fruit cooling and storage to sustain fruit quality (Ngcobo *et al*., 2012d; Ngcobo *et al*., 2013b). Multi-scale packaging system increases airflow resistance and reduces cooling rate during postharvest handling of fresh fruits. This can affect the storability of fruit (Ngcobo *et al*., 2013b). Previous studies on table grape multi-scale packaging (Delele *et al*., 2012; Ngcobo *et al*., 2012a; Ngcobo *et al*., 2012b) have focused on investigating the effect of liner films on resistance to airflow, cooling rate and patterns. Results from these studies showed that plastic liner films contributed the highest resistance to airflow, ranging from 40.33 ± 1.15 % for macro-perforated liner film to 83.34 ± 2.13 % for non-perforated liner film.

2.2.1 Packaging levels of fresh fruit

Depending on the stage of the value chain, different internal packages are applied to serve a specific purpose at a given packaging level (Figure 2.1).

2.2.1.1 Consumer and retail packaging (Level 1)

At this level, the fruit is packaged in the smallest, economically affordable and easy to carry quantities, making them convenient for the consumers. This level of packaging usually comes in direct contact with the fruit themselves thereby qualifying as primary packages and also protects the fruits against microbial contamination. The package may include a single fruit or a number of fruit, in which case individually wrapped fruit is convenient for any time snacking while multiple fruit in a pack can be good for small group consumption. Nanda *et al*. (2001) and D'Aquino *et al*. (2010) demonstrated that pomegranate fruit can individually be packed using heat shrinkable wrappers made from polyolefin films. Mangoes were individually shrink wrapped using polyolefin and low density polyethylene (LDPE) films (Rao & Shivashankara, 2014). Similarly, other types of fruit such as apples can also be individually packaged in heat shrinkable wrappers of polyolefin and LDPE (Sharma *et al*., 2013).

The criteria for packaging several fruits in one pack is mostly based on a required total weight or number of fruit (Hortgro, 2016a; Hortgro, 2016b). Several types of fruit like apples can be displayed either on trays, contained in liners, punnets or thrift bags (Gruyters, 2014). Bunches of table grapes can be primarily packed in perforated LDPE bunch carry bags, clamshell punnets and open top punnets (Ngcobo *et al*., 2012d; Ngcobo *et al*. 2013b).

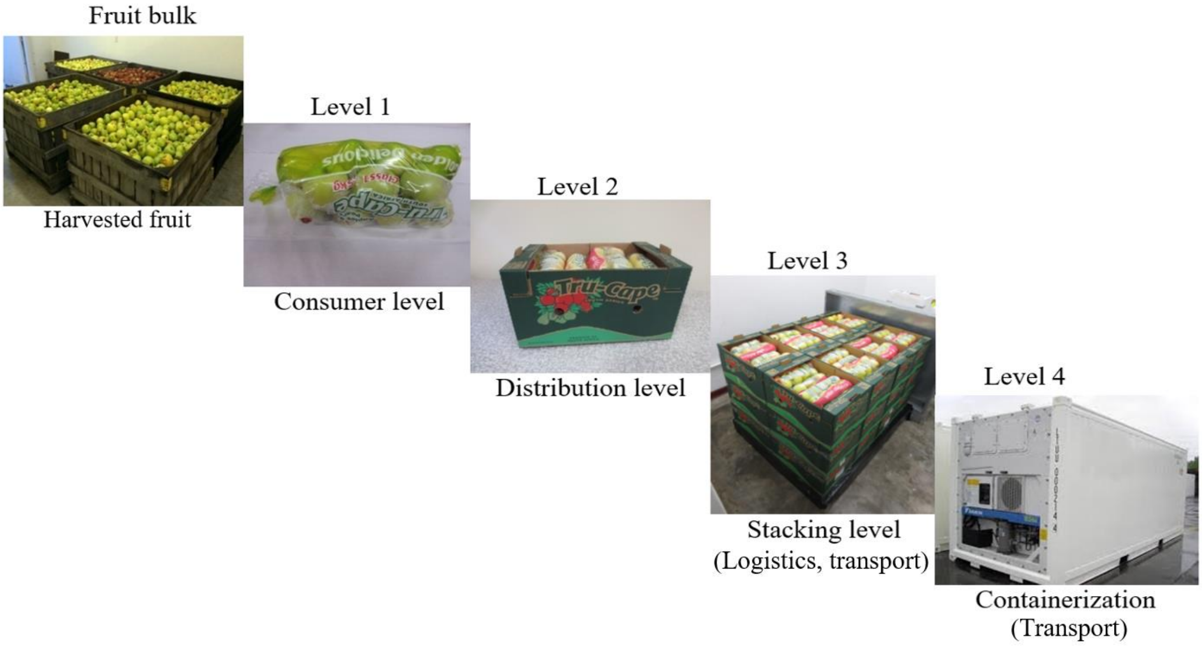

Figure 2.1 Levels of packaging along the fresh fruit value chain
NB. Some of the pictures were got from internet sources

2.2.1.2 Whole sale and distribution packaging (Level 2)

A specific number of Level one packaging are placed in a single unit pack (Level two), thereby aiding easy distribution. This level mostly functions as secondary type of packaging by not coming in direct contact with fruit. Level two packaging protects fruit against mechanical injury (bruising and compression damages), facilitates unitizing, conditioning and promoting the produce (Hortgro, 2016a; Hortgro, 2016b).

Returnable plastic crates (RPC) and wooden boxes are used, however, the most commonly applied packaging at this level is the ventilated fibre board carton (VFBC) boxes (Kader, 2002; Berry *et al*., 2015) Cartons are relatively cheap, versatile and light weight of about 0.5kg (Vigneault *et al*., 2009b). In the USA, over 90 % of the packaging that is used in fruit transport is corrugated fibreboard or fibreboard (Little & Holmes, 2000). Fibreboard cartons were found to offer the best protection to apples against impact damage compared to wooden and plastic crates, when dropped from a 0.5 m height onto a concrete floor (Holt & Schoorl, 1984; Acican *et al*., 2007). They exist in diverse designs with different recommended load weights, ventilation area depending on the fruit, market and legal requirements. Markets in the UK prefer generic black and green cartons with the tendency to promote own trademark rather than the exporter's trade mark. For example, Tesco supermarkets require green cartons while Sainsbury supermarkets prefer black cartons (Hortgro, 2016a). The telescopic carton type consisting of a two piece interlocking closing mechanism and facilitates packaging of fruit in more than one layer on trays (FEFCO & ESBO, 2007; Berry, 2013). The display carton type (folder type and tray) on the other hand has a sizeable inbuilt window and can be used for retailing purposes with fruits usually packed in a single layer (FEFCO & ESBO, 2007; Berry, 2013). Unlike wooden crates and RPC, corrugated cartons easily lose strength with time and even more severely when exposed to high relative humidity environment of 90 % during cold storage, losing 60 % of their original factory strength (Thompson *et al*., 2002).

2.2.1.3 Stacking packaging (Level 3)

In this case, a specified number of VFBC boxes or RPC are stacked onto a common base or platform, forming a single unit. These platforms are commonly known as pallets made from wood or plastic and my exist in various sizes (Vigneault *et al*., 2009b). A 1m by 1.2 m pallet is commonly used on European markets with a recommended capacity of 20 to more than 100 cartons depending on carton size (Thompson *et al*., 2002). For export purposes, wooden pallets should be made from de-barked heat or methyl bromide treated wood (Hortgro, 2016a). A pallet is so important in stacking up fruit boxes so as to efficiently utilize space during storage in cold rooms and transportation in cold temperature conditioned trucks.

To avoid sliding and toppling of the stacked boxes in cold storage and especially during transportation, palletizing glue, plastic stretch films, net wrapping, plastic or cardboard corner tabs and banding may be used to keep the stacks in position and single unit, as opposed to the majority of RPC with self-interlocking system to keep them in position. Corner tabs prevent banding tapes from crushing carton corners and a 50 x 50 x 1900 mm poly-coated corner pieces are recommended on standard pallets. Palletizing glue with high shear strength can be applied on top of each carton for stabilization and yet allows easy detaching of individual boxes because of its low tensile strength. Depending on carton type and design, specific securing stripes with standard metal buckles are required to stabilize the stack. A set of four strips placed at different carton layers of a stack is usually applied in stone fruit (Boyette *et al*., 1996; Vigneault & Émond, 1998; Thompson *et al*., 2002; Vigneault *et al*., 2009a; Hortgro 2016b).

The height of stacking of boxes on a pallet is very important consideration dependent on the wooden pallet base (155 mm and 176 mm high for standard and CHEP pallets respectively), strength of cartons, loading ramps and transport container. A maximum height of 2.14 m and 2.4 m are recommended for conventional shipping containers and hi-cube integral containers respectively. Pallet caps which are usually strapped down the stack, may be applied to protect exposed fruits on top of the stack from contamination and damage. However they contribute towards un-necessary obstruction of vertical air flow (Hortgro, 2016b).

2.2.1.4 Refrigerated Container (packaging Level 4)

At level four, pallets of stacked fruit are put in large metallic containers for shipping across long distances by road, rail and sea. The containers provide outstanding protection to fruit and cartons against possible mechanical damage and injuries associated with harsh weather conditions which the carton boxes could not withstand. Usually these fruit containers have a cooling system for maintaining a required minimum fruit temperature to minimize quality deteriorations during transportation.

When loading the containers, the red line fixed at a specified recommended height should not be exceeded to guarantee that airflow is not restricted and allow easy operation of forklifts by providing sufficient space above the carton stacks (Hortgro, 2016b). Unnecessary spaces in between stacks provide alternative routes of lesser resistance thereby preventing cooling air from flowing through the stacks to remove respiration heat.

Refrigerated shipping containers are used extensively in exporting fruit and vegetables, and they usually consist of an insulated body having a built on refrigeration unit cable of supplying cold air at a regulated temperature. In top air delivery refrigerated containers, cold air is supplied at the ceiling level and at floor level for bottom air delivery containers. Bottom air delivery containers are the most widely used at the moment (SAL, 2007). Products should be sufficiently pre-cooled to the recommended temperature before loading into the refrigerated container. The product temperature should be ± 1^{o} C that of the refrigerated container to be used because the refrigerated unit of the container is designed to just maintain the produce temperature and unable to rapidly lower the temperature (SAL, 2007; Vigneault *et al*., 2009a). The vents of the container should be kept closed during road transportation to avoid ethylene contamination from car exhaust fumes as well as during controlled atmosphere for specific horticultural produce (SAL, 2007). More modernized RC have a designed in humidification system for maintaining a high (about 90 %) RH atmosphere to minimize wilting of the fresh fruits. On the other hand, a de-humidifier may be installed with the ability to lower RH to 50 and 80 % so as to prevent moulding of the produce (SAL, 2007).

2.2.2 Internal packaging used for handling horticultural produce

Internal packaging (IP) includes packaging components placed inside the main (external) package for protection, containment and modification of the product environment. Internal packaging is defined depending on level of packaging along the fresh fruit value chain. In this review, IP is defined with respect to wholesale and distribution (Figure 2.1) as described in section 2.2.1. The size, shape and type of IP largely depends on the type of produce they contain and the target market (Robertson, 2006; Hortgro, 2016a; Hortgro, 2016b). Single or several IP can be applied in combination as observed in table grape (Ngcobo *et al*., 2012d). Different types of IP and packaging combinations used on different fruit are summarised in Table 2.1 and illustrated in Figure 2.2. Internal packaging can play both an aesthetic and functional role in the postharvest handling of fruit (Berry, 2013). Internal packaging types such as trays, thrift bags, punnets and polyethylene liner bags may be used, to facilitate the handling, improve storage potential and enhance marketability of the produce (Robertson, 2006).

2.2.2.1 Thrift bags

Thrift bags allow several fruit to be placed inside them and then placed into a carton to facilitate handling and retail marketing (Vigneault *et al*., 2009b). Display packages, can through the use of internal packaging such as thrift bags and punnets, offer retail ready pre-packaged fruit, and therefore add additional marketing value to the package. The Econo-T design carton is also used predominantly with thrift-bags of apples in the local market (Berry, 2013). Apple cultivars susceptible to shrivel are packed in 37.5 µ or 60 µ bags. Thrift bags minimize shrivelling and help maintain flesh firmness and skin colour, prevent compact bruises and rub marks by firmly holding apples together (Crouch, 2003).

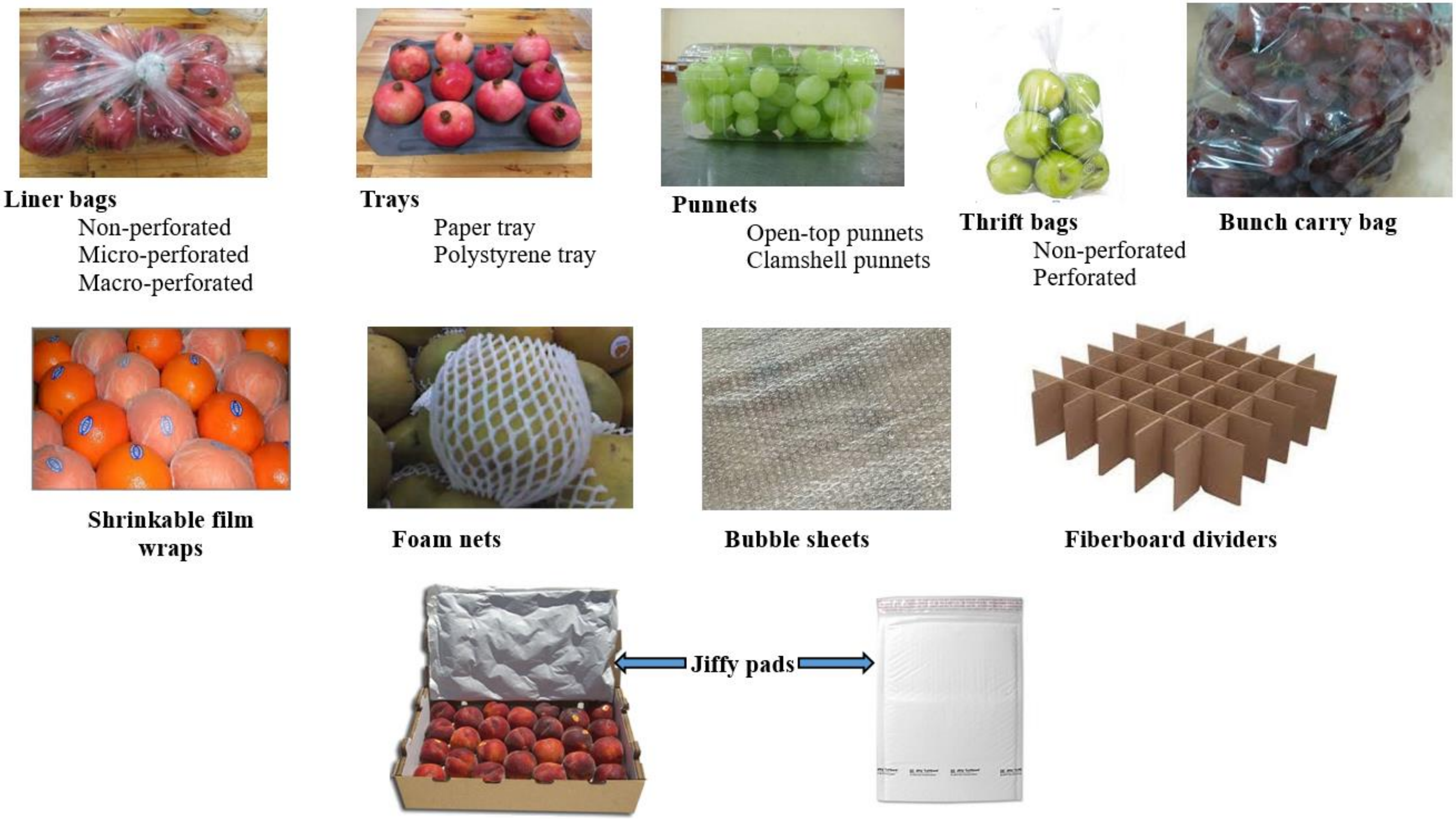

Figure 2.2 Types of internal packaging used for handling horticultural produce.
NB. Some of the pictures were got from internet sources

Table 2.1 Different types of internal packaging and their packaging combinations as applied in selected fresh fruits

Main packaging (terminology of source retained)	**Internal Packaging**	**Type and design of internal package**	**Fruit**	**Related objective on the internal package**	**Reference**
CFB carton	Liner film with riffle sheets, bunch carry bag, moistsure absorption sheet & SO_2 pad.	Perforated HDPE & Non-perforated LDPE, LDPE carry bag & corrugated riffle sheet	Table grapes (cv. Regal seedless)	Effect of the liners on cooling rate & quality	Ngcobo *et al*., 2012d
CFB carton	Shrinkable film wrappers	Co-extruded & multi-layered polyolefin heat-shrinkable films	Pomegranates (cv. Ganesh)	How they affect shelf life & quality	Nanda *et al*., 2001
CFB carton	Liner film, Punnets , moisture absorption pad & SO_2 pad	Open-top punnet & Clamshell punnet, perforated liners	Table grapes (cv. Regal Seedless)	Effect of punnets on airflow, cooling rate & quality	Ngcobo *et al*., 2013a
CFB carton	Trays	Moulded pulp paper tray in fibreboard cartons	Apples (cv. Granny Smith)	Package protection	Holt & Schoorl, 1984
CFB cartons	Liners	Xtend® MH/MAP & PP liners (12.5, 25 & 37.5 microns)	Mangoes (cv. Baneshan)	Effect of packaging on quality & shelflife	Kumar *et al*., 2013b

Main packaging (terminology of source retained)	**Internal Packaging**	**Type and design of internal package**	**Fruit**	**Related objective on the internal package**	**Reference**
CFB cartons	Liners	Non-perforated, macro and micro perforated liners	Kiwifruits (cv. California)	Impact of perforated liners on quality & cooling	Wiley *et al*. 1999
CFB carton	Trays alone, Trays & liner film	Polystylene tray & 37.5µm non-perforated PE film	Apples	Effect on mass loss, cooling rate & patterns	Berry, 2013
CFB carton	Trays	Paper mould trays	Apples (cv. Royal Delicious)	Enhancing storage quality	Wijewarden & Guleria, 2013
	liners	LDPE liners			
CFB carton	Liner film, Riffle sheet, Bunch carry bag, Moisture absorption pad & SO_2 pad.	Perforated liners	Table grapes (cv. Regal Seedless)	Effect of carry bag on air flow, cooling rate & quality	Ngcobo *et al*., 2013a
CFB carton	Suspended tray in clamshell	Made from 0.127mm and 0.483 mm PVC sheets respectively	Pears (cv. Californian Bartlett)	Protection from transport vibrational mechanical damages	Thompson *et al*., 2008b
	Conventional clamshell	From 0.432mm PVC			
	Conventional tray	From 0.102mm PVC			

Main packaging (terminology of source retained)	**Internal Packaging**	**Type and design of internal package**	**Fruit**	**Related objective on the internal package**	**Reference**
CFB cartons	Clampshell punnets, moisture absorption pad & SO_2pad inliners.	Perforated liner films	Table grapes (cv.Crimson seedless)	Potential of humidification to control moisture loss and quality.	(Ngcobo *et al*., 2013a)
	Closed top punnets, moisture absorption pad & SO_2pad in liners.	Perforated liner films			
	Bunch carry bags, moisture absorption pad & SO_2pad in liners.	Perforated liner films			
CFB cartons	Clampshell punnets, moisture absorption pad & SO_2 pad in liners	Perforated liner films	Table grapes (cv.Regal seedless)	Impact of the punnets and liners on cooling rate,air resistance & quality was assessed	Ngcobo *et al*., 2013b
	Closed top punnets, moisture absorption pad & SO_2 pad in liners.	Perforated polyliner films			

Main packaging (terminology of source retained)	**Internal Packaging**	**Type and design of internal package**	**Fruit**	**Related objective on the internal package**	**Reference**
	Bunch carry bags, moisture absorption pad & SO_2 pad in liners.	Perforated polyliner films			
CFB carton	Liner film & Thrift bag	37.5µm PE (perforated bag & non-perforated film)	Apples	Effect on mass loss, cooling rate & patterns	Berry, 2013
CFB carton	Suspended tray supported by interlocking strips of CFB at the base	Tray made from PVC	Avocados (cv. Californian Hass)	Protection from transport vibrational mechanical damages	Thompson *et al*., 2008b
	Conventional tray	Pulped paper			
	Conventional loose packaging	No internal packaging			
CFB and RPC	Clamshells	Ventilated 0.45kg minimum weight, plastic clamshell	Strawberries	Forced-air cooling of strawberries	Anderson *et al*., 2004

Main packaging (terminology of source retained)	**Internal Packaging**	**Type and design of internal package**	**Fruit**	**Related objective on the internal package**	**Reference**
CFB & plastic crates	Liners	HDPE & LDPE liners	Pears (cv. Punjab Beauty)		Kaur *et al*., 2013
Cartons	Punnets in liners	250g ventilated punnets, 20µm Xtend bags.	Strawberries (cv. Oso Grande, Sharon, Yael, Dorit, Malach &Tamar)	Controlling humidity to improve MAP	Aharoni *et al*., 2008
	Punnets	250g ventilated punnet, no liner.			
Cartons	Liners	Xtend® bag,4-5kg package liners, with easy to tear nortch	Pomegranates (cv. Wonderful)	Preserving quality with MAP & MH	Porat *et al*., 2009
Cartons	Liners	'ZOEpac', MAP. Non-perforated	Pomegranate (cv. Wonderful)	Effect of MAP and film wrapping on biochemical and physiological attributes	Mphahlele *et al*., 2016
	Shrinkable film wrappers	Polyolefin film, double layered, co-extruded			

Main packaging (terminology of source retained)	**Internal Packaging**	**Type and design of internal package**	**Fruit**	**Related objective on the internal package**	**Reference**
Cartons	plastic shrinkable wrappers	Individual heat shrinkable films, polyolefin BDF, 25mm	Pomegranate (cv. Wonderful)	Impact of film wrapping on postharvest quality.	Abd-elghany *et al*., 2012
Carton	Liners	Micro-perforated Xtend bag, 20µm (MAH) And macro-perforated Xtend bag, 20µm (MH)	Grapefruit (cv. Star Ruby)	Impact of MAP on phytochemicals	Chaudhary *et al*., 2015
Carton box	Liners	ViewFresh®, Xtend®, LifeSpan®, Breatheway®, Primpro® and Macro-perforated PE	Cherry (cv. Bing & Sweetheart)	Impact of different gas atmospheres on quality	Wang & Long, 2014
Carton boxes	Liners Paper wrapper &Liner	Lifespan L257 (MAP). Individual paper wrap inside PE liners (standard pear package).	Pears (cv. Bartlett)	Impact of MAP on quality, under regular and controlled atmospheres	Drake *et al*., 2004

Main packaging (terminology of source retained)	**Internal Packaging**	**Type and design of internal package**	**Fruit**	**Related objective on the internal package**	**Reference**
Carton boxes	Liners & BCB	Perforated & non perforated liners slotted BCB	Table grapes (cv. Regal seedless)	The impact of the liners on resistance to air flow in a multiscale packaging	Ngcobo *et al.*, 2012a
Open top corrugated trays	Punnet	Clamshell	Strawberries	Designing guidelines for Forced-air cooling	Ferrua & Singh, 2009
Returnable plastic crate	Suspended tray in clamshell	Both made from PVC	Avocados (cv. Californian Hass)	Protection from transport vibrational mechanical damages	Thompson *et al.*, 2008b
Plastic box	Liners	HDPP, 30µm, perforated	Table grapes (cv. Redglobe, Zainy & Thompson seedless)	Evaluating storage of fruits in boxes with SO_2 releasing pads and an internal liner or external wrap.	(Lichter *et al.*, 2008)
Plastic boxes	Shrinkable film wrappers	Polyolephinic heat shrinkable film wrappers	Pomegranates (cv. Primosole)	Impact of film wrapping on quality	D'Aquino *et al.*, 2010

LDPE, low-density polyethylene; HDPE, high-density polyethylene; PVC, Polyvinyl chloride; CFB, Corrugated Fibre Board; RPC, Returnable plastic crate; MAP, Modified atmosphere packaging; MH, Modified humidity; MAH, modified atmosphere and humidity; TSS, total soluble solids; BCB, Bunch carry bag.

2.2.2.2 Trays

Trays are the most commonly used internal packages of pome fruit in local market display cartons, enabling consumer purchase of individual fruit for snack (Berry, 2013). A carton may contain one, two or more trays of fruit. (Berry, 2013). According to Holt & Schoorl (1984), trays can be moulded from paper pulp or polystylene and are commonly used in telescopic cartons to hold fruit. Plastic trays made from polyvinyl chloride (PVC) have been applied in packaging ‘Californian Bartlett’ pears and ‘Californian Hass’ avocados (Thompson *et al*., 2008b). Trays are moulded in shapes suitable for holding particular produce. They provide impact protection against breakages by giving location, improve stability and contribute a degree of springiness (Kirwan, 2012). Various sizes are made with respect to the carton of application. For instance, in stone fruit industry of South Africa trays of dimensions 400 mm × 600mm and 400 mm × 300 mm are being used (Hortgro, 2016b). Trays have been applied successfully on nectarines, plums, peaches, apples and pears (Hortgro, 2016a; Hortgro, 2016b).

An advance in tray packaging has been described by (Thompson *et al*., 2008b) as a suspended tray. Compared to the conventional tray, the suspended tray is designed with deep pockets of smooth, sloping and flexible sides, able to accommodate fruit of varying sizes and shape. The tray is able to keep produce motionless to minimize bruising during transportation that could have resulted from rubbing on neighbouring fruit and or surfaces. The tray pockets are kept suspended above the bottom of the container in a clamshell or corrugated fibreboard carton.

2.2.2.3 Plastic liner bags

These are made from plastic material (polypropylene or polyethylene) of different thickness and molecular weight. Liners are flexible, sealable, printable and have a good barrier against water vapour and to some extent pathogens of the surrounding environment (Boyette, *et al*., 1996). Three predominant liner bag film thicknesses (20, 37.5 and 60 µm) are commonly used in combination with trays in telescopic and display packages of apples (Berry, 2013). Liner bags are applied in modified atmosphere packaging of fruit (Linke & Geyer, 2013; Selcuk & Erkan, 2014; Selcuk & Erkan, 2015).

One of the major transformations that has been made to enhance the performance and promote wider use of liners is through perforation. Both micro-perforated and macro-perforated liners of varying percentage ventilation areas have been applied in the postharvest packaging of table grape (Table 2.2), pomegranate and other types of fresh fruit (Table2.3). This has resulted into modification of relative humidity and gas atmosphere around the fruit, thereby influencing fruit quality (Boyette, *et al*., 1996). Pallets, cartons and internal packaging should be well ventilated to permit sufficient air flow within the pallet load, minimizing temperature and cooling variability (Vigneault *et al*., 2009a).

Table 2.2 Ventilation characteristics of different liners applied as internal packaging on table grape

Fruit	**External packaging**	**liner packaging**	**Perf. diameter (mm)**	**Perf. number**	**Vent area (%)**	**Reference**
Table grapes (cv. Regal seedless)	CFB	Grape bulk	-	-	100.00%	Ngcobo *et al*., 2012a
		Non-perf. liner film	Non-perf.	0	0.00%	
		Perf. liner film	Micro-perf.	-	-	
		Perf. Liner film	2mm	30	0.01	
		Perf. Liner film	2mm	54	0.02	
		Perf. Liner film	2mm	120	0.05	
		Perf. Liner film	4mm	36	0.05	
Table grapes (cv. Regal seedless)	CFB	LDPE (control)	Non-perf.	0	0.00	Ngcobo *et al*., 2012d
		HDPE	Pin hole	9		
		HDPE	2mm	30	0.01	
		HDPE	2mm	54	0.02	
		HDPE	2mm	120	0.05	
		HDPE	4mm	36	0.05	
Table grapes (cv. Redglobe, Zainy & Thompson seedless)	Plastic crates & cardboard boxes	LDPE external wrap	Non-perf.		0.00%	Lichter *et al*., 2008
		HDPP internal liner	6mm	-	0.20	

Perf, perforated; LDPE, low-density polyethylene; HDPE, high-density polyethylene; HDPP, high-density polypropylene; CFB, corrugated fibreboard.

Table 2.3 Ventilation characteristics of different liners applied as internal packaging on selected fresh fruit

Fruit	External packaging	liner packaging	Perf. diameter (mm)	Perf. number	Vent area (%)	Reference
Grape fruit (cv. Star Ruby)	CFB	No-liner (control)	-	-	-	Chaudhary *et al.*, 2015
		Xtend (MAH)	Micro-perf.	-	0.002%	
		Xtend (MH)	Macro-perf.		0.06%	
Kiwi fruit (cv. California)	CFB	Solid liner (control)	Non-perf.*	0	0,00%	Wiley *et al.*, 1999
		Perf. liner	Macro-perf.	-	0.60	
		Perf. liner	Micro-perf.	-	1.20	
Kiwi fruit (cv. California)	CFB	Solid liner (control)	Non-perf.*	0	0,00%	Wiley *et al.*, 1999
		Perf. liner	Macro-perf.	-	0.30	
		Perf. liner	Macro-perf.	-	3.30	
Peaches (cv. Shan-e–Punjab)	Tray	No-liner (control)	-	-	-	Singh *et al.*, 2005
	No-box	PE 500g bag	Non-perf.*	-	0,00%	
		PE 500g bag	4mm	-	2.5%	
		PE 500g bag	4mm	-	5,00%	
		PE 500g bag	4mm	-	7.5%	
Plums (cv. Friar)	CFB	No-liner (control)	-	-	-	Cantı´n *et al.*, 2008
		Lifespan L316^	Non-perf.*	0	0.00	
		FF-602^	Non-perf.*	0	0,00%	
		FF-504^	Non-perf*.	0	0,00%	
		Hefty 66034^	Non-perf.*	0	0,00%	
		FF-602^	-	-	2,00%	
Pomegranate (cv. Mollar de Elche	Plastic crates	No-liner (control)	-	-	-	Artés *et al.*, 2000
		PP	Non-perf.*	0	0.00	
		PP	1mm	$6/100cm^2$	0.05	

Perf, Perforated; LDPE, low-density polyethylene; PP, polypropylene; PE, polyethylene; CFB, corrugated fibreboard; MH, modified humidity; MAH, modified atmosphere and humidity.
*Solid liners, without visible macro-perforations; ^ source naming retained.

2.2.2.4 Punnets and clamshells

Punnets are small light weight regular baskets containing fruit like small tomatoes and berries (Vigneault *et al.*, 2009). Punnets are made from polyethylene (PE), polyethylene-terephathalate (PET), polyvinyl chloride (PVC) or cardboard, and are designed to accommodate different weights of product (Boyette, *et al.*, 1996; Moras, 2005; Hortgro, 2016b). For example, stone fruits can be packed in 500 g or 700 g punnets (Hortgro, 2016b). The PET punnets are often chosen for horticultural produce because of their light weight, availability, remarkable transparent display of the contained product and physical barrier to gasses. Though expensive, they are increasingly more preferred by UK supermarkets (Boyette, *et al.*, 1996; Cagnon *et al.*, 2013). Because of their rigid physical structure, PET punnets are applied to offer protection from mechanical damage and contamination during handling, transportation and marketing of sensitive fruit like strawberries (Cagnon *et al.*, 2013). The application of punnets in handling different types of fresh fruit is summarised in Table 2.1.

Punnets have vent holes to allow for gas and moisture exchange between the inside and outside environments. Clamshells are punnets having the base and the lid attached along one edge as a single piece (Pathare *et al.*, 2012). Tight fitting rigid lids or over wrapping thin plastic films are often used to seal open top punnets (Boyette, *et al.*, 1996; Hortgro, 2015). General punnet designs may result in inefficient quality maintenance of particular products because of differences in postharvest biology and physiology. Advances are on-going using tailor made punnets for specific horticultural produce. For instance, Cagnon *et al.* (2013) designed a package specifically for strawberries using a PET punnet and a wheat gluten paper lid with the ability to easily release the impregnated 2-nonanone active ingredient against *Botrytis* cinerea mould growth, when the package is put under high relative humidity environment. This active package delayed mould growth and extended shelf life of strawberries for 3 days under ambient conditions of 20 ^{o} C compared to 1 day by passive punnet packages. In addition, Ferrua & Singh (2011) have reported the design of new clamshell packaging for handling strawberries with improved cooling uniformity of fruit and reduced resistance to air airflow.

2.2.2.5 Bunch carry bags

Bunch carry bags are used in the multi-scale packaging of table grapes (Ngcobo *et al.*, 2012a). Berry (2013) reports that bunch carry bags used as IPs in packaging of grapes are similar to the thrift bags IPs of pome fruit. Bunch carry bags usually have some slits on them which open when loaded with fruit. The slits are intended for gaseous exchange with surrounding environment (Berry, 2013).

2.2.2.6 Heat shrinkable film wraps

Shrink films are made from different types of plastic such as polyolephin, polyethylene, polypropylene, polyvinyl chloride and may consist of single or multiple plastic layers. Shrinkable films are made by applying force (especially heat) on the film thereby straightening the molecular chains to allow stretching of the films. The film is then cooled in a special way to keep it in the stretched position and reheating the film causes it to shrink back to its original state. The heat shrinkable films have been used to individually wrap different fresh fruit before packaging in external boxes as observed in citrus, pomegranates, kiwifruit (Table 2.3), apples, mangoes as well as vegetables like cabbages. The films prevent fruit to fruit rubbing and bruising, microbial contamination, moisture loss and provide surface for stick-on labels (Boyette, *et al*., 1996). Two multiple-layer polyolephin films of varying gas and water permeability were used to keep quality and prevent moisture loss in pomegranate fruit (Nanda *et al*., 2000).

2.2.2.7 Skin coatings

One of the challenges of adding internal packaging in the fruit packaging system is that they contribute an additional cost on the product and yet they are discarded in the end, contributing to municipal waste. If not properly disposed of, plastic packaging materials may endanger the environment. In an effort to solve these challenges and yet retain some of the advantages of shrink wrapping like minimised weight loss, edible skin coatings have been applied on fresh fruit. They are applied by dipping fruits in the prepaid mixture and allowed to air dry. Sucrose polyesters have been applied on pomegranate fruit (Nanda *et al*., 2001), Apples (Park *et al*., 1994) and oranges (Nisperos-Carriedo *et al*., 1990).

2.2.2.8 Mechanical damage insulators

Mechanical insulators used in the fresh fruit packaging industry are made out of paper, plastic, foam material or a combination of these materials. They minimize mechanical damage by providing cushioning, minimize vibration by immobilizing the fruit, and prevent fruit rubbing and contact. Jiffy pad insulators may consist of macerated or shredded paper material held between two paper sheet laminates. The pads (Figure 2.2) are applied at the bottom of wooden crates to avoid hard contact with fruit and at the top to immobilize fruit during transportation. They are applied in the packaging of plums, peaches, apricots, pears, grapes and apples (Hortgro, 2016a, Hortgro, 2016b).

Bubble sheets are usually transparent plastic mats with protruding air filled discs on one side and a flat surface on the opposite side. The size and density of the bubbles vary depending on the purpose. They are majorly formed using LDPE and are more flexible, able to fill the gaps between fruits. Bubble sheets are applied in the same way and are a cheaper alternative to jiffy pads. In South Africa, they are applied in stone and pome fruit packaging (Hortgro, 2013;Hortgro, 2015).

Fibreboard dividers are made out of corrugated fibreboard paper cards. They commonly consist of slitted horizontal and vertical paper cards which fit into each other at right angles to create partitions within the corrugated fibreboard cartons. They are good at preventing fruit to fruit contact and help in immobilization by keeping fruit in position. They can be applied on fruit like water melons.

Foam nets are commonly formed by forcing expanded polyethylene material into a net mould using steam heat at high pressures. They are commonly used for holding individual fruit. They have been applied on apples, pears, citrus, water melons (Jarimopas *et al*., 2007; Zhou *et al*., 2008). Foam nets were reported to reduce risk of mechanical damage in golden delicious apples (Amer Eissa *et al*., 2012). Other internal packages used in minimizing mechanical damage may include ruffled papers.

2.2.3 The roles of internal packaging in fresh fruit industry

Packaging is a big role player in protecting, containing, storing, preserving, communicating, convenience of use, selling and distributing agricultural products (Robertson, 2006; Opara, 2011; Robertson, 2013).

2.2.3.1 Protection

Packaging shields fruits from external environment including pathogens and infections (Thompson, 2003). Horticultural packages are designed to offer sufficient physical protection to fruit they contain throughout cold storage, distribution and sale, maintaining product integrity (Burdon, 2001). In addition to the external packaging like corrugated fibreboard cartons, internal packaging components such as bubble pads, jiffy pads, ruffled paper, trays, punnets and form nets can be included to protect against mechanical damage by absorbing impact and compression energy (Holt & Schoorl, 1984; Thompson *et al*., 2008b). Internal packages minimize bruising by preventing fruit to fruit rubbing and contact with packaging wall (Peleg, 1985; Amer Eissa *et al*., 2012; Berry, 2013). Liners, thrift bags, carry bags and shrinkable film wraps minimize fruit exposure to environmental microbial contamination and offer protection against moisture loss.

2.2.3.2 Containment

Table 2.1 shows the containment of various fruit in diverse internal packaging. Packaging partially or wholly encloses the product, provides means of unitizing and easy handling of fruit. The containment function of packaging contributes greatly to its protective role (Schoorl & Holt, 1982). Packaging containers can be designed specifically to contain a single individual fruit or a number of fruit. A container imposes movement restrictions to a specific quantity (volume, weight or number) of fruit minimizing breakages and bruising. According to Berry (2013) containment addresses the need for packaging to increase fruit density (fruits per volume of space). While as external packaging plays a big role in containing the fruit during storage and distribution, internal packages contain the sizeable convenient units bought by the consumers. Internal packages such as heat shrinkable film wraps allow the containment of single fruit making it easy for consumer snacking. Punnets and carry bags may often contain a bunch of fruits of a specific weight as observed in the packaging of table grapes (Ngcobo *et al*., 2013b) while as thrift bags contain a number of fruit as observed in the packaging of apples (Berry, 2013). Trays are used to contain fruit even during retail market display as observed for oranges, apples, pears and pomegranates.

2.2.3.3 Convenience

Convenience is a fundamental component relevant in the design of fruit packages. Horticultural produce tend to be bulky and yet very tender and susceptible to damages. External packages such as corrugated fibreboard cartons and returnable plastic crates are often designed with side holes to facilitate convenient manual handling (Singh *et al*., 2008). However, internal packages are more convenient to the consumer (Section 2.2.1). The convenience of fruit packed in internal packages lies in consumer affordability, choice fruit sizes, ease of hand carrying and packed ready for consumption.

2.2.3.4 Information and communication

The visual and graphic designs on branded packages play a role in attracting customers to the products inside. The package also provides relevant information to the customers about the product such as best before date, nutritional information, product type and grade, distributor information, use and handling information depending on legal requirements (Thompson, 2003). However, it is of great importance that relevant consumer information be included on the internal packages because they stand higher chances of reaching the final consumers as opposed to the external packages (cartons) as discussed earlier under levels of packaging (Section 2.2.1). This is commonly observed in the packaging of apples and pears in print-on thrift bags (Figure 2.3A) on South Africa and European Union markets. Stick-on labels with relevant consumer information are put on individual punnets containing table grapes and stone fruit (Figure 2.3B-D)

Figure 2.3 Packaged fruit ready for supermarket display: A) Apples in print-on thrift bags, displayed on supermarket shelf; B) Peach fruit packed in polystylene tray and film wrap, with stick on label; C) Peach fruit in open-top punnet, wrapped with plastic film and D) Peach fruit packed on paper tray inside paper box, wrapped with plastic film.

2.3 The impact of internal packaging on airflow resistance and cooling characteristics of fresh fruit

2.3.1 Pressure drop and air resistance

With advances in postharvest cold chain management of pomegranate and other fresh produce, it has become common practice to pre-cool fruit after harvest and pre-packing in cartons or crates and on pallets (Delele *et al*. 2008; Ngcobo *et al*., 2013b). This practice also minimizes chances of fruit contamination, mechanical damage and promotes easy mechanical handling of produce. Forced-air cooling (FAC) has been widely applied as a pre-cooling technique for many packaged fresh fruit. One of the major drawbacks of FAC is airflow resistance by fruit and packaging (Vigneault *et al*., 2004; Delele *et al*., 2008). With the multi-scale packaging application in the industry, internal packages have been reported to further exacerbate this problem as observed in table grapes and apples (Ngcobo *et al*. 2012a; Ngcobo *et al*., 2012d; Berry, 2013). An understanding of the impact of internal packages on pressure drop and air resistance gives a better understanding of cooling patterns and therefore aiding the design and choice of packaging in the fresh fruit industry.

A pressure drop experiment conducted in a wind tunnel on different table grape packaging components (Ngcobo *et al*., 2012a) showed that introducing bunch carry bags in the fruit bulk greatly increased pressure drop across the fruit stack by more than 150 Pa m^{-1}. More than 50 % of the pressure drop across the multi-scale packages was due to liner bags, with 83.3 % for non-perforated and less than 69.0 % for perforated liners. However, an unexpected increase of pressure drop with vent hole ratio of the liners was observed. Different packaging combinations affect pressure drop differently. In another experiment (Ngcobo *et al*., 2013b), clamshell and open top punnet internal packaging of table grapes registered a lower pressure drop increment compared to bunch carry bag treatment. Adding liners in the treatments resulted in the bunch carry bag showing lower increment in pressure drop than clamshell and open top punnet treatments. Furthermore, air-flow resistance studies on packaged apples revealed that packing fruit in thrift bags resulted in a 39.0 % lower resistance coefficient value than fruit packed on trays inside liners (Berry, 2013).

2.3.2 Cooling rate

Freshly harvested fruit come with bulk of heat from the field. High temperature facilitates rapid deterioration in postharvest fruit quality by influencing physiological and physical chemical processes like respiration. It is therefore expedient that temperature is lowered in the most efficient way possible (Thompson *et al*., 1998; Zou *et al*., 2006a; Zou *et al*., 2006b; Thompson *et al*., 2008a). This makes cooling rate a very important factor in maintaining fruit quality during pre-cooling.

Packaging has considerable influence on cooling rate and cooling patterns of horticultural produce by playing a role in airflow distribution (Smale *et al*., 2006; Zou *et al*., 2006a; Zou *et al*., 2006b) and the presence of internal packaging is a key factor. The impact of internal packages on cooling rate of fresh fruit, especially liners, trays, thrift and carry bags, punnets and clamshells have been examined mostly on table grape and apples (Table 2.4). Table grapes packed in open top punnets were found to cool faster than fruit in clamshell and bunch carry bag multi-scale packages (Ngcobo *et al*., 2013b). Berry (2013) observed that adding liners or thrift bags to apples in cartons delayed cooling and lowered cooling rate by 78 % and 24 % respectively, while as fruit tray treatment had significantly the highest cooling rate. The differences can be attributed to less barrier effect of the trays allowing more convective heat exchange, promoting faster cooling than conductive means. The thrift bags provide alternative air flow routes and more surfaces for conductive heat exchange than for the solid liners within the cartons (Laguerre *et al*., 2006; Berry 2013).

The most studied internal package on cooling rate is the liners. Non-perforated liners increase the time taken to lower temperature difference between the initial product and cooling medium temperatures to a required minimum (Ngcobo *et al*., 2012b). This can be attributed to their barrier effects that prevent easy circulation and flow of cooling air within the bulk of the fruit (Thompson *et al*., 2008a). One of the vast applied techniques to improve cooling rate in liners is perforation which reduces on the barrier effect of the liners by improving circulation flow of cooling air within the stack or individual fruits. Ngcobo *et al*. (2012b) illustrated that seedless table grapes packed in perforated liners cooled 84 minutes faster than in non-perforated liners. However, there was no observable difference in cooling rate between the micro-perforated liners and the non-perforated liners because of their very tinny openings limiting air circulation. From an unexpected end, slowest cooling was observed in the grapes packed in 30 × 2 mm perforated liner. These results suggest that perforation size and number are important in improving cooling rate. A number of researchers have investigated different liner perforation sizes, numbers and ventilation area on cooling and quality of fresh fruit as summarised in Tables 2.2 and 2.3. In Kiwifruit (cv. California), using perforated liners reduced cooling time by 50 % compared with non-perforated liners at 0.0005 $m^3s^{-1}kg^{-1}$ flowrate (Wiley *et al*., 1999). Fruit cooling rate increased with increasing ventilation area, for fully packed cartons (Wiley *et al*., 1999). However, adding internal packages such as moisture absorption pads, SO_2 pads and bunch carry bags for table grapes inside the liners reduced the effectiveness of perforations (Ngcobo *et al*., 2012a; Ngcobo *et al*., 2012d). Therefore, alignment of liner perforations and carton ventilation holes is important for effective cooling.

Table 2.4 A summary on the effect of different internal packaging combinations on cooling characteristics of selected fruits

Internal packaging applied	**Fruit**	**Effect of internal packaging on cooling characteristics**	**Reference**
Clamshell punnet, open top punnet & bunch carry bag	Table grapes (cv. Regal seedless)	Inner packages increased pressure drop. Higher cooling rate for open top punnets. Lower moisture loss rate for bunch carry bags	Ngcobo *et al*., 2013b
Liners, polystylene trays or perforated thrift bags	Apples	Perforated thrift bags showed a lower resistance to air flow than liners	Berry, 2013
Liners, polystylene trays or perforated thrift bags	Apples	78% and 24% Cooling rate reduction by liners and thrift bags respectively	Berry, 2013
Non-perforated, macro and micro perforated liners	Kiwifruits (California)	Micro-perforated liners had higher cooling uniformity &reduced cooling time by about 40% because of their high ventilation area	Wiley *et al*., 1999
Non-perforated and perforated liners	Kiwifruits (California)	Lower cooling time for perforated liners	Wiley *et al*., 1999
Perforated and non-perforated PE liners	Table grapes (cv. Regal seedless)	Delayed cooling in non-perforated liners	Ngcobo *et al*., 2012d
Perforated and non-perforated liners	Table grapes (cv. Regal seedless)	Highest resistance to air flow in non-perforated liners	Ngcobo *et al*., 2012a

2.3.3 Cooling uniformity

During forced-air cooling of fresh fruit, a cooling gradient was created across the stack with the fruit at the front cooling fastest, followed by the fruit in the middle and then slowest at the back of the stack in relation to the airflow direction (Baird *et al*., 1988; Berry, 2013). This phenomenon is exaggerated by packaging (Smale *et al*., 2006) and if not addressed can impose threats on the postharvest quality of the fruit along the cold chain, especially in multi-scale packaging. Multi-scale packages may lead to heterogeneous (non-uniform) cooling in table grapes, affecting fruit quality (Ngcobo *et al*., 2013b). Cooling variations where also observed during a study on apples (Berry, 2013), were the fruit at the centre and on the left cooled 21 % faster than fruit on the right hand side and it was attributed partly to the liners. In comparison, there was a lesser cooling heterogeneity between the fruit on both sides of the stack without liners, which improved air circulation within the stack. To promote rapid, uniform and efficient cooling process of horticultural produce, a combination of ventilated packaging and minimal amount of internal packaging is promoted (de Castro *et al*., 2005b; Thompson *et al*., 2010). The application of perforated liners has been shown to improve cooling uniformity in fresh fruit. Micro- and macro-perforated liners of different ventilation area were found to increase cooling uniformity within ‘California’ Kiwifruit across the pallet (Wiley *et al*., 1999).

2.3.4 Energy consumption and efficiency

The effectiveness and efficiency of a cooling process and facility are important in the horticultural fruit industry for produce quality and business profitability. Energy consumption of a pre-cooling process depends largely on the time taken to achieve a required temperature reduction (Thompson *et al*., 2010). Furthermore, cooling time depends on pre-cooling method, fruit geometry and physiological state, package design, ventilation and stacking orientation, as well as the internal packaging involved (Delele *et al*., 2008; Thompson *et al*., 2008a; Teruel *et al*., 2011; Pathare *et al*., 2012). Previous studies have suggested reducing pre-cooling energy consumption by improving carton ventilation and porosity as solution (Vigneault & Goyette, 2002; Thompson *et al*., 2010). A container ventilation area of 8-16 % was suggested for optimum energy consumption (de Castro *et al*., 2005b). However, with the incorporation of internal packaging in ventilated packaging, more energy is consumed resulting from blocked ventilation (Delele *et al*., 2008; Ngcobo *et al*., 2012). There is a positive correlation between resistance to air flow and energy consumption (Delele *et al*., 2008). Therefore, internal packages like non-perforated liners which pose high resistance to air flow, will increase the time needed to achieve a required temperature reduction and thus increased energy consumption. It also follows that perforation of liners which have been found to reduce resistance to cooling air-flow (Ngcobo *et al*., 2012a) will thus minimize energy consumption during FAC. Therefore, energy consumption depends to a large extent on pre-cooling time (Thompson *et al*., 2010). Hence, increasing ventilation effectiveness and reducing quantity of internal packages will minimize energy consumption.

2.4 Impact of internal packages on the postharvest quality of fresh fruit

2.4.1 Fruit physiology and atmosphere around the fruit

2.4.1.1 Physiological weight loss

After harvest, fresh fruit is highly prone to moisture loss by transpiration across the skin through minute openings (Elyatem & Kader, 1984; Nanda *et al*., 2001). Moisture loss results into shrinkage, shrivel, wilt, quantitative loss in weight, loss in visual appearance, taste and overall acceptability of fruit, hence financial loss (Ben-Yehoshua & Rodov, 2003; Vigneault *et al*., 2009b). This is highly dependent on the temperature, relative humidity and air movements of the surrounding atmosphere of the fruit. Internal packages affect the environment surrounding the packaged fruit. Techniques such as fruit surface coating; individual fruit heat shrink-wrapping and internal packages like plastic poly-liners have been applied through the industry to reduce moisture loss.

Individual shrink-wrapping

Heat shrinkable films have been successfully applied to minimize moisture and weight loss in fresh whole fruit like apples (Sharma *et al*., 2013), oranges and grape fruit. Using pomegranate as a case study because of its novelty attracted to its high nutrient content with emphasis on antioxidants. D’Aquino *et al*. (2010) reports 3.1 and 12.7 % weight loss in wrapped and un-wrapped pomegranate (cv. Primosole) fruit respectively, after 84 days of cold storage plus 7 days of shelf storage. Nanda *et al*. (2001) observed 1.5 % weight loss in shrink-wrapped pomegranate (cv. Ganesh) compared to 14.0 % for un-wrapped fruit after 25 days at 25 ^{o}C. In addition, wrapping significantly minimized rind weight and thickness loss compared to un-wrapped fruit at 8 ^{o}C storage.

Shrink wrapping excels over chemical treatments in reducing weight loss in pomegranate (cv. Wonderful) where wrapping alone registered 2.2 % weight loss compared to 7.1 and about 4.0 % in un-wrapped and calcium chloride treated fruit, respectively (Abd-elghany *et al*., 2012). Shrivelling is expected to be observed in pomegranates after a 5 % loss in weight compared to 4 % in Kiwifruit (Wiley *et al*., 1999; Elyatem & Kader, 1984). Therefore, shrink wrapping successfully prevents shrivelling in pomegranates, hence retaining good marketability. This is attributed to the barrier nature of wrap films maintaining high relative humidity around the fruit, reducing vapour pressure deficit and transpiration across fruit rind. Wrapping film with a lower water vapour transmission rate had a better impact on reducing rind moisture loss than the film with higher moisture permeability (Nanda *et al*., 2001). However, shrink wrapping, surface coating or waxing can lead to anaerobic respiration by creating an oxygen deficit around the fruit, producing off flavours and taste deterioration (Truter *et al*., 1994; Taylor *et al*., 1995; Gil *et al*., 1996; Cantı´n *et al*., 2008).

Perforated and non-perforated liners

It is important that a high relative humidity be kept around the products after cooling as a measure to minimize moisture and weight loss (Thompson *et al*., 2008a). With success, non-perforated liners have been shown to solve the problem of moisture condensation and physiological weight loss in fresh whole fruit (Table 2.5). The use of HDPE or LDPE liners in corrugated cartons greatly minimised weight loss in ‘Punjab Beauty’ pears for 75 days of cold storage compared to cartons alone (Kaur *et al*., 2013). Similar results have been obtained for plums, pomegranates and table grapes as shown in Table 2.5. This trend is because the liners maintain a high relative humidity environment around the fruit and therefore minimize moisture loss across the fruit skin (Suparlan & Itoh, 2003; Ngcobo *et al*., 2012d). The difference in ability to minimize moisture loss between different liners is related to the varying water vapour transmission rates of the liner bags as reports Selcuk & Erkan (2014).

Table 2.5 The impact of liners on the percentage weight loss of selected fruit

Fruit type	**Storage**	**Percentage weight loss / moisture loss**			**Reference**
		Control (no-liner)	**^MAP/ Non-perforated liner**	**Perforated liner**	
Grape berries	1.2 ± 0.3°C, 89.1 ± 2.6RH%, 72days	8.68%	3.62%		Ngcobo *et al.*, 2012b
Grape stems		88.55%	49.24%		
Grape bunches		7.31%	0.41%	5.16-6.35%	
Grape fruit (cv. Star Ruby)	10°C, 80-85%RH, 16wks +1wk at 20°C	4.24%	3.29%	3.74%	Chaudhary *et al.*, 2015
Kiwifruits (cv. California)	0°C, 120days		0.75%	3.0-4.5%	Wiley *et al.*, 1999
	0°C, 18wks		0.70%	**2.4-5.2%	
Mangoes (cv. Baneshan)	12.5±1°C, 28days	>10.00%	<4.00%		Kumar *et al.*, 2013b
Pears (cv. Punjab Beauty)	0-1°C, 90–95% RH, 75days	*5.9-6.9%	*3.4-5%		Kaur *et al.*, 2013
Plums (cv. Friar)	0°C, 85%RH, 60days	6.0%	0.1-0.3%	2.0%	Cantı´n *et al.*, 2008
Pomegranates (cv. Hicrannar)	6 ± 0.5°C, 90 ± 5%RH, 120days	17.24%	1.48-4.42%		Selcuk & Erkan, 2014
Pomegranates (cv. Mollar de Elche)	2°C, 95%RH, 12weeks	0.14%	0.06%	0.96%	Artés *et al.*, 2000
Sweet cherry (cv. Bing & Sweetheart)	0°C, 6wks		<1.00%	<1%	Wang & Long, 2014

*Visually estimated from the graph; **Includes both macro and micro-perforated liners; ^Without visible perforations; RH, Relative humidity.

On the contrary, no significant weight loss was observed between liner and no-liner packed grape fruit (cv. Star Ruby) after 16 weeks of cold storage (Chaudhary *et al.*, 2015). Non-perforated liners have delayed pre-cooling process increasing energy consumption and facilitated moisture condensation around the fruit, promoting decay (Wiley *et al.*, 1999; Ngcobo *et al.*, 2012a; Berry, 2013; Ngcobo, 2013; Ngcobo *et al.*, 2013b). In addition, using non-MAP liners could create a fear of anaerobic respiration due to low O_2 and high CO_2 concentration for sensitive fruit with relatively high respiration rate resulting into production of off flavours (Rodov *et al*., 1996; Fishman *et al*., 1996). Using MAP and modified humidity liners significantly minimised weight loss in mangoes compared to packing fruit with polypropylene bags of varying thickness (Kumar *et al*., 2013b). However, in a similar experiment, lowest weight loss was observed in pomegranate stored in polypropylene liners compared to fruit in modified humidity and MAP liners throughout the cold storage of 120 days at 4 ^{o}C (Kumar *et al*., 2013a). This has resulted into increased use of perforated liners in the industry to attempt strike a balance between weight loss and moisture condensation (Ben-Yehoshua *et al*., 1988).

As shown in Table 2.5, perforated liners are able to minimize weight loss in various fresh fruit compared to no-liner treatment. In sweet cherries, a standard macro-perforated PE box liner greatly minimized weight loss with no significant difference compared with 5 different MAP box liners (Wang & Long, 2014). However, besides the type of fruit and prevailing storage conditions like temperature, storage time and relative humidity, the success of perforated liners greatly depends on the perforation number and size of a given liner (Tables 2.2 and 2.3). Ngcobo *et al*. (2012a) reports significantly higher weight loss for table grapes in macro-perforated liners compared to fruit in micro-perforated and non-perforated liners. In Kiwifruit weight loss increased with increasing ventilation area with 0.75 , 3.0 and 4.5 % for 0, 0.3 and 3.3 % ventilated liners (Wiley *et al*., 1999). In a similar experiment, 1.2 and 5.2 % weight loss was observed in kiwifruit packed with micro-perforated liners, resulting into shrivelling compared to 2.4 % loss for fruit packed in 0.6 % ventilation liner treatment (Wiley *et al*., 1999). Optimization of liner perforation is important to avoid excessive moisture loss in cases of very high ventilation or minimum moisture loss but high risk of condensation in case of very low ventilation. This may explain the observation by Ngcobo *et al*. (2012b) of no significant difference in weight loss of grape berries and stems between perforated liner treatments and no-liner control treatment. Therefore, further research is still needed on optimising ventilation area in liner bags used for postharvest handling of fresh fruit.

Punnets, carry bags and trays

With no significant difference in weight loss rate, bunch carry bags minimized weight loss in table grapes better than both clamshell and open-top punnets, in their respective multi-scale packaging combinations. Likewise, stem dehydration was highest in bunch carry bags, followed by clamshell punnets and highest in open-top punnet packaging combinations (Ngcobo *et al*., 2013b). The difference was directed to variations in relative humidity percentages which was higher in bunch carry bag combination and hence a lower vapour pressure deficit compared to punnets combinations (Ngcobo *et al*., 2013a). The differences in percentage relative humidity with the packaging combinations can be related to the difference in percentage ventilation areas of the packaging components. According to Ngcobo *et al*. (2012a) and Ngcobo *et al*. (2013b) a higher percentage of ventilation area allows more direct contact of air flow with the fruit therefore facilitating moisture loss. A lower vapour deficit implies a lower risk of transpiration and hence minimized weight loss.

2.4.1.2 Moisture condensation

Challenges of liner application in cold chain management of fruit weight loss include moisture condensation and associated fruit decay (Ben-Yehoshua *et al*., 1998). Because of the barrier nature of plastic liners to moisture transmission, a build-up in relative humidity occurs creating a saturated environment within the bags (Suparlan & Itoh, 2003; Kaur *et al*., 2013). Relative humidity inside plastic bags can go as high as 100 % (Ngcobo *et al*., 2012d). Therefore condensation occurs when fruit is moved from ambient temperature to cold storage and vice versa or during temperature fluctuations during storage or transport. Condensation can take place even within small temperature range fluctuations. Condensation becomes visible when the water vapour transmission rate of the liner wall does not match the rate of vapour accumulation inside the bags. Wiley *et al*. (1999) attributed the significantly higher decay levels in Kiwifruit to higher condensation in non-perforated liners on transferring fruit from 0 to 5 to 20 °C to simulate transportation and shelf life. The researchers observed that perforated liners minimised condensation. A MAP liner (Xtend®) eliminated moisture condensation in pomegranate fruit because of its high water vapour transmission compared to polypropylene bags which showed progressive moisture accumulation (Kumar *et al*., 2013a). Heat shrinkable film wrapping on fruit have been found to solve the problem of condensation because of their ability to stick on the skin of fruit thereby blocking the micro-pores through which moisture diffusion occurs (Patterson *et al*., 1993; Maguire *et al*., 2001).

Impact of perforation on condensation

Fruit decay and spoilage facilitated by condensation have been minimized by bags with high water vapour transmission rate (Porat *et al*., 2009; Kumar *et al*., 2013a). One of the major ways of improving vapour transmission in liners is through perforation. Perforation minimizes vapour condensation in MAP liners, due to changes in vapour transmission capability of the liners (Ben-Yehoshua *et al*., 1988). Higher moisture condensation (2.99g) was quantified on upper inside of the non-perforated film compared to perforated film (0.013g) for bell peppers in cartons. A similar trend of condensation was observed on the fruit themselves (Ben-Yehoshua *et al*., 1988).

On the contrary, though using perforated liners resulted into significantly lower relative humidity inside the bags, condensation still occurred in table grapes packages (Ngcobo *et al*. 2012d). Therefore, condensation can still occur in perforated liners and modified humidity box liners if the water vapour transmission rate of the liner wall does not match the rate of vapour accumulation of the bags. Hence, the optimization of liner perforation is required to strike a balance between excessive moisture condensation and excessive weight loss in fresh fruit (Ben-Yehoshua *et al*., 1988). Xtend® MAP liners have been found to prolong good quality in a number of fresh fruit, though relatively expensive compared to similar products on the market (Ben-Yehoshua, & Rodov, 2003; Aharoni *et al*., 2008). Other techniques such as in-cooperation of hygroscopic substance inside bell pepper packages lowered percent relative humidity, moisture condensation as well as decay (Ben-Yehoshua *et al*., 1988). Also non-perforated polyamide bags were found to minimize moisture loss, decay of Bell peppers as well as solve moisture condensation problems just as the perforated polyolefin films in cartons. This was attributed to the high water vapour transmission rate of these non-perforated bags (Ben-Yehoshua *et al*., 1996).

2.4.1.3 Decay and spoilage

Internal packaging significantly minimize or facilitate decay in harvested fruit depending on the technology applied with respect to the biology of the fruit and the prevailing storage-handling conditions.

The effect of liners

There is a noticeable effect of liner bags on reducing fruit spoilage. Kaur *et al*. (2013) compared pears (cv. Punjab Beauty) packed in CFB cartons and crates lined with HDPE and

LDPE bags versus no liner in wooded boxes, crates and CFB cartons. High spoilage was in no-liner packed fruit with maximum spoilage in wooded boxes (6.91 %) and low spoilage in liner packages, especially HDPE in CFB (3.1 %). The HDPE liners showed better ability to prevent spoilage as compared to LDPE in both CFB and crates. This could be attributed to differences in liner permeability to gases and moisture. Specifically, on decay, MAP liners have been found to significantly minimize decay incidence during storage of various fruit (Table 2.6). This can be attributed to the low O_2 and high CO_2 atmosphere inside the bags that may un-favour microbial proliferation. High CO_2 and low O_2 atmospheres inhibit fungal growth and decay in pomegranates (Hess-Pierce & Kader, 2003; Palou *et al*., 2007). At the end of 42 days cold storage, Ngcobo *et al*. (2012d) recorded no observable decay for table grapes packed in multi-scale packaging with five different perforated and one non-perforated liners. The high levels of decay at the end of shelf life show the importance of maintaining a cold chain alongside packaging. In simulated airfreight transportation, MAP liners significantly controlled Rhizopus and Botrytis decay in strawberries compared to the no-liner packed fruit, reducing total decay by more than 6 times (Aharoni *et al*, 2008).

The challenge of using MAP is the fear that it may lead to excessive levels of CO_2 and low O_2 atmospheres thereby supporting anaerobic respiration and the subsequent production of off flavour compounds. In addition, incidences of very high relative humidity support moisture accumulation inside the bags because of lower moisture permeability which fuels microbial spoilage (Hardenburg, 1971; Zagory & Kader, 1988; Wiley *et al*., 1999; Tavora *et al*., 2004; Ngcobo *et al*., 2012d). The use of perforated film significantly minimized *Botrytis* decay in bell peppers to 7 folds lower than in non-perforated carton film treatment (Ben-Yehoshua *et al*., 1988). In addition, lower moisture condensation was quantified in perforated than non-perforated treatment (Ben-Yehoshua *et al*., 1988). Application of appropriate fungicides, ventilated packaging and packaging practices like sealing bags only after transfer to cold conditions and opening bags during ambient conditions will minimize fruit decay (Porat *et al*., 2009). The in-cooperation of hygroscopic substance inside bell pepper packages lowered percent relative humidity, moisture condensation and decay (Ben-Yehoshua *et al*., 1988).

Table 2.6 Effect of internal packaging on percentage decay of selected fruit during specified storage conditions

Fruit	**Storage**	**Packaging**	**% Decay**	**Reference**
Kiwifruits (cv. California)	0°C, 6months + 5°C, 5dys + 20°C, 3dys	Control	-	Wiley *et al.*, 1999
		MAP liner	7.60	
		Perf. liner	1.00 & 2.50	
Pear (cv. Punjab Beauty)	0-1°C, 90-95%RH, 60dys	^Control	“6.0 to 7.0	Kaur *et al.*, 2013
		Non-perf. liners	“3.1 to 5.0	
Pomegranate (cv. Primosole)	8°C, 90% RH, 12wks	*Control	10.00	D’Aquino *et al.*, 2010
		Film-wrap	13.00	
Pomegranate (cv. Hicrannar)	6°C, 90%RH, 120 dys +20°C, 3dys,	^Control	40.00	Selcuk & Erkan, 2014
		MAP liner	13.33 & 26.67 %	
Pomegranates (cv. Mollar de Elche)	2°C, 95%RH, 12wks	^Control	0.00	Artés *et al.*, 2000
		MAP liner	0.00	
		Perf. Liner	2.10	
	5°C, 95%RH, 12wks	^Control	0.00	
		MAP liner	0.00	
		Perf. Liner	0.00	
Pomegranate (cv. Ganesh)	8°C, 70-75%RH, 12wks	*Control	-	Nanda *et al.*, 2001
		Film-wrap	8.30 & 13.30	
	25°C, 40-60%RH, 25dys	*Control	<12.00	
		Film-wrap	13.30 &16.60	
Strawberries (cv. Sharon)	1°C, 1dy + 5°C, 2dys +17°C, 2dys	^Control	78.60	Aharoni *et al.*, 2008
		MAP liner	12.10	
Table grapes (cv. Regal seedless)	-0.5°C, 42dys	Non-perf. liner	0.00	Ngcobo *et al.*, 2012d
		Micro-perf. liner	0.00	
		Perf. liners	0.00	

Perf: Perforated (especially macro-perforated), MAP: Modified atmosphere packaging (may be micro-perforated), * Un-wrapped, “percentage spoilage visually read from graph, ^ No-liner.

Effect of shrink wrapping

The sole application of shrink wrapping may not solve fruit decay as illustrated below. There wasn't any significant difference in pomegranate (cv. Primosole) decay between the un-wrapped control and the solely wrapped fruit for 3 months of cold storage. An additional week at 20 °C resulted in significantly higher decay (35 %) in the solely wrapped fruit compared to all other treatments (D'Aquino *et al*., 2010). Similar results have been reported (Table 2.6). This can be attributed to low moisture permeability of the wrap films.

However, different plastic film wraps of varying gas permeability did not affect decay of pomegranate fruit at the end of the cold storage period and an additional 6 days at shelf conditions (Artés *et al*., 2000). Un-expectedly, higher decay percentage was registered in fruit wrapped in a film of higher gas permeability and water transmission rate than a film of lower gas and water permeability at different temperatures of storage (Nanda *et al*., 2001). This may be attributed to the elevated CO_2 and lower O_2 levels hindering microbial spoilage especially Penicillium sp. which was suspected to be the major cause of decay in the study (Nanda *et al*., 2001). The sole use of chemical treatments may have an edge in controlling fruit decay compared to sole shrink wrapping. Due to limitation of chemical treatments on fruit moisture loss, a combination with film wrapping may be considered. D'Aquino *et al*. (2010) observed 5, 13 and 6 % decay in 'Primosole' pomegranate after three month of cold storage for sole chemical treatment, sole wrapping and a combination of both chemical and wrapping treatments, respectively.

2.4.1.4 Respiration rate

A high respiration rate is associated with rapid deterioration in quality due to break down of specific compound reserves. Respiration rate depends on fruit temperature, gaseous atmosphere around the fruit, and type of fruit. Wang & Long (2014) reported that only 2 of the 5 MAP liners registered a significantly lower respiration rate of sweet cherries (cv. Bing and Sweetheart) compared to the macro-perforated liner. Liners have minimized respiration rate because of their ability to facilitate a low O_2 and high CO_2 gas concentration atmosphere around the fruit. However excessively high levels of CO_2 can result into toxicity and damaging of cells while as very lower O_2 levels trigger anaerobiosis producing off flavours (Gil *et al*., 1996; Cantı´n *et al*., 2008). Abd-elghany *et al*. (2012) reported that shrink wrapping significantly reduced respiration rate in pomegranate (cv. Wonderful), attributed to low gas permeability of the wrapping film. Similar results had been reported by Nanda *et al*. (2001) on 'Ganesh' pomegranate fruit. On the other hand, un-wrapped fruit had a lower respiration rate compared to shrink wrapped fruit. This could be attributed to senescence of un-wrapped fruit. Furthermore, D'Aquino *et al*. (2010) did not observe significant difference in respiration rate between wrapped and un-wrapped pomegranate fruit (cv. Primosole) after 6 weeks of cold storage.

2.4.1.5 Gas composition

Fruit tissues continue to respire utilizing O_2 from the atmosphere and releasing CO_2 as a by-product. Depending on the O_2 and CO_2 permeability of the packaging material, the atmosphere surrounding the fruit is passively modified. Table 2.7 summarises the influence of packaging on gas composition around fruit.

The achievement of a relatively good O_2 and CO_2 combination was responsible for good quality pears (cv. Bartlett) inside MAP box liners (without controlled atmosphere) and no significant internal tissue breakdown observed (Drake *et al*., 2004). The quality of pears under MAP was comparable to that of fruit stored under the more expensive technology of controlled atmosphere (Drake *et al*., 2004). MAP treatments significantly delayed quality loss of pomegranate fruit compared to no-liner control treatment (Selcuk & Erkan, 2014) (Table 2.6). However the two liners influenced quality with a significant difference and this was attributed to the differed ability (gas permeability) of altering O_2 and CO_2 concentrations around the fruit

However, excessive accumulation of CO_2 and very low O_2 levels promote anaerobic respiration of fruit leading to CO_2 injury, internal tissues breakdown, production of volatile off flavour compounds and many associated physiological disorders affecting quality of different fruit (Truter *et al*., 1994; Taylor *et al*., 1995; Gil *et al*., 1996; Cantı´n *et al*., 2008). Wang & Long (2014) tested 5 different MAP liners on 2 cultivars of sweet cherries (Table 2.7) and recorded different oxygen and carbon dioxide equilibria points for each liner. However, it was also noted that only the liners whose O_2 and CO_2 levels equilibrated within the ranges of 2 to 8 % and less than 7 % respectively, were able to prevent quality loss associated with anaerobiosis.

Table 2.7 Effect of liners on gas composition around selected packaged fruits

Fruit	**Storage condition**	**Liner**	**Gas composition**		**Effect on quality**	**References**
			O_2 %	**CO_2 %**		
Pears (cv. Bartlett)	1°C, 90 days	MAP	1.6-9.0	2.9-6.5	No evidence of Internal breakdown	Drake *et al.*, 2004
		MAP in CA	<0.5	5.5	Internal breakdown	
Plums (cv. Friar)	0°C, 85%RH, 60days	4MAP liners	10-20	0-10	Off flavours, high translucency & gel breakdown detected in liners that affected gas composition	Cantı´n *et al.*, 2008
		2% Perf. liner	^20	^0		
Pomegranate (cv. Hicrannar)	6°C, 90%RH, 120 days	MAP1	13.5	8.1	Significant delay in quality loss than in no-liner control	Selcuk & Erkan, 2014
		MAP2	4.4	5.9		
Pomegranate (cv. Mollar de Elche)	5°C, 75% RH, 12weeks	PPP	^21	^0	No significant difference in decay and chilling injury for both liners and storage conditions	Artés *et al.*, 2000
	2°C, 75% RH, 12weeks	NPP	*6	*12		
		PPP	^21	^0		
		NPP	*8	*10		
		2% Perf. liner	^20	^0		
Sweet cherry (cv. Bing)	0°C, 6weeks	1-5MAP liners	1.8-13.0	7.3-12.9	Superior fruit flavour in MAP4-5 than in MAP1-3 & Perf. Liner. Only MAP4-5 affected respiration rate	Wang & Long, 2014
		Perf. Liner	^21	^0		
(cv.Sweetheart)		1-5MAP liners	2.2-14.4	5.7-10.1		
		Perf. Liner	^21	^0		

NPP, Non-perforated polypropylene; PPP, perforated polypropylene; Perf., Perforated; MAP, Modified atmosphere packaging (passive); CA, Cotrolled atmosphere. ^ conditions of normal air, * At steady state conditions

Storing Friar plums in MAP liners for a 60 days was associated with significantly high levels of chilling injury, translucent flesh and breakdown of fruit gel (associated with low O_2 and high CO_2 levels) compared to plums in no-liner and high gas permeability liners (Cantı´n *et al*., 2008). Drake *et al*. (2004) observed deteriorated fruit quality for pears stored in MAP liners under controlled atmospheres because of the very low O_2 levels, less than 5 %.

To try overcoming such problems, both micro and macro-perforated liners have been applied in the industry to control gas permeability across the liner surface to bring about relatively optimal levels of O_2 and CO_2 within the bags. However, it is quite impossible for macro-perforated liners to create a modification in the atmosphere. On pomegranates, Artés *et al*. (2000) reported a no significant difference in gas composition for air within perforated polypropylene and regular atmosphere. Similar results observed for plums packaged in high gas permeability MAP and perforated liner (Cantı´n *et al*., 2008), as well as in sweet cherries (Wang & Long, 2014).

2.4.2 Physical properties of fruit

2.4.2.1 Firmness

Fruit firmness as a desirable postharvest textural quality parameter can be associated to maturity, freshness and crispness (Bernstein & lustig, 1981). Firmness of sensitive fruit such as cherries, peaches and nectarines relates to susceptibility to mechanical damage and consumer acceptability (Brown & Bourne, 1988). After harvest, fruit firmness is generally expected to decrease with storage time (Kumar *et al*., 2013a; Kumar *et al*., 2013b). This is associated with disintegration and softening of cell wall structural components by enzymes such as cellulase, endopolygalacturonase, galactosidases and pectinmethylesterase (Martin-Cabrejas *et al*., 1994). A combination of cold chain and packaging is applied to retain fruit firmness.

Plastic liners and heat shrinkable wrapping films maintain desirable firmness in table grapes, pomegranates, pears , apples, cherries and mangoes among other fruit (Nanda *et al*., 2001; D'Aquino *et al*., 2010; Abd-elghany *et al*., 2012; Ngcobo *et al*., 2012d; Kumar *et al*., 2013a; Wang & Long, 2014). Attributed to barrier effect of internal packages, maintaining relatively high humidity around the fruit, minimising moisture loss and preserving high cell turgidity.

Storing pomegranate and cherries in MAP bags significantly retained a higher firmness than in polypropylene bags and or in no-liner control treatments (Kumar *et al*., 2013a; Wang & Long, 2014). Drake *et al*. (2004) observed that 'Bartlett' pears stored under controlled atmosphere lost no firmness throughout the storage period, with or without MAP liners. He further demonstrated that storing fruit at low temperatures of 1 ° C in MAP liners greatly minimized a loss in firmness than just storing them under regular atmosphere. The firmness of the fruit stored in MAP liners for 90 days was still higher than for fruit at regular atmosphere for 30 days. This can be attributed to the ability of the MAP liners to passively control gaseous exchange across a semi-permeable barrier, in a way reducing the oxygen but increasing carbon dioxide concentrations around the fruit. Therefore, the fruit physiological and biochemical activities that weaken tissues through ripening and senescence will be suppressed (Valero & Serano, 2010; Wills & Golding, 2015). Physiological activities like respiration which involve utilisation of part of the fruit mass in the presence of oxygen so as to support the fruit life and yet results in structural weakness, can in away be lowered by MAP liners and thus maintain firmness.

However, it has been reported that fruit firmness increased in cherries during cold storage, and a higher firmness was observed for liner packed fruit than with no-liner (Kappel *et al*., 2002; Wang & long, 2014). Film wrapping of pomegranate fruit did not significantly affect fruit firmness compared to the un-wrapped control during cold storage at 8 ° C, retaining harvest firmness at 6 and 12 weeks in all treatments (D'Aquino *et al*., 2010). The differences in results from these studies suggests the possibility of complex interactions among many factors, suggesting a need for a more detailed research.

2.4.2.2 Colour

Colour is a visual-quality attribute affecting consumer preference of fruit (Pathare *et al*., 2013), giving indication for freshness, palatability, nutritional value, ripeness and aging of fruit (Haisman & Clarke, 1975; Kidmose *et al*., 2002). Postharvest technologies have retained acceptable fruit colour through MAP and temperature control. Pigments like chlorophylls, carotenoids, betalains and flavonoids (like anthocyanins) are responsible for the bright colour of fresh fruit and vegetables (Kidmose *et al*., 2002).

Though temperature is the most contributing factor, atmospheric gases and ethylene production contribute to colour pigment degradation after fruit harvest (Kader, 1987). Low O_2

and high CO_2 concentration created by MAP liners inhibit ethylene production and delays ripening and colour developments in climacteric fruit like avocado, pear, plum and grapefruit (Kader, 1986; Meir *et al*., 1995; Gorny & Kader, 1996; Díaz-Mula *et al*., 2011a).

A strong impact of MAP liners and storage time on the external peel and or internal flesh colour has been reported on pears, pomegranate and plum (Cantı´n *et al*., 2008; Kumar *et al*., 2013b). According to Drake (2004) the MAP liners preserved more of the green colour in 'Bartlett' pears at 90 days of cold storage than did the pears under regular atmosphere at 30 days of storage. After a 2 days ripening period, MAP pears were still greener than pears under regular atmosphere. In 'Hicrannar' pomegranate higher lightness was obtained for fruit stored under MAP liners with the fruit looking brighter and fresher compared to the no liner control fruit at the end of 4 months of cold storage and additional 3 days of shelf life (Selcuk & Erkan, 2014). In addition, MAP liners caused a lower change in the hue angle than the control. In a similar way, heat shrinkable wrapping of pomegranate, oranges and apples has retained external fruit peel colour attributes (lightness, chroma and hue angle) allowing only minimal changes from the time of harvest compared to the non-wrapped control fruit (Nanda *et al*. 2001; D'Aquino e*t al*., 2010).

2.4.2.3 Mechanical damage

Mechanical injury of fruit such as compression, bruising and impact damage become purchase barriers, leading to product downgrading, microbial contamination, decay, stress reactions, senescence and financial loss (Opara, 2007; Harker, 2009; Qiang & Mingjie, 2012). Trays and punnets are among the most applied internal packages used in minimizing mechanical damage in boxed fresh fruit. A good internal packaging component is expected to have the ability to absorb impact energy and prevent contact between individual fruits (Peleg, 1985). Lesser bruising was observed for cartoned apples packed on polystyrene trays, medium bruising for apples in polyethylene bags and higher bruise damage for fruit on paper pulp trays (Tabil & Sokhansanj, 2000). Paper trays were reported not being effective in minimizing impact damage for fruit in plastic and bamboo crates (Peleg, 1985). This can be attributed to the soft contact by polystyrene trays on the apples acting as better shock absorbers compared to pulp paper trays. Form nets are commercially applied to minimize impact damages in fruit (Chonhenchob & Singh, 2004). The impact of foam nets and paper trays as internal cushioning materials in apple fibreboard cartons was studied (Eissa *et al*., 2012). Golden delicious apples in foam nets registered the lowest vibration frequency, force and acceleration, as well as lowest bruise damage, volume and bruise spot ratio compared to apples on paper trays. Vibration and bruise damage was highest in control treatment of no internal cushioning material. This was attributed to the elasticity and springiness texture of foam net material acting as better shock absorbers compared to paper material (Eissa *et al*., 2012). Holt & Schoorl (1984) observed that fibreboard cartons fitted with trays provided the most protection against bruising, with approximately 15 % of the kinetic energy being absorbed by the apples. Returnable crate was next, with approximately 50 % of the energy absorbed and lastly the wooden boxes had 66 to 100 % of the kinetic energy absorbed in bruising, depending on the tightness of the pack and the presence of energy-absorbing side-wall packing material. Internal packages like shrivel, sponge and bubble pack sheets, riffled paper and jiffy pads provide mechanical damage insulation between fruit and package walls (Berry, 2013).

Thompson *et al*. (2008b) studied soft fruit protection from mechanical damage using a special type of internal packaging tray called the suspended tray in clamshell, with conventional tray and conventional clamshell, all placed in corrugated boxes. The 'Californian Bartlett' pears were subjected to a 30-minute vibration test. At 38 SIQ units of firmness, 92.3, 66.7 and 13 % of fruit packed in conventional clamshell, conventional tray and suspended tray-clamshell packages, respectively suffered mechanical damage. The authors applied the same study on 'Californian Hass' avocado packaged in suspended tray-clamshell-returnable plastic crate, suspended tray in corrugated box, conventional paper tray stacked in corrugated box and conventional loose filling in corrugated box. At 25 SIQ units of firmness, damages were highest in the conventional package without internal packaging (86.2 %), followed by conventional tray (77.8 %), suspended tray clamshell (23.5 %) and lowest for suspended tray (17.7 %). The use of different package designs of each fruit type makes comparison unrealistic. However, both studies demonstrated that the type of internal packaging affected fruit damage incidence.

2.4.2.4 Postharvest physiological disorders and defects

Postharvest disorders, defects or blemishes influence consumer choice because of their impact on the overall appearance and quality of fruit (Kader, 2002). The use of internal packages may minimize or even enhance the occurrence and progression of some of the postharvest physiological defects and disorders.

Packing fruit inside MAP liners resulted in lower scores of peel defects and no-internal breakdown on ‘Bartlett’ pears than fruit under regular atmosphere after a 2 day ripening period (Drake *et al*., 2004). Furthermore, there were no scalding incidence but lower pedicel defects on pears in MAP liners than for pears under regular atmosphere after 90 days of cold storage (Drake *et al*., 2004). MAP liners significantly lowered incidence of peel shrivelling and skin discolouration in ‘Hicrannar’ pomegranates (Selcuk & Erkan, 2014). Furthermore, Xtend® MAP liners registered lower aril browning in pomegranate (cv. Baghwa) compared to polypropylene liners (Kumar *et al*., 2013a). Other techniques such as heat shrinkable film wrapping of individual fruit may have similar impact on fruit defects as MAP liners such as in pomegranate (cv. Primosole) where heat shrinkable films registered zero signs of peel browning and scalding after 6 weeks of cold storage and an additional 7 days of shelf storage (D’Aquino *et al*., 2010).

On the contrary, the use of liners has promoted the incidence of specific disorders in some fruit. Using HDPE and LDPE liners in crates and box cartons resulted in highest core browning in pears (cv. Punjab Beauty) compared to fruit packed with no-liner in crates and box cartons (Kaur *et al*., 2013). This was attributed to the accumulation of carbon dioxide and lowering of oxygen around the fruit due to continued respiration, resulting in production of ethanol and acetaldehydes. Similarly, Cantı´n *et al*. (2008) observed highest incidences of chilling injury, flesh translucency, off odours and maximum gel breakdown in ‘Friar’ plums packed with MAP liners than with no-liner after 60 days of cold storage and additional 7 days at 20 °C. The use of sulphur dioxide releasing sheets in the multi-scale packaging of table grapes promoted a risk of SO_2 injury with higher incidence at places of contact between berries and internal packaging (Ngcobo *et al*., 2013a). This phenomenon was attributed to moisture condensation forming acidic environment with the released SO_2. However, lower incidence SO_2 injury was recorded in bunch carry bag than both clamshell and open-top punnet multi-scale packaging treatments of table grapes (Ngcobo *et al*., 2013a). Furthermore, perforated liners significantly reduced SO_2 injury and berry drop incidence in table grapes compared to non-perforated liners (Ngcobo *et al*., 2012d). Therefore, the problems above can be minimized by improvement in ventilation of the internal packages applied. The use of perforated polypropylene liners as internal packaging were observed to significantly reduce chilling injury in pomegranate fruit (cv. Mollar de Elche) stored at 2 °C or 5 °C for 12 weeks (Artés *et al*., 2000). Perforated liners also successfully controlled husk scald and pitting throughout the cold storage periods.

2.4.3 Fruit chemical characteristics

2.4.3.1 Soluble solids, acidity, sugars and pH

Titratable acidity (TA), total soluble solids (TSS), pH and sugars are associated with sensory attributes and therefore influence consumer's choice. Total soluble solids and titratable acidity are correlated to sweetness and sourness tastes, respectively (Tandon *et al*., 2003). Apples with a higher TSS to TA ratio are more preferred by consumers (Boylston *et al*., 1994). A reduction in TA is associated with the utilization of organic acids as metabolites in the respiration process (Kader *et al*., 1984). A change in TSS levels is attributed to hydrolysis of starch and polysaccharides into respiration substrate sugars (Verano & Serano, 2010). D'Aquino *et al*. (2010) observed a higher reduction in TA for shrink-wrapped pomegranate (cv. Primosole) fruit compared to un-wrapped fruit (Table 2.8).

Liners minimised increase in TSS, reducing sugars and TSS:TA ratio compared to no-liner packed fruit for pears (cv. Punjab Beauty) in the first 60 days of cold storage (Kaur *et al*., 2013). An increase in TSS can be attributed to loss of moisture and concentration of soluble solids (Kaur *et al*., 2013; Selcuk & Erkan, 2014). Pears packed with no-liner in plastic crates, wooden and paper boxes had greater losses in weight and higher levels of TSS and reducing sugars compared to fruit packed in HDPE and LDPE liners during cold storage period (Kaur *et al*., 2013).

Besides temperature, specific packaging technologies such as shrink film wrapping and liners minimise the general reduction in TA and increase in TSS (Table 2.8). Packing pomegranate (cv. Hicrannar) in MAP1 liners significantly reduced loss in TA compared to the no-liner packed fruit at the end of cold storage period (Selcuk & Erkan 2014). Furthermore, the MAP treated fruit had minimal losses in TSS compared to no-liner packed fruit. Similarly, Drake *et al*. (2004) reported significantly higher values of TSS and TA for pears (cv. Bartlett) packed inside MAP liner compared to paper wrapped fruit inside polyethylene (PE) liners after 90 days of cold storage at regular atmosphere.

Liners passively modify gas composition around fruit minimising respiration rate and utilization of sugars as respiration substrates and organic acids as alternative metabolic substrates (Echeverria & Valich, 1989). The effect of these packages on respiration rate has been discussed in section 2.4.1.4.

Table 2.8 Impact of internal packaging of the sugar solids and acidity of different types of selected fruit

Fruit	**Storage conditions**	**Packaging type**	**Effect of internal packaging on %loss**				**References**
			TA	**TSS**	**Sugars**	**TSS/TA ratio**	
Grape fruit (cv. Star Ruby)	16wks at 10°C & 80-85%RH + 1wk at 20°C	Control (no-liner)	15.00 ↓	4.92 ↓		6.8	Chaudhary *et al.*, 2015
		Liner1	20 ↓	2.56 ↑		8.0	
		Liner2	20 ↓	0		7.5	
Plums (cv. Friar)	60days at 0°C & 85%RH,	Control (bulk packed)	45.24 ↓	9.21 ↓		60.0	Cantı´n *et al.*, 2008
		MAP1	40.48 ↓	11.84 ↓		55.0	
		MAP2	42.86 ↓	12.5 ↓		54.6	
		MAP3	38.10 ↓	15.13 ↓		50.4	
		MAP4	33.33 ↓	13.82 ↓		48.2	
		MAP5	45.24 ↓	15.13 ↓		56.4	
Pomegranate (cv Primosole)	12wks at 8°C & 90% RH + 1wk at 20°C & 65–70% RH	Control (un-wrapped)	28.57↓	3.85↓	2.82↑Gs 1.88↑Fs		D'Aquino *et al.*, 2010
		Film wrap	50↓	6.41↓	8.05↓Gs 15.18↓Fs		
Pomegranate (cv. Hicrannar)	120 days at 6°C & 90%RH,	Control (no-liner)	45.07↓	2.27↓			Selcuk & Erkan, 2014
		MAP1	38.03↓	0.57↑			
		MAP2	43.66↓	0.63↑			
Pomegranate (cv. Ganesh)	12wks at 8°C & 70-75%RH	Control (un-wrapped)	31.20 ↓	13.38 ↓	9.63 ↓		Nanda *et al.*, 2001
		Film wrap1	11.11 ↓	12.10 ↓	3.70 ↓		
		Film wrap2	15.38 ↓	15.92 ↓	2.22 ↓		

Gs-glucose, Fs-Fructose, liner1(micro-perforated), liner2 (macro-perforated). ↓ Decrease; ↑ Increase

In other cases, internal packages have been found to have no impact on TSS and TA (Porat *et al.*, 2004). In grape fruit (cv. Star Ruby), the macro and micro-perforated liners did not have any effect on TSS, TA and TSS:TA ratio after 16 weeks of cold storage at 10 °C and a subsequent week of storage at ambient conditions (Chaudhary *et al.*, 2015). For pomegranate (cv. Ganesh), Nanda *et al.* (2001) reported a no significant effect between film wrapped and non-wrapped fruits on TSS and total sugars content. Wiley *et al.* (1999) reports that TSS and

TA of kiwifruit (cv. California) was maintained in all treatments of non-perforated, macro-perforated and micro-perforated liners throughout the whole cold storage period of 17 weeks at 0 °C. These inconsistences in findings from different studies suggest critical examination of factor interactions on chemical attributes of fruit during storage.

2.4.3.2 Phytochemicals and antioxidant activity

The major nutritional qualities of fruit are highly associated to their resourcefulness in phytochemicals which have been associated with minimizing the risk of various disease conditions like cancers and cardiovascular diseases in humans because of their ability to scavenge oxygen free radicals (Dragsted *et al*., 1993; Steinmetz & Potter, 1996). The global consumption of some specific fruit like pomegranates is highly on the increase partly due to consumer demand for products associated with better health outcomes. The highest contribution to antioxidant capacity of most fruit comes from polyphenols, anthocyanins and flavonoids (Wang *et al*., 1996), which also contribute to the astringency and bitter taste as well as visual colour in fruit such as apples (Robards & Antolovich, 1997). It is during the ripening period that maximum levels of antioxidants and their capacitive activity is recorded in fresh fruit (Wang & Lin, 2000). However, Gibson *et al*. (2013) reported a reduction in flavanols and total polyphenols during ripening of ‘Lowbush’ blueberry fruit but an increase in the anthocyanins. These phytochemicals may be expected to decrease with progressive development of fruit to a more stable level during maturity or ripening (Awad *et al*., 2001).

These bio-active compounds have been found to either increase or decrease during postharvest storage of various fruit (Serrano *et al*., 2012). Liners and shrink wrap films, modify the atmosphere and retard biosynthesis of ethylene, minimizing rate of ripening and accumulation of phytochemicals (Díaz-Mula *et al*., 2011b). Low oxygen concentrations may increase the stability of the phytochemicals against enzymatic degradation by polyphenol oxidases and against free radical oxidation (Pourcel *et al*., 2007). Modified atmospheres may also retard the activity of enzymes like anthosyanidinsythase responsible for the synthesis of phytochemicals (Desjardins, 2008).

Nanda *et al*. (2001) reported that, film-wrapped pomegranate fruit (cv. Ganesh) retained more vitamin C than un-wrapped fruit after 12 weeks of cold storage. Similar results were recorded by Abd-elghany *et al*. (2012) on ‘Wonderful’ cultivar after 60 days of cold storage. However, in grape fruit (cv. Star Ruby), the use of micro and macro-perforated MAP liners did not have effect on vitamin C content throughout the 16 weeks of cold storage (Chaudhary *et al*., 2015). After 16 weeks of cold storage, packaging with micro and macro perforated MAP liners significantly minimized the increase in beta carotene and lycopene levels as compared to the no-liner control treatment on grape fruit (Chaudhary *et al*., 2015). Similar results were observed in plums (Díaz-Mula *et al*., 2011b). These findings may be attributed to the ability of MAP liners to slow down fruit ethylene production, hence, delaying pigment development during ripening process. A faster uncontrolled ripening rate of climacteric fruit after harvesting is associated to faster deterioration in fruit quality. In another study, Selcuk & Erkan (2014) observed that at the end of 100 and 120 days of cold storage at 6 °C, pomegranate (cv. Hicrannar) packed in MAP liners had significantly lower content of total phenols compared to fruit with no-liner packaging treatment.

However, in other studies researchers have reported no significant impact of internal packaging on concentration of phytochemicals in fruit. After12 weeks cold storage, film wrapping did not have significant impact on anti-oxidative capacity and total phenolics compared to un-wrapped pomegranates, except for total anthocyanins were un-wrapped pomegranates (cv. Primosole) retained nearly 100 % but were significantly lost in wrapped fruit (D'Aquino *et al*., 2010). At the end of an additional week at ambient conditions, wrapped fruit registered a significant loss in anti-oxidative capacity, total phenolics and anthocyanins while as un-wrapped fruit retained the harvest values (D'Aquino *et al*., 2010). Generally, packaging did not have a significant impact on the anthocyanin content of pomegranate (cv. Mollar de Elche) during storage at different temperatures (Artés *et al*., 2000). Mphahlele *et al.* (2014) reported that the impact of MAP on fruit bioactive compounds is not well established, implying that many factor interactions influence antioxidant activity. The differences in antioxidant results reported in different studies can be attributed to variation in fruit cultivar, maturity and growing region (Mphahlele *et al.,* 2014).

2.4.4 Keeping quality and sensory properties of fruit

2.4.4.1 Shelf life and keeping quality

Fresh fruit are highly perishable products immediately after harvest given their high water activity and on-going physiological activities resulting into loss of quality. Postharvest handling and measures are therefore aimed at minimizing losses through prolonging the keeping quality of fruit. Film wrapping has been shown to successfully extend the shelf life and keeping quality of fresh fruit (Table 2.9). At all the 3 different storage temperature, wrapped pomegranate still had higher keeping qualities than the un-wrapped fruit (Nanda *et al*., 2001). In this example it was observed that keeping quality decreased with increasing storage temperature thus portraying the importance of maintaining a cold chain in combination with packaging for better quality preservation. Perforated and non-perforated box liners with relatively optimised gas and moisture permeability minimised fruit weight loss and retarded physiological disorders, extending keeping quality (Artés *et al*., 2000).

Table 2.9 Impact of internal packaging on shelf life and cold storage keeping quality of different selected fruits

Fruit	**Storage condition**	**Internal Packaging**	**Storage length of marketable quality**		**Reference**
			Cold chain	**Shelf life**	
Pears (cv. Punjab Beauty)	0-1°C & 90–95 % RH	No-liner HDPE liner	60 days 75 days		Kaur *et al*., 2013
Pomegranate (cv. Hicrannar)	6°C & 90 % RH	No-liner	80 days	80 days cold + 3 days warm	Selcuk & Erkan, 2014
		MAP liners	100 days	100 days cold + 3 days warm	
Pomegranate (cv. Ganesh)	8°C & 70–75 % RH	Un-wrapped Film wrapped	7 weeks 12 weeks		Nanda *et al*., 2001
	15°C & 65–70 % RH	Un-wrapped Film wrapped	5 weeks 9 weeks		
	25°C & 40–60 % RH	Un-wrapped Film wrapped	1 week 3.5 weeks		
Pomegranate (cv. Wonderful)	6°C	No liner MAP	4 weeks 10 weeks		Porat *et al*., 2009

RH, Relative humidity

2.4.4.2 Sensory properties

The intrinsic constituents of fruit contribute much to quality, however the level to which they appeal and satisfy the consumer upon perception will determine consumer choice and acceptability (Shewfelt, 1999). The major sensory quality parameters of colour, taste, smell and texture are perceived subjectively by human senses versus objectively by instrumentation. However, there is a high correlation between the subjectively measured parameters and the objective measurement by sensitive instruments (Tandon *et al*., 2003). The balance of acids and sugars determines taste in fruits (Crisosto *et al*., 2003). Organic acids greatly influence the sour taste while reducing sugars majorly affect the sweet taste of fruit (Kamal *et al*., 2001; Tandon *et al*., 2003) and different inherent pigments are responsible for the bright colour of fruit. Liners and film wrapping modify gaseous environment around fruit, retarding ethylene production, ripening, development and inter-conversion of colour pigments, retarding use of organic acids and reducing sugars in respiration (Jacxsens *et al*., 1999; Saito & Rai, 2005).

Effect of film wrapping

Individually, wrapped pomegranate (cv. Ganesh) generally registered significantly higher organoleptic scores for freshness, aril colour, taste, and juiciness than un-wrapped fruit at the end of 12 weeks cold storage at 8 ^{o}C or 10 weeks at 15 ^{o}C (Nanda *et al*., 2001). The un-wrapped fruit were reported to have turned dull in appearance and desiccated after 1 week at 25 ^{o}C while wrapped fruit retained the characteristic bright yellowish-red colour of the pomegranate skin (Nanda *et al*., 2001). Similar results were reported by Abd-elghany *et al*.(2012) on pomegranate (cv. Wonderful) where wrapped fruit retained better appearance and bright rind colour compared to un-wrapped fruit, stored for 2 months at 5 ^{o}C and subsequent 2 weeks at 20 ^{o}C. After 12 weeks of cold storage (8 ^{o}C), wrapped pomegranate (cv. Primosole) retained high overall acceptability score with no detectable off flavours compared to the un-wrapped control fruit which registered a lower overall acceptability with some detectable off flavours (D'Aquino *et al*., 2010). The lower overall acceptability of the un-wrapped fruit was associated to peel browning, scalding and very high moisture loss.

Effect of liners

Using MAP liners significantly maintained higher overall appearance and flavour of mandarin fruit cv. Nagpur (Ladaniya, 2007). Kumar *et al*. (2013a) observed significantly higher scores for external appearance of pomegranate (cv. Baghwa) in MAP liners, and higher organoleptic scores for their arils than the no-liner control fruit and the treatments in propylene liners of different microns during cold storage. In another study, pears (cv. Punjab Beauty) packed in HDPE and LDPE lined carton boxes, wooden boxes and crates generally showed higher overall sensory ratings compared to fruit in boxes and crates with no liner (Kaur *et al*., 2013). This was attributed to the fact that the liners retained high quality levels and a higher permeability to CO_2 than O_2 (Kaur *et al*., 2013). The low sensory scores in no-liner treatments in this study were attributed to development of bitter taste and shrivelling in texture. However, Chaudhary *et al*. (2015) reported that storing of grape fruit (cv. Star Ruby) for 16 weeks at 10 ^{o}C plus 1 week at 20 ^{o}C in MAP liners did not have any significant impact on taste of the fruit. Very low oxygen and high carbon dioxide environment created by some MAP liners can result in production of unwanted off odours during anaerobic respiration. Cantı´n *et al*. (2008) reports detection of off odours in ‘Friar’ Plums packed in three of the five MAP liners at the end of the 60 day cold storage period.

2.5 Internal packaging and fruit price

Differences in the price of fruit packed in different types of packaging were investigated in five local supermarkets in Stellenbosch, South Africa in January 2016. No attempt was made to evaluate the quality of fruit inside the packages; however, records on price were only taken at each shop/retailer when the same fruit cultivar and batch were packed in different types of packaging. Were fruit were sold in bulk container, prices were standardised by converting into a unit basis (Rands per kg). The results clearly showed that the type of packaging and use of packaging affected fruit price (Table 2.10). Irrespective of fruit type, retailing fruit inside packaging increased price by more than 35 %, except for the case of apples sold in thrift bags and this may be attributed to generally low price of apples compared with other fruit. For instance, table grape sold in clamshell punnet were 35 % more expensive than loose on loose display, while bananas sold in small retail carton were nearly 45 % higher in price. The‘Yellow cling’ peaches packed in polystylene tray with film wrap had the highest price difference (52.50 %), followed by banana packed in small paperboard box (44.95 %). Overall, while these finding do not conclusively demonstrate the effects of packaging (including internal packaging) on fruit price, they do, however, show that the type of internal packaging reviewed in this article contribute to retail price of fresh fruit sold in supermarkets.

Literature evidence reported in the preceding parts of this article have shown that the use of internal packages may indirectly affect product quality and shelf life. The fact that most of these internal packages have adverse effects on the environment when dumped, the taxes imposed on retailers may translate into product price. This in turn may force some stakeholders to reduce the use of internal (retail) packages effort to maintain manageable consumer prices. However, given that the quality of un-packed fruit may not exactly match that of packed fruit, both retailer and consumer have to strike a compromise between price and quality.

2.6 Conclusion and future prospects

Ventilated corrugated fibreboard cartons are the most frequently used external package in which internal packages are applied, compared to returnable plastic crates and wooden boxes. Liners are the most commonly applied internal packaging with far reaching effects on the cooling characteristics and postharvest quality of fresh fruit. The effects of internal packages on cooling of stacked produce is apparent. However, the corresponding effects on produce quality and storability of fruit is difficult to evaluate. This is because of the vast physiological factors affecting the quality of fruit after harvest. Perforation can greatly improve cooling characteristics of fruit. Physical and physiological quality parameters are more affected by internal packages as compared to the chemical attributes of fruit. The impact of internal packaging on quality is attributed mainly to the ability to alter relative humidity, gaseous atmosphere around the fruit and protection against physical forces and contamination. More research is needed concerning the optimising of the permeability of liners to moisture and gases to accommodate faster cooling rate, minimizing weight loss without necessarily facilitating condensation within the bags.

The handling of sensitive fruit of high respiration rate and high susceptibility to mechanical damage combined with consumer demand for ready to eat convenient fruit necessitates designing and proper application of internal packaging. Optimizing the use of these internal packages is important given their contribution to product price, delayed fruit cooling and municipal waste. Given that most internal packaging is made from plastic, feature research on internal packages should focus more on greener technology (environmentally friendly) approaches such as edible internal packaging and more lighter packaging materials that are easily recyclable and degradable. For instance, adding of starch to polyethylene can tremendously improve its degradability rate in landfills.

Table 2.10 Influence of internal packaging on fruit price

Fruit	**Packaging**	**Price**		**Market**
		(ZAR per kg)	**Max. difference**	
Apples (cv. Golden delicious)	Loose bulk	16.99	2.16 %	SP (supermarket)
	Thrift bag (1.5kg)	16.63		
Bananas	Loose bulk	14.95	44.95 %	PP (supermarket)
	Thrift bag (0.75kg)	19.3		
	Small carton (1.2kg)	21.67		
Mangoes	Loose bulk	21.98	25.07 %	WW (supermarket)
	Transparent plastic tray & film wrap (0.94kg)	27.49		
Nectarine (cv. Alpine yellow)	Loose bulk	34.99	42.84 %	FL (supermarket)
	Clamshell (0.75kg)	49.98		
Peach (cv. Yellow cling)	Loose bulk	26.99	52.50 %	WW (supermarket)
	Punnet (0.75kg)	41.16		
	Polystyrene tray & film wrap (0.5kg)	34.99		
	Paper tray & film wrap (1.2kg)	28.56		
Table grapes (cv. Red seedless)	Loose bulk	36.99	35.12 %	SP (supermarket)
	Clamshell (0.5kg)	49.98		

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SECTION II

Chapter 3. Effect of Internal Packaging (liners) on Airflow Resistance and Cooling Characteristics of Packed Pomegranate Fruit (cv. Wonderful)

3 Effect of Internal Packaging (liners) on Airflow Resistance and Cooling Characteristics of Packed Pomegranate Fruit (cv. Wonderful)

Abstract

High resistance to airflow (RTA) is a challenge of forced-air cooling (FAC) technique during pre-cooling of pre-packaged fruit. The application of liners as internal packaging (IP) in the multi-scale packaging (MSP) of pomegranate fruit worsens the problem. Resistance to airflow of stacks with non-perforated 'Decco' liner, micro-perforated Xtend® liner, macro-perforated 'Decco' liners (2 mm × 70 and 4 mm × 18) and macro-perforated HDPE liners (2 mm × 54 and 4 mm × 36), were measured in a wind tunnel. Generally, fruit stack packed with non-perforated 'Decco' and micro-perforated Xtend® liners increased RTA of the no-liner packed fruit by 175.7 and 238.4 %, respectively, with differences attributed more to the nature of liners rather than perforation. However, using macro-perforated 2 and 4 mm 'Decco' liners increased RTA of the no-liner packed fruit by only 69.2 and 113.6 %, respectively. The impact of non-perforated 'Decco' and micro-perforated Xtend® liners on cooling characteristics were carried out to quantify cooling rate, energy consumption and cooling heterogeneity of fruit stack during FAC. Pre-cooling fruit from a temperature of 17 ± 3 ^{o} C in no-liner stack had a cooling uniformity of 64.2 ± 0.2 %. However, we obtained high cooling uniformity of 81.6 ± 1.7 % by packing fruit in non-perforated 'Decco' liners and 78.7 ± 1.5 % in micro-perforated Xtend® liners. The seven-eighth cooling time (SECT) of fruit stack packed with no-liner was 3.5 ± 0.2 h compared to 8.1 ± 0.1 h for non-perforated 'Decco' and 8.5 ± 0.1 h for micro-perforated Xtend® liners. As a result, using non-perforated 'Decco' liners increased energy consumption by 301.0 % of the no-liner packaging treatment during FAC while the application of micro-perforated Xtend® liners increased energy consumption by 375.2 %. Generally, our results showed a high correlation (r^2 = 99.0 %) between superficial air velocity and pressure in all treatments, except for macro-perforated HDPE liners. In this study, the macro-perforated 2 mm 'Decco' liner showed the best perforation quality for minimizing RTA in pomegranate fruit because of higher perforation number and good distribution.

Key words: *Pressure drop, Cooling, Internal packaging, Liner, Pomegranate.*

Nomenclature

a	Resistance coefficient	Kg $S^{(b-2)}$ $m^{-(b+2)}$
b	Resistance exponent	
K	Darcy permeability	m^2
p	Pressure	Pa
r^2	Coefficient of determination	
u	Velocity vector	m s^{-1}
β	Forchheimer drag coefficient	m^{-1}
µ	Dynamic viscosity	
ρ	Density	kg m^{-3}

3.1 Introduction

Conditioned environment in terms of temperature, relative humidity and gas composition is commonly applied to horticultural produce, both in bulk and in packages to minimize moisture loss and other quality deteriorations (Verboven *et al.* 2006). With advances in postharvest cold chain management of pomegranates and other fresh produce, it has become common practice to pre-cool fruit after harvest and pre-packing in cartons or crates and on pallets (Delele *et al.* 2008; Ngcobo *et al.*, 2013). This practice also minimizes chances of fruit contamination, mechanical damage and promotes easy mechanical handling of produce. Forced-air cooling (FAC) is a commonly used pre-cooling technique (Kader, 2002; de Castro *et al.*, 2004) to remove field heat from pre-packed fruit in ventilated cartons and crates. The technique involves forcing cold air through the stack of fruit by using suction/blowing fan. This method achieves faster cooling compared to room cooling of fruit.

The challenge with FAC technique has been resistance to airflow (RTA) by packaging material and to some extent the fruit, resulting in delayed cooling of produce, increased energy consumption and fruit quality deterioration. This challenge is exacerbated in multi-scale packaging (MSP) of pomegranates and other fruit, where internal packaging (IP) such as liners are applied inside external packaging (EP). However, the application of proper ventilation in the packaging of fruit is reported to reduce RTA (Vigneault & Goyette, 2002; de Castro *et al*., 2004; Vigneault *et al*., 2004; de Castro *et al*., 2005a; de Castro *et al*., 2005b; Ngcobo *et al*., 2012a; Delele *et al*., 2013b).

Resistance to airflow (RTA) is monitored through variation in air velocity, mass flow rate and most commonly changes in air pressure. In horticultural industry, RTA has been studied using either harvested fruit or artificial product simulators as specimen. Furthermore, predictive models like computerised fluid dynamics and air velocity-pressure drop correlation models of Ramsin and Darcy-forchheimer have been applied in RTA studies across porous media (Haas *et al*., 1976; Neale & Messer, 1976; Vigneault & Goyette, 2002; Delele *et al*., 2008; Tutar *et al*., 2009; Dehghannya *et al*., 2011; Ferrua & Singh, 2011; Delele *et al*, 2012; Delele *et al.*, 2013a). Researchers have used different experimental setups in the studies by applying FAC equipment setup and wind tunnel setup, furthermore considering different ways of product packaging. Some have examined the contribution to RTA by fruit or vegetable bulk (Neale & Messer, 1976; Gaffney & Baird, 1977; Chau *et al*., 1985; Irvine *et al*., 1993; Tabil *et al*., 2003; Verboven *et al*., 2004; Shahbazi & Rajabipour, 2007), while for others, product in EP cartons (Wang & Tunpun, 1969; Chau *et al*., 1985; Yun *et al*., 1995; van der Sman, 2002). Of recent, little work has been done on multi-scale packaging (MSP) which involves a combination of EP and IP especially on table grapes and apples (Ngcobo *et al*., 2012a; Berry, 2013; Gruyters, 2014, Mukama, 2015). Though currently attracting research, there is still very little work done on the contribution of IP to RTA, most especially for the pomegranate fruit. The objective of this study was to assess the impact of internal packaging (liners) on RTA in ventilated packaging of pomegranate fruit. The impact of liners on cooling rate, uniformity and energy consumption during forced-air cooling was also investigated. An understanding of the impact of internal packages on air resistance, give a better apprehension of cooling patterns by cold air streams and therefore aid the design and choice of appropriate packaging in the fresh fruit industry.

3.2 Materials and Methods

3.2.1 Fruit supply

Pomegranate fruit of 'Wonderful' cultivar at commercial maturity were procured from a farm in Bonnievale (33°58'12.02" S, 20°09'21.03" E), Western Cape, South Africa. The fruit was delivered by a conditioned refrigerated truck to Postharvest Technology Research Laboratory, Stellenbosch University for cooling experiments. Studies on resistance to airflow were conducted in a wind tunnel setup at the Mechanical and Mechatronics engineering laboratory of Stellenbosch University, South Africa.

3.2.2 Packaging material and treatments

Each carton was packed with 12 fruit. Individual cartons in the stacking have an average weight of 3.5 ± 0.41 kg. A total of eight treatments were examined: stack of empty cartons; stack of package with no-liner; and six different stacks each with a particular type of internal liner. The six liner types were: non-perforated 'Decco' (Decco); micro-perforated Xtend®; macro-perforated 'Decco', 70 × 2 mm (2 mm Decco); macro-perforated 'Decco', 18 × 4 mm (4 mm Decco); macro-perforated HDPE, 54 × 2 mm (2 mm HDPE); macro-perforated HDPE, 36 × 4 mm (4 mm HDPE). Packaging characteristics of the different liners are summarised in Tables 3.1 and 3.2. The macro-perforated 2 mm 'Decco' and 4 mm 'Decco' liners were made by perforating the 'Decco' liners using specific drill punches.

Table 3.1 Liner perforation and fruit-liner aspect ratio

Liner bag	**Liner perforation**		**Height of liner (mm)**$^{+}$	**% Distance from base**		
	Number	**Diameter**		**Upmost Perforation**$^{+}$	**Twisting****	**Fruit cover***
Decco	0	0	635	0.00	55.1	47.2
Xtend	-	-	565	0.00	61.9	54.9
2 mm Decco	70	2 mm	635	52.8	55.1	47.2
4 mm Decco	18	4 mm	635	52.8	55.1	47.2
2 mm HDPE	54	2 mm	525	56.2	72.4	57.1
4 mm HDPE	36	4 mm	538	76.6	79.9	55.8

*Immediate portion of the bag containing fruit.
**Closing point of the bag (portion containing fruit and all perforation).
$^{+}$ Demonstrated in Figure 3.1.

Table 3.2 Expected effective ventilation of packaging components

		Total surface area (m^2)		Vent area (m^2)	Ventilation area (%)	
Component		**General***	**Active****		**General***	**Active****
Carton:	Length	0.033	0.033	0.00309	9.264	9.26
Stack:	Cross section	0.267	0.267	0.02472	9.264	9.26
Liner:	Decco	0.907	0.500	0	0	0
	Xtend	0.712	0.441	-	-	-
	2 mm Decco	0.907	0.500	0.00022	0.025	0.05
	4 mm Decco	0.907	0.500	0.00023	0.025	0.05
	2 mm HDPE	0.789	0.571	0.00017	0.022	0.03
	4 mm HDPE	0.806	0.644	0.00045	0.056	0.07

*Entire bag before packaging.
**Portion of bag containing fruit after packaging.

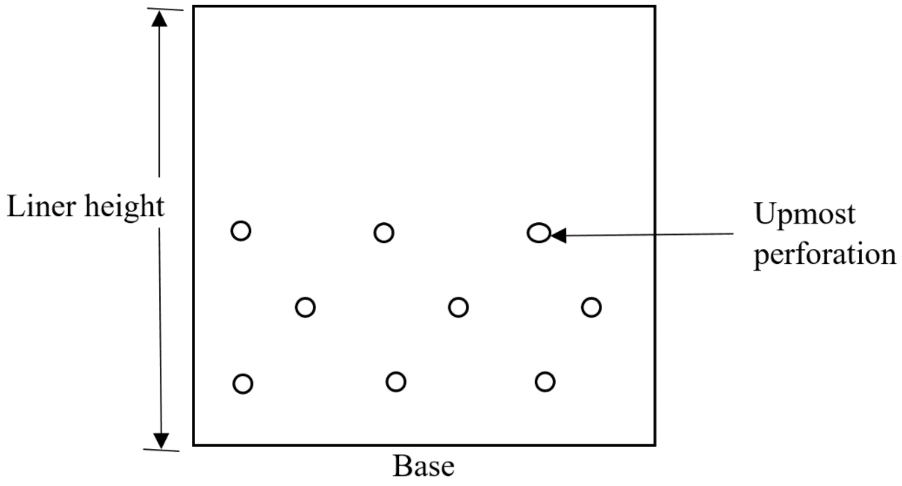

Figure 3.1 Perforated liner layout

3.2.3 Experimental setup for resistance to airflow (RTA) experiments

A wind tunnel set up was used to determine RTA across the stack of fruit (Figure 3.2). A rectangular test chamber of cross section area 0.65 m^2 and depth 1.2 m was constructed from wood and mounted unto the main body of the wind tunnel. The stream of air was generated by suction fan. Pressure transducers were used to digitally measure pressure drop across the sample in the test chamber. A stack of 16 cartons (2 × 2 per layer × 4 layers high) of fruit was mounted and tightly fitted at the forefront in the test chamber. The orientation of the stack was such that the face with the highest vent area (9.26 % vent-hole ratio) is perpendicular to airflow direction. Adhesive tape was used to ensure airtight seal at stack edges and in between cartons. Air was sucked in through carton ventilations at the exposed face of the stack, by the suction fan of the wind tunnel. Superficial air velocity through the stack ranging from 0.06 to 1.39 m s^{-1} were generated during the test by varying the fan frequencies from 10 to 40 Hz. The prevailing atmospheric conditions of temperature, percentage relative humidity and pressure were also recorded. The experiment was done in triplicates for each treatment.

Figure 3.2 Cartons of pomegranate fruit in the wind tunnel test chamber

3.2.4 Pressure drop equations

The equations of Ramsin (1; Chau *et al*., 1985) and Darcy-Forchheimer (2; Forchheimer, 1901) have been applied in many studies to estimate RTA in packed fruit and vegetables (Vigneault *et al*., 2004; Delele *et al*., 2008; Ngcobo *et al*., 2012a; Mukama, 2015). Each equation provides a correlation between pressure drop (PD) and air velocity. Resistance coefficient a and exponent b of the power-law in Equation (1) are dependent on fruit size, stack porosity and stacking pattern. In addition to these factors, the Darcy permeability constant $\frac{1}{K}$ and Forchheimer drag coefficient β of the second order polynomial in Equation (2) are dependent on fruit shape, roughness, container vent hole ratio and air properties (Chau *et al*., 1985; Eisfeld & Schnitzlein, 2001; van der Sman, 2002; Smale, 2004; Verboven *et al*, 2004, Verboven *et al*., 2006; Delele, 2008).

$$\nabla p = -au^{b} \tag{1}$$

$$\nabla p = -\frac{\mu}{K}u - \beta\rho|u|u \tag{2}$$

3.2.5 Experimental setup for forced-air cooling (FAC) experiments

Experimental setup is summarised in Figures 3.3 to 3.6 below. A stack of 96 cartons (8 layers × 12 cartons) on a standard pallet (1.2 m × 1 m) was used. Each carton of about 3.5 kg consisted of 12 fruit packed in a single layer. The cartons were positioned with their length (of 8.84 % ventilation area as opposed to 6.68 % for width) facing the 1m side of the pallet. Temperature sample fruits were located in layers 2, 4 and 6 (Figure 3.4). For each layer, five fruit from positions 1-5 (Figure 3.5) were selected, each position representing the centre fruit in a carton of 12 fruit. The T-type thermocouples (Thermocouple products Ltd, Edenvale, South Africa, with −30 to 100 ° C operation range and ± 0.025 % accuracy) were inserted into the core of sample fruits to measure fruit pulp temperatures, automatically recorded by Data Logger Switch Unit (model 34970a, Agilent Technologies, Santa Clara CA 95051, USA), every 300 second interval. The stack was then placed in front of the forced-air cooling (FAC) setup equipment with the 1 m pallet side perpendicular to airflow direction. The stack was then covered with an airtight plastic sheet leaving one face of the stack open to cold air entry. Relative humidity and temperature of the room were monitored using Tinytang sensors (Tinytag TV-4500, Hastings Data Loggers, Australia) at intervals of 10 minutes. Pressure drop across the stack was measured by differential pressure meter (Air Flow Meter Type A2G-25/air2guideF, Wika, Lawrenceville GA 30043, USA) and a data controller (WCS-13A, Shinko Technos CO LTD, Osaka, Japan). Air velocity into the stack was measured using an air velocity meter based on hotwire anemometry (Alnomar velometer AVM440, USA). Experimental tests were performed in triplicates for each packaging treatment.

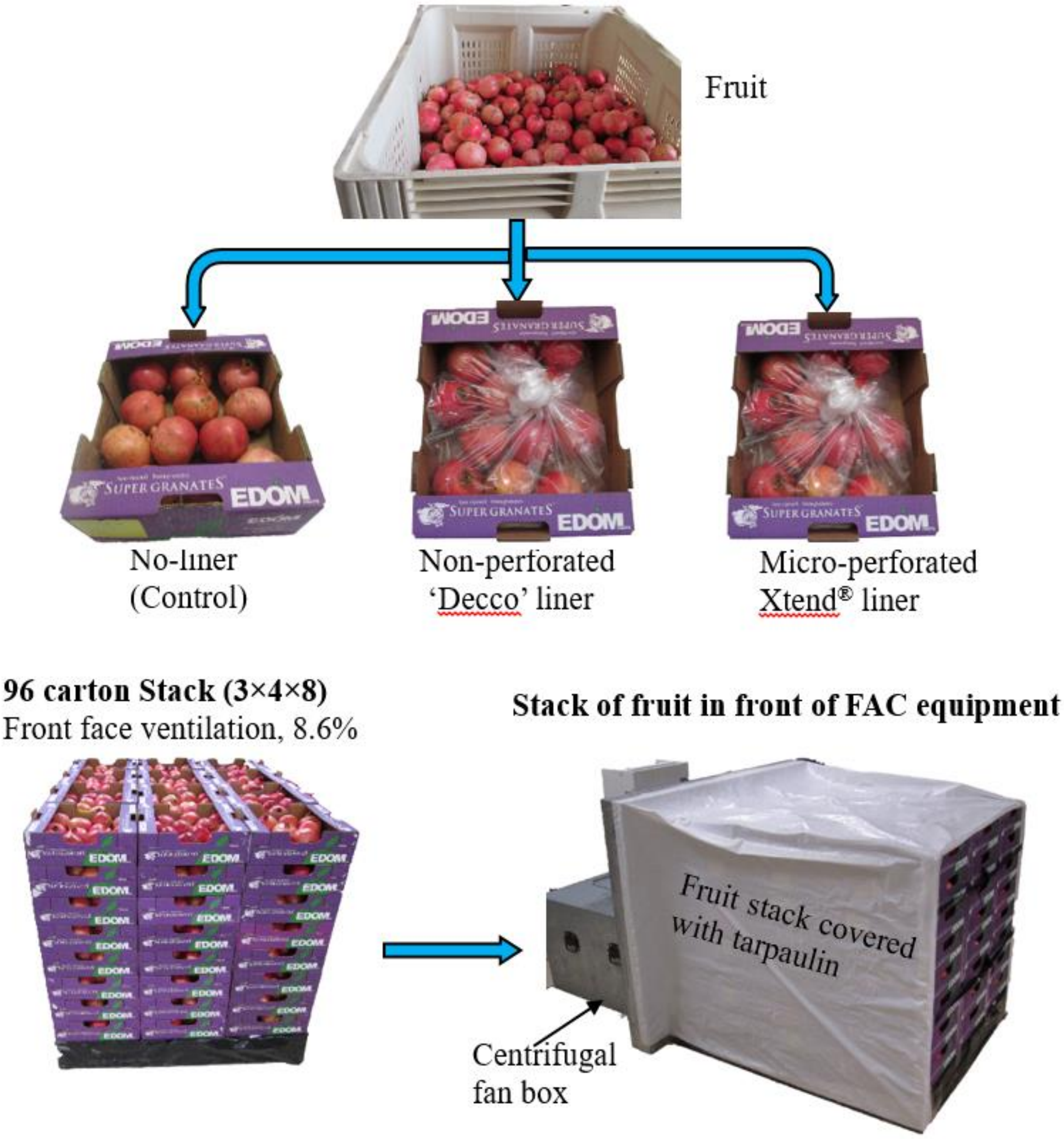

Figure 3.3 Setup of the forced-air cooling experiment

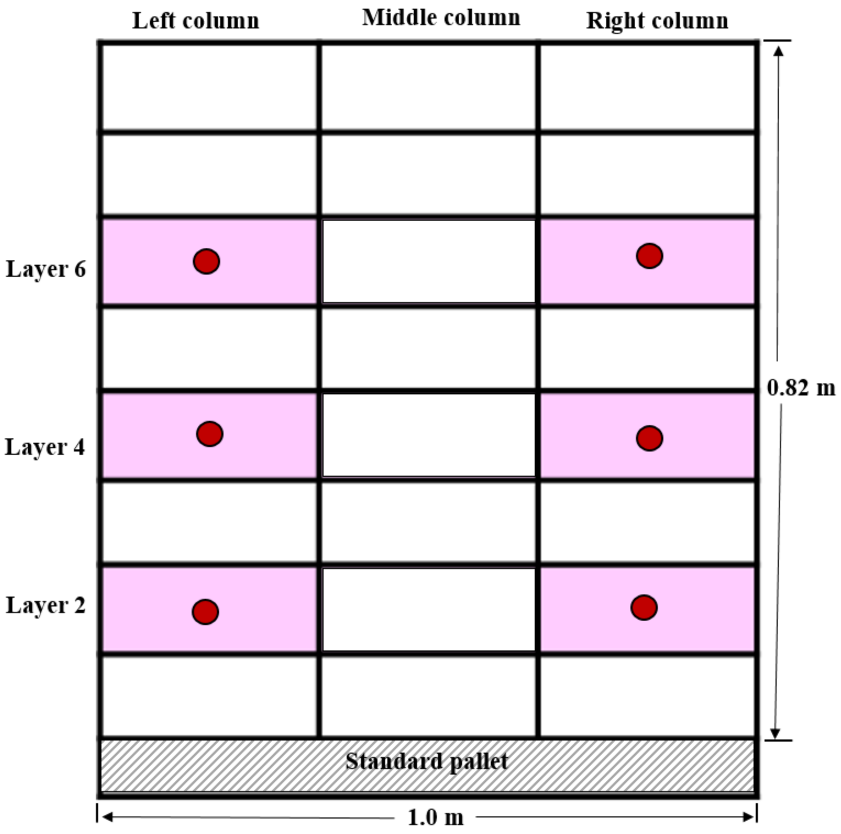

Figure 3.4 Front face of the stack showing selected layers 2, 4 and 6 for fruit core temperature monitoring

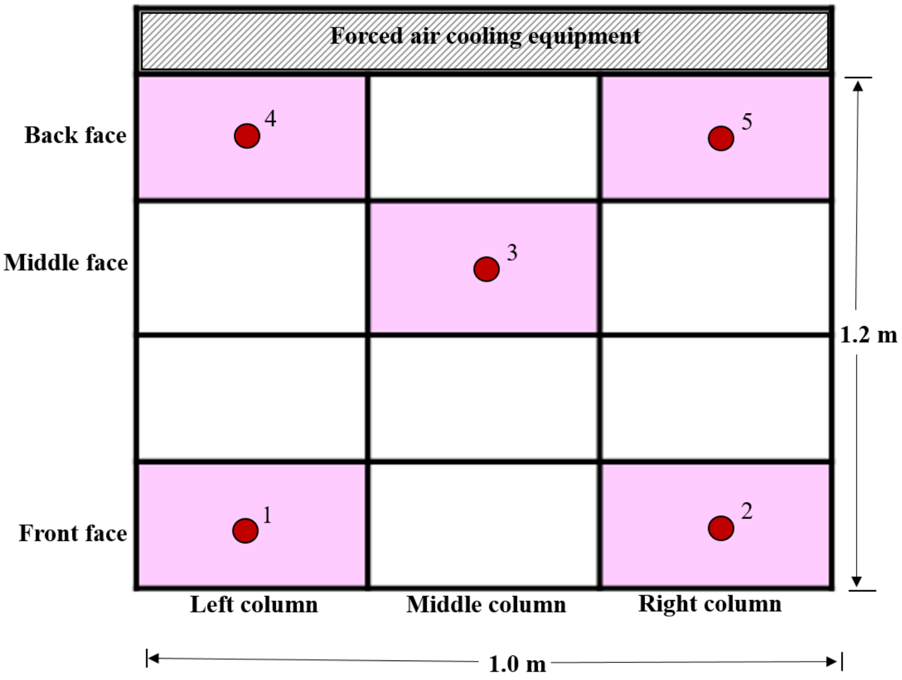

Figure 3.5 Lay out of an individual stack layer showing selected fruit positions 1-5 for core temperature monitoring

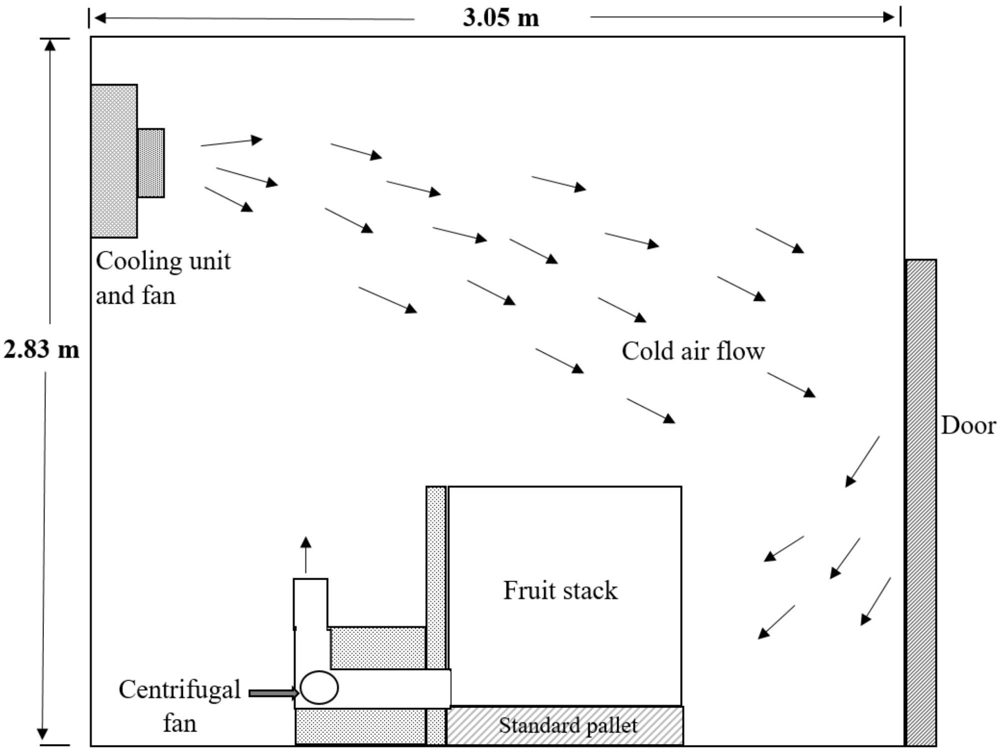

Figure 3.6 Cross sectional experimental set up during cooling of fruit

3.2.6 Pre-cooling of fruit

Cold air at 6 ± 1.5 °C and 90 ± 5 % RH was sucked through the stack by a centrifugal fan of the FAC equipment (Figure 3.3) at a constant airflow rate of 0.5 $Ls^{-1}kg^{-1}$, cooling the fruit from an initial temperature of about 17 ± 3 °C.

3.2.6.1 Fruit cooling rate

Fruit cooling data were processed into exponential graphs depicting the rate of change of dimensionless temperature based on, equation 3 (Dincer, 1995), and the dimensionless temperature calculated using equation 4, was applied to account for the unaccomplished fractional temperature difference.

$$T_d = J\exp(-Ct) \tag{3}$$

where T_d is dimensionless temperature and t is cooling time (s). According to Dincer (1995), the lag factor J is a function of fruit shape, size and thermal properties; cooling coefficient C

(s^{-1}) is the rate of change in fruit temperature for every degree of the difference in temperature between fruit and cooling medium.

$$T_d = \frac{(T - T_a)}{(T_i - T_a\,)} \tag{4}$$

Where, T_d, T, T_a and T_i is dimensionless temperature, fruit core temperature (° C) at a given time, cooling air and initial fruit core temperatures (° C), respectively (Dincer, 1995). The time required to reduce the difference in temperature between T_i and T_a by half or seven eighths, is half-cooling time (HCT) and seven-eighths cooling time (SECT), respectively (Brosnan & Sun, 2001). By substituting 0.5 and 0.125 in place of T_d in Equation (3), the HCT (Equation 5) and SECT (Equation 6), were calculated, respectively (Dincer, 1995). The SECT is important in commercial pre-cooling facilities because it indicates that fruit temperature sufficiently reached to the required storage temperature that the produce can be placed into storage facilities where the remaining heat load can be removed with less energy costs (Thompson *et al*., 2008). For this study, results were presented as SECT.

$$HCT \;=\; \frac{[\ln(2J)]}{C} \tag{5}$$

$$SECT \;=\; \frac{[\ln(8J)]}{C} \tag{6}$$

3.2.6.2 Estimating energy consumption during precooling of fruit

The energy (joules) required for pre-cooling a stack of fruit was estimated using equation 7 as the product of the power P_w (Watts) needed to force cooling air across the stack and the seven-eighths cooling time SECT (hours) (Defraeye *et al*., 2014). The amount of power was given as the product of pressure drop ΔP (Pa) and volumetric flowrate G_a($m^3\,s^{-1}$) across the stack (equation 8). Results were presented in kilowatt hour per metric tonne (kwh.MT^{-1}).

$$Energy\;(J) = \;P_w\;\times SECT \tag{7}$$

$$P_w = \;\Delta P \times G_a \tag{8}$$

3.2.6.3 Fruit cooling uniformity

During commercial FAC of produce, individual fruit cool at varying cooling rates and therefore attain specific required storage temperature at different times. Room airflow dynamics, fruit position and layer in the stack influence cooling heterogeneity. Cooling heterogeneity was calculated by determining percentage relative standard deviation (% RSD) of SECT values calculated from time- temperature history of sample pomegranates at different positions inside the stack (Equation (9) and Equation (10). Cooling uniformity was calculated using Equation 11.

$$SD = \sqrt{\frac{\sum(SECT - SECT_{avg})^2}{N - 1}} \tag{9}$$

$$\% \, RSD = \frac{SD}{SECT_{avg}} \times 100 \tag{10}$$

$$Cooling \; uniformity \; (\%) = 100 - (\% \, RSD) \tag{11}$$

Where SD is standard deviation; $SECT$ seven-eighth cooling time of a particular fruit in the sample; $SECT_{avg}$ mean seven-eighth cooling time of the sample; N number of fruit in the sample.

3.2.7 Statistical analysis

Analysis of variance was carried out using Statistica software (Statistica version 13, StatSoft Inc., Tulsa, USA). Means were separated using Duncan’s multiple range test and significant difference between means was considered at P < 0.05. Variations were compared between treatments, stack faces, stack layers and different fruit positions within layers. Graphical presentation were generated using GraphPad Prism software version 4.03 (GraphPad Software, Inc., San Diego, USA).

3.3 Results and discussion

3.3.1 Resistance to airflow

3.3.1.1 Characteristics of airflow velocities through stacked pomegranate fruit

A reduction in air velocity implies reduced flow and increased resistance to airflow (RTA) of the stack. At a given fan motor frequency, the superficial air velocity through the stack varied depending on packaging combination (Table 3.3). Generally, for all fan frequencies superficial air velocity decreased with decreasing ventilation. Air velocity increased with fan frequency for each treatment except for macro-perforated 2 mm HDPE liner and 4 mm HDPE liners. These two liners show some deviation from the expected trend at frequencies above 25 Hz.

Generally, with respect to airflow through empty test chamber, the empty cartons (external packaging) reduced air velocity by 37.4 %. Interestingly, pomegranate loaded cartons also has almost same resistance, a 39.5 % reduction compared to the empty test chamber. This demonstrated the fact that the external packaging (EP) is the major causes of the airflow resistance. The incorporation of liners as internal packaging (IP) in the fruit stack further decreased the superficial air velocity, because of the barrier effect of liners to airflow. Fruit stack with non-perforated 'Decco' liners reduced air velocity by 58.9 % compared to 61.3 % for micro-perforated Xtend® liners. However, stacks with macro-perforated 2 mm 'Decco' and 4 mm 'Decco' liners reduced air velocity by 51.1 % and 53.8 %, respectively. This is because macro-perforations of liners improved airflow permeability compared to non-perforated and micro-perforated liners. The percentage decrease in air velocity correlates with pressure drop contribution where a higher percentage reduction in air velocity, reflects a greater contribution to pressure drop. These results agree with findings from Ngcobo *et al*. (2012a) on seedless table grapes.

However, fruit stacks packed with macro-perforated 2 mm HDPE and 4 mm HDPE liners showed a large reduction in air velocity of 65.1 % and 76.1 %, respectively. This could be associated with blocking of carton ventilation by the liners (Figure 3.7). Following good packaging practices, twisting (closure) of the bags was done such that all perforations were retained within the portion of the bag containing fruit and as close as possible to the fruit. There was more free space left within the 2 mm HDPE and 4 mm HDPE liners after twisting, resulting in blocking of carton ventilation, compared to other liners (Table 3.1).

Table 3.3 Variation in superficial velocity of air entering into the stack at different fan frequencies

	Superficial air velocity (ms^{-1}) at different fan frequencies				
Treatment	**10 (Hz)**	**15 (Hz)**	**20 (Hz)**	**25 (Hz)**	**30 (Hz)**
Empty tunnel	0.185 ± 0.001^{ij}	0.279 ± 0.002^{f}	0.372 ± 0.004^{b}	0.465 ± 0.004	0.558 ± 0.005^{a}
Empty cartons	0.115 ± 0.001^{pq}	0.173 ± 0.001^{k}	0.233 ± 0.001^{g}	0.292 ± 0.000^{e}	0.351 ± 0.001^{c}
No-liner	0.111 ± 0.000^{pq}	0.167 ± 0.000^{jk}	0.225 ± 0.003^{g}	0.281 ± 0.000^{ef}	0.336 ± 0.003^{d}
Decco	0.076 ± 0.003^{tuv}	0.113 ± 0.003^{pq}	0.153 ± 0.003^{l}	0.191 ± 0.000^{i}	0.225 ± 0.003^{g}
Xtend	0.072 ± 0.000^{tw}	0.107 ± 0.003^{q}	0.144 ± 0.003^{lm}	0.178 ± 0.003^{ik}	0.204 ± 0.009^{h}
2 mm Decco	0.091 ± 0.000^{rsu}	0.137 ± 0.000^{mn}	0.182 ± 0.003^{ij}	0.228 ± 0.003^{g}	0.277 ± 0.005^{f}
4 mm Decco	0.086 ± 0.005^{rs}	0.130 ± 0.000^{no}	0.172 ± 0.005^{jk}	0.211 ± 0.005^{h}	0.248 ± 0.005^{x}
2 mm HDPE	0.094 ± 0.001^{s}	0.115 ± 0.001^{pq}	0.130 ± 0.002^{no}	0.123 ± 0.005^{op}	0.119 ± 0.005^{opq}
4 mm HDPE	0.067 ± 0.002^{vw}	0.080 ± 0.003^{rt}	0.089 ± 0.001^{rs}	0.07 ± 0.005^{tw}	0.062 ± 0.000^{w}

The values with any similar superscript letter(s) are not significantly different ($P \leq 0.05$).

Figure 3.7 Blocking of carton vent holes by the liner, in a wind tunnel

3.3.1.2 Characteristics of the airflow resistances of stacks with liner Vs no liner packaging

Figure 3.8 depicts the pressure drop vs. air velocity (superficial) data of stacked empty cartons, stack with no liner and with liner. Clearly, the pressure drop characteristics of stack of empty cartons and stack of pomegranate-loaded cartons were closer to each other. At a given airflow rate (0.2 ms^{-1}), stack of packed pomegranates with no-liner increased the pressure drop by 13.5 % compared to the stack of empty cartons. The packing cartons were the main cause of airflow resistance (88.1 %) compared to the fruit (11.9 %) in the no-liner packed stack. Ngcobo *et al*.

(2012b) associated the airflow resistance of the cartons to the active percentage ventilation and vent-hole ratio of the carton face perpendicular to the airflow path. On the other hand, the stack with liner increased the pressure drop by 213 %, where the internal packaging ('Decco' liner) was responsible for the highest PD (63.4 %) compared to the cartons (32.2 %) and the fruit (4.4 %). This can be attributed to the blocking of the carton ventilation by the liner, hence restricting flow of air. Similar results were observed (Ngcobo *et al.*, 2012a; Berry, 2013) where the internal packages (such as liners and thrift bags) contributed the highest PD than the cartons in the different multi-level packaging combinations of table grapes and apples. Therefore, packing pomegranates with liners produces a higher RTA compared to no-liner packaging.

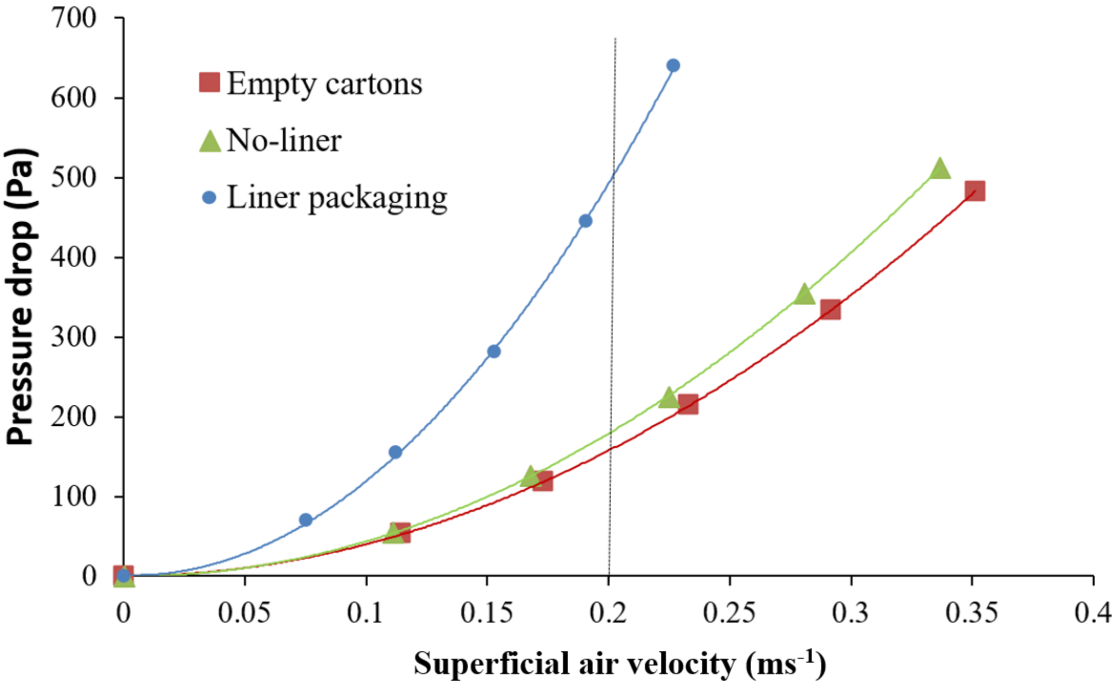

Figure 3.8 Pressure drop across different packaging level combinations of pomegranate fruit, at relatively low air velocities. Results were compared at 0.2 ms^{-1} air velocity.

In this section, PD across stacks of fruit packed with different liners was compared (Figure 3.9). Generally, PD across fruit stacks packed with liners was quite high, compared to results by Ngcobo *et al.* (2012a) on seedless table grapes packed in multi-packages, majorly due to differences in stack size and carton design. However, high PD was reported by other researchers, in studies where IP were not even considered (Smale, 2004; Delele, 2008). Delele *et al.*, 2013b reported PD of 703.4 Pa at 0.3 ms^{-1} air velocity on simulated citrus fruit. Similar characteristic trend curves of pressure drop increasing with increasing airflow velocity have been obtained by different researchers on other fruit and vegetables (Chau *et al.*, 1985; Shahbaz

& Rajabipour, 2007; Ngcobo *et al*., 2012a).

Figure 3.9 depicts the pressure drop vs. superficial velocity data of the different liner packaging combinations. Pressure drop across liner combinations was in the order of Xtend® > 'Decco' > 4 mm 'Decco' > 2 mm 'Decco'. At a given superficial air velocity (0.2 ms^{-1}), packing fruit with non-perforated 'Decco' liners increased PD by 175.7 % with respect to the stack with no-liner. Packing fruit in micro-perforated Xtend® liners increased PD by 238.4 %, instead. This can be attributed to difference in liner properties. The micro-perforated Xtend® liner has a more rigid and crispy texture, making it more difficult to twist properly compared to the non-perforated 'Decco' liner. A neat twist of the 'Decco' liner permits an easy flow of air passed the top of the bags with less resistance. Packing fruit in macro-perforated 2 mm 'Decco' and 4 mm 'Decco' liners increased PD by just 69.2 and 113.6 %. Liner perforations minimized RTA by improving permeability of packaging. The higher number of perforations on the 2 mm 'Decco' liner provides increased chances of ventilation alignment with the cartons, hence a more effective airflow through the stack compared to using 4 mm 'Decco' liners.

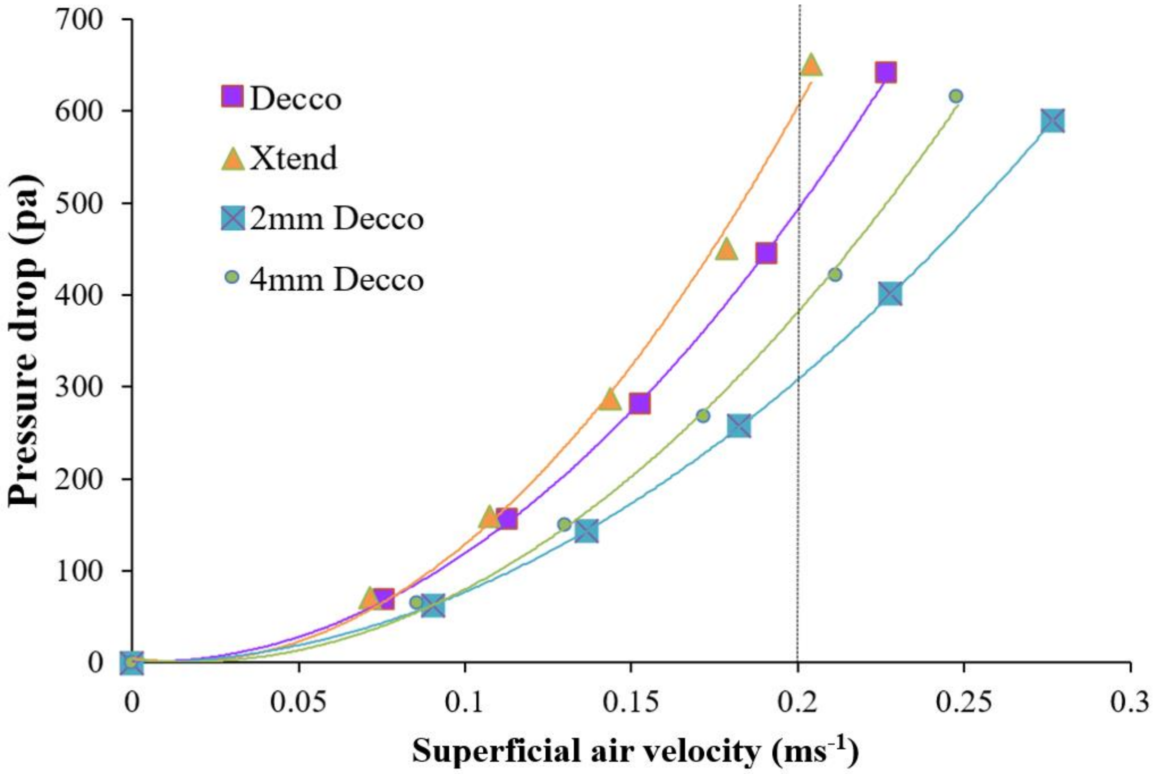

Figure 3.9 Pressure drop across multi-scale packaging combinations with differing liners, at relatively low air velocities. Results were compared at 0.2 ms^{-1} air velocity.

3.3.1.3 Correlating the pressure drop vs. flow rate curves to Ramsin and Darcy-Forchheimer models

There was a very high correlation between pressure drop and superficial air velocities according to both the power-law (Ramsin) and Darcy-Forchheimer models as shown by the high regression coefficients above 0.99 in Tables 3.4 and 3.5, respectively. A high resistance coefficient (a) and resistance exponent (b) of the Ramsin equation (Table 3.4) reflect a high RTA imposed by the packaging components. Treatments with higher pressure drop (Figure 3.8 and 3.9) also had higher values of a and b. The empty cartons had the lowest a values. However, packing fruit with no-liner increased a by 21.0 %. Furthermore, the a value of the no-liner packing combination increased by 163.4 % when non-perforated 'Decco' liners were used. Using micro-perforated Xtend® liners further increased a value of the non-perforated 'Decco' by 26.8 %. However, using macro-perforated 2 mm 'Decco' and 4 mm 'Decco' liners minimized the a value of the non-perforated 'Decco' liner combination by 33.7 % and 17.1 %, respectively. Berry, 2013 reported considerable increase in a value when thrift bags, poly-liners and fruit trays were added to empty cartons, for studies about RTA in packed apples. Ngcobo *et al.* (2012a) observed higher Ramsin and Darcy-Forchheimer constants for a stack of seedless table grapes packed with bunch-carry bags compared to bulk packaging, implying higher RTA in carry bag packaging than in bulk packaging. The values of a are highly dependent on ventilation area (Smale, 2004).

Table 3.4 Resistance coefficient and exponent of the Ramsin equation

Treatment	***a*** **(**Kg $S^{(b-2)}$ $m^{-(b+2)}$)	***b***	$\mathbf{r^2}$
Empty cartons	3.86E+03	1.988	1.000
No-liner	4.67E+03	2.028	1.000
Decco	1.23E+04	2.006	0.999
Xtend	1.56E+04	2.055	1.000
2 mm Decco	8.16E+03	2.029	1.000
4 mm Decco	1.02E+04	2.062	0.999

Resistance coefficient, a; resistance exponent, b; Regression coefficient, r^2.

Table 3.5 Coefficients of Darcy-Forchheimer equation

Treatment	$\boldsymbol{\beta}$ **(m^{-1})**	***K*** **(m^{2})**	**r^{2}**
Empty cartons	3.18E+03	1.60E-06	1.000
No-liner	3.76E+03	1.35E-06	1.000
Decco	1.02E+04	1.79E-07	0.999
Xtend	1.25E+04	1.35E-07	0.999
2 mm Decco	6.73E+03	2.52E-07	0.999
4 mm Decco	8.34E+03	1.11E-07	0.999

Forchheimer drag constant, β; Darcy permeability, K; Regression coefficient, r^{2}.

The Forchheimer drag constant (β) is a measure of resistance in the flow of fluids per unit distance while as the Darcy permeability (K) is a measure of porosity in a given mass. The higher β values (Table 3.5) for all the liner treatments than the no-liner treatment imply a higher RTA due to the presence of IP. The lower K values of the liner packed fruit compared to the no-liner treatment, reflect that liners as IP reduced the porosity of the stack, restricting airflow, thus increased RTA. The empty cartons had the lowest drag constant (β) and the highest permeability (K), thus the lowest RTA. However, packing fruit with no-liner increased drag (β) and decreased permeability (K) of the empty cartons by 18.2 % and 15.6 %, respectively. The β value of the no-liner packing combination was increased by 171.3 % when non-perforated 'Decco' liners were added in the combination. Using micro-perforated Xtend® liners further increased the β value of the non-perforated 'Decco' liner combination by 22.5 %. However, using macro-perforated 2 mm 'Decco' and 4 mm 'Decco' liners minimized the β value of the non-perforated 'Decco' liner combination by 34.0 % and 18.2 %, respectively. Packing fruit with the 2 mm macro-perforated 'Decco' liner also improved permeability (K) by 40.8 %, compared to packing fruit with non-perforated 'Decco' liners. Our results agreed with observations by Ngcobo *et al*. (2012a) on Regal seedless table grapes, where perforated liner packaging combinations had lower β values than non-perforated liner combinations. Mukama (2015) reported that addition of other packaging components such as polyliners and trays for pomegranate fruit, increased forchheimer drag constant β and thus increased RTA. The Author observed a 53.0 % and 50.2 % increase in β value by liner packaging combination compared to no-liner combination in CT1 and CT2 cartons, respectively. However, it was observed that the forchheimer term dominated the Darcy term, and curve fitting based on the forchheimer term only gave high regression coefficient values (well above 0.9), implying that the impact of K can be neglected. The Forchheimer term is expected to be dominant at relative high speeds while the Darcy term is expected to dominate at relatively low speeds.

3.3.1.4 Specific contribution to RTA by individual packaging components

The exponent b in the Ramsin model (Equation 1) was approximately equal to two for all treatments (Table 3.4). Hence, airflow resistance characteristics of the different packaging combinations were compared based on coefficient a of the Ramsin model (Figure 3.10). The pressure drop (PD) contribution of the fruit was calculated by subtracting PD of empty cartons from PD of carton plus fruit. In the no-liner combination, 82.78 ± 0.56 % of RTA was contributed by the carton and the remaining portion of resistance was due to the presence of fruit. A higher air resistance in vented cartons occurred at entrance and exit of the box (Smale, 2004). For both the non-perforated 'Decco' and micro-perforated Xtend® packaging combinations, liners contributed twice the RTA of the cartons. However, in macro-perforated 2 mm 'Decco' packaging combination, liners contributed well below the RTA by the cartons, while there was no significant difference in RTA contribution by the liner and carton in the macro-perforated 4 mm 'Decco' packaging combination.

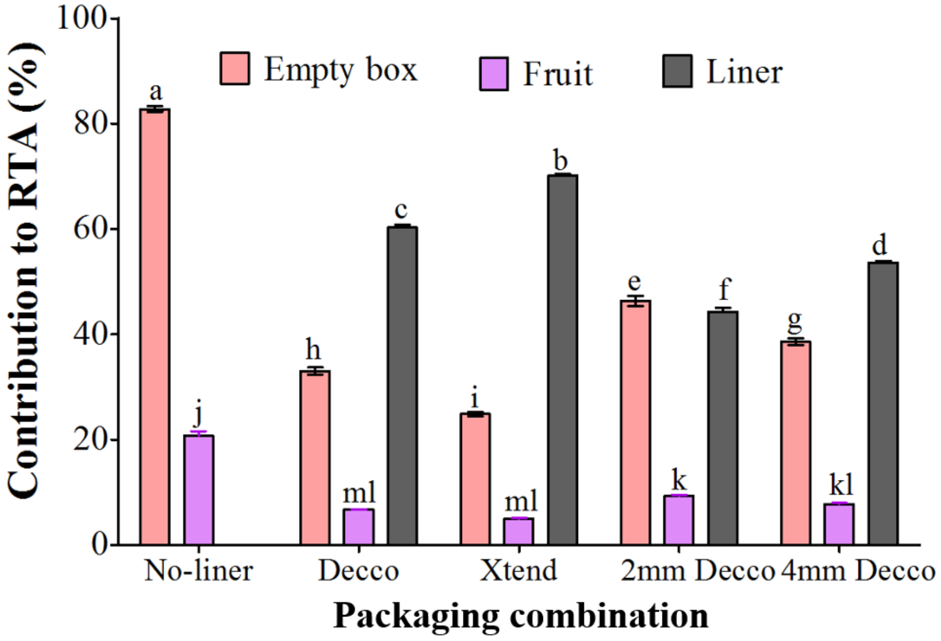

Figure 3.10 Contribution of individual components (box, fruit and liner) to air resistance across fruit stacks of different packaging combinations.

Generally, using non-perforated 'Decco' and micro-perforated Xtend® liners increased RTA of the no-liner packed fruit by 62.0 and 70.0 %, respectively. However, using macro-perforated 2 mm and 4 mm 'Decco' liners increased RTA of the no-liner packed fruit by 42.7 and 53.4 %, respectively. Although macro-perforated 2 mm 'Decco' and 4 mm 'Decco' liners had the same active ventilation of 0.05 % (Table 3.2), the 2 mm 'Decoo' liner had four times the number of perforations (70), providing more openings and less resistance to the flow of air, compared to 4 mm 'Decco' liner (18 perforations). Therefore, 2 mm 'Decco' could have had more perforations aligned with the vent holes of the carton for easy airflow compared to 4 mm 'Decco' liner. Ngcobo *et al*. (2012a) observed quite similar results in multi-scale packaging of seedless table grapes where the perforated liners contributed less pressure drop than the non-perforated liners.

3.3.2 Cooling characteristics

3.3.2.1 Effect of packaging on cooling rate

A higher rate of cooling was observed in the no-liner packed fruit, compared to liner packed fruit (Figure 3.11). The SECT of the stack packed with no-liner was 3.5 ± 0.2 h, compared to 8.1 ± 0.1 and 8.5 ± 0.1 h for the stack with non-perforated 'Decco' and micro-perforated Xtend® liners, respectively (Figure 3.12). Packing fruit with non-perforated 'Decco' and micro-perforated Xtend® liners delayed cooling by 133.1 and 143.1 % (2.33 and 2.43 times slower), respectively, compared to the stack with no-liner. This is due to the direct contact between fruit and cooling air in the absence of liners, resulting in high convective effect for heat transfer. Liners act as barriers preventing convective heat exchange between fruit and cooling air (Thompson *et al*., 2008). As discussed in section 3.3.1 above, liner promoted increased airflow resistance across the stack. There was no significant difference in the SECT for fruit packed with non-perforated 'Decco' and micro-perforated Xtend® liners. Mukama (2015) reported a 61.2 to 64.3 % faster cooling for pomegranate fruit (cv. Wonderful) packed without liners as compared to fruit in liners using two different carton designs. In a study about apples, Berry (2013) observed that adding liners or thrift bags in multi-scale packaging delayed cooling and lowered cooling rate by 78 % and 24 % respectively. Liners were reported to create delays during forced-air cooling of seedless table grapes (Ngcobo *et al*., 2012b). There was a general trend that fruit in layer 2 (closer to base) cooled fastest, followed by fruit in layer 4 (mid-stack) and then fruit in layer 6 (closer to top), for all packaging treatments (Figure 3.13). Mukama (2015) observed similar results during forced-air cooling studies on pomegranate (cv.

Wonderful) fruit packed in different ventilated cartons. This can be attributed to faster air velocities at the bottom of the stack than at the top owing to the positioning of the centrifugal fan of the forced-air cooling equipment and airflow circulation inside the cold room (Figure 3.6) (Thompson *et al*., 2008; Delele *et al*., 2009; Mukama, 2015). Airflow measurement showed higher flow of cooling air at the bottom of the stack than at the top (Table 3.6).

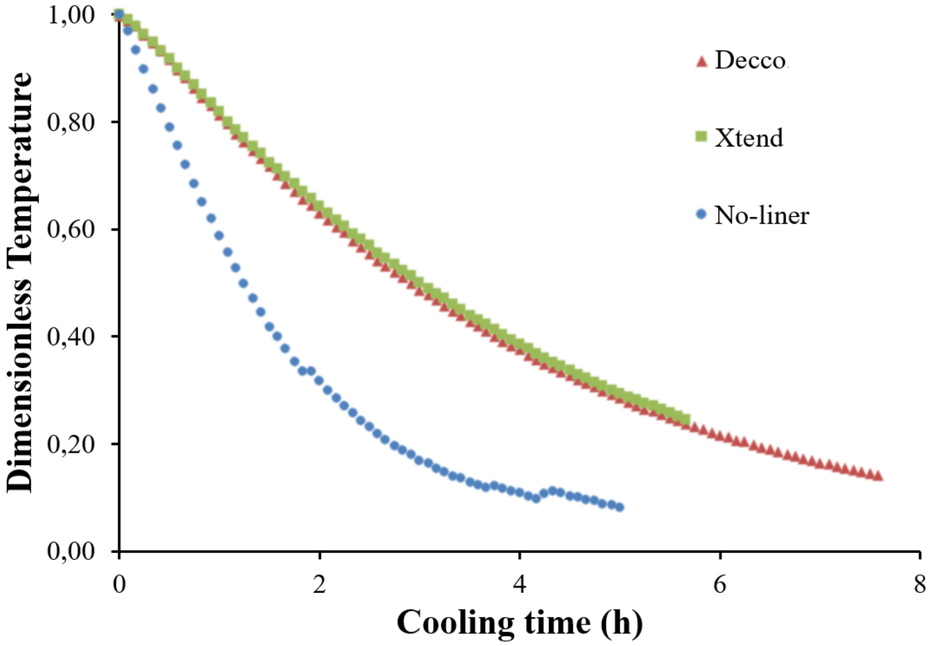

Figure 3.11 Cooling curves demonstrating cooling rate of pomegranate fruit stack

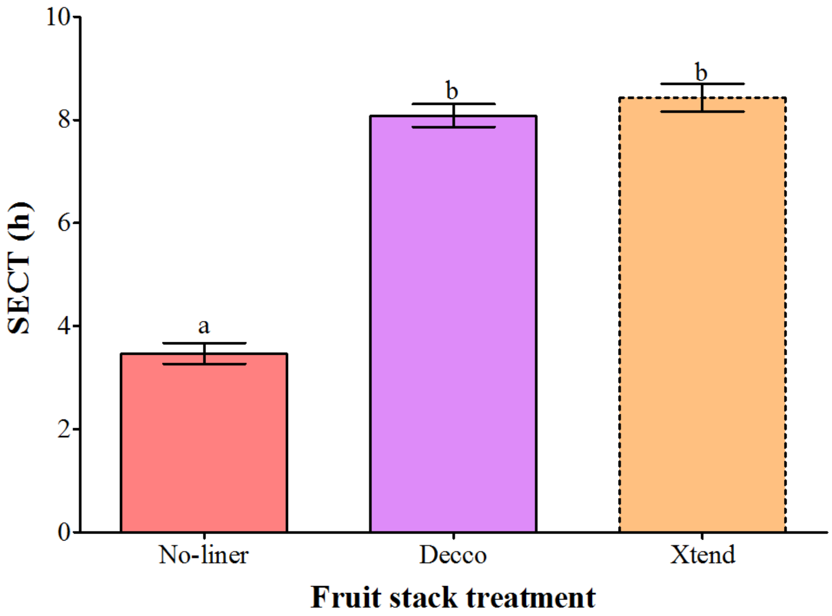

Figure 3.12 Average seven-eighth cooling time (SECT) of pomegranate fruit stacks

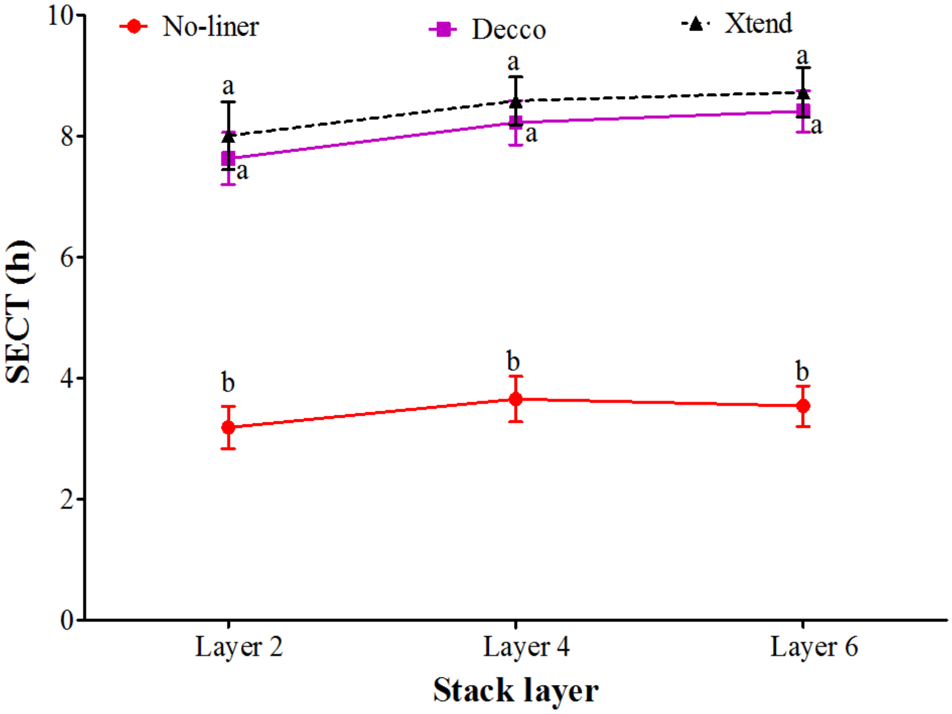

Figure 3.13 Average seven-eighth cooling time (SECT) across selected stack layers

Table 3.6 Velocity of cooling air entering the stack at different stack levels

	Velocity of cold air entering the stack (ms^{-1})		
Treatment	**Upper stack layers**	**Mid stack layers**	**Lower stack layers**
No-liner	3.589 ± 0.037	3.687 ± 0.084	5.387 ± 0.124
Decco	2.783 ± 0.197	2.986 ± 0.188	4.864 ± 0.151
Xtend	2.946 ± 0.238	3.097 ± 0.212	5.073 ± 0.181

Generally, for all treatments, fruit in stack face 1 (front face) cooled fastest, followed by fruit in stack face 2 (mid stack) and then fruit in stack face 3 (back face) as demonstrated in Figures 3.14 and 3.15. This can be attributed to the warming up of cooling air by picking heat from fruit as it moves from front to the back of the stack. In layer 2 (closer to the base), a significant difference was observed in SECT for fruit at the front, middle and back faces of the stack irrespective of the packaging treatment. Similar results were observed in layers 4 and 6 for fruit packed in non-perforated 'Decco' and micro-perforated Xtend® liners. There were no significant difference in SECT of fruit in the middle and back of layer 4 and layer 6 of the stack packed with no-liner. Fruit at the front of the stack cooled 44.3, 19.9 and 26.1 % faster than fruit in the middle and 54.5, 29.8 and 35.0 % faster than fruit in the back stack, for fruit packed with no-liner, non-perforated 'Decco' liner and micro-perforated Xtend® liner, respectively. This was probably due to a faster heat transfer rate within the no-liner packed fruit because of conductive and convective cooling processes, compared to fruit packed in liners were cooling was mainly by conduction across plastic liners (poor heat conductors). Similar results were reported by Mukama (2015) where pomegranate fruit at the front of stack cooled up to 44.4 % and 24.4 % faster than fruit at the back of the stack for the no-liner and liner treatments, respectively. There was no significant difference in cooling rate between fruit on the left (positions 1 and 4) and right (positions 2 and 5) hand sides of the stack for all treatments (Figure 3.14). This could be because of proper positioning of fruit stack with respect to suction fan of FAC equipment and a more perpendicular directional flow of air through the stack.

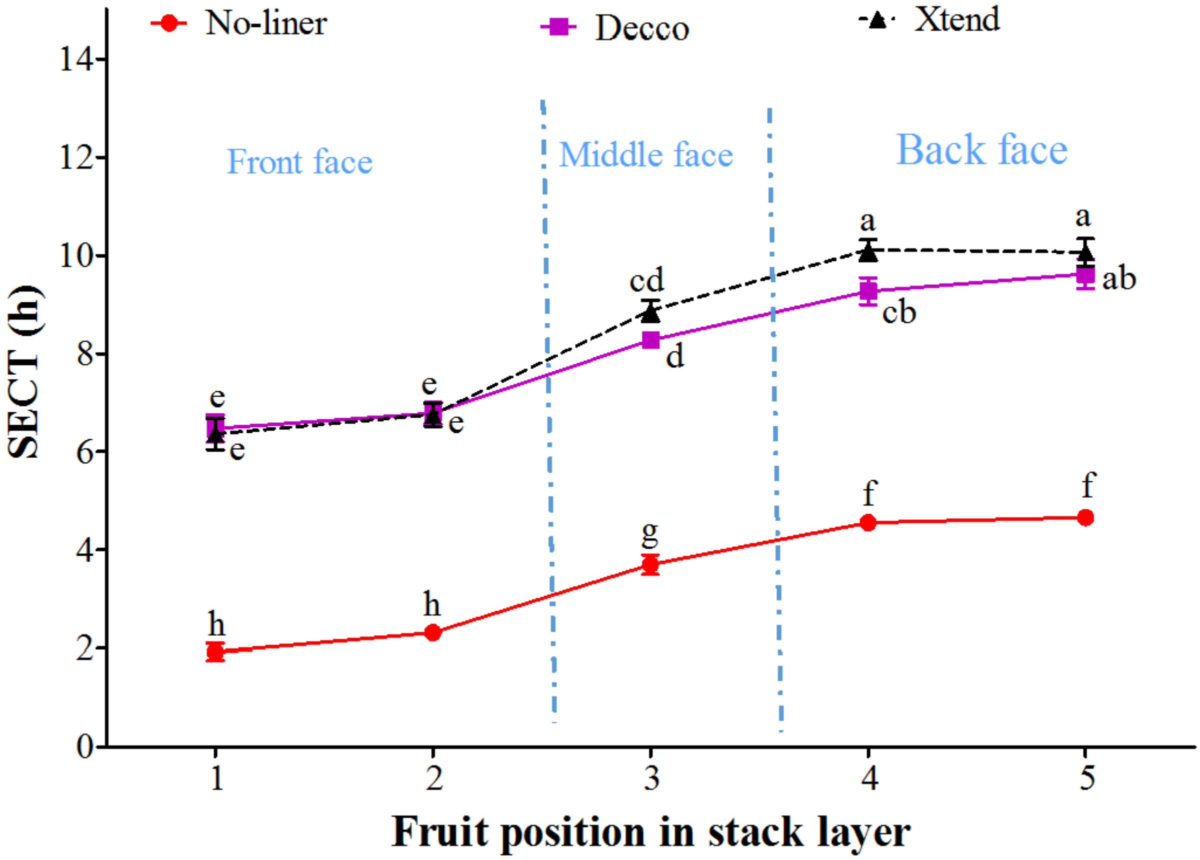

Figure 3.14 Seven-eighth cooling time (SECT) of individual fruit positions in a stack layer

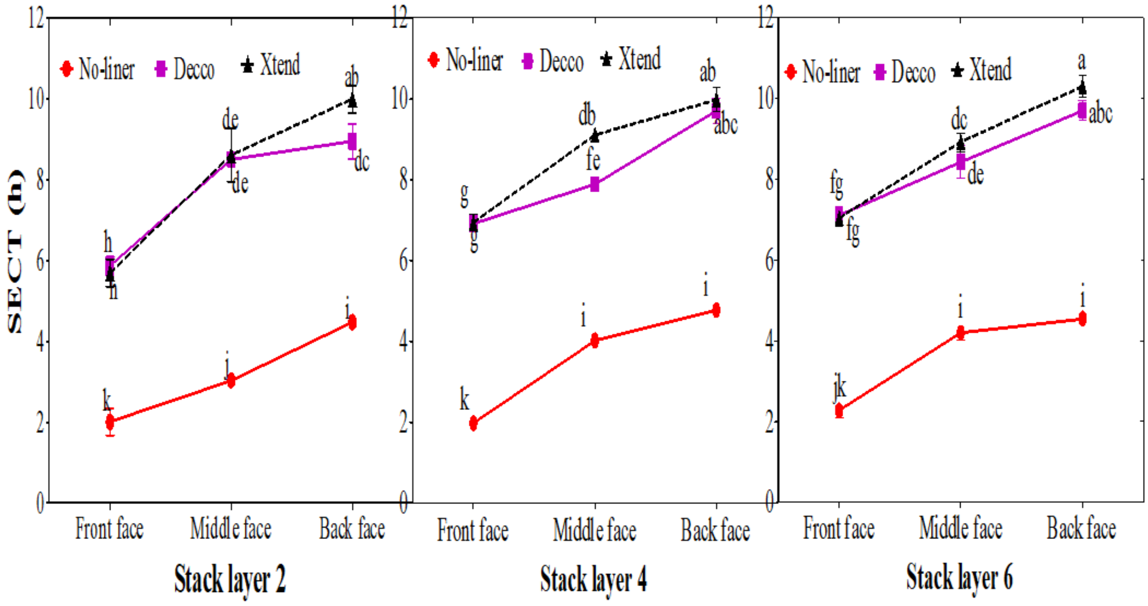

Figure 3.15 Average seven-eighth cooling time (SECT) across stack faces

3.3.2.2 Effect of liners on fruit cooling homogeneity and heterogeneity inside the stack

Cooling heterogeneity (non-uniformity) refers to a phenomenon where fruit in a stack cools at different rates and is dependent of differences in fruit geometry, positioning, packaging and airflow dynamics. However, a more homogeneous (uniform) cooling of the fruit stacks is desirable. Fruit that cool faster are prone to chilling injury while fruit that cool slowest are prone to weight loss and other quality deterioration. Results of cooling uniformity are summarised in Figure 3.16. Generally, fruit stack packed with no-liner showed the lowest cooling uniformity of 64.2 ± 0.2 % (35.8 % heterogeneity). However, packing fruit in non-perforated 'Decco' and micro-perforated Xtend® liners improved whole stack cooling uniformity to 81.5 ± 1.7 % (18.5 % heterogeneity) and 78.7 ± 1.5 % (21.3 % heterogeneity), respectively. It was observed that the no-liner packed fruit which had the highest cooling rate, had the lowest cooling uniformity (highest heterogeneity) compared to all liner packed fruit. Therefore, adding liners in the packaging of pomegranate fruit greatly improves cooling uniformity of products and thus minimizing risk of quality disorders like chilling injury. Probably the liners created a steadier flow of cooling air within the stack by minimizing air velocity around the fruit, increasing residence time of cooling air within the stack. The high air velocity through the no-liner fruit stack could have facilitated a more turbulent flow with reduced residence time of cooling air. Similarly, Mukama (2015) reports higher cooling heterogeneity in the no-liner treatment compared to liner treatment for pomegranate fruit packed in two different carton designs.

Fruit cooling uniformity varied significantly between stack layers and faces, especially for the no-liner packed fruit (Figure 3.16). Generally, the stack layers and faces that had higher SECT, were observed to have lower cooling uniformity. Stack layers had a bigger influence on cooling uniformity compared to stack faces. In the no-liner packed fruit, layer 4 (middle layer) had the highest cooling uniformity (66.1 ± 0.1 %), compared to 58.2 ± 0.8 % and 62.4 ± 2.1 % for layer 2 (closer to the base) and layer 6 (closer to the top), respectively. However, in both liner treatments (‘Decco’ and Xtend$^{®}$), cooling uniformity was highest in layer 6 (87.6 ± 1.0 % and 80.9 ± 0.1 %) and lowest in layer 2 (79.7 ± 0.1 % and 73.6 ± 1.9 %), respectively. This can be attributed to the difference in air flow rate at the entrances of individual stack layers (Table 3.6). A higher flow rate of cooling air into carton ventilation was recorded for both lower and upper layers compared to middle layers, for the no-liner packed fruit. This suggests a higher residence time of cooling air in layer 4 compared to layers 2 and 6. However, for both liner treatments, airflow rate was highest at the lower layers of the stack, followed by middle layers and then upper layers. Therefore, the was a higher residence time of cooling air in layer 6 than in layers 2 and 4, for fruit packed in liners. In all treatments, cooling uniformity was higher at the front face of the stack, followed by middle face and lowest at back face, but with no significant differences, except for the fruit stack packed with no-liner.

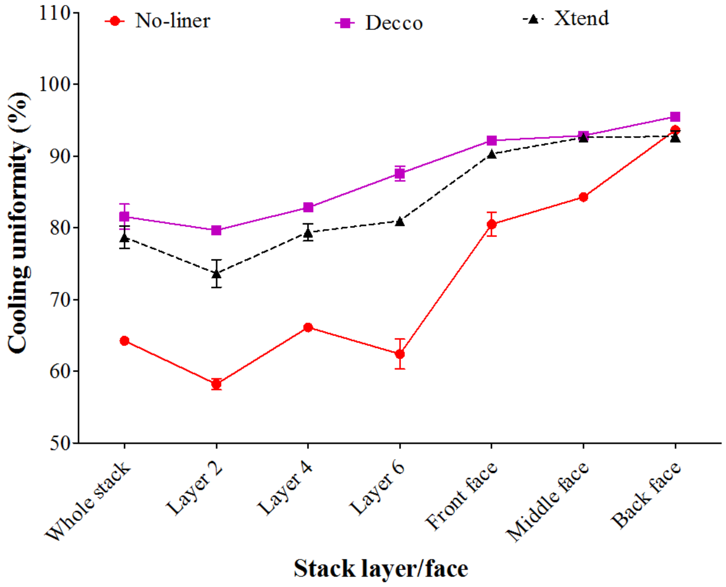

Figure 3.16 Average fruit cooling uniformity across fruit stack

3.3.2.3 Effect of liners on energy consumption

Packaging fruit in liner bags compared to no-liner packaging tremendously increased the amount of energy required during the precooling of stacked fruit to the seven-eighth cooling time (Figure 3.17). Non-perforated 'Decco' liners increased energy consumption by 301.0 % of the no-liner packing treatment during FAC while the application of micro-perforated Xtend® liners increased energy consumption by 375.2 %. Liner bags prevent direct contact of fruit with cooling air, block ventilation, and increase resistance to airflow giving rise to delayed cooling and increased energy consumption (Thompson *et al.*, 2008; Ngcobo *et al.*, 2012a; Makama, 2015). Similar results were reported on pomegranate fruit were liner bags increased energy consumption by 76 % and 81 % as compared to no-liner packaged fruit in CT1 and CT2 cartons respectively (Mukama, 2015).

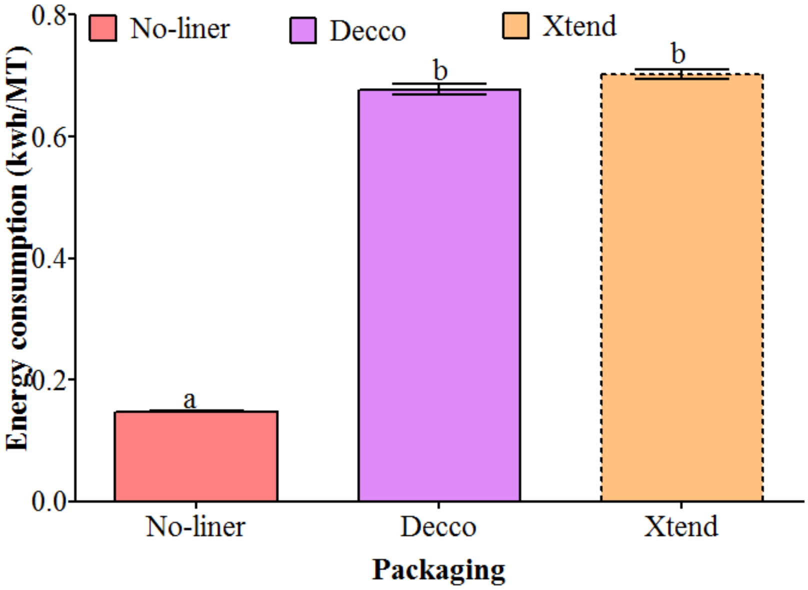

Figure 3.17 Energy consumption during forced-air cooling of pomegranate fruit to seven-eighth cooling time.

3.4 Conclusions

Internal packages (liners) play a central role on the degree of resistance to airflow in ventilated multi-scale packaging of pomegranate fruit. Using liners of good perforation quality in terms of number, size, distribution and alignment can greatly minimize resistance to airflow. For liners of same percentage ventilation area, the number of macro-perforation will have a better impact on reducing resistance to air flow as compared to size of macro-perforation. In this study the 2 mm macro-perforated 'Decco' liner showed the best perforation quality for minimizing resistance to airflow in pomegranate fruit and therefore expected to achieve a faster cooling and minimized energy consumption during forced-air cooling. Further research should focus more on the alignment of these perforations with carton vent holes.

Overall, the incorporation of liners in the packaging of pomegranate fruit delays cooling and increases energy consumption as compared to no-liner packaging. However, using liners improves cooling uniformity within the stack and therefore minimizes risk of quality disorders like chilling injury. Use of macro-perforated liners instead of the micro-liners will significantly improve cooling rate of fruit. However, there is need to ascertain how the different liners affect the quality of fruit so as to strike a balance between improving cooling rate during pre-cooling exercise and improving keeping quality of fruit during prolonged cold storage.

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SECTION III

Chapter 4. Impact of packaging liners on moisture dynamics, physical & physiological quality attributes of pomegranate

Chapter 5. Effect of packaging liners on chemical & phytochemical properties and anti-oxidant activity of pomegranate fruit

4 Impact of Internal Packaging (liners) on Moisture Dynamics, Physical and Physiological Quality of Pomegranate Fruit during Cold Storage

Abstract

Weight loss and decay are common physiological disorders during postharvest handling and storage of pomegranates. Internal packaging (IP) materials like plastic liners are commonly used in the cold chain to minimize the weight loss. In this study, freshly harvested pomegranate (cv. Wonderful) fruit were portioned into 6 IP treatments; the no-liner control, non-perforated ‘Decco’, non-perforated ‘Zoe’, micro-perforated Xtend®, 2 mm perforated high density polyethylene (HDPE) and 4 mm perforated HDPE plastic liners. The moisture transmission capacity of the different liner films was measured using a diffusion cup test. Fruit were stored at 5 °C and 90-95 % relative humidity (RH) for 12 weeks and periodically assessed for weight loss and changes in size dimensions, textural properties, colour parameters, decay, shrivelling, respiration rate, and gas composition and moisture condensation inside the film packages. After 12 weeks of cold storage, fruit packed with no-liner lost 15.6 ± 0.3 % of initial weight. Non-perforated (Decco and Zoe) liners minimized loss in weight to 0.79 and 0.82 %, compared to Xtend® micro-perforated (4.17 %), 2 mm macro-perforated HDPE (2.44 %) and 4 mm macro-perforated HDPE (4.17 %) liners, respectively. Clearly, micro and macro-perforation of liners allowed moisture exchange between fruit and air, minimized moisture condensation. Interestingly, micro and macro perforation of liners decreased fruit decay and shrivel severity. After 12 weeks of cold storage, fruit packed with no-liner lost 28.3 % of the initial whole fruit firmness (116.1 ± 2.0 N). However, non-perforated ‘Decco’ and ‘Zoe’ liners reduced fruit firmness by 8.0 % and 6.8 % only. The 2 mm and 4 mm macro-perforated HDPE and Xtend® micro-perforated liners reduced fruit firmness by 15.8 %, 15.5 % and 12.0 %, respectively. Potential financial losses due to decay incidence outweighed financial losses due to weight loss. Therefore, using micro-perforated Xtend® and macro-perforated 4 mm HDPE can be considered to minimize postharvest losses often associated with inadequate environment control inside packaging, compared to the use of non-perforated liners.

Key words: *Internal packaging, Quality, Pomegranate, Weight loss, Cold storage*

4.1 Introduction

Production and consumption of Pomegranate (*Punica granatum* L.) fruit is on the increase, worldwide. The fruit has an edible portion of about 55-60 % (Fawole & Opara, 2013a) and can be eaten fresh or processed into juice, wine and jam (Kader, 2006; Opara *et al*., 2009; Wetzstein *et al*., 2011). Freshly harvested fruit is kept under cold storage awaiting export to distant markets. Fruit from South Africa takes about 6 weeks to reach Europe as the major export market destination and therefore a need to maintain good postharvest quality during prolonged storage and export conditions. The postharvest quality of pomegranate fruit can be preserved up to 12 weeks at 5 ^{o}C and 90-95 % RH (Artés, 1992). Storing pomegranate (cv. Wonderful) for 3 months at 5 ° C and above 92 % RH minimizes physiological disorders, maintains internal and external quality attributes (Arendse *et al*., 2014). Chilling injury increases with storage duration and temperatures lower than 5 ° C (Elyatem & Kader, 1984).

However, in postharvest fruit handling, weight loss and fruit decay are common physiological disorders among others like chilling injury and scalding, contributing to quantitative and qualitative loss (Elyatem & Kader, 1984; Köksal, 1989; Caleb *et al*., 2012). Pomegranates are highly prone to moisture loss owing to the relatively high water permeability across the skin through minute openings, despite having a thick rind (Elyatem & Kader, 1984; Nanda *et al*., 2001; Opara *et al*., 2010). Fruit moisture loss if not well controlled results into shrinkage, shrivel, quantitative loss in weight, taste and overall acceptability of the fruit, hence market loss (Vigneault *et al*., 2009).

Internal packaging techniques have been used in the fresh fruit industry to minimize moisture loss. Internal packaging refers to additional packaging materials applied around the fruit within the external package. Surface coating and waxing has been applied on apples, oranges and pomegranate to minimize moisture loss (Nisperos-Carriedo *et al*., 1990; Park *et al*., 1994; Küpper 1995; Nanda *et al*., 2001). For pomegranates, heat shrinkable wraps on individual fruit in cartons have also been applied (Artés *et al*., 2000; Nanda *et al*., 2001; D'Aquino *et al*., 2010). On the other hand, shrink wrapping, surface coating or waxing can lead to anaerobic respiration by creating an oxygen deficit and yet promoting a high CO_2 atmosphere around the fruit. These result in production of off flavours and a change in taste (Gil *et al*., 1996; Cantı´n *et al*., 2008). Plastic liners have minimized weight loss in pomegranate fruit (Küpper, 1995). In South Africa, plastic liners are a commonly applied internal packaging to minimize moisture loss for pomegranate fruit packaged in ventilated cartons.

The impact of packaging pomegranate fruit in plastic liner has been assessed by quite a few researchers with major focus on the ability of the plastic liners to modify gaseous atmosphere around the fruit, preserving physical and physio-chemical quality (Artés *et al*., 2000; Selcuk & Erkan, 2014). This research focuses on relating the ability of plastic liners as internal packaging to modify both gaseous and moisture atmosphere around the fruit to moisture dynamics, physical and physiological quality of pomegranate fruit (cv. Wonderful) during prolonged cold storage.

4.2 Materials and methods

4.2.1 Fruit supply

Commercially mature, harvested pomegranate fruit (cv. Wonderful) of uniform diameter 81.8 ± 2.5 mm and mass 286 ± 15 g were procured from a farm in Bonnievale (33^{o}58'12.02"S, 20^{o}09'21.03"E), Western Cape, South Africa. Fruit were transported in refrigerated truck to Postharvest Technology Research Laboratory at Stellenbosch University.

4.2.2 Packaging and storage

Fruit was portioned into six treatments: no-liner (control); non-perforated 'Decco' liner; non-perforated 'Zoe' liner (ZOEpac, South Africa); micro-perforated Xtend® liner; 2 mm perforated HDPE liner (2 mm × 54 perforations); 4 mm perforated HDPE liner (4 mm × 36 perforations). For each treatment, 11 ventilated cartons each, loaded with 12 fruit (Figure 4.1) were stored in cold rooms at 5 ^{o} C and 90-95 % RH for 12 weeks. For each treatment, 12 fruit were randomly taken from the stack, and assessed for quality after 4, 6, 8 and 12 weeks of cold storage.

4.2.3 Film and fruit properties

4.2.3.1 Gas composition analysis

Gas composition was tested in triplicates, for each of the five liner treatments. Each replicate consisted of 12 fruit of known mass packed in plastic liner and carton. A gas analyser (Checkmate 3, PBI Dansensor, Ringstead, Denmark) having a precision of ± 0.5 % was used to assess the gas atmosphere inside liners, daily for 30 days of cold storage. The gas analyser needle accessed the internal atmosphere of the liner bag through a planted rubber septum on the packaging film.

Figure 4.1 Pomegranate fruit packed with plastic liner and carton

4.2.3.2 Water vapour transmission rate (WVTR)

During storage of packaged fruit, moisture moves across films by diffusion force as a result of a concentration gradient created on opposite sides of the film. A modification of the dry cup technique (ASTM, 2005 method E96-95) was used to determine WVTR gravimetrically, as descried by Hussein (2014) and Opara *et al*. (2015). Film samples of each of the five liners were cut out in the areas of no-perforation to test vapour transmission across the liner surface. For each of the macro-perforated liners (2 mm HDPE and 4 mm HDPE), a sample with one perforation (2 mm and 4 mm diameter respectively) was also used so as to assess vapour transmission across the perforations. The experiment was carried out in triplicates.

Set 1 and set 2 of clean and dry aluminium test cups (diameter 5.6 cm and depth 1.5 cm) with open top-screw lid (Comar International, Cape Town, South Africa) were conditioned for 18 hours at ambient temperatures 20 °C and 5 °C, respectively. Test cups were filled with 8.0 ± 0.5 g of anhydrous calcium chloride salt ($CaCl_2$). The cups were fitted with an O-ring and grease to provide proofing against moisture and air (Figure 4.2). A film sample was then laid on top and the cup tightly closed giving an active surface area of 25 cm^2. Precaution was taken to ensure that macro-perforations were centred, where applicable.

Set 1 and 2 of the cups were then weighed and stored at 20 °C, 65 % RH and 5 °C, 90 % RH respectively. Set 1 cups were stored in an environmental test chamber (Sanyo Electric Co., Osaka, Japan) with controlled constant air movement, while set 2 cups were stored in a cold room. The gain in weight of each cup was monitored per day, for 30 days. The WVTR (g/m^2.day) of films was calculated basing on mass of water gained by $CaCl_2$ salt in the cup over time, using equation 1.

$$WVTR = \frac{(W_t - W_i)}{\Delta_t} \times \frac{1}{\Delta_p} \quad (1)$$

Where W_i is the initial weight of test cup (g); W_t, weight of test cup at a given time t (in days); and Δ_p, differential water vapour pressure (kPa) across the test cup (Δp= 1; given the assumption that the internal cup pressure and external atmospheric pressure were the same).

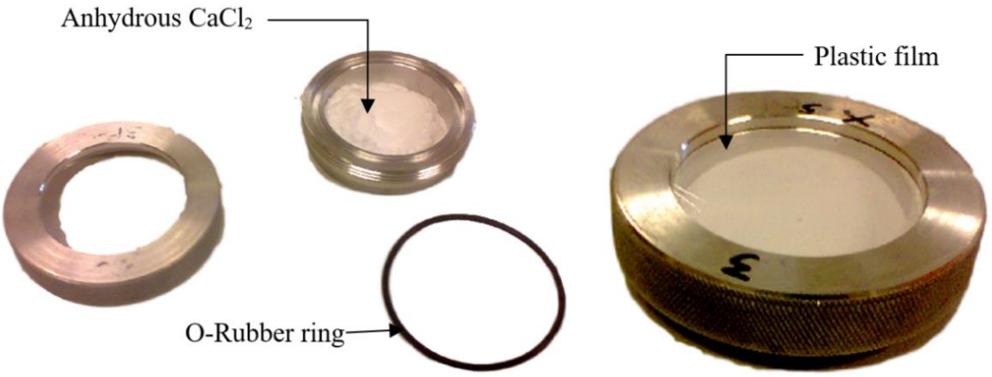


Figure 4.2 Diffusion of water vapour across plastic film using anhydrous salt

4.2.3.3 Moisture condensation measurement

Studies on moisture condensation with the five different liners was carried out in two set ups. The first set up was to determine how much visible condensate could be quantified inside the liner bags. Fruits were conditioned at ambient conditions of 17 ± 2 °C and 65 ± 5 % RH for 12 hours, weighed individually, packed and sealed in dozens in plastic liners, and placed inside ventilated cartons. Fruit was then stored on pallets in a cold room at 5 °C and 90 ± 5 % RH for 24 hours. Relative humidity and temperature of the room and inside individual carton liners was monitored using Tinytang sensors (Tinytag TV-4500, Hastings Data Loggers Australia) at intervals of 10 minutes. Dry clean paper pads of known mass were used to sponge off the condensate water from the inside of the bag and on the fruit. The weight of wet pads was then immediately recorded. The amount of condensate was expressed in g/m^{2}day and as a percentage of the fruit mass. The experiment was repeated three times. The amount of condensate was also scored on a scale of 0-10 score scale (where 0 = none; 1-2 = trace; 3-4 = slight; 5-6 = moderate; 7-8 = severe; 9-10 = extremely severe).

The second set up of the experiment was to determine the rate of change in the condensate within the bags over a period of time. In this case, fruit were conditioned at ambient temperatures while as the packaging material was conditioned at 5 °C in cold room for 12 hours. The packed fruit were then weighed before storage at 5 °C and 90 ± 5 % RH for 7 days. The condensate within the bags was scored on a 0 to 5 scale and the change in weight of the packed fruit was monitored per day. At the end of 7 days, the amount of remaining condensate in the liners was quantified as described in phase one above and the weight of fruit was also recorded. The rate of change in condensate was calculated in g/m^2.day.

4.2.3.4 Fruit weight and size loss

Twelve fruit were randomly selected, numbered, weighed and length, diameter and circumference reference points on each sample pomegranates were explicitly marked for each test. The same individual fruits were monitored for fruit weight, length, diameter and circumference after 4, 6, 8 and 12 weeks of storage. Fruit weight was monitored using a digital scientific scale (Mettler Toledo, model ML3002E, Switzerland, 0.0001g accuracy). Fruit circumference (C) was measured twice per sample fruit in the horizontal plane, using a fruit size (circumference) measurer strap band (GÜSS-FTA, South Africa) (Figure 4.3) and results were automatically recorded by computer. Fruit length (L) and diameter (D) were measured at two opposite longitudinal (excluding the fruit calyx) and equatorial fruit perimeters, respectively (Figure 4.4), using a digital Vernier calliper (Mitutoyo, Kawasaki, Japan, ± 0.01 mm). Cumulative loss in fruit weight, length, diameter and circumference were calculated using equation 2.

$$Y = \frac{(Y_i - Y_t)}{Y_i} \times 100 \qquad (2)$$

Where Y is percentage cumulative loss; Y_i and Y_t are initial and periodic measurements, at the start of the cold storage and at a given sampling time during cold storage, respectively. Results were reported as means ± S.E.

Figure 4.3 Measuring fruit circumference using a fruit size measurer

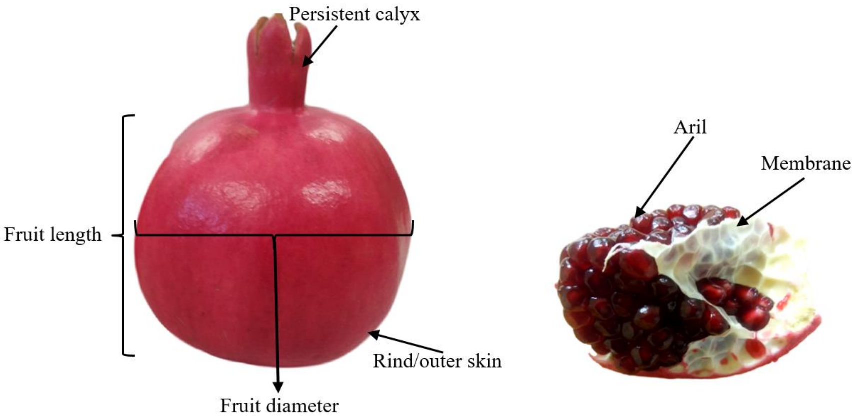


Figure 4.4 External and internal pomegranate fruit morphological structure

4.2.3.5 Peel thickness measurement

Peel thickness was measured at four points per fruit using a pair of digital Vernier callipers (Mitutoyo, model CD-6 CX, Japan) of accuracy 0.01mm. Two opposite segmental peels were selected and thickness measured at mid-longitudinal points of the right and left sides of each segmental peel (Figure 4.5). The average peel thickness of 12 fruit per treatment was then calculated.

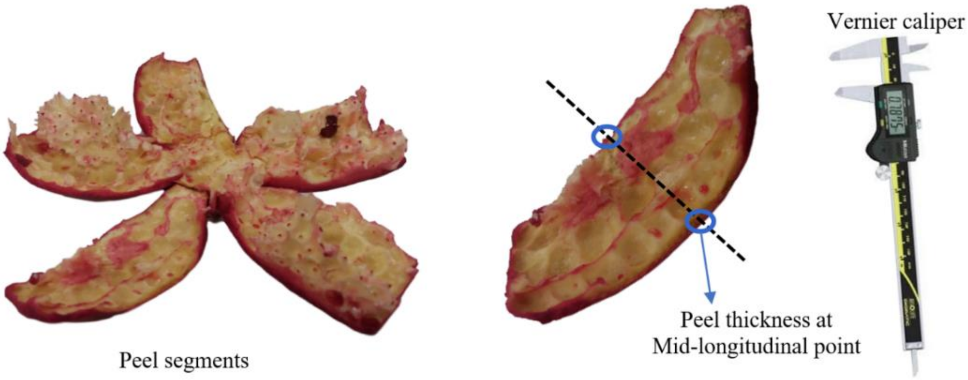


Figure 4.5 Pomegranate fruit peel segments

4.2.3.6 Fruit shriveling and decay

Incidence and severity of fruit physiological disorders of decay and shrivelling, were assessed per treatment after 4, 6, 8 and 12 weeks of storage. The severity of a particular physiological disorder was assessed subjectively using a hedonic scale, where 0 = none; 1 = trace; 2 = slight; 3 = moderate; 4 = severe; 5 = extremely severe. Only severe injuries could be considered as commercially unacceptable (Artés *et al.*, 1998). Shrivel and decay indices were calculated by multiplying the scores of severity by the number of fruit affected, divided by the total number of fruit (Artés *et al.*, 1998; Fawole & Opara, 2013b).

4.2.3.7 Respiration rate

A closed system method (Caleb *et al*., 2012) was applied to measure fruit respiration using five replicates per treatment (Figure 4.6). For each replicate, two fruit of known mass were placed inside a three litre glass jar, air-tightly sealed with a lid having a rubber septum. The jars were incubated for 4 hours at 5 °C and 90 % RH. The accumulation of CO_2 inside each glass jar was monitored using an O_2/CO_2 gas analyzer (Checkmate 3, PBI Dansensor, Denmark) and respiration rate presented as mean ± S.E (ml CO_2 $kg^{-1}h^{-1}$).

Figure 4.6 Measuring respiration rate using a closed system setup

4.2.3.8 Fruit puncture resistance

The ability of the fruit to resist a penetrating force was determined by a fruit puncture (‘Texture’) analyser (GÜSS-FTA, South Africa) with a 5 mm diameter probe as described by

Arendse *et al*. (2014). The probe was set to penetrate 8.9 mm into the fruit at 10 mms^{-1}. Test was carried out on opposite sides per each of the 12 fruit per treatment, and the peak force (N) required to puncture the fruit was reported as puncture resistance mean ± S.E.

4.2.3.9 Aril texture analysis

Aril compression test was performed as described by Fawole and Opara, (2013b). Four arils were randomly chosen from each fruit segment to make a pool and then two arils selected from the pool, giving a total of 24 arils per treatment. A 35 mm diameter probe of the texture profile analyser TA. XT (Stable Micro System, UK) was used to compress the aril at a test speed of 0.5 m ms^{-1} and 0.20 N trigger force. Aril firmness was calculated as maximum force (N) required to completely break the aril. The means (± S.E) of 24 determinations were reported per treatment.

4.2.3.10 Colour properties

A digital colorimeter (Minolta, model CR-400, Tokyo, Japan) was used. Fruit peel colour was monitored at two selected and ring-marked positions per fruit. Aril colour was monitored in a petri dish at two random spots per sample. Values of L*(lightness), a^* (redness), b^*(yellowness), hue angle (colour nuance) and chroma (saturation) were measured according to Commission Internationale de l'Eclairage (CIE), 1976. Chroma (C*) was calculated by equation 3 (Pathare *et al*., 2012). Twelve replicates were considered per packaging treatment.

$$c^* = \sqrt{{a^*}^2 + {b^*}^2} \qquad (3)$$

4.2.4 Statistical analysis

Analysis of variance (ANOVA) was performed using Statistica software (Statistica 13.0, StatSoft Inc., Tulsa, OK, USA). A 2-way ANOVA was applied where applicable with packaging treatments and storage time being the major categories. Means were separated using Duncan's multiple range test and significant difference between means was considered at P < 0.05. Relationship among selected parameters was determined by subjecting data to principal component analysis (PCA) using XLSTAT software version 2012.04.1 (Addinsoft, France).

4.3 Results and discussion

4.3.1 Liner properties

4.3.1.1 Gas composition inside liners

There was a decrease in oxygen and an increase in carbon dioxide gas composition with in non-perforated ‘Decco’ and ‘Zoe’ liners and to a slight extent inside micro-perforated Xtend$^{®}$ liners (Figure 4.7). Non-perorated liners provide the barrier that restricts movement of gases across packaging walls. However, there was no change in gas composition of the atmosphere inside the 2 mm macro-perforated and 4 mm macro-perforated HDPE liners. For fruit packed non-perforated ‘Decco’ and ‘Zoe’ liners, O_2 composition inside the liners decreased from 21.4 to 15.9 and 15.6 % respectively, while CO_2 composition increased from 0.0 to 2.2 and 2.4 % respectively, after 5 days of cold storage. At 28 days of cold storage, CO_2 composition further increased to 3.1 % and 4.0 %, inside non-perforated ‘Decco’ and ‘Zoe’ liners, respectively. After 28 days, gas composition inside non-perforated liners remained more stable. Mphahlele *et al*. (2016) observed a more stable O_2 concentration inside polyliners after a month of storing pomegranate (cv. ‘Wonderful’) at 7 °C. However, a more steady decrease in O_2 and increase in CO_2 concentrations inside different MAP liners was observed for other pomegranate cultivars (‘Hicaznar’ and ‘Hicrannar’) stored at 6 °C (Selcuk & Erkan, 2014; Selcuk & Erkan, 2015). Selcuk & Erkan (2014) reported an increase in CO_2 from 0.0 to 3.9 and 2.5 % for pomegranate packed in MAP1 and MAP2 liners, respectively, after 20 days of storage at 6 °C.

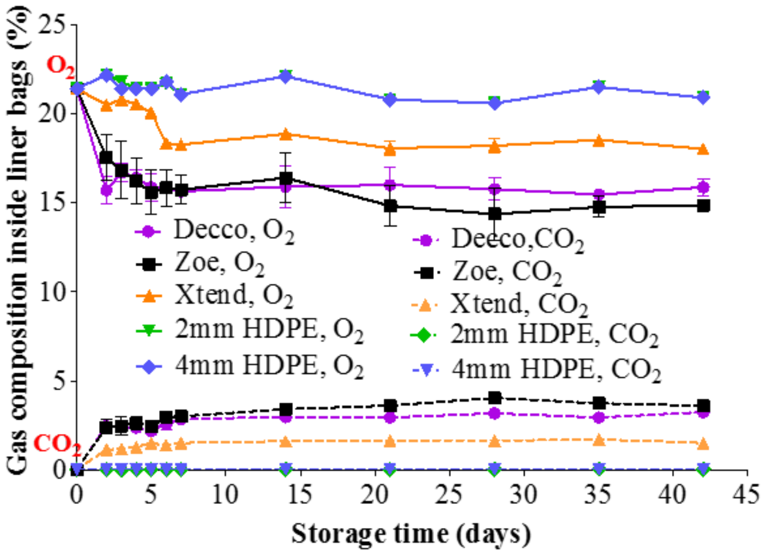


Figure 4.7 Gas composition inside plastic liners packed with pomegranate fruit (cv. Wonderful) stored at 5 °C and 90 % RH.

4.3.1.2 Water vapour transmission rate

The rate at which a plastic liner is able to allow moisture across its wall is important in controlling humidity within the bag and around the fruit, and hence reducing condensation and associated risks of fruit decay during prolonged storage (Almenar *et al*., 2007; Mistriotis *et al*., 2011). Water vapour transmission rate (WVTR) is dependent on liner permeability and prevailing storage temperatures and humidity differences inside and outside the plastic bags (Dirim *et al*., 2004; Mastromatteo *et al*., 2012; Hussein, 2014; Opara *et al*., 2015). Generally, for all treatments WVTR decreased with time and then became more stable after about 15 days. Water vapour transmission rate was higher at 20 ^{o}C and 65 ± 5 % RH than at 5 ^{o}C and 95 % RH (Figures 4.8 and 4.9). The micro-perforated Xtend® liner exceptionally had a higher WVTR of 72.2 7 g/m^2.day and 78.7 g/m^2.day at 5 ^{o}C and 20 ^{o}C, respectively. There was no difference in WVTR across all non-perforated films, irrespective of the type of plastic material and temperature of storage.

Perforations improved the WVTR of the HDPE films. The presence of one 4 mm diameter perforation improved ventilation area of the HDPE film by 2.56 % compared to 0.64 % by one 2 mm diameter perforation. At 20 ^{o} C, the HDPE film with one 4 mm diameter perforation had 66.6 % and 44.6 % faster WVTR compared to micro-perforated Xtend® film and HDPE film with one 2 mm diameter perforation, respectively (Figure 4.10). Therefore, the size of perforation plays a significant role in moisture transmission and controlling condensation within bags. Dirim *et al*. (2004) reported a good relationship between film perforation area and WVTR at different temperature and RH conditions. Similar to our results, Opara *et al*. (2015) observed increased WVTR with increased temperature, across biodegradable and synthetic polyfilms. The authors reported that increasing the number of perforation increased WVTR more than increasing storage temperature. Studies on water permeability across polypropyrene films showed increasing WVTR with increasing perforation diameter (Mastromatteo *et al*., 2012).

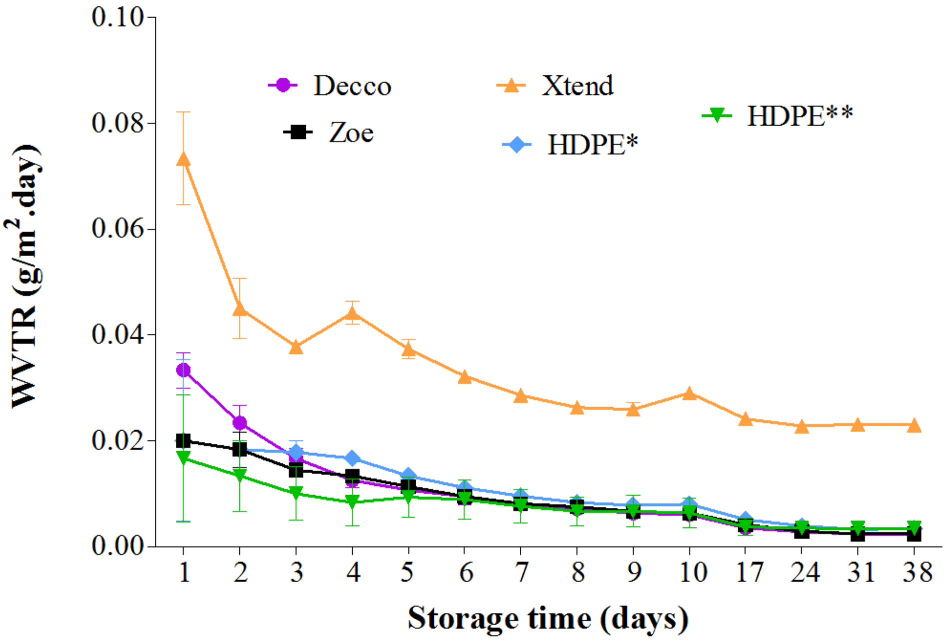


Figure 4.8 Water vapour transmission rate (WVTR) across plastic liner films, under controlled environment of 5 °C and 90 % RH. The non-perforated film section of the 2 mm HDPE (*) and 4 mm HDPE (**) liners were used.

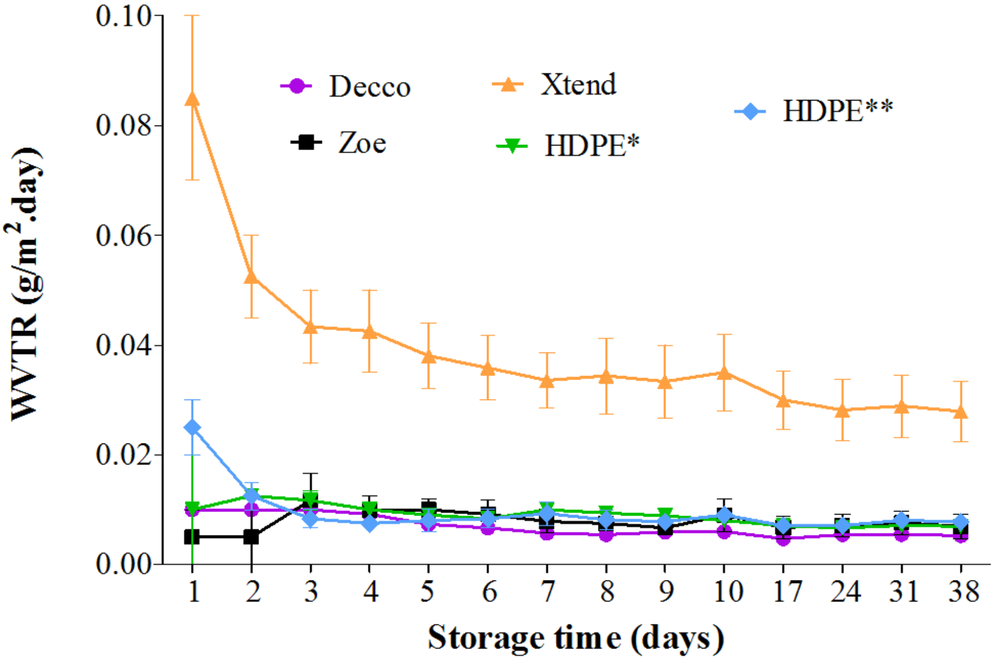


Figure 4.9 Water vapour transmission rate across plastic liner walls under controlled environment of 20 °C and 65 % RH. The non-perforated film section of the 2 mm HDPE (*) and 4 mm HDPE (**) liners were used.

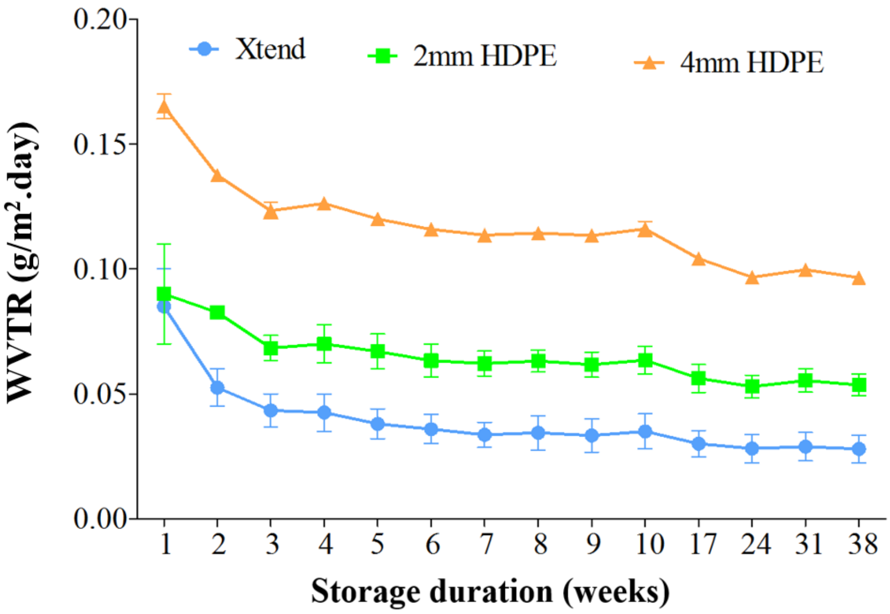


Figure 4.10 Effect of perforation on water vapour transmission rate (WVTR) under controlled environment of 20 °C and 90 % RH.

4.3.1.3 Moisture condensation dynamics

One-day condensation characteristics

The barrier effect of the liners permits them to retain a high relative humidity around the fruit (Ngcobo *et al.*, 2013) resulting in moisture condensation. Generally, the rate of one-day condensate build-up was higher in non-perforated liner treatments than in perforated liner treatments (Table 4.1). Perforations improve vapour transmission capability of the liners, minimizing vapour condensation inside MAP liners (Ben-Yehoshua *et al.*, 1988). One-day condensate build-up was high in 2 mm macro-perforated HDPE liners probably because of low perforation area (0.022 %). However, one-day condensate build-up was lowest in micro-perforated Xtend® liners and in 4 mm macro-perforated HDPE liners because of their high perforation area. Similarly, a higher one-day condensation severity score was observed in non-perforated liners than in perforated liners. One-day condensation severity was such that non-perforated 'Decco' > non-perforated 'Zoe' > 2 mm macro-perforated HDPE > 4 mm macro-perforated HDPE > micro-perforated Xtend® liners (Table 4.2). A difference in the general characteristics (size and distribution) of condensate droplets formed within the different liner bags was observed (Table 4.2).

Table 4.1 Rate of moisture condensation and corresponding weight loss for pomegranate inside plastic liner bags, at 5 °C and 90 % RH

Treatment	**Weight loss (g/day)**	**Condensation rate** (g/m^2.day)
Xtend	5.55	2.3232
Decco	4.267	3.3702
Zoe	3.463	2.8483
2mm HDPE	5.497	3.4948
4mm HDPE	6.813	2.4842

Table 4.2 Condensate characterisation inside plastic liner bags for pomegranate fruit stored at 5 °C and 90 % RH

Treatment	**Condensation score (0-10)***	**Condensate characteristics**
Xtend	3.470	Large droplets. Condensate entirely on the inside-top wall of the liner. Droplets uniformly distributed on top wall. Very little condensate in the bottom corner. No condensation on fruits.
Decco	5.667	Medium droplets. Condensate on both the top and side walls within the liner. Droplets uniformly distributed on the walls Visible condensate droplets on the fruits.
Zoe	5.333	Medium to large droplets. Condensate on both the top and side walls within the liner. Droplets non-uniformly distributed, creating a patch like pattern Visible condensate droplets on the fruits.
2 mm HDPE	4.033	Very tinny/misty droplets on top of the bag. No condensation on the fruit and immediate area around perforations Uniformly distributed
4 mm HDPE	3.500	Very tinny/misty droplets on top of the bag. No condensation on the fruit and immediate area around perforations Uniformly distributed

* Condensation was scored using 0-10 score scale (where 0 = none; 1-2 = trace; 3-4 = slight; 5-6 = moderate; 7-8 = severe; 9-10 = extremely severe).

Condensation behaviour over prolonged period

Condensate behaviour over time gives an insight about water vapour transmission properties of the liners. A lower rate of condensation in the perforated liners suggests a faster moisture transmission rate across the walls of the liners, hence delayed build-up of humidity within the bags compared to non-perforated liner treatments. Severity of condensate within the bags decreased with time (Figure 4.11). The decrease in observable condensate was slowest in non-perforated liners compared to perforated liners. The rate at which condensate was decreasing was lowest in non-perforated 'Zoe' liners, followed by non-perforated 'Decco' liners. Condensate reduction rate was highest in micro-perforated Xtend® liners, followed by 4 mm macro-perforated HDPE and 2 mm macro-perforated HDPE liners, respectively. This can be attributed to a higher water vapour transmission rate across the micro-perforated liner compared to the rest of the liners as explained in section 4.3.1.2. After 3 days of monitoring, condensation severity was in traces for micro-perforated Xtend® and 4 mm macro-perforated HDPE liners. By the end of 7 days of condensate monitoring, the micro-perforated Xtend® and macro-perforated 4 mm HDPE liners retained none of the condensate while macro-perforated 2 mm HDPE, non-perforated 'Zoe' and 'Decco' liners retained 10.2, 33.7 and 29.8 %, respectively (Figure 4.12). In another study, a particular MAP liner (Xtend®) was reported to eradicate vapour condensation in pomegranate fruit because of its high water vapour transmission compared to polypropylene bags which showed progressive moisture accumulation (Kumar *et al*., 2013).

Condensation and fruit mass loss

The liner treatments with a lower rate of condensate reduction (high condensate retention) had a lower rate of fruit weight loss while treatments with a higher condensate reduction had a higher rate of fruit weight loss. Fruit in non-perforated liner treatments had a lower rate of weight loss than fruit in perforated liners during the 7 days of condensate monitoring (Figure 4.13). Fruit weight loss is commonly as a result of moisture loss, while condensation results from the moisture lost by the fruit. In non-perforated 'Decco' and 'Zoe' liners, 79.6 and 84.4 % of fruit moisture loss per day was retained as condensate compared to 42.1, 63.9, and 36.4 % for micro-perforated Xtend®, 2 mm macro-perforated and 4 mm macro-perforated HDPE liners, respectively (Figure 4.12).

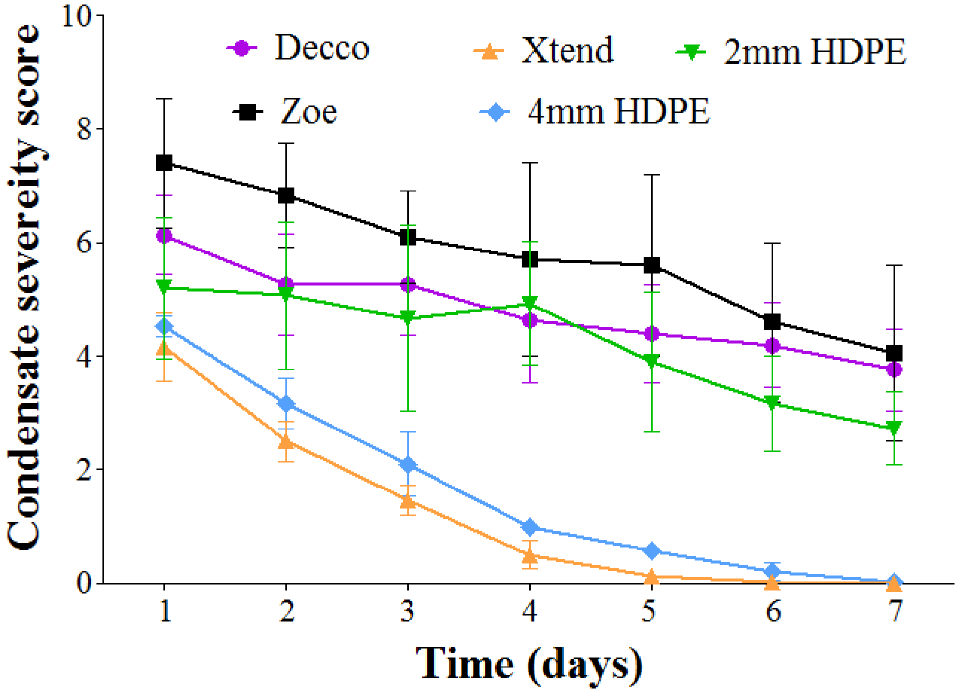


Figure 4.11 Variation of condensate inside liner bags, as depicted by 0-10 score scale (where 0 = none; 1-2 = trace; 3-4 = slight; 5-6 = moderate; 7-8 = severe; 9-10 = extremely severe). Pomegranate (cv. Wonderful) stored at 5 ° C and 90 % RH.

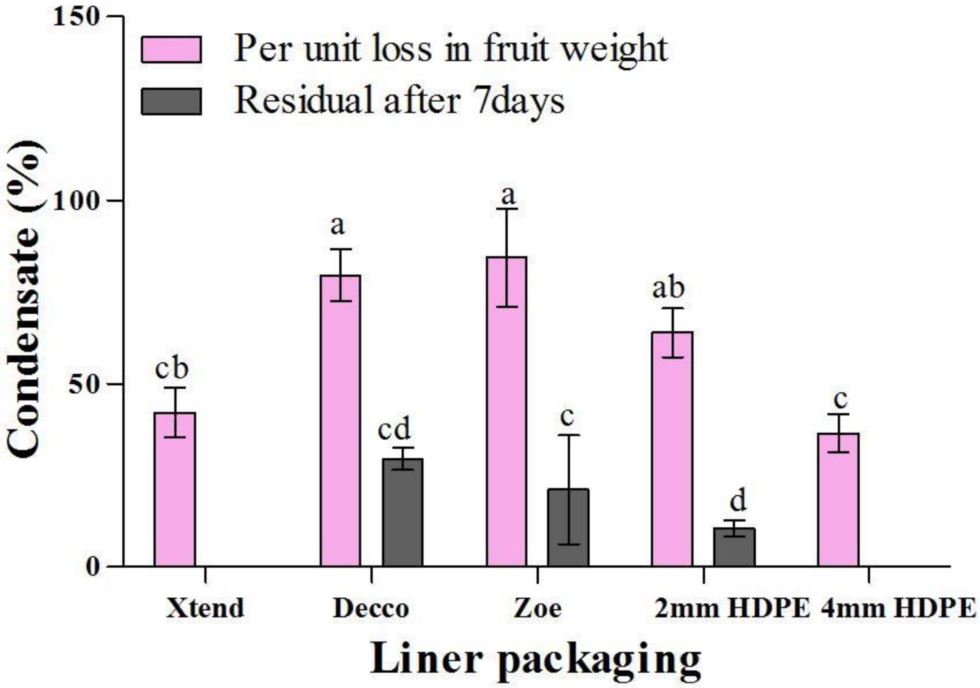


Figure 4.12 Condensate within liner bags with respect to weight lost from pomegranate (cv. Wonderful) stored at 5 ° C and 90 % RH for 1 day and condensate retained within plastic bags after a period of 7 days at 5 ° C and 90 % RH. Histograms columns with different letters are significantly different ($P < 0.05$). Vertical bars represent standard error (SE).

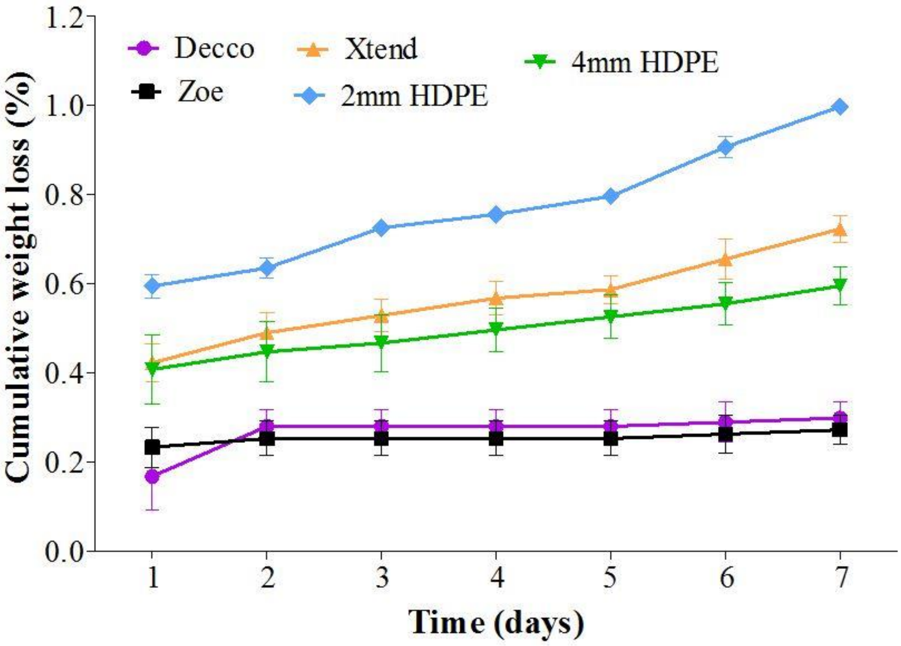


Figure 4.13 Cumulative percentage loss in weight during condensation variation within liner bags. Pomegranate (cv. Wonderful) stored at 5 °C and 90 % RH

4.3.2 Weight loss, lineal size loss and shrivel

4.3.2.1 Fruit weight loss

Moisture loss is the major contributor to weight loss of harvested fruit during postharvest handling. Other physiological activities like respiration can contribute to mass loss through the utilization of fruit contents like the carbohydrates in generating energy to support life processes of the fruit (Kader *et al*., 1984; Waelti, 2010). During storage, fruit packed with no-liner lost more weight than fruit packed in liners. At the end of 12 weeks of cold storage, the no-liner packed fruit lost 15.6 ± 0.3 % of initial weight (Figure 4.14). However, fruit packed in non-perforated 'Decco' and 'Zoe' liners lost only 0.79 and 0.82 %. Fruit packed in micro-perforated Xtend® liners lost 4.17 %, compared to 2.44 and 4.17 % by fruit packed in 2 mm macro-perforated HDPE and 4 mm macro-perforated HDPE liners, respectively. Non-perforated ('Decco' and 'Zoe') liners minimized fruit weight loss by 94.0 % compared to Xtend® micro-perforated (73.2 %), 2 mm macro-perforated HDPE (84.3 %) and 4 mm macro-perforated HDPE (62.5 %) liners, respectively. Packing fruit with no-liner for 12 weeks would have costed the pomegranate industry of South Africa 2.3 million US dollars at the export market in Europe, as a result of excessive weight loss (Table 4.3). However, packing fruit in non-perforated and perforated liners would have minimised financial loss due to fruit weight loss, to less than 610 thousand US dollars. Weight loss increased with increasing ventilation area of the liners, as observed in kiwifruit (Wiley *et al*., 1999). The impact of liners on weight loss can be attributed to the fact that liners act as barrier to the moisture exchange between the immediate environment of the fruit inside liners and the outside environment. A high RH around the fruit minimizes moisture loss from the fruit (Thompson *et al*., 2008). Liners maintain a high RH around the fruit, reducing the difference in vapour pressure inside the skin surface and immediate surrounding, hence reducing moisture diffusion (Ngcobo *et al*., 2013). Similar to our results, packing pomegranate (cv. Hicrannar) in MAP liners minimized fruit weight loss to 1.5 and 4.4 % compared to 17.2 % for fruit packed with no-liner, after 120 days of storage at 6 ^{o}C (Selcuk & Erkan, 2014). Al-Mughrabi *et al.* (1995) observed 18.3 % average weight loss for pomegranate fruit ('Taeifi', 'Banati' and 'Manfaloti' cultivars) packed in plastic crates only (without liners) for 6 weeks at 5 ° C. Storing pomegranate (cv. Wonderful) fruit in MAP liners and shrink wraps maintained a weight loss less than 2 % throughout storage period of 4 months, compared to 16.5 % for fruit packed with no-liner after 3 months of storage at 7 ^{o} C (Mphahlele *et al*., 2016). Mukama (2015) reported that pomegranates packed in ventilated cartons without liners had a 17.5 % more moisture loss than fruit packed in liners.

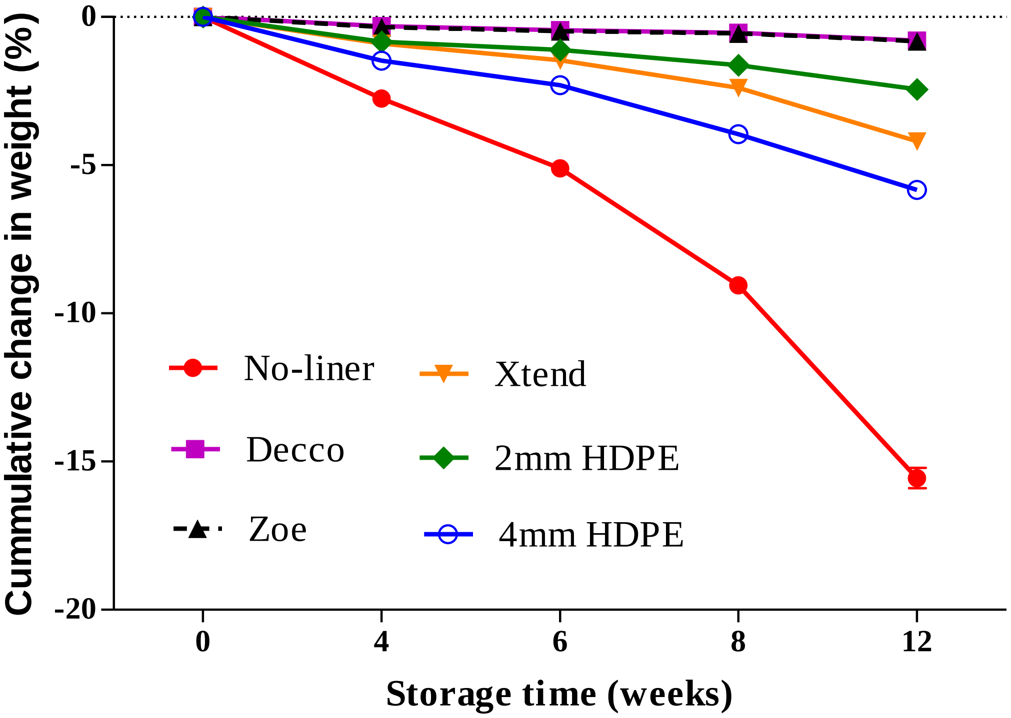


Figure 4.14 Percentage cumulative change in weight during prolonged cold storage of pomegranate fruit (cv. Wonderful) at 5 ^{o}C and 90 % RH

Table 4.3 Potential financial loss (risk) associated with weight loss in export fruit packed in different liner bags after 12 weeks of storage at 5 °C and 90 % RH

		Per kg		Total exports		Total production	
Treatment	**Weight loss (%)**	**(USD)**	**(ZAR)**	**(1,000) USD**	**(1,000) ZAR**	**(1,000) USD**	**(1,000) ZAR**
No-liner	15.6	0.546	7.753	2,278	32,350	5,063	71,809
Decco	0.79	0.028	0.393	117	1,640	260	3,644
Zoe	0.82	0.029	0.408	121	1,702	269	3,783
Xtend	4.17	0.146	2.072	609	8,646	1,354	19,213
2mm HDPE	2.44	0.085	1.213	355	5,061	788	11,248
4mm HDPE	4.17	0.146	2.072	609	8,646	1,354	19,213

European Union market price per kg; USD3.5 / ZAR49.7; POMASA, 2015; South African exports 4172643kg and total production 9272539 kg.

4.3.2.2 Contribution of arils to fruit weight loss

The percentage of arils by weight generally increased with storage duration for fruit packed with no-liner, while aril percentage decreased in fruit packed with liners (Figure 4.15). This can be attributed to the higher loss of moisture from the peel of the no-liner packed fruit compared to fruit packed with liners (section 4.3.2.5). The non-perforated liners minimized the loss in aril mass more than the perforated liners. At the end of 12 weeks of cold storage, the percentage of arils in the fruit had increased by 2.9 % for no-liner treatment. On the other hand, the percentage of arils decreased by 2.5 % and 1.5 % for fruit packed with non-perforated 'Decco' and 'Zoe' liners, respectively. In the micro-perforated Xtend® liners, the percentage of arils reduced by 2.5 % compared to 2.2 and 3.0 % for fruit packed with 2 mm macro-perforated and 4 mm macro-perforated HDPE liners, respectively. Results by Al-Mughrabi *et al.* (1995) on different pomegranate cultivars stored in plastic boxes at different temperatures showed an increase in the percentage fruit pulp in 4 weeks followed by a decrease at 8 weeks of storage. Similarly to our results, these finding corresponded with a decrease in percentage rind (peel) at 4 weeks followed by an increase at 8 weeks.

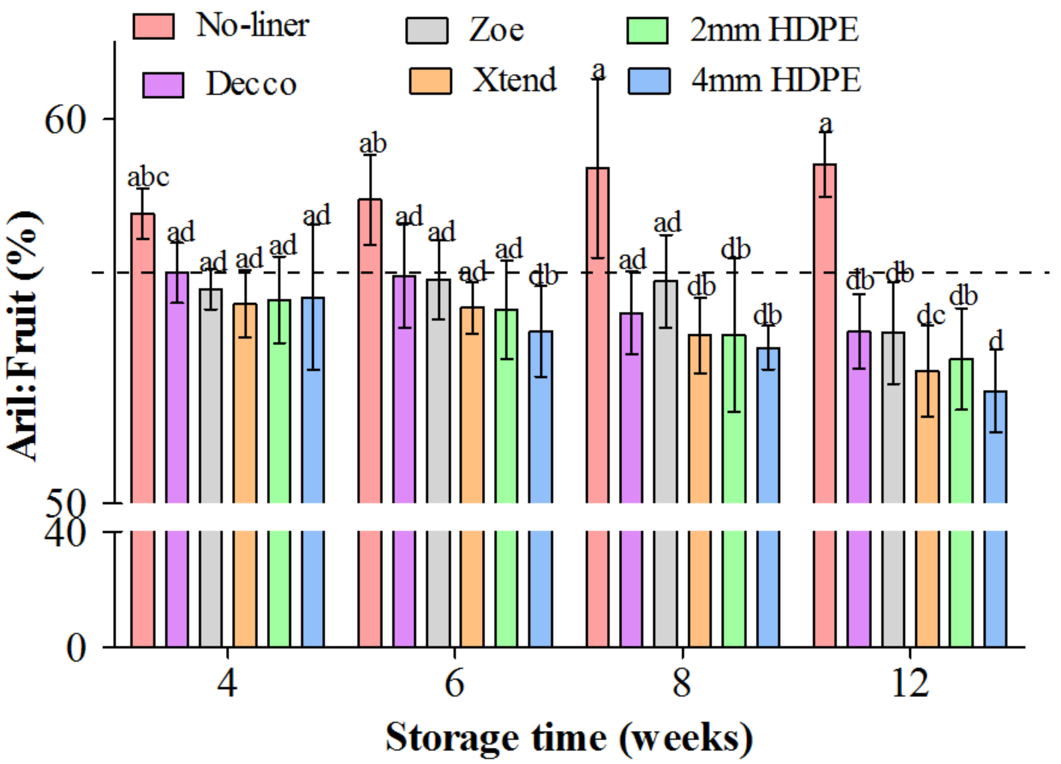


Figure 4.15 Change in aril proportion for pomegranate fruit stored at 5 °C and 90 % RH

4.3.2.3 Changes in juice yield

The percentage of juice to fruit mass and juice to aril mass progressively decreased with storage time. The decrease in juice to aril percentage was highest in no-liner packed fruit, followed by fruit packed with perforated liners and lowest in fruit packed with non-perorated liners (Figure 4.16A). At 12 weeks of cold storage, the percentage of juice to arils mass reduced by 6.9 % in the no-liner packaging treatment compared to 2.9 and 2.5 % in non-perforated 'Decco' and 'Zoe' liners, respectively. Percentage of juice to aril decreased to 4.1 % in macro-perforated Xtend® liner, 3.0 and 4.3 % in 2 mm macro-perforated and 4 mm macro-perforated HDPE liners, respectively. However, the decrease in percentage juice to fruit mass was generally higher in no-liner treatment at 8 and 12 weeks of cold storage than in perforated liner treatments (Figure 4.16B). This is probably due to a higher moisture loss from the no-liner fruit peels and other membranes surrounding the arils, compared to the moisture loss from the arils. Al-Mughrabi *et al.* (1995) studied the quality changes of different pomegranate cultivars conventionally stored in plastic boxes at different temperatures and found an increase in the percentage of juice to fruit at 4 weeks followed by a decrease at 8 weeks of storage. Furthermore, the percentage of juice to fruit pulp increased throughout storage for some cultivars.

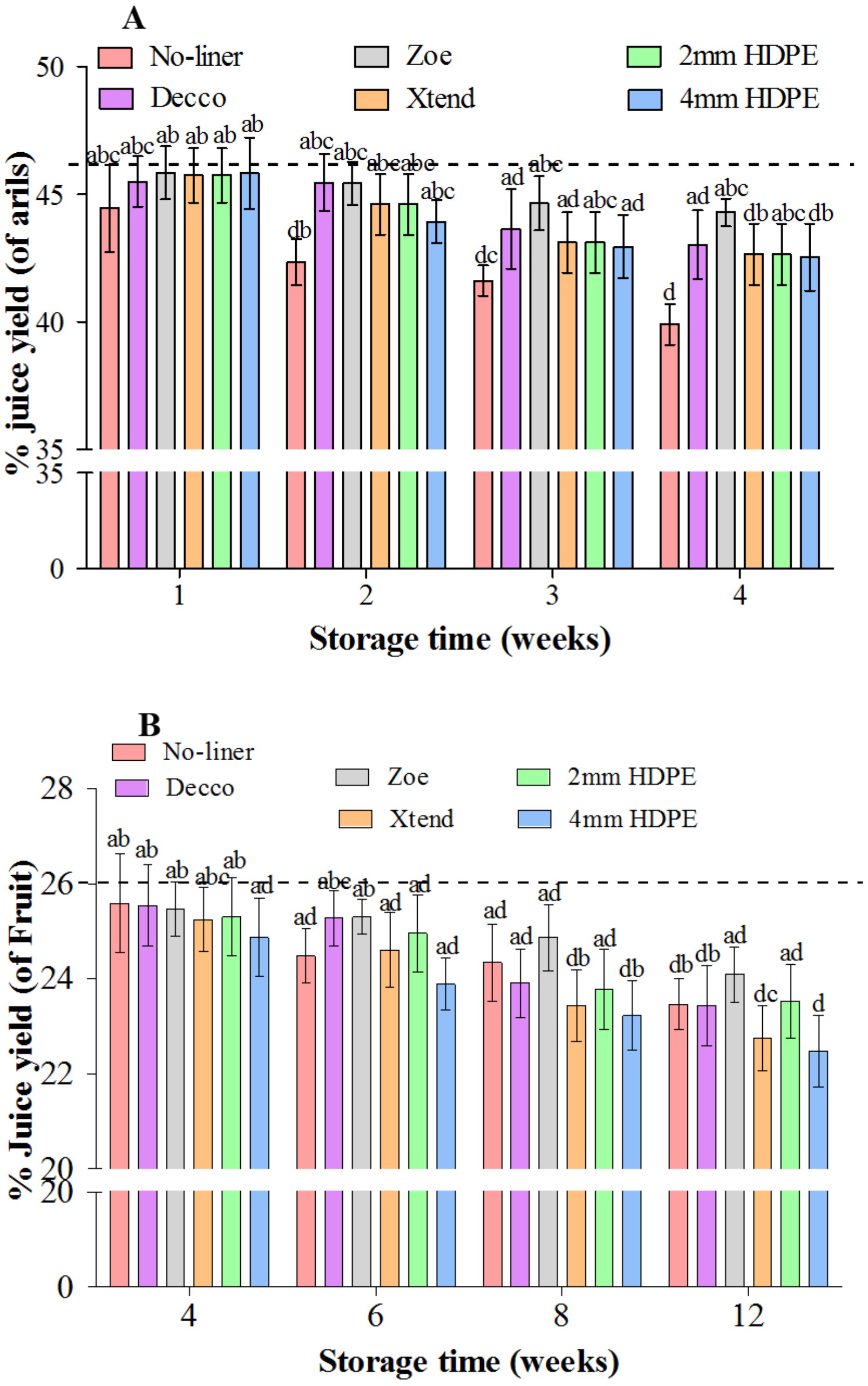


Figure 4.16 (A and B) Change in juice yield for pomegranate fruit stored at 5 °C and 90 % RH

4.3.2.4 Fruit lineal size

The susceptibility of pomegranate fruit to weight loss is attributed to free water movement across the porous peel (Elyatem & Kader, 1984). The loss in moisture and weight leads to loss in fruit length, diameter, fruit circumference and sphericity which may lead to shrivelling, shrinkage and loss in visual appeal. Generally, all liner treatments minimized loss in fruit length, diameter and circumference compared to the no-liner treatment throughout the storage period. The non-perforated 'Decco' and 'Zoe' liners were significantly better in minimizing loss in fruit length, diameter and circumference compared to micro-perforated Xtend®, 2 and 4 mm macro-perforated HDPE liners (Table 4.4).

At the end of the 12 week of cold storage, fruit in no-liner lost 8.6 % of the initial fruit length, while fruit packed in non-perforated 'Decco' and 'Zoe' liners lost 1.2 % and 1.0 % in fruit length, respectively. Fruit in micro-perforated Xtend® liners lost 2.7 % of initial fruit length compared with 3.4 and 5.1 % for fruit packed in 2 and 4 mm macro-perforated HDPE liners, respectively. A similar pattern was observed for loss in fruit diameter, where fruit packed with no-liner lost 5.4 % compared to 1.1 and 0.8 % for fruit packed with non-perforated 'Decco' and 'Zoe' liners, respectively. Micro-perforated Xtend®, 2 mm macro-perforated HDPE and 4 mm macro-perforated HDPE liners minimized loss in fruit diameter to 2.2, 2.1 and 3.7 %, respectively. A reduction in fruit circumference is a direct indicator of fruit shrinkage. After 12 weeks of cold storage, fruit packed with no-liner lost 4.1 % of their initial circumference, compared to 1.0 % and 0.8 % for fruit packed in non-perforated 'Decco' and 'Zoe' liners, respectively. Perforated liners minimized the loss in fruit circumference to about half the loss in no-liner. Fruit packed with micro-perforated Xtend® liners lost 2.3 % of their initial circumference compared to 1.8 and 2.8 % for fruit packed in 2 and 4 mm macro-perforated HDPE liners, respectively.

Generally, the loss was more in fruit length than in fruit diameter. Shrivelling was more concentrated on the base of the fruit than on the sides. Quite similar results observed by Al-Mughrabi *et al.* (1995) on different pomegranate cultivars conventionally stored in plastic boxes at storage temperatures of 5 °C, 10 °C and ambient temperature for 8 weeks. The authors observed that the loss in fruit length and diameter is influenced by storage time, temperature and cultivar. In their study, the cv. 'Manfaloti' with relatively lower fruit weight loss, also registered lower loss in fruit diameter and length, as compared to cv. 'Banati', respectively.

Table 4.4 Effect of plastic liner treatment on percentage cumulative loss in fruit length, diameter and circumference of pomegranate (cv. Wonderful) fruit stored at 5 °C and 90 % RH

		Cumulative loss (%)		
Time	**Treatment**	**Length**	**Diameter**	**Circumference**
4 weeks	No-liner	2.126 ± 0.068^{def}	1.668 ± 0.169^{def}	1.066 ± 0.184^{jg}
	Decco	0.635 ± 0.128^{ih}	0.339 ± 0.063^{jk}	0.378 ± 0.090^{l}
	Zoe	0.453 ± 0.068^{i}	0.230 ± 0.058^{k}	0.355 ± 0.074^{l}
	Xtend	1.396 ± 0.372^{geh}	0.757 ± 0.173^{jkh}	0.810 ± 0.072^{jl}
	2mm HDPE	0.688 ± 0.181^{gi}	0.843 ± 0.070^{jh}	0.545 ± 0.087^{lk}
	4mm HDPE	1.520 ± 0.208^{ge}	1.667 ± 0.157^{def}	0.860 ± 0.122^{jli}
6 weeks	No-liner	3.851 ± 0.130^{c}	3.011 ± 0.123^{c}	2.100 ± 0.075^{cd}
	Decco	1.114 ± 0.30^{gi4}	0.649 ± 0.181^{jki}	0.706 ± 0.114^{jl}
	Zoe	0.616 ± 0.073^{ih}	0.393 ± 0.089^{jk}	0.680 ± 0.139^{jl}
	Xtend	2.199 ± 0.635^{de}	1.194 ± 0.217^{gfhi}	1.422 ± 0.155^{fegh}
	2mm HDPE	1.503 ± 0.079^{ge}	1.297 ± 0.104^{gfh}	0.948 ± 0.193^{jhk}
	4mm HDPE	2.787 ± 0.118^{d}	2.036 ± 0.107^{de}	1.503 ± 0.119^{feg}
8 weeks	No-liner	5.385 ± 0.120^{b}	3.735 ± 0.176^{b}	2.933 ± 0.156^{b}
	Decco	1.336 ± 0.339^{gfh}	0.844 ± 0.145^{jh}	0.864 ± 0.105^{jli}
	Zoe	0.778 ± 0.055^{gi}	0.496 ± 0.166^{jk}	0.844 ± 0.162^{jli}
	Xtend	2.808 ± 0.147^{d}	1.582 ± 0.250^{dg}	1.882 ± 0.139^{cde}
	2mm HDPE	2.058 ± 0.057^{def}	1.50 ± 0.120^{ge}	1.342 ± 0.238^{fghi}
	4mm HDPE	3.561 ± 0.144^{c}	2.740 ± 0.104^{c}	2.074 ± 0.150^{cd}
12 weeks	No-liner	7.409 ± 0.137^{a}	5.270 ± 0.084^{a}	4.097 ± 0.166^{a}
	Decco	1.338 ± .318^{gfh}	1.091 ± 0.167^{ghi}	1.012 ± 0.095^{jhk}
	Zoe	0.979 ± 0.082^{gi}	0.823 ± 0.177^{jh}	0.889 ± 0.012^{jik}
	Xtend	3.868 ± 0.489^{c}	2.639 ± 0.467^{c}	2.340 ± 0.036^{c}
	2mm HDPE	2.671 ± 0.104^{d}	2.091 ± 0.112^{d}	1.726 ± 0.129^{fd}
	4mm HDPE	4.928 ± 0.241^{b}	3.713 ± 0.101^{b}	2.831 ± 0.031^{b}

Results presented as mean ± standard error (SE). Different letter(s) on column per liner treatment indicate statistically significant differences ($p \leq 0.05$) according to Duncan's multiple range test.

4.3.2.5 Peel thickness

The dynamics of moisture loss of fruit may influence each of the fruit fractions differently. The porous nature and position of the pomegranate fruit skin makes it so prone to moisture loss because it comes into direct contact with the surrounding. Moisture loss in pomegranate fruit is primarily from the peel resulting in a reduction in peel thickness (Arendse *et al*., 2014; Mukama, 2015). The greatest loss in peel thickness was observed in fruit packed with no-liner. Fruit packed in non-perforated liners retained more peel thickness than fruit packed in perforated liners (Figure 4.17). After 12 weeks of cold storage, fruit packed with no-liner lost 41.8 % of the initial peel thickness. However, non-perforated 'Decco' and 'Zoe' liners minimized the loss in fruit peel thickness to 14.8 and 13.2 %, respectively. Fruit lost 26.8 % peel thickness when packed in micro-perforated Xtend® liners, 22.0 and 26.7 % in 2 mm macro-perforated and 4 mm macro-perforated HDPE liners, respectively. Similarly, Arendse *et al*. (2014) reported decrease in peel thickness with storage time of pomegranate (cv. Wonderful) packed in conventional corrugated boxes and stored at different temperatures (5, 7.5, 10 and 21 ° C). The authors attributed the drastic decrease in peel thickness at 21 ^{o}C to low RH and high temperature. The thicker peel of fruit packed with non-perforated liners can be attributed to higher RH inside bags, compared to fruit packed with perforated liners.

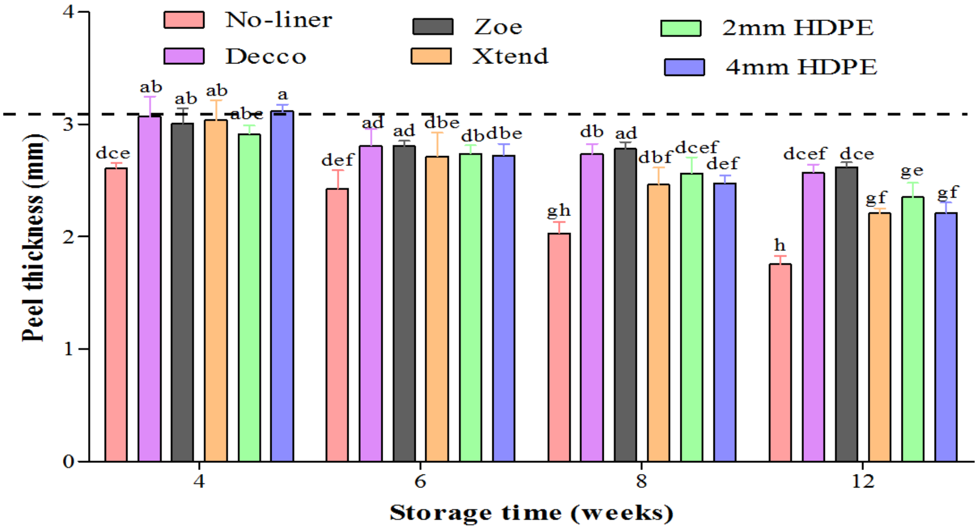


Figure 4.17 Peel thickness of pomegranate (cv. Wonderful) fruit stored at 5 ^{o}C and 90 % RH

4.3.2.6 Fruit shriveling

The effect of liner packaging on fruit shrivelling is summarised in Figures 4.18A and 4.18B. Fruit shrivelling results from moisture loss and subsequent loss in cell turgor pressure (Paull, 1999). In pomegranates, shrivelling is expected after a 5 % loss in fruit weight (Kader *et al*., 1984). Fruit shrivelling was evident at 6 weeks of cold storage after 5.1 % loss in weight for fruit packed with no-liner, with 86.1 % incidences of shrivelling (Figure 4.18 A). At 8 weeks of cold storage, shrivel incidence increased to 100 % for fruit packed with no-liner. However, there was no incidences of fruit shrivelling observed for fruit packed with non-perforated 'Decco' and 'Zoe' liners throughout 12 weeks of storage. Slight shrivelling was observed especially at the crown area for fruit packed with micro-perforated Xtend® and 2 mm macro-perforated HDPE liners after 12 weeks of storage, with a shrivel incidence of 83.3 and 85.7 %, respectively. However, shrivelling started at 8 weeks for fruit packed with 4 mm macro-perforated HDPE liners with an incidence of 72.7 %.

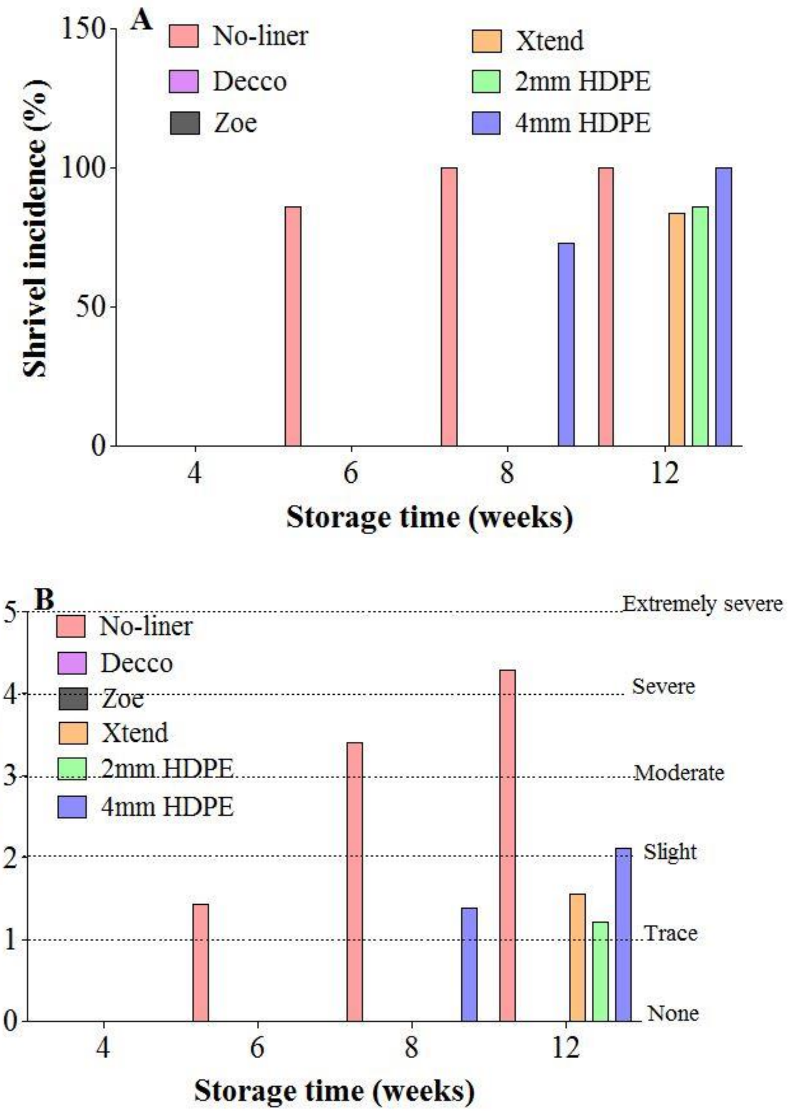


Figure 4.18 Percentage of total shrivelled fruit (shrivel incidence) (A) and shrivel index (incidence) (B) observed on pomegranate fruit stored for 12 weeks at 5 °C and 90 % RH

The severity of fruit shrivelling (shrivel index) increased with storage time (Figure 4.18 B). At 12 weeks of storage, fruit packed with no-liner were severely shrivelled with a shrivelling index of 4.3 (86.0 %) compared to cases of extreme shrivelling with an index of 5 (100 %). However, fruit packed with micro-perforated Xtend® and 2 mm macro-perforated HDPE liners were tracely shrivelled with shrivel index of 1.6 (31.1 %) and 1.2 (24.3 %). Fruit packed with 4 mm macro-perforated HDPE liners were slightly shrivelled, having a shrivel index of 2.1 (42.0 %). The high shrivel incidence and index in fruit packed with no-liner is attributed to excessive moisture loss during storage. Plastic liners due to their barrier ability, maintain high relative humidity around the fruit, minimizing moisture loss and subsequent shrivelling. Wiley *et al*. (1999) did not observe shrivelling in Kiwi fruit packed in non-perforated and macro-perforated liners, but reported shrivelling for fruit packed with micro-perforated liners, after 17 weeks storage at 0 ^{o}C.

4.3.3 Respiration rate

Respiration rate (RR) of pomegranates (non-climacteric fruit) was generally low and the decrease with storage period (Figure 4.19) may be attributed to senescence after harvest. Throughout the storage period, respiration rate was highest in fruit packet with no-liner, followed by fruit packed with perforated liners and lowest in fruit packed with non-perforated liners. Respiration rate for fruit packed in non-perforated liners decreased from 8.1 to about 3.3 ml CO_2 kg^{-1} h^{-1} within 6 weeks of cold storage and remained stable to the end of storage. Mphahlele *et al*. (2016) reports quite similar trend for pomegranate (cv. Wonderful) packed in MAP liners, where RR decreased within 4 weeks and stayed stable throughout 12 weeks of storage at 7 ^{o}C. The authors observed higher RR in control fruit than fruit packed with MAP at the end of 3 months. The initial respiration rate of fruit before storage, decreased by 28.4 % at the end of 12 weeks of storage for fruit packed with no-liner, compared to 61.7 and 59.3 % for fruit packed in non-perforated 'Decco' and 'Zoe' liners, respectively. Micro-perforated Xtend® and 4 mm macro-perforated HDPE liners reduced respiration rate of the fruit by 42.0 % compared to 37.0 % by 2 mm macro-perforated HDPE liners, respectively.

Other researchers also reported a decline in respiration rate with storage time for pomegranate fruit (Elyatem & Kader, 1984; Artes *et al*., 1996). Passive MAP achieved by non-perforated 'Decco' and 'Zoe' liners is probably responsible for the low respiration rate. Nanda *et al*. (2001) reported that MAP inform of shrink wrapping reduced respiration rate of pomegranate and attributed it to the ability of the films having a low permeability to gases. Furthermore, the lower RR in fruit packed with non-perforated and perforated liners compared to fruit packed with no-liner, can be attributed to alleviation of water stress from around the fruit (Dhall *et al.*, 2012).

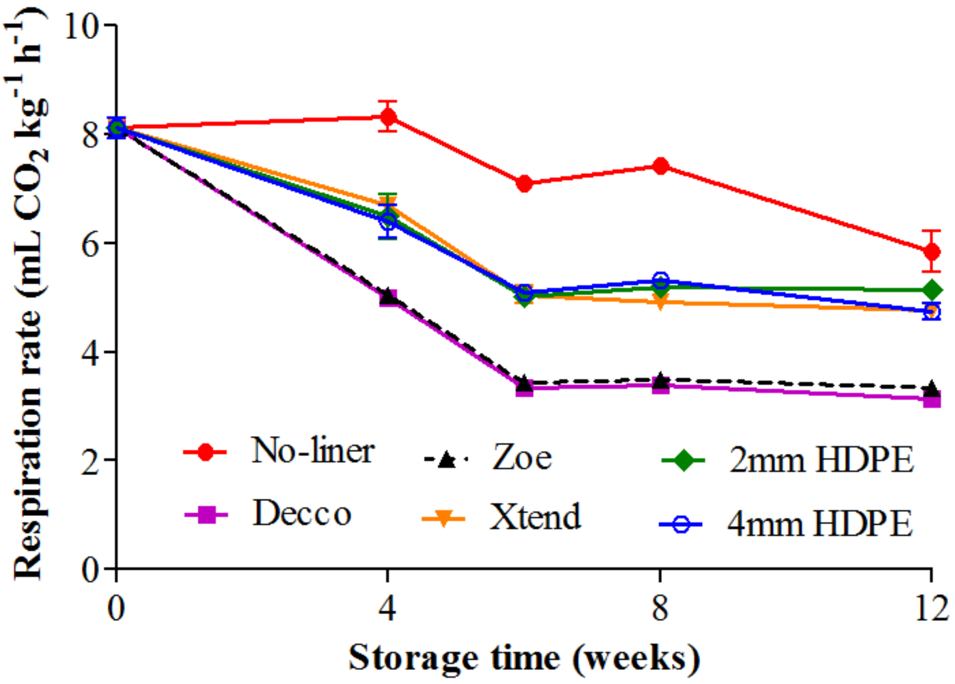


Figure 4.19 Respiration rate of pomegranate fruit determined by a closed system at 5 °C and 90 % RH

4.3.4 Textural properties

4.3.4.1 Fruit puncture resistance

The ability of harvested fruit to resist a puncturing force gives information on the structural integrity. There was a decline in fruit puncture resistance with storage time, for all treatments. The baseline (initial) fruit texture was best retained by fruit packed with non-perforated liners followed by fruit packed in perforated liners and no-liner packaging, respectively. At the end of 12 weeks of cold storage, fruit packed with no-liner lost 28.3 % of the initial whole fruit firmness (116.1 ± 2.0 N). However, packing fruit in non-perforated 'Decco' and 'Zoe' liners reduced fruit firmness by 8.0 and 6.8 %, respectively. Micro-perforated Xtend® liners minimized fruit firmness by 12.0 % compared to 15.8 and 15.5 % by 2 mm macro-perforated HDPE and 4 mm macro-perforated HDPE liners, respectively (Table 4.5). The general decline in texture with storage time can be attributed to fruit softening resulting from enzymatic disintegration of cell wall structure (Martin-Cabrejas *et al*., 1994). Similar results reported by Mansouri *et al*. (2011) and Arendese *et al*. (2014) reported declines in whole fruit firmness with storage time for different conventionally packed pomegranate fruit (cv. Hondos-e-Yalabad, Malas-e-Saveh and Wonderful) in boxes. The higher respiration rate observed in fruit packed with no-liner and macro-perforated liners may have contributed to the higher loss in fruit texture, compared to fruit packed in passively modified atmosphere by non-perforated liners. Drake *et al*. (2004) observed that 'Bartlett' pears at low temperatures of 1 °C packed in MAP liners retained more fruit firmness than pear packed under regular atmosphere. The authors reported that storing pears under controlled atmosphere retained fruit firmness throughout cold storage, irrespective of packaging treatment. Similar to our results, Kumar *et al*. (2013) reported that pomegranate (cv. 'Baghwa') packed in Xtend® MAP liners retained better and desirable firmness compared to fruit packed with polypropylene liners and with no-liner, stored at 4 °C for 120 days.

4.3.4.2 Aril firmness

Generally, aril firmness increased in fruit packed with no-liner, compared to decreasing aril firmness in fruit packed with liners (Table 4.5). The increase in aril firmness for fruit packed with no-liner could be attributed to moisture loss leading to hardening of aril tissues. The decrease in aril firmness is often associated to quality deterioration and may be due to physiological activity like respiration that bring about softening and disintegration of cell wall structure (Martin-Cabrejas *et al*., 1994; Ekrami-Rad *et al*. 2011). There was no significant difference in aril firmness for fruit packed with liners throughout the storage period. Fruit packed with non-perforated 'Decco' and 'Zoe' liners retained more aril firmness compared to fruit packed with perforated liners. At the end of 12 weeks of storage, fruit packed in either of the non-perforated ('Decco' and 'Zoe') liners lost 2.0 % of initial aril firmness (143.9 ± 1.5 N), compared to 2.8, 5.5 and 3.5 % for fruit in micro-perforated Xtend®, 2 mm and 4 mm macro-perforated HDPE liners, respectively. Liners have been reported to maintain desirable firmness in pomegranate and table grape (Kumar *et al*. 2013; Ngcobo *et al*., 2013). Similar results have been reported with the application of heat shrinkable films on pomegranate fruit (Nanda *et al*. 2001; D'Aquino *et al*. 2010).

Table 4.5 Aril firmness for pomegranate fruit packed in different liner bags for 12 weeks at 5 °C and 90 % RH.

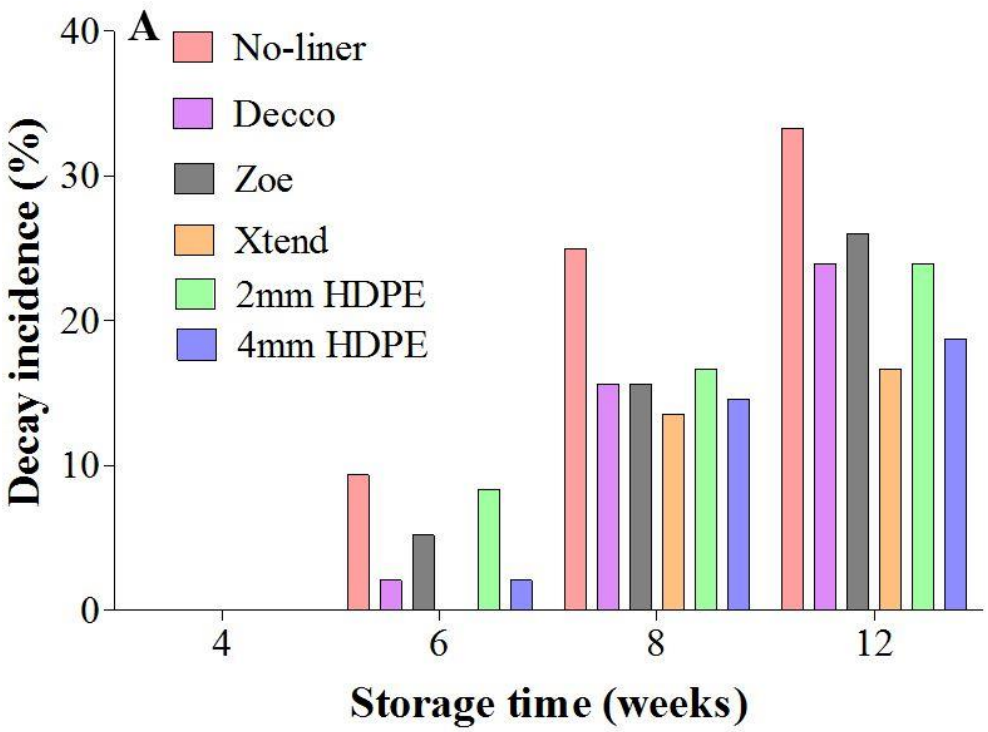
Storage time	Treatment	Whole fruit puncture resistance (N)	Aril firmness (N)
0 weeks		116.105 ± 1.960^{ab}	143.906 ± 1.512^{dce}
4 weeks	No-liner	119.657 ± 2.993^{a}	146.426 ± 1.959^{db}
	Decco	114.540 ± 2.194^{abc}	143.112 ± 2.203^{de}
	Zoe	114.998 ± 1.896^{abc}	143.386 ± 3.931^{de}
	Xtend	114.511 ± 2.455^{abcd}	142.224 ± 2.112^{df}
	2 mm HDPE	113.788 ± 2.622ab^{cd}	141.867 ± 1.687^{df}
	4 mm HDPE	114.360 ± 2.300ab^{cd}	140.865 ± 2.010^{df}
6 weeks	No-liner	104.501 ± 2.057^{hf}	150.665 ± 2.018^{ab}
	Decco	114.879 ± 1.392^{abc}	142.839 ± 2.044^{df}
	Zoe	115.002 ± 1.705^{abc}	142.975 ± 1.590^{df}
	Xtend	111.744 ± 1.337^{eb}	138.256 ± 1.981^{fe}
	2 mm HDPE	109.864 ± 2.520^{ebf}	140.064 ± 2.107^{df}
	4 mm HDPE	106.851 ± 1.611^{eh}	138.863 ± 1.946^{fe}
8 weeks	No-liner	92.676 ± 1.654^{i}	153.931 ± 2.269^{a}
	Decco	113.048 ± 1.359^{eb}	141.302 ± 1.049^{df}
	Zoe	113.894 ± 2.171^{abcg}	142.763 ± 1.513^{df}
	Xtend	109.304 ± 1.049^{ecf}	139.836 ± 1.897^{df}
	2 mm HDPE	102.506 ± 1.967^{hgi}	138.739 ± 1.247^{fe}
	4 mm HDPE	101.149 ± 2.027^{hi}	140.292 ± 1.604^{df}
12 weeks	No-liner	83.300 ± 2.603^{j}	149.817 ± 1.296^{abc}
	Decco	106.815 ± 1.155^{eh}	141.692 ± 1.338^{df}
	Zoe	108.175 ± 1.498^{edfg}	141.009 ± 1.530^{df}
	Xtend	101.386 ± 1.802^{hi}	139.8172 ± 1.161^{df}
	2 mm HDPE	97.737 ± 1.045^{ji}	135.977 ± 0.748^{f}
	4 mm HDPE	98.085 ± 1.430^{ji}	138.884 ± 1.240^{fe}

Mean values with different letters are significantly different ($p \leq 0.05$), according to Duncan's multiple range test.

4.3.5 Fruit decay

The incidence of decayed fruit increased with storage time in all treatments. Similar trend was observed in pomegranate cultivars 'Mollar de Elche' and 'Wonderful' stored at 6 °C and 7 °C, respectively (Laribi *et al.*, 2012; Mphahlele *et al.*, 2016). At the end of 12 weeks of cold storage, 35.4 % of fruit packed with no-liner were lost to visible mould. However, packing fruit in non-perforated 'Decco' and 'Zoe' liners minimized decay incidence to 24.0 and 26.0 %, respectively. Furthermore, packing fruit in micro-perforated Xtend® liners minimized fruit decay incidence to 17.7 %, compared to 24.0 and 18.5 % for fruit packed in 2 mm macro-perforated and 4 mm macro-perforated HDPE liners, respectively (Figure 4.20A). Packing fruit with no-liner for 12 weeks would have cost the pomegranate industry of South Africa about 5.2 million US dollars at the export market in Europe, as a result of fruit decay and mold (Table 4.6). However, packing fruit in non-perforated and perforated liners would have minimised financial loss due to fruit weight loss, to less than 3.8 million US dollars. Financial loss due to decay is lowest for fruit packed with micro-perforated Xtend® and macro-perforated 4 mm HDPE liners. Selcuk & Erkan (2014) reported similar results on 'Hicrannar' pomegranate stored at 6 °C for 120 days, where the no-liner control registered 40 % decay compared to 13.3 and 26.7 % for MAP liner treatments. On the contrary, Laribi *et al*. (2012) and Mphahlele *et al*. (2016) reported higher decay incidence in pomegranate (cv. 'Mollar de Elche' and 'Wonderful') packed with MAP liners than with no-liners, at the end of 12 and 20 weeks of cold storage, respectively. However, no significant difference in decay incidence between shrink wrapped and non-wrapped pomegranate (cv. 'Primosole) at 10 weeks of cold storage was reported by D'Aquino *et al*. (2010). The higher decay incidence of fruit packed in non-perforated liners could be attributed to higher moisture condensation within liner bags and lower WVTR across film, resulting into accelerated fruit moulding compared to fruit packed in perforated liners (Figure 4.20A).

Fruit decay severity give insight on how serious was the decay on a particular fruit. The influence of packaging treatments on fruit decay severity was different from their influence on decay incidence. Fruit packed with no-liner had the highest decay severity index than fruit packed in liners. The severity (index) of decay was higher in fruit packed with perforated liners compared to fruit packed in non-perforated liners (Figure 4.20B). This could be attributed to a lower respiration rate observed in fruit packed with non-perforated 'Decco' and 'Zoe' liner compared to fruit packed in perforated liners. Selcuk & Erkan (2014) reported a no significant difference in decay index for control treatment and MAP liner treatments for pomegranate stored at 6 °C for 120 days.



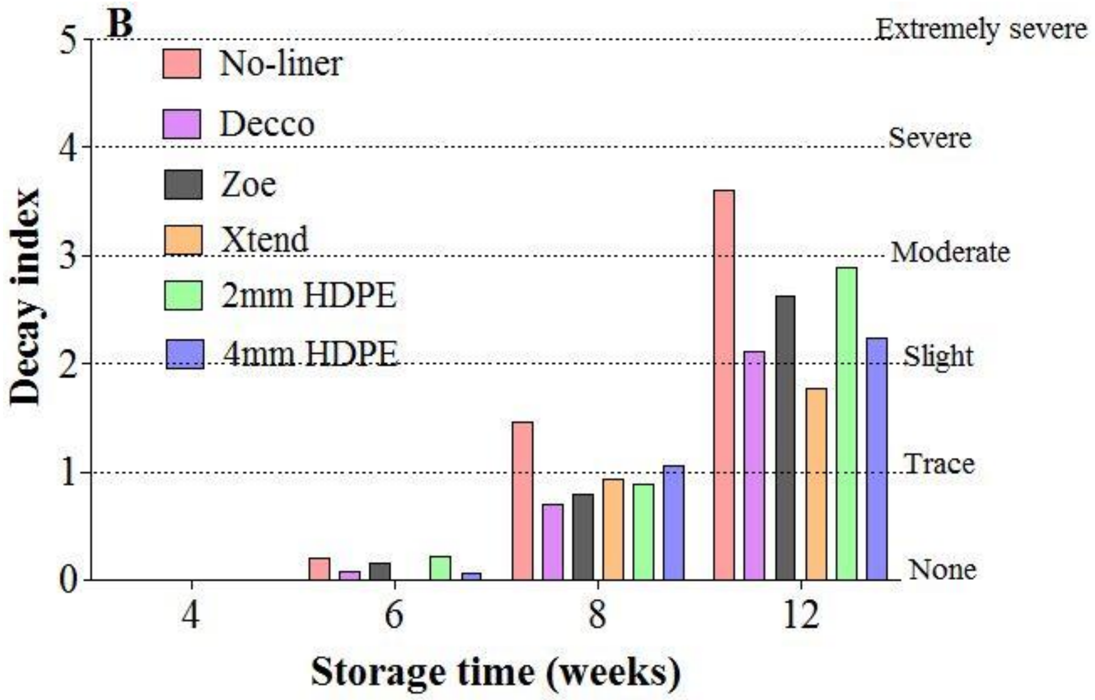


Figure 4.20 Percentage cumulative decay incidence (A) and cumulative decay index (severity) (B) on pomegranate fruit stored for 12 weeks at 5 ^{o}C and 90 % RH.

Table 4.6 Potential financial loss (risk) associated with decay incidence in export fruit packed in different liner bags after 12 weeks of storage at 5 °C

Treatment	Decay (%)	Total fruit loss (1000kg)	Financial loss 1,000 (USD)	Financial loss 1,000 (ZAR)
No-liner	35.4	1,477	5,170	73,413
Decco	24	1,001	3,505	49,771
Zoe	26	1,085	3,797	53,919
Xtend	17.7	739	2,585	36,706
2mm HDPE	24	1,001	3,505	49,771
4mm HDPE	18.5	772	2,702	38,365

European Union market price per kg; USD3.5 / ZAR49.7; POMASA, 2015; South African exports 4,173 tonnes and total production 9,273 tonnes.

4.3.6 Colour attributes

4.3.6.1 Fruit peel colour

Fruit peel colour is an important contributor to visual appeal and acceptance of pomegranate fruit by consumers. Generally, there was a progressive decline in the lightness (L*) values with storage time (Table 4.7). Fruit skin lightness was 51.7 ± 2.4 before storage, after 12 weeks of storage; fruit packed with no-liner lost 30.0 % of the lightness. This can be attributed to excessive moisture loss causing the peel to become pale. However, packing fruit with non-perforated 'Decco' and 'Zoe' liners significantly ($P \leq 0.05$) minimized the loss in skin colour lightness to 5.7 % and 3.6 %, respectively. Fruit packed with micro-perforated Xtend® lost 14.1 % compared to 15.0 % and 15.7 % for fruit packed with 2 mm macro-perforated and 4 mm macro-perforated HDPE liners, respectively. The difference in results can be attributed to differences in the ability of liners to minimise moisture loss and respiration rate. Similarly, Selcuk & Erkan (2014) reported higher skin colour lightness for pomegranate (cv. 'Hicrannar') fruit stored under MAP liners with the fruit looking brighter and fresher compared to the no liner control fruit at the end of 4 months of cold storage and additional 3 days of shelf life.

There was no difference in peel redness colour (a*) among treatments throughout the study, however at 12 weeks, fruit packed with micro-perforated Xtend®, non-perforated 'Decco' and 'Zoe' liners retained the initial skin redness colour (a*) before storage. However, Drake (2004) reported that packing pears in MAP liners preserved more of the green colour at

90 days of cold storage than did the pears under regular atmosphere at 30 days of storage. This could be attributed to the ability of liners modifying the atmosphere around the fruit thereby minimising break down of colour pigments.

Table 4.7 Impact of liners on pomegranate fruit peel colour parameters. Fruit was stored at 5 °C and 90 % RH

Time	**Treatment**	**L***	**a***	**C***
0 Weeks		51.702 ± 2.362^{a}	29.736 ± 0.339^{a}	40.723 ± 0.510^{ab}
4 Weeks	No-liner	51.394 ± 2.100^{a}	29.152 ± 0.661^{ab}	40.561 ± 0.730^{ab}
	Xtend	50.106 ± 2.363^{ab}	29.729 ± 1.560^{a}	40.737 ± 0.981^{ab}
	Decco	51.320 ± 1.674^{a}	29.848 ± 1.397^{a}	40.361 ± 0.781^{ab}
	Zoe	51.213 ± 1.999^{a}	29.677 ± 1.801^{a}	40.910 ± 0.940^{a}
	2mm HDPE	50.831 ± 2.784^{a}	29.705 ± 1.756^{a}	40.161 ± 1.71^{ab}
	4mm HDPE	51.403 ± 1.524^{a}	29.559 ± 1.077^{ab}	41.162 ± 0.697^{a}
6 Weeks	No-liner	46.224 ± 1.077^{ad}	27.098 ± 0.663^{ad}	38.050 ± 0.585^{db}
	Xtend	48.564 ± 1.717^{abc}	29.209 ± 1.607^{ab}	39.981 ± 0.950^{ab}
	Decco	49.149 ± 1.800^{abc}	28.333 ± 1.675^{abc}	39.967 ± 1.022^{ab}
	Zoe	51.073 ± 2.186^{a}	28.719 ± 0.424^{ab}	40.047 ± 0.776^{ab}
	2mm HDPE	48.991 ± 2.784^{abc}	28.953 ± 2.006^{ab}	39.739 ± 1.369^{ab}
	4mm HDPE	50.114 ± 1.095^{ab}	27.174 ± 0.520^{ad}	39.671 ± 0.496^{ab}
8 Weeks	No-liner	41.683 ± 0.54^{1d}	26.752 ± 0.760^{ad}	36.448 ± 0.556^{dec}
	Xtend	46.388 ± 0.985^{ad}	26.746 ± 0.654^{ad}	39.414 ± 0.440^{ab}
	Decco	49.129 ± 1.222^{abc}	26.329 ± 0.483^{ad}	39.446 ± 0.475^{ab}
	Zoe	49.947 ± 2.462^{ab}	27.015 ± 0.356^{ad}	39.906 ± 0.493^{ab}
	2mm HDPE	46.237 ± 1.092^{ad}	26.809 ± 0.196^{ad}	38.008 ± 1.200^{db}
	4mm HDPE	46.274 ± 0.851^{ad}	25.833 ± 0.511^{db}	38.920 ± 0.726^{abc}
12 Weeks	No-liner	36.196 ± 0.847^{e}	24.228 ± 0.478^{d}	32.900 ± 0.669^{e}
	Xtend	44.437 ± 0.582^{db}	26.427 ± 0.594^{ad}	38.535 ± 0.557^{ab}
	Decco	48.750 ± 1.188^{abc}	26.153 ± 0.488^{ad}	38.801 ± 0.468^{abc}
	Zoe	49.838 ± 0.701^{ab}	26.898 ± 0.677^{ad}	38.060 ± 0.896^{abc}
	2mm HDPE	43.947 ± 0.717^{dc}	24.913 ± 0.415^{dc}	35.429 ± 0.655^{d}
	4mm HDPE	43.584 ± 0.766d^{c}	24.466 ± 0.468^{d}	35.991 ± 0.401^{d}

Mean values with different letters are significantly different ($p \leq 0.05$), according to Duncan's multiple range test.

The effect of storage time on Chroma (C*) was only significant on fruit packed with no-liner and macro-perforated HDPE liners. At 12 weeks of cold storage, fruit packed with non-perforated 'Decco', non-perforated 'Zoe' and micro-perforated Xtend® liners significantly retained the initial skin C* (colour saturation), compared fruit in other treatments. Furthermore, fruit packed with macro-perforated HDPE liners significantly retained higher C* than fruit packed with no-liner. Selcuk & Erkan (2014) reported a no significant impact of liner packaging on the chroma (C*) for 'Hicrannar' pomegranate stored for 120 days at 6^{o}C. A decrease in skin colour parameters L* and C* was observed with minimal changes for wrapped fruit compared to un-wrapped pomegranate (cv. Primosole) stored at 8 ^{o} C for 12 weeks storage (D' Aquino *et al*., 2010).

4.3.6.2 Aril colour

The colour of arils is very important especially in the consumption of fresh pomegranate fruit. There was a significant effect of storage time on lightness (L*), redness (a*) and chroma (C*) colour attributes of arils for all treatments (Table 4.8). Fruit packed with liners significantly retained higher L* and a* aril colour attributes than fruit packed with no-liner at 12 weeks of cold storage. Fruit packed with no-liner retained 55.7 % of the initial aril L* colour attribute, compared to 82.4 and 76.9 % for fruit packed with non-perforated 'Decco' and 'Zoe' liners, respectively. Fruit packed in micro-perforated Xtend® liner retained 67.3 % of aril L* colour attribute, with no significant difference compared to 68.4 and 70.4 % for fruit packed with 2 mm macro-perforated and 4 mm macro-perforated HDPE liners, respectively. These results could be attributed to the influence of liner packaging on fruit weight loss and respiration rate. Excessive loss of moisture and high respiration rate by the no-liner packed fruit could have resulted in the loss of aril colour lightness and redness, due to water stress and degradation of colour pigments.

There was no significant difference in a* and C* aril colour attributes among all fruit packed with liners (Table 4.8). Therefore, perforation of liners did not have an effect on the redness and tone saturation colour attributes of the arils. Similarly, Arendse *et al*. (2014) observed significant decrease of aril colour parameters L*, a* and C* with storage time for pomegranate (cv. 'Wonderful') fruit packed in boxes and stored at different temperature conditions.

Table 4.8 Impact of liner treatment on pomegranate aril colour parameters: fruit stored for 12 weeks at 5 ^{o}C and 90 % RH

Time	**Treatment**	**L***	**a***	**C***
0 Weeks		20.861 ± 0.381^{abc}	19.190 ± 0.411^{a}	21.090 ± 0.656^{a}
4 Weeks	No-liner	20.801 ± 0.538^{abc}	18.201 ± 1.550^{abc}	19.780 ± 1.713^{abcd}
	Xtend	21.902 ± 0.682^{a}	18.081 ± 0.461^{abc}	20.296 ± 0.547^{abc}
	Decco	21.498 ± 0.512^{ab}	18.826 ± 0.521^{ab}	20.325 ± 0.587^{abc}
	Zoe	21.585 ± 1.059^{ab}	18.597 ± 0.621^{ab}	20.662 ± 0.909^{ab}
	2mm HDPE	21.094 ± 0.420^{abc}	18.246 ± 0.834^{abc}	19.748 ± 1.016^{abcd}
	4mm HDPE	21.895 ± 1.438^{a}	18.303 ± 0.522^{abc}	19.967 ± 0.390^{ab}cd
6 Weeks	No-liner	16.563 ± 1.055^{ei}	15.313 ± 1.076^{fd}	16.454 ± 1.205^{ge}
	Xtend	19.044 ± 1.252^{eb}	17.012 ± 1.309^{abcde}	18.376 ± 1.416^{abcdef}
	Decco	19.646 ± 0.390^{abcd}	15.099 ± 0.914^{fd}	16.324 ± 1.035^{ge}
	Zoe	19.349 ± 0.884^{abcd}	16.430 ± 1.011^{fb}	17.668 ± 1.155^{gb}
	2mm HDPE	18.774 ± 1.062^{ecf}	14.491 ± 0.672^{feg}	15.737 ± 0.832^{geh}
	4mm HDPE	18.146 ± 0.897^{edfg}	15.861 ± 0.659^{fc}	17.057 ± 0.824^{gd}
8 Weeks	No-liner	14.023 ± 0.692^{i}	12.260 ± 0.748^{hg}	13.473 ± 0.892^{ih}
	Xtend	16.347 ± 0.397^{if}	15.797 ± 0.657^{fc}	17.816 ± 0.616^{gb}
	Decco	17.418 ± 0.424ed^{fg}	17.158 ± 0.443^{abcd}	18.300 ± 0.566^{abcdef}
	Zoe	18.051 ± 0.348ed^{fg}	17.365 ± 0.592^{abcd}	18.581 ± 0.737^{abcde}
	2mm HDPE	17.289 ± 1.455ed^{fg}	16.034 ± 0.828^{fc}	17.483 ± 0.914^{fgc}
	4mm HDPE	15.600 ± 0.632^{ig}	15.477 ± 0.511^{fd}	16.952 ± 0.566^{gd}
12 Weeks	No-liner	11.616 ± 0.683^{j}	11.342 ± 0.433^{h}	12.941 ± 0.623^{i}
	Xtend	14.138 ± 0.763^{i}	14.037 ± 0.290^{fg}	15.244 ± 0.308^{gi}
	Decco	17.193 ± 0.673^{edfgh}	16.039 ± 1.057^{fc}	17.220 ± 1.226^{gd}
	Zoe	16.036 ± 0.563^{ig}	16.010 ± 0.724^{fc}	18.032 ± 0.943^{gb}
	2mm HDPE	14.264 ± 0.594^{i}	14.497 ± 0.580^{feg}	15.391 ± 0.640^{gif}
	4mm HDPE	14.691 ± 0.576^{ih}	14.459 ± 0.584^{feg}	16.677 ± 0.832^{ge}

Mean values with different letters are significantly different ($p \leq 0.05$), according to Duncan's multiple range test.

4.3.7 Principal component analysis

The averages of quality attributes of pomegranate fruit packed with no-liner, non-perforated ‘Decco’ and ‘Zoe’, micro-perforated Xtend®, macro-perforated 2 and 4 mm HDPE liners are shown in Figures 4.21 and 4.22. Total variability was explained by five principal factors. Shipping fruit takes 6 weeks across the Atlantic Ocean from South Africa to Europe, which is the main export market. After 6 weeks of storage, the first two principal factors (F1 and F2) explained 85.8 % of the total variability. Along F1 (explaining 70.9 % of total variability), packaging fruit with no-liner was associated with higher weight loss, shrivelling, high respiration rate and aril hardening, by 6 weeks of storage. The same attributes associated with no-liner packaging had high negative values along F1 (Table 4.9). On the other hand, packing fruit with both non-perforated and perforated liners was associated with retaining fruit puncture resistance and peel colour attributes of L*, C* and a^*. The same attributes associated with liner packaging had high positive values along F1 (Table 4.9). Along F2 (explaining 14.9 % of total variability), packing fruit with no-liner, non-perforated ‘Decco’ and ‘Zoe’ and macro-perforated 2 mm HDPE were associated to facilitating fruit decay (incidence and index). Variables of decay incidence and index had high positive values along F2 (Table 4.9).

After 12 weeks of storage, a clearer separation between packaging treatments was observed (Figure 4.22). In this case, the first two component factors (F1 and F2) explained 92.6 % of the total variability with F1 and F2 accounting for 75.2 and 17.4 %, respectively. Along F1, packaging fruit with No-liner, macro-perforated 2 and 4 mm HDPE liners was associated to facilitating fruit weight loss, shrivelling (incidence and index), respiration rate, and decay index. On the other hand, packing fruit with non-perforated ‘Decco’ and ‘Zoe’ and micro-perforated Xtend® liners was associated with retaining fruit puncture resistance, and peel colour attributes of L*, C* and a^*. Along F2, packing fruit with no-liner, non-perforated ‘Decco’ and ‘Zoe’ liners was associated with decay incidence and aril firmness (or hardness as applicable to no-liner packed fruit).

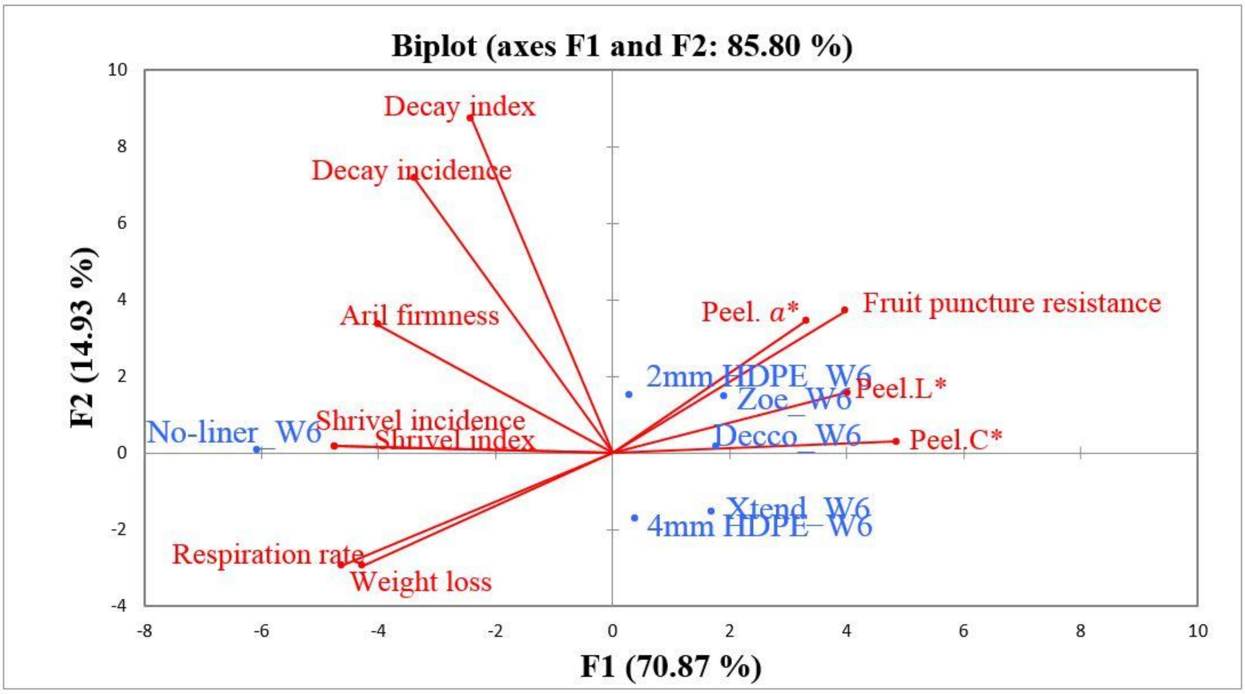


Figure 4.21 Principal component analysis of the first two factors (F1 and F2) due to physical and physiological attributes of pomegranate (cv. Wonderful) after 6 weeks of storage at 5 °C and 95 % RH.

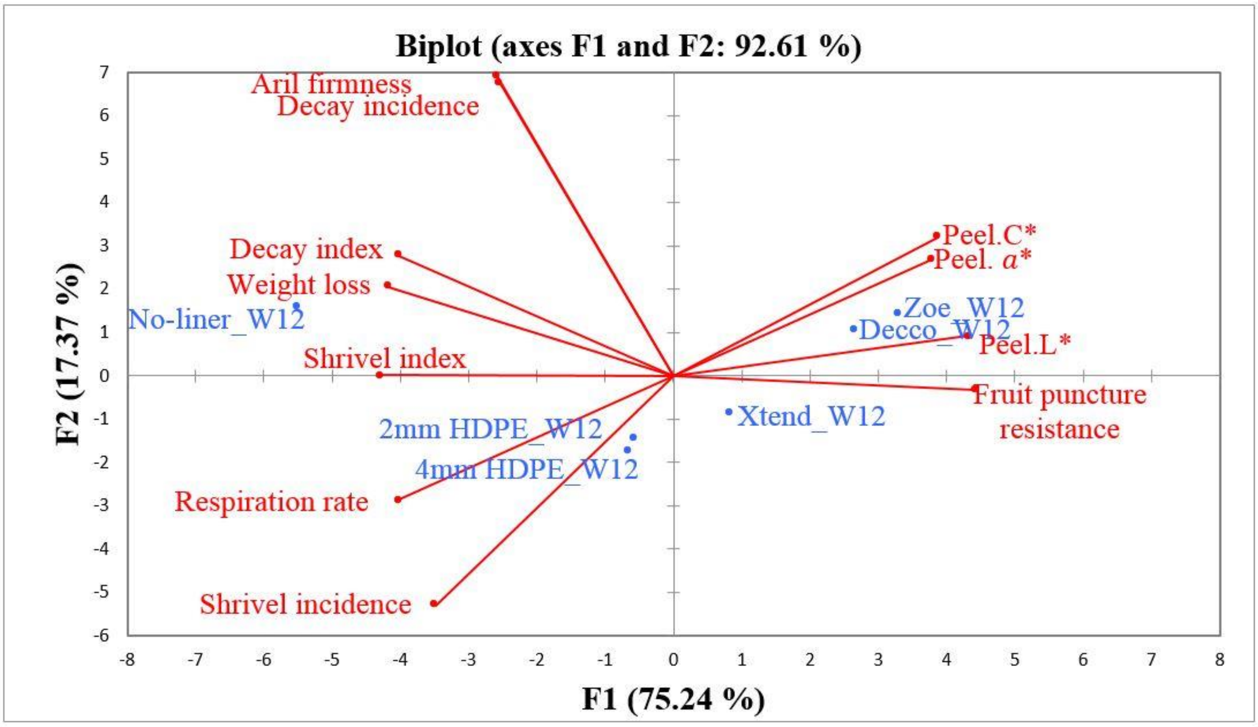


Figure 4.22. Principal component analysis of the first two factors (F1 and F2) due to physical and physiological attributes of pomegranate (cv. Wonderful) after 12 weeks of storage at 5 °C and 95 % RH.

Table 4.9 Factor loadings and scores for the first two principal factors for pomegranate packed in no-liner and with different liners

	6 weeks of storage		**12 weeks of storage**	
	F1	**F2**	**F1**	**F2**
Factor loadings				
Weight loss	-0.955	-0.278	-0.945	0.224
Fruit firmness	0.818	0.349	0.999	-0.036
Aril firmness	-0.824	0.317	-0.588	0.755
Decay incidence	-0.695	0.674	-0.579	0.741
Decay index	-0.496	0.825	-0.913	0.302
Shrivel incidence	-0.972	0.017	-0.791	-0.578
Shrivel index	-0.972	0.017	-0.973	0.003
Respiration rate.	-0.879	-0.279	-0.913	-0.312
Peel.L*	0.826	0.150	0.979	0.102
Peel.a*	0.682	0.328	0.858	0.292
Peel.C*	0.998	0.029	0.878	0.348
Factor scores				
No-liner_W6	-6.070	0.050	-5.506	1.587
Decco_W6	1.782	0.166	2.648	1.042
Zoe_W6	1.898	1.486	3.296	1.419
Xtend_W6	1.709	-1.537	0.821	-0.869
2mm HDPE_W6	0.300	1.536	-0.584	-1.453
4mm HDPE_W6	0.380	-1.701	-0.676	-1.727

4.4 Conclusions

The use of plastic liners as internal packages in the multi-scale packaging of pomegranate fruit plays a major role in minimizing quantitative and qualitative losses during prolonged cold storage. Packaging pomegranate (cv. Wonderful) in non-perforated liners greatly minimizes mass loss, maintains fruit colour and textural quality during cold storage for 12 weeks at 5 °C. Micro-perforated Xtend® and 4 mm macro-perforated HDPE liners were able to minimize moisture condensation within the bags and reduced decay incidence, which are some of the challenges of packing fruit in non-perforated liners. Packing fruit with perforated liners also greatly minimized fruit mass and size loss and retained acceptable quality during prolonged storage, compared to packing fruit with no-liner.

Financial losses due to decay incidence (associated to non-perorated liner packed fruit) outweigh financial losses due to weight loss (associated to no-liner and perforated liner packed fruit). Therefore, using micro-perforated Xtend® and macro-perforated 4 mm HDPE can be considered to minimize postharvest losses often associated with inadequate environment control inside packaging, compared to the use of non-perforated liners (note that 4 mm HDPE liners are over 3 times cheaper than micro-perforated Xtend® liners).

4.5 References

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5 Effect of Internal Packaging (liners) on Chemical and Phytochemical Properties and Anti-oxidant Activity of Pomegranate Fruit during Cold Storage and Shelf Life

Abstract

The study was carried out to assess the impact of liners (MAP) on the phenolic, antioxidant activity and general chemical sensory quality attributes of pomegranate (cv. Wonderful) fruit during prolonged cold storage and shelf life conditions. Fruit was procured and packed into five different commercial plastic liners as internal packaging inside ventilated cartons; Xtend®, ‘Decco’, ‘Zoe’, 2mm high density polyethylene (HDPE) and 4mm HDPE. A no-liner control treatment was considered. All fruit was stored at 5 °C and 90-95 % RH for 12 weeks. For each treatment 24 fruit were randomly sampled at 4, 6, 8 and 12 weeks, 12 fruit were immediately assessed for quality and other 12 fruit were analysed after additional 5 days at 20 °C and 65 ± 5 % RH to mimic shelf life conditions. Chemical and phytochemical assessment on total soluble solids (TSS), titratable acidity (TA), pH, juice colour, Vitamin C, total phenols, and anti-oxidant activity was carried out at the end of 12 weeks of cold storage, no-liner packed fruit retained the initial TA (1.15 ± 0.05 %) by 60.6 %. Non-perforated (‘Decco’ and ‘Zoe’) liners retained fruit juice TA by 74.3 % and 75.8 % respectively, with no significant difference among all liner treatments. The TSS of juice decreased from 15.3 % to 15.0 % (no-liner) and 14.6 % (macro-perforated 4 mm HDPE) with no significant difference for juice from fruit packed in liner treatments. Generally, there was no significant difference in juice colour attributes of L* (lightness), a* (redness) and C* (saturation) for all treatments, except for juice from fruit packed in non-perforated liners with more a* and C*. Juice from fruit packed in non-perforated ‘Decco’ liners retained slightly higher total phenolic concentration (2.2 %) compared to fruit packed in 2 mm macro-perforated HDPE, with no significant difference for all liner packed fruit at the end of 12 weeks of cold storage. At the end of 12 weeks of cold storage and additional 5 days of shelf life, anti-oxidant activity of juice from fruit packed in different liners was as follows; micro-perforated Xtend® (42.4 %) > non-perforated ‘Decco’ (37.6 %) > non-perforated ‘Zoe’ (35.2 %) > 4 mm macro-perforated HDPE (32.1 %) > 2 mm macro-perforated HDPE (28.9 %) > no-liner (28.5 %). However, juice from fruit packed in any of the perforated liners retained more vitamin C than juice from fruit packed in non-perforated liners at the end of both cold storage and shelf life periods. Generally, fruit packed

in non-perforated ‘Zoe’ liners retained better quality compared to fruit packed in other liners for storing ‘Wonderful’ pomegranate fruit for 12 weeks at 5 ^{o} C.

Key words: *Pomegranate, Modified atmosphere packaging, Internal packaging, Cold storage, shelf life, Phenolic compounds, Antioxidant activity.*

5.1 Introduction

The pomegranate (Punica granatum L.) of the family Punicaceae, is one of the oldest known edible fruit (Singh, 1997) with about 55-60 % edible portion (Fawole & Opara, 2013a). Global production, promotion and consumption of pomegranate fruit has been increasing over years, attributed to relatively high bioactive compounds within the fruit and increasing public health and nutrition awareness (Holland & Bar-Ya’akov, 2008; Holland *et al.*, 2009; Viuda-Martos *et al.*, 2010). Due to high antioxidant and bioactive compounds, pomegranate has been used in the treatment of various diseases (Opara *et al.*, 2009; Fawole *et al.*, 2012). The need to preserve quality of the fruit throughout prolonged cold storage, shipping conditions and market shelf conditions still exits.

The pomegranate fruit is highly prone to weight loss, fruit decay, chilling injury and other physiological disorders that might ultimately affect fruit internal quality during prolonged storage (Elyatem & Kader, 1984; Koksal, 1989; Caleb *et al.*, 2012). A combination of packaging and cold chain management is applied in the industry to minimize postharvest losses. Storing pomegranate (cv. Wonderful) at 5 ° C and above 92 % RH for up to 3 months minimizes physiological disorders, maintains internal and external quality attributes (Arendse *et al.*, 2014a). Chilling injury increases with time and temperature below 5 ° C (Elyatem & Kader, 1984).

Modified atmosphere packaging (MAP) has been successfully applied to prolong the quality of various cultivars of pomegranate fruit, through the application of internal packaging such as shrinkable wrap films and plastic liners. Weight loss and physiological disorders have been minimized and internal quality maintained with application of shrink wraps on ‘Ganesh’ (Nanda *et al.*, 2001), ‘Primosole’ (D’Aquino *et al.*, 2010), and ‘Wonderful’ (Abd-elghany *et al.*, 2012; Mphahlele, 2016). Plastic liners have also been applied on ‘Mollar de Elche’ (Artés *et al.*, 2000; Laribi, *et al.*, 2012), ‘Shlefy’ (Ghafir *et al.*, 2010), ‘Hicrannar’ (Selcuk & Erkan, 2014), ‘Hicaznar’ (Selcuk & Erkan, 2015) and ‘Wonderful’ (Mphahlele *et al.*, 2016). There is still minimal information about MAP and specifically plastic liners as internal packaging on phytochemical quality of the cultivar 'Wonderful' of pomegranate grown in South Africa. This cultivar is the most widely grown in the country (Pomegranate Association of South Africa, 2015). The Aim of the research was to investigate the effect of internal packaging (liners) on chemical and phytochemical quality of pomegranate (cv. Wonderful) fruit during cold and shelf life storage.

5.2 Materials and Methods

5.2.1 Fruit

Commercially mature, harvested pomegranate fruit (cv. Wonderful) of uniform diameter 81.8 ± 2.5 mm and mass 286 ± 15 g were procured from a farm in Bonnievale (33°58'12.02"S, 20°09'21.03"E), Western Cape, South Africa. Fruit were transported in refrigerated truck to Postharvest Technology Research Laboratory at Stellenbosch University.

5.2.2 Packaging material

Plastic liners were procured from commercial pomegranate pack houses and from packaging distributors in Western Cape, South Africa. Plastic liners included: a) Xtend Stetpac liners (micro-perforated. Modified atmosphere packaging (MAP) and modified humidity packaging (MHP). b) Decco (Non-perforated liner). c) Zoe (non-perforated). d) 2 mm HDPE (macro-perforated. 2 mm × 54 perforations). e) 4 mm HDPE (macro-perforated. 4 mm × 36 perforations). The liners were applied as internal packaging inside ventilated paperboard cartons.

5.2.3 Experimental set up and measurements

A total of 73 cartons, each containing 12 fruit were used. Fruit were portioned into six treatments, each comprised of 11 cartons. The no-liner control, non-perforated 'Decco' liner, non-perforated 'Zoe' liner, micro-perforated Xtend® liner, 2 mm perforated HDPE liner (2 mm × 54 perforations) and 4 mm perforated HDPE liner (4 mm × 36 perforations). Fruit was placed inside plastic liners within ventilated cartons, stored in cold rooms maintained at 5 °C and 90-95 % RH for 12 weeks. For each treatment, 24 fruit were randomly sampled after 4, 6, 8 and 12 weeks, 12 fruit were assessed for quality and other 12 fruit were analysed after additional 5 days at 20 °C and 65±5 % RH to mimic shelf life conditions.

5.2.3.1 Titratable acidity, total soluble solids, pH and juice colour

Fresh juice was extracted from the fruit using a blender (Mellerware, South Africa). Titratable acidity (TA) was quantified using a Titrosampler (Metrohm 862, Herisau, Switzerland). A sample of 2 ml juice diluted in 70 ml of distilled water and titrated with 0.1N NaOH until an endpoint of pH 8.2 was reached. Acidity was expressed as g citric acid/ 100 mL of juice. Total soluble solids (TSS) was determined by a digital refractometer (Atago, Tokyo, Japan) and results presented in percentage. A ratio of TSS/TA was determined. BrimA index was determined: $TSS - k \times TA$ where k is a tongue's sensitivity index ranging from two to ten (Jordan *et al*., 2001; Fawole & Opara, 2013a). A k value of two was used to avoid negative BrimA results (Fawole & Opara, 2013a). The pH of juice was determined by a digital pH meter (Crison, Barcelona, Spain). Analytical tests were performed on 12 fruit per treatment at ambient room temperature.

Juice colour was assessed by a digital colorimeter (Minolta, model CR-400, Tokyo, Japan). Colour was monitored in a petri dish at two random spots per sample. Values of L* (lightness), a^* (redness), b^* (yellowness) were measured according to Commission Internationale de l'Eclairage (CIE), 1976. Chroma (*C*)* was calculated (Pathare *et al*., 2012). Twelve replicates were considered per packaging treatment.

$$c^* = \sqrt{{a^*}^2 + {b^*}^2} \tag{1}$$

5.2.3.2 Ascorbic acid (Vitamin C) concentration

Vitamin C was quantified as described by Klein and Perry (1982) with modifications (Barros *et al*., 2007). Fruit juice (0.5 ml) was diluted with 14.5 ml of 1 % metaphosphoric acid (MPA) in centrifuge tubes. The tubes were vortexed for 30 seconds, sonicated in ice for 3 minutes and centrifuged at 5000 rpm for 10 minutes. To 1 ml of the extract, 9 ml of 2, 6 dichlorophenol-indophenol dye (0.0025 %) was added and mixed by shaking. The mixture was incubated in the dark for 10 minutes and absorbance reading taken at 515 nm. Vitamin C concentration was then quantified using a calibration curve of authentic L-ascorbic acid (0.01–0.1 µg/mL) and presented as ascorbic acid equivalents per ml crude juice (µg AAE /g).

5.2.3.3 Sample preparation for phenolic and anti-oxidant activity determination

Preparation of juice samples for phenolic compositions and antioxidant activity were prepared as described by Fawole & Opara (2013b) with slight modification. Pomegranate juice (2 ml) was mixed with 10 ml of cold 50 % aqueous methanol in a centrifuge tube. This was followed by vortexing, sonication in cold water for 5 minutes, centrifuging at 10,000 rpm (10 minutes, 4 ° C and supernatant carefully collected in tubes.

5.2.3.4 Total phenolic concentration (TPC)

In triplicates, TPC was assessed by the Folin-Ciocalteu (Folin-C.) colourimetric method (Makkar, 2000). To 50 µl of juice extract, 450 µl of 50 % methanol were added followed by 500 µl Folin–C and then 2.5 ml of 2 % Na_2CO_3 solution after two minutes. After vortexing, absorbance readings taken at 725 nm using a UV–visible spectrophotometer (Thermo Scientific Technologies, Madison, Wisconsin). Using a gallic acid standard curve (0.02−0.10 mg/mL), TPC was quantified as milligram gallic acid equivalent per 100 ml juice (mg GAE/100 ml). Analysis was done in triplicates for each treatment.

5.2.3.5 Free radical scavenging activity (FRSA)

The FRSA of juice against a stable radical 2,2-diphenyl-l-picrylhydrazyl (DPPH) was assessed as described by Karioti *et al*. (2004) with modifications (Fawole *et al*., 2012). The test was performed under dim lights. To 15 µl of extract, 735 µl of 100 % methanol was added, and 750 µl of 0.1 mM solution of methonolic DPPH, respectively. Mixtures were kept in dark for 30 minutes under ambient conditions and absorbance reading taken at 517 nm using a UV–visible spectrophotometer (Thermo Scientific Technologies, Madison, Wisconsin). Using an ascorbic standard curve, the FRSA was determined and expressed as mg of ascorbic acid equivalent per 100 ml of crude juice (mg AAE per 100 ml). The assessment was done in triplicates per treatment.

5.2.4 Statistical analysis

Analysis of variance (ANOVA) was performed using Statistica software (Statistica 13.0, StatSoft Inc., Tulsa, OK, USA). A 2-way ANOVA was applied with packaging treatments and storage time being the major categories. Means were separated using Duncan's multiple range test and significant difference between means was considered at $P < 0.05$.

5.3 Results and discussions

5.3.1 Chemical attributes of pomegranate juice

Generally, pH increased with storage time for all liner packaging treatments. After 12 weeks of storage, pH was higher in liner packed fruit compared with no-liner. However, there was no significant difference ($P < 0.05$) in pH among all fruit packed in liners (Table 5.1). The same trend was observed during shelf life with slight increase in pH (Table 5.1). Artés *et al*. (2000) also reported that pH increased with storage time for 'Mollar de Elche' pomegranate fruit. The researchers also observed significantly large increase in pH for fruit packed with liners than with no-liner at the end of both cold storage and shelf life periods. Laribi *et al*. (2012) reported a no significant impact of no-liner and liner packaging treatments on pH for 'Mollar de Elche' pomegranate fruit. The differences among these studies could be attributed to different gas permeability properties of the liners used by researchers to pack fruit.

The organoleptic quality of pomegranate juice is commonly assessed based on TSS, TA and TSS/TA ratio (Al-said *et al*., 2009). Titratable acidity was presented as percentage of citric acid. Given that it is the major organic acid contributing to the acidity of pomegranates (Melgarejo *et al*., 2000; Shwartz *et al*., 2009) as well as the taste and general chemical quality of the fruit. Titratable acidity decreased significantly with storage time. At the end of 12 weeks of cold storage, no-liner packed fruit lost 39.4 % of the initial TA (1.15 ± 0.05 %). However, fruit packed in non-perforated ('Decco' and 'Zoe') liners lost 25.7 % and 24.2 % of the initial TA, respectively (Table 5.2). With respect to no-liner packaging, fruit packed in non-perforated 'Zoe' and micro-perforated Xtend® liners significantly retained higher TA compared to fruit packed with other liner treatments. Titratable acidity further decreased in fruit packed with and without liners, after subsequent 5 days of shelf life (20 °C) at each sampling period. However, there was no significant difference in fruit juice TA among all treatments at each sampling period (Table 5.3). Selcuk and Erkan (2014) reported quite similar results for 'Hicrannar' pomegranate fruit stored at 6 °C for 120 days and additional 3 days at 20 °C. Nanda *et al*. (2001) observed that wrapping fruit with heat shrinkable films significantly retained more citric acid compared to non-wrapped fruit. The decrease in TA could be attributed to the utilization of organic acids in metabolic and respiration process. A decrease in TA with no significant difference among treatments was reported on various pomegranate cultivars packed in MAP (Laribi *et al*., 2012; Selcuk & Erkan, 2014; 2015).

Table 5.1 Effect of liner packaging on juice PH, for 'Wonderful' pomegranate fruit

Storage time	**Treatment**	**pH**	
		Cold storage*	**Shelf life****
0 weeks	#Base line	3.025 ± 0.018^{i}	3.025 ± 0.018^{i}
4 weeks	No-liner	3.259 ± 0.069^{hf}	3.287 ± 0.038^{gh}
	Xtend	3.296 ± 0.045^{he}	3.339 ± 0.054^{ghd}
	Decco	3.23 ± 0.048^{hg}	3.364 ± 0.026^{ghc}
	Zoe	3.298 ± 0.056^{he}	3.232 ± 0.042^{h}
	2mm HDPE	3.222 ± 0.038^{h}	3.258 ± 0.052^{gh}
	4mm HDPE	3.232 ± 0.035^{hg}	3.226 ± 0.082^{h}
6 weeks	No-liner	3.273 ± 0.042^{hf}	3.308 ± 0.033^{ghe}
	Xtend	$3.378 \pm 0.041^{abcdefg}$	3.375 ± 0.053^{ghc}
	Decco	3.273 ± 0.053^{hf}	3.371 ± 0.057^{ghc}
	Zoe	3.320 ± 0.035^{he}	3.295 ± 0.042^{ghf}
	2mm HDPE	3.337 ± 0.060^{hd}	3.367 ± 0.061^{ghc}
	4mm HDPE	3.293 ± 0.045^{he}	3.362 ± 0.036^{ghc}
8 weeks	No-liner	3.364 ± 0.052^{hb}	3.378 ± 0.036^{ghc}
	Xtend	3.442 ± 0.053^{abcde}	3.393 ± 0.058^{gb}
	Decco	3.295 ± 0.037^{he}	3.507 ± 0.026^{abc}
	Zoe	3.353 ± 0.043^{hc}	3.518 ± 0.042^{abc}
	2mm HDPE	3.485 ± 0.031^{abc}	3.452 ± 0.032^{abcdef}
	4mm HDPE	3.389 ± 0.031^{abcdef}	3.520 ± 0.023^{abc}
12 weeks	No-liner	3.438 ± 0.050^{abcde}	3.460 ± 0.039^{abcde}
	Xtend	3.503 ± 0.046^{ab}	3.493 ± 0.066^{abcd}
	Decco	3.473 ± 0.032^{abcd}	3.593 ± 0.037^{a}
	Zoe	3.492 ± 0.018^{abc}	3.599 ± 0.067^{a}
	2mm HDPE	3.489 ± 0.054^{abc}	3.540 ± 0.041^{ab}
	4mm HDPE	3.516 ± 0.051^{a}	3.544 ± 0.070^{ab}

*Stored at 5 °C and 90-95 % RH
**Stored at 5 °C and 90-95 % RH plus 5 days at 20 °C and 65-70 % RH
#Before treatment and storage.

Table 5.2 Effect of liner packaging on juice total soluble solids (TSS), titratable acidity (TA), TSS/TA ratio and BrimA for 'Wonderful' pomegranate fruit stored at 5 °C and 90-95 % RH

Storage time	Treatment	TSS (%)	TA (%)	TSS/TA	BrimA index
0 weeks	#Base line	15.253 ± 0.089^{a}	1.147 ± 0.044^{ab}	13.589 ± 0.551^{h}	12.959 ± 0.128^{c}
4 weeks	No-liner	15.173 ± 0.196^{ab}	1.079 ± 0.031^{abcd}	14.143 ± 0.339^{hf}	13.015 ± 0.181^{cb}
	Xtend	14.992 ± 0.151^{ac}	1.124 ± 0.028^{abcd}	13.411 ± 0.308^{h}	12.743 ± 0.143^{c}
	Decco	15.009 ± 0.167^{ac}	1.108 ± 0.041^{abc}	13.715 ± 0.487^{hg}	12.793 ± 0.183^{c}
	Zoe	15.0167 ± 0.145^{ac}	1.165 ± 0.090^{a}	$13.660 \pm 0.939h^{g}$	12.687 ± 0.235^{c}
	2mm HDPE	14.927 ± 0.183^{ac}	1.020 ± 0.061^{abcdef}	15.215 ± 0.975^{ehd}	12.887 ± 0.269^{c}
	4mm HDPE	14.975 ± 0.180^{ac}	1.058 ± 0.076^{abcde}	14.961 ± 1.056^{eh}	12.858 ± 0.247^{c}
6 weeks	No-liner	15.155 ± 0.126^{ab}	0.7645 ± 0.058^{ki}	20.855 ± 1.421^{ab}	13.625 ± 0.145^{a}
	Xtend	15.075 ± 0.140^{ac}	0.924 ± 0.052^{gdhi}	17.127 ± 1.361^{ecfg}	13.227 ± 0.193^{ac}
	Decco	15.118 ± 0.209^{ab}	1.002 ± 0.028^{gb}	15.189 ± 0.393^{ehd}	13.115 ± 0.185^{ac}
	Zoe	15.175 ± 0.226^{ab}	0.955 ± 0.060^{gch}	16.800 ± 1.359^{ehc}	13.265 ± 0.246^{ac}
	2mm HDPE	14.825 ± 0.233^{ac}	0.821 ± 0.042^{kh}	18.611 ± 1.041^{abcd}	13.183 ± 0.232^{ac}
	4mm HDPE	14.858 ± 0.179^{ac}	0.846 ± 0.034^{gk}	17.895 ± 0.782^{eb}	13.167 ± 0.187^{ac}
8 weeks	No-liner	15.108 ± 0.075^{ab}	0.759 ± 0.060^{ki}	21.365 ± 1.724^{a}	13.590 ± 0.130^{ab}
	Xtend	14.817 ± 0.080^{ac}	0.862 ± 0.083^{gfhij}	19.877 ± 2.668^{abc}	13.093 ± 0.209^{ac}
	Decco	15.000 ± 0.101^{ac}	0.905 ± 0.022^{gehij}	16.677 ± 0.477^{ehc}	13.189 ± 0.126^{ac}
	Zoe	15.058 ± 0.146^{ac}	0.905 ± 0.047^{gehij}	17.156 ± 0.923^{ecfg}	13.248 ± 0.186^{ac}
	2mm HDPE	14.773 ± 0.094^{ac}	0.802 ± 0.041^{kh}	18.870 ± 0.915^{abc}	13.169 ± 0.102^{ac}
	4mm HDPE	14.809 ± 0.100^{ac}	0.814 ± 0.052^{kh}	18.940 ± 1.170^{abc}	13.182 ± 0.156^{ac}
12 weeks	No-liner	15.036 ± 0.064^{ac}	0.695 ± 0.015^{k}	21.756 ± 0.494^{a}	13.647 ± 0.065^{a}
	Xtend	14.717 ± 0.056^{cb}	0.872 ± 0.032^{gfhij}	$17.135 \pm 0.635^{ec}fg$	12.973 ± 0.094^{c}
	Decco	14.925 ± 0.095^{ac}	0.852 ± 0.023^{gk}	$17.665 \pm 0.501^{eb}f$	13.222 ± 0.105^{ac}
	Zoe	14.880 ± 0.077^{ac}	0.869 ± 0.027^{gfhij}	17.283 ± 0.579^{ecf}	13.142 ± 0.110^{ac}
	2mm HDPE	14.750 ± 0.096^{cb}	0.771 ± 0.041^{ki}	19.547 ± 0.882^{abc}	13.208 ± 0.080^{ac}
	4mm HDPE	14.610 ± 0.089^{c}	0.738 ± 0.023^{kj}	19.962 ± 0.606^{abc}	13.134 ± 0.098^{ac}

TA, titratable acidity; TSS, total soluble solids.
The values within a column with different superscript letters are significantly different at $P \leq 0.05$ according to the Duncan’s multiple range test.
#Before treatment and storage.

Table 5.3 Effect of liner packaging on juice total soluble solids (TSS), titratable acidity (TA), TSS/TA ratio and BrimA for 'Wonderful' pomegranate fruit stored at 5 °C and 90-95 % RH plus 5 days at 20 °C and 65-70 % RH of shelf life

Storage time	**Treatment**	**TSS (%)**	**TA (%)**	**TSS/TA**	**BrimA**
0 weeks	$^{\#}$Base line	15.253 ± 0.089^{a}	1.147 ± 0.091^{a}	14.499 ± 1.121^{g}	12.95 ± 0.211^{ab}
4 weeks + 5 days	No-liner	14.917 ± 0.081^{ab}	0.875 ± 0.081^{bc}	18.735 ± 1.722^{fb}	13.167 ± 0.136^{ab}
	Xtend	14.709 ± 0.121^{db}	0.855 ± 0.036^{bcdef}	15.640 ± 1.687^{fg}	13.127 ± 0.177^{ab}
	Decco	14.850 ± 0.151^{ad}	0.912 ± 0.034^{b}	16.466 ± 0.569^{fgd}	13.026 ± 0.152^{ab}
	Zoe	14.809 ± 0.124^{db}	0.911 ± 0.022^{b}	16.375 ± 0.460^{fge}	12.988 ± 0.144^{ab}
	2mm HDPE	14.640 ± 0.148^{db}	0.841 ± 0.026^{bcdef}	17.562 ± 0.578^{fgb}	10.798 ± 1.462^{c}
	4mm HDPE	14.709 ± 0.141^{db}	0.828 ± 0.023^{bcdef}	17.916 ± 0.580^{fgb}	11.965 ± 1.098^{cb}
6 weeks + 5 days	No-liner	14.900 ± 0.090^{abc}	0.714 ± 0.047^{gc}	21.752 ± 1.266^{abcde}	13.472 ± 0.118^{ab}
	Xtend	14.827 ± 0.182^{ad}	0.774 ± 0.065^{bg}	20.679 ± 1.869^{abcde}	13.280 ± 0.232^{ab}
	Decco	14.925 ± 0.156^{ab}	0.863 ± 0.074^{bcde}	18.898 ± 1.758^{fb}	13.198 ± 0.237^{ab}
	Zoe	14.875 ± 0.110^{ad}	0.868 ± 0.034^{bcd}	17.428 ± 0.663^{fge}	13.14 ± 0.091^{ab}
	2mm HDPE	14.611 ± 0.123^{db}	0.781 ± 0.087^{bg}	20.713 ± 2.325^{abcd}	13.049 ± 0.213^{ab}
	4mm HDPE	14.609 ± 0.100^{db}	0.782 ± 0.065^{bg}	19.860 ± 1.452^{fb}	13.045 ± 0.187^{ab}
8 weeks + 5 days	No-liner	14.844 ± 0.080^{ad}	0.719 ± 0.024^{gc}	20.854 ± 0.775^{abc}	13.407 ± 0.105^{ab}
	Xtend	14.690 ± 0.250^{db}	0.728 ± 0.059^{bg}	21.415 ± 1.731^{abc}	13.234 ± 0.274^{ab}
	Decco	14.758 ± 0.119^{db}	0.803 ± 0.033^{bg}	18.746 ± 0.811^{fb}	13.153 ± 0.139^{ab}
	Zoe	14.810 ± 0.125^{db}	0.804 ± 0.072^{bg}	19.576 ± 1.459^{fb}	13.202 ± 0.147^{ab}
	2mm HDPE	14.442 ± 0.116^{dc}	0.759 ± 0.039^{bg}	19.632 ± 1.108^{fb}	12.923 ± 0.159^{ab}
	4mm HDPE	14.625 ± 0.100^{db}	0.753 ± 0.028^{bg}	19.776 ± 0.830^{fb}	13.120 ± 0.095^{ab}
12 weeks + 5 days	No-liner	14.808 ± 0.105^{db}	0.630 ± 0.033^{g}	24.222 ± 1.309^{a}	13.548 ± 0.123^{a}
	Xtend	14.475 ± 0.156^{db}	0.680 ± 0.019^{ge}	21.453 ± .579^{abc}	13.115 ± 0.150^{ab}
	Decco	14.692 ± 0.137^{db}	0.788 ± 0.026^{bg}	18.875 ± 0.674^{fb}	13.115 ± 0.171^{ab}
	Zoe	14.729 ± 0.094^{db}	0.787 ± 0.031^{bg}	18.870 ± 0.679^{fb}	13.154 ± 0.109^{ab}
	2mm HDPE	14.500 ± 0.111^{db}	0.672 ± 0.035^{gf}	21.889 ± 1.091^{ab}	13.154 ± 0.127^{ab}
	4mm HDPE	14.429 ± 0.119^{d}	0.687 ± 0.049^{gd}	21.587 ± 1.405^{abc}	13.054 ± 0.177^{ab}

TA, titratable acidity; TSS, total soluble solids.
The values within a column with different superscript letters are significantly different at $P \leq 0.05$ according to the Duncan's multiple range test. $^{\#}$Before treatment and storage.

There is a high correlation between total soluble solids (TSS) and sweetness taste (Tandon *et al*., 2003). Generally the was a decrease in TSS content from 15.3 % before storage to 15.0 % for fruit packed with no-liner, compared to 14.6-14.9 % for all fruit packed with liners at the end of 12 weeks of cold storage (Table 5.2). However, there was no significant difference in fruit juice TSS among all treatments throughout storage. A similar trend was observed after shelf life period with TSS of 14.7 % for fruit packed with no-liner and 14.4-14.8 % for fruit packed with liners at the end of cold storage and subsequent shelf life (Table 5.3). The reduction in TSS could be attributed to utilization of sugars in respiration life processes of the fruit during storage. The higher value of TSS for fruit packed with no-liner could be attributed to significantly higher moisture loss during storage. Our results were within similar range compared to findings by Selcuk & Erkan (2015) who also observed similar trends on 'Hicaznar' pomegranate fruit. A decline in TSS has been reported by several researchers on different cultivars of pomegranate fruit packed in MAP (Artés *et al*, 2000; Nanda *et al*., 2001; D'Aquino *et al*., 2010 Laribi *et al*., 2012; Mphahlele *et al*., 2016). Contrary to our results, Selcuk & Erkan (2014) reported a higher TSS for 'Hicrannar' pomegranate packed in MAP liners than in no-liner control at the end of 120 days of cold storage at 6 ^{o}C.

The ratio of TSS/TA has an influence on the quality and consumer preference (taste) depending on the fruit. Apples with a higher TSS/TA ratio were found to be more preferred by consumers (Boylson *et al*., 1994). The TSS/TA ratio of fruit juice significantly increased with storage time in all treatments (Table 5.2), due to a higher decrease in TA than TSS. Fruit packed with no-liner had significantly higher TSS/TA ratio compared to fruit packed with non-perforated 'Decco,' non-perforated 'Zoe' and micro-perforated Xtend® liners at the end of 12 weeks of cold storage. This is probably because of the low TA and relative high TSS for fruit packed with no-liner. However, no significant difference in TSS/TA ratio observed among fruit packed with liners. A similar trend was followed during shelf life periods (Table 5.3). Artés *et al*. (2000) reported a significant increase in TSS/TA ratio for 'Mollar de Elche' pomegranate fruit stored in non-perforated MAP liners from harvest to the end of 12 weeks of cold storage at 2 and 5 ^{o}C compared to fruit packed with perforated liners and no-liner.

BrimA index is a variant of TSS/TA ratio that puts into consideration the tongue's taste sensitivity (Fawole & Opara, 2013a) and can be used to assess the effect of chemical changes on flavour (Jordan *et al*., 2001). BrimA index increased for the first 6 weeks and then remained more stable up to the end of 12 weeks of cold storage (Table 5.2). The effect of storage time on BrimA index was significant in fruit packed with no-liner, except in all liner packed fruit. The no-liner packed fruit had significant ($P \leq 0.05$) increase in BrimA index of about 5.2 % at 6 weeks and 12 weeks of cold storage compared to no significant increase of less than 2.0 % for all fruit packed in liners. This is attributed to the lower TA and quite high TSS values observed in the no-liner fruit. During shelf life, an increase in BrimA index was observed for all treatments with no significant difference from the base line (before storage), except for fruit packed with 2 mm macro-perforated HDPE at 4 weeks and no-liner at 12 weeks (Table 5.3). Arendse (2014) reported an increase in BrimA index for 'Wonderful' pomegranate fruit conventionally stored at different temperatures between 5 to 21 ^{o} C. However, Fawole & Opara (2013c) reported a decrease in BrimA index for 'Ruby' pomegranate stored conventionally at different temperatures between 5 to 21 ^{o} C for 4 months. The differences in results observed in these studies can be attributed to differences in fruit cultivars and level of maturity.

5.3.2 Colour attributes of pomegranate juice

Colour, an important direct visual-quality attribute greatly affecting consumer preference (Pathare *et al*., 2013) and is an indicator for freshness and nutritional quality (Haisman & Clarke, 1975; Kidmose *et al*., 2002). Before storage (baseline), fruit juice colour had an L* value of 24.989. There was a significant ($P \leq 0.05$) decline in the lightness (L*) value of the pomegranate juice colour with storage duration, irrespective of treatment during cold and ambient storage periods (Table 5.4 and 5.5). Generally, lower juice colour L* values were observed for fruit packed with no-liner, compared to juice from fruit packed with liners throughout cold storage period. However, at 12 weeks of cold storage there was no significant difference in L* values among treatments. At the end of 12 weeks of cold storage and subsequent 5 days of shelf life, fruit packed with non-perforated 'Zoe' liner maintained significantly higher juice colour L* than in all other treatments.

The redness (a*) of the juice colour decreased significantly with time during cold storage and ambient storage periods of fruit irrespective of treatments. At 12 weeks of cold storage, juice from fruit packed with non-perforated liners had higher a* values compared to fruit juice from other treatments. However, there was no significance difference in juice a* among fruit from all treatments, except from non-perforated 'Zoe' liners. After 12 weeks of cold storage and additional 5 days under shelf conditions, there was no significant difference ($P \leq 0.05$) in juice a* among fruit from all treatments (Table 5.5).

Table 5.4 Effect of liner packaging on juice colour parameters of L*, a* and C* for 'Wonderful' pomegranate fruit stored at 5 ° C and 90-95 % RH

Storage time	**Treatment**	**L***	**a***	**C***
0 weeks	$^{\#}$Base line	24.989 ± 0.550^{ab}	25.872 ± 0.497^{a}	29.695 ± 0.704^{c}
4 weeks	No-liner	22.964 ± 0.477^{bc}	24.306 ± 0.521^{ac}	32.673 ± 1.359^{ab}
	Xtend	25.111 ± 0.605^{ab}	24.966 ± 0.437^{ab}	30.055 ± 0.607^{cb}
	Decco	24.650 ± 0.701^{ab}	24.55 ± 0.455^{ab}	29.1597 ± 0.693^{c}
	Zoe	25.716 ± 1.082^{a}	24.713 ± 0.533^{ab}	30.797 ± 0.931^{cb}
	2mm HDPE	24.711 ± 0.377^{ab}	24.653 ± 0.355^{ab}	34.496 ± 1.049^{a}
	4mm HDPE	24.960 ± 0.620^{ab}	24.913 ± 0.430^{ab}	31.844 ± 0.660^{ac}
6 weeks	No-liner	20.668 ± 1.019^{df}	23.516 ± 0.550^{cb}	26.133 ± 0.667^{d}
	Xtend	23.370 ± 0.864^{b}	23.190 ± 0.359^{cb}	24.136 ± 0.336^{def}
	Decco	23.612 ± 0.525^{ab}	23.532 ± 0.373^{cb}	24.806 ± 0.450^{d}
	Zoe	23.790 ± 0.778^{ab}	23.981 ± 0.484^{ac}	24.701 ± 0.444^{d}
	2mm HDPE	18.706 ± 0.424^{f}	23.226 ± 0.456^{cbd}	24.270 ± 0.504^{de}
	4mm HDPE	20.275 ± 0.538^{df}	23.030 ± 0.559^{cbd}	23.938 ± 0.532^{defg}
8 weeks	No-liner	19.112 ± 0.485^{fe}	19.642 ± 0.418^{fg}	21.042 ± 0.577^{hg}
	Xtend	21.380 ± 1.092^{dc}	19.837 ± 0.633^{fg}	23.241 ± 1.282^{defg}
	Decco	21.272 ± 0.603^{dce}	20.157 ± 0.660^{feg}	21.388 ± 0.793^{he}
	Zoe	19.854 ± 0.257^{df}	19.681 ± 0.604^{fg}	21.224 ± 0.707^{hf}
	2mm HDPE	23.042 ± 0.795^{bc}	21.038 ± 1.406^{fd}	23.288 ± 1.798^{defg}
	4mm HDPE	21.193 ± 0.566^{dce}	22.218 ± 1.074^{cde}	24.329 ± 1.306^{de}
12 weeks	No-liner	19.234 ± 0.633^{df}	16.288 ± 0.498^{h}	17.940 ± 0.551^{i}
	Xtend	18.712 ± 0.384^{f}	16.606 ± 0.634^{h}	17.733 ± 0.710^{i}
	Decco	19.194 ± 0.201^{fe}	18.025 ± 0.687^{hg}	19.337 ± 0.776^{hi}
	Zoe	20.423 ± 0.553^{df}	19.803 ± 1.409^{fg}	21.377 ± 1.605^{he}
	2mm HDPE	19.451 ± 0.496^{df}	16.660 ± 1.320^{h}	17.834 ± 1.473^{i}
	4mm HDPE	19.803 ± 0.493^{df}	16.765 ± 1.312^{h}	18.175 ± 1.497^{i}

The values within a column with different superscript letters are significantly different at $P < 0.05$ according to the Duncan's multiple range test.

$^{\#}$Before treatment and storage.

Table 5.5 Effect of liner packaging on juice colour parameters of L*, a* and C* for 'Wonderful' pomegranate fruit stored at 5 °C and 90-95 % RH plus 5 days at 20 °C and 65-70 % RH of shelf life

Storage time	**Treatment**	**L***	**a***	**C***
0 weeks	Base line#	24.989 ± 0.550^{a}	25.872 ± 0.497^{a}	29.695 ± 0.704^{a}
4 weeks +	No-liner	20.314 ± 0.721^{bcde}	19.203 ± 1.499^{bcd}	20.978 ± 1.860^{bcde}
5 days	Xtend	20.899 ± 0.606^{bc}	20.735 ± 1.211^{b}	23.075 ± 1.457^{b}
	Decco	20.755 ± 0.698^{bcde}	20.451 ± 1.243^{b}	22.606 ± 1.562^{b}
	Zoe	19.987 ± 0.649^{gc}	19.754 ± 1.328^{bc}	21.555 ± 1.642^{bcd}
	2mm HDPE	21.021 ± 0.864^{bc}	21.088 ± 1.863^{b}	23.248 ± 2.316^{b}
	4mm HDPE	20.814 ± 0.492^{bcd}	20.905 ± 0.889^{b}	22.816 ± 1.079^{b}
6 weeks +	No-liner	18.877 ± 0.527^{gehi}	16.349 ± 1.220^{fc}	17.702 ± 1.413^{gd}
5 days	Xtend	18.535 ± 0.387^{gjf}	16.383 ± 1.376^{fc}	17.556 ± 1.534^{gd}
	Decco	20.922 ± 0.845^{bc}	20.283 ± 1.551^{b}	22.214 ± 1.963^{bc}
	Zoe	19.400 ± 0.277^{gch}	16.852 ± 0.792^{fc}	18.161 ± 0.899^{gc}
	2mm HDPE	19.713 ± 0.342^{gc}	18.941 ± 0.793^{bcd}	20.384 ± 0.910^{bcde}
	4mm HDPE	22.024 ± 0.677^{b}	21.480 ± 1.451^{b}	24.138 ± 1.789^{b}
8 weeks +	No-liner	18.979 ± 0.422^{gdhi}	14.247 ± 0.489^{f}	15.100 ± 0.568^{g}
5 days	Xtend	18.782 ± 0.514^{gfhi}	15.760 ± 1.052^{fd}	17.089 ± 1.279^{ge}
	Decco	19.237 ± 0.621^{gch}	16.240 ± 1.115^{fd}	17.733 ± 1.342^{gd}
	Zoe	18.336 ± 0.410^{gj}	15.293 ± 0.499^{fe}	16.294 ± 0.608^{gf}
	2mm HDPE	20.034 ± 0.473^{gc}	15.989 ± 1.199^{fd}	17.473 ± 1.414^{gd}
	4mm HDPE	21.104 ± 0.767^{bc}	18.063 ± 0.676^{bcde}	20.742 ± 0.951^{bcde}
12 weeks	No-liner	16.719 ± 0.281^{j}	13.670 ± 0.329^{f}	14.337 ± 0.336^{g}
+ 5 days	Xtend	17.132 ± 0.354^{ji}	14.635 ± 0.426^{fe}	15.517 ± 0.440^{g}
	Decco	17.633 ± 0.412^{jh}	15.191 ± 0.580^{fe}	15.473 ± 0.569^{g}
	Zoe	18.642 ± 0.370^{gfhi}	15.032 ± 0.721^{fe}	15.790 ± 0.597^{g}
	2mm HDPE	17.094 ± 0.446^{ji}	14.962 ± 0.655^{fe}	15.767 ± 0.631^{g}
	4mm HDPE	17.214 ± 0.212^{ji}	15.898 ± 0.445^{fd}	17.355 ± 0.458^{gd}

The values within a column with different superscript letters are significantly different at $P \leq 0.05$ according to the Duncan's multiple range test.

#Before treatment and storage.

Chroma (C*) is an indicator of the tone for product colour. Generally, a lower C* was observed for juice from fruit packed with no-liner than from fruit packed with liners, throughout cold storage and shelf life periods (Tables 5.4 and 5.5). There was no significant difference in juice C* for fruit from all treatments, except for fruit packed with non-perforated 'Zoe' liner at 12 weeks of cold storage. At the end of 12 weeks of cold storage plus 5 days of shelf life, there was no significant difference in juice C* among fruit from all treatments. Gil *et al*. (1996) observed no significant difference in pomegranate juice colour for fruit stored at 0 °C and 5 °C. Nanda *et al*. (2000) reported slight changes in juice colour for both wrapped and un-wrapped 'Ganesh' pomegranate stored at different storage conditions.

5.3.3 Phytochemicals and antioxidant activity

5.3.3.1 Vitamin C content of pomegranate juice

Generally, there was a significant decrease in vitamin C content of juice from fruit packed in different packaging treatments with time, during both cold storage and shelf life periods (Table 5.6 and 5.7). For both cold and ambient storage conditions, Vitamin C content decreased within 4 weeks, increased at 6 weeks, remaining quite stable up to 8 weeks and then decreased to the end of 12 weeks. Fruit packed with no-liner maintained highest Vitamin C concentration, followed by fruit in perforated liners and lowest in fruit packed with non-perforated liner. At the end of 12 weeks of cold storage vitamin C concentration was 3.40, 3.01-3.21 and 2.70-2.73 mg AAE/100ml for fruit packed with no-liner, perforated liners and non-perforated liners, respectively. Selcuk & Erkan (2015) reported a similar range of results 0.16-9.24 mg AA/100g for 'Hicaznar' pomegranate stored at 6 °C and additional 3 days at 20 °C. The authors observed progressive decline in vitamin C content in the first 120 days and higher vitamin C concentration in no-liner control than in MAP liner treated fruit. The reduction in vitamin C concentration could be attributed to delayed biosynthesis or rapid degradation in MAP-stored fruit (Khan & Singh, 2008) or conversion of ascorbic acid to dehydroascorbic acid by ascorbic acid oxidase (Singh *et al*., 2005). However, Miguel *et al*. (2006) reports a significant increase in vitamin C levels in pomegranate fruit (cv. Mollar de Elche and Assaria) stored at 5 °C for 4 months. Abd-elghany *et al*. (2012) observed higher Vitamin C in wrapped fruit than in un-wrapped fruit.

Table 5.6 Effect of liner packaging on vitamin C, total phenolic concentration and anti-oxidant capacity of 'Wonderful' pomegranate fruit stored at 5 ° C and 90-95 % RH for 12 weeks

Storage time	Treatment	Vitamin C (mg AAE/100ml)	Total phenolics (mg GAE/100ml)	Anti-oxidant activity (% inhibition)
0 weeks	#Base line	3.490 ± 0.007^{ab}	624.854 ± 12.101^{a}	45.472 ± 7.148^{abc}
4 weeks	No-liner	2.785 ± 0.056^{ge}	587.537 ± 3.215^{ab}	46.892 ± 5.144^{ab}
	Xtend	3.543 ± 0.041^{ab}	545.898 ± 4.530^{cbd}	30.250 ± 1.432^{he}
	Decco	2.802 ± 0.072^{ge}	548.255 ± 39.569^{cbd}	32.379 ± 1.579^{h}d
	Zoe	2.720 ± 0.014^{gf}	552.183 ± 36.717^{cb}	36.050 ± 2.251^{abcdefg}
	2mm HDPE	2.563 ± 0.058^{g}	521.150 ± 34.373^{cbde}	35.756 ± 3.773^{abcdefg}
	4mm HDPE	2.817 ± 0.032^{gd}	461.442 ± 36.743^{ghe}	32.550 ± 4.138^{hd}
6 weeks	No-liner	3.800 ± 0.038^{a}	543.148 ± 3.788^{abd}	37.494 ± 1.656^{hd}
	Xtend	3.366 ± 0.071^{cb}	528.614 ± 31.631^{cbd}	33.970 ± 1.442^{hc}
	Decco	3.351 ± 0.076^{cb}	505.438 ± 12.037^{cdef}	30.519 ± 3.917^{he}
	Zoe	3.146 ± 0.036^{cbde}	460.657 ± 14.766^{ghe}	32.599 ± 3.598^{hd}
	2mm HDPE	3.291 ± 0.086^{cb}	402.127 ± 21.861^{h}	25.110 ± 2.945^{hg}
	4mm HDPE	3.291 ± 0.086^{cb}	404.091 ± 7.200^{h}	27.827 ± 2.017^{hf}
8 weeks	No-liner	3.241 ± 0.173^{cbd}	560.432 ± 27.082^{cb}	44.665 ± 3.413^{abcd}
	Xtend	3.174 ± 0.045^{cbde}	483.440 ± 9.060^{gd}	37.885 ± 4.961^{abcdef}
	Decco	3.184 ± 0.066^{cbde}	455.550 ± 11.908^{ghf}	22.418 ± 2.170^{h}
	Zoe	3.216 ± 0.313^{cbde}	435.909 ± 21.740^{gh}	34.459 ± 2.966^{hb}
	2mm HDPE	3.573 ± 0.065^{ab}	449.265 ± 2.187^{ghf}	38.436 ± 7.599^{abcdef}
	4mm HDPE	3.331 ± 0.048^{cb}	443.373 ± 10.808^{ghf}	47.920 ± 4.486^{a}
12 weeks	No-liner	3.398 ± 0.463^{ac}	525.079 ± 9.387^{cbde}	46.084 ± 3.131^{abc}
	Xtend	3.186 ± 0.033^{cbde}	425.696 ± 7.738^{gh}	42.413 ± 4.711^{abcde}
	Decco	2.700 ± 0.079^{gf}	461.835 ± 25.720^{ghe}	37.592 ± 3.056^{abcdefg}
	Zoe	2.728 ± 0.052^{gf}	452.407 ± 12.601^{ghf}	46.353 ± 1.870^{abc}
	2mm HDPE	3.206 ± 0.090^{cbde}	451.622 ± 6.950^{ghf}	37.910 ± 2.755^{abcdef}
	4mm HDPE	3.009 ± 0.045^{cdef}	447.694 ± 1.178^{ghf}	44.983 ± 4.742^{abcd}

The values within a column with different superscript letters are significantly different at $P \leq 0.05$ according to the Duncan's multiple range test.

#Before treatment and storage.

Table 5.7 Effect of liner packaging on vitamin C, total phenolic concentration and anti-oxidant capacity of 'Wonderful' pomegranate fruit stored at 5 ^{o}C and 90-95 % RH for 12 weeks plus 5 days at 20 ^{o}C and 65-70 % RH of shelf life

Storage time	Treatment	Vitamin C (mg AAE/100ml)	Total phenolics (mg GAE/100ml)	Anti-oxidant activity (% inhibition)
0 weeks	Base line	3.490 ± 0.007^{ac}	624.854 ± 12.101^{a}	45.839 ± 6.796^{a}
4 weeks	No-liner	3.311 ± 0.064^{cb}	586.751 ± 15.589^{ab}	43.490 ± 8.615^{ab}
+ 5 days	Xtend	3.543 ± 0.041^{ac}	452.407 ± 12.601^{hid}	45.472 ± 2.680^{a}
	Decco	2.802 ± 0.072^{fe}	548.255 ± 22.794^{cb}	$32.379 \pm 1.579^{abcdefg}$
	Zoe	3.588 ± 0.015^{ab}	491.296 ± 0.680^{cdef}	29.320 ± 4.948^{hc}
	2mm HDPE	2.563 ± 0.058^{f}	457.121 ± 4.249^{hd}	23.544 ± 1.164^{hf}
	4mm HDPE	$2.817 \pm 0.032f^{d}$	461.442 ± 36.743^{hd}	$32.550 \pm 4.138^{abcdefg}$
6 weeks	No-liner	3.800 ± 0.038^{a}	$514.080 \pm 19.747^{abde}$	$37.494 \pm 1.656^{abcdef}$
+ 5 days	Xtend	3.366 ± 0.071^{cb}	528.614 ± 31.631^{cbd}	$33.970 \pm 1.442^{abcdefg}$
	Decco	3.351 ± 0.076^{cb}	$481.476 \pm 17.550^{cdefg}$	42.095 ± 1.623^{abcd}
	Zoe	3.146 ± 0.036^{cde}	460.657 ± 14.766^{hd}	$32.599 \pm 3.598^{abcdefg}$
	2mm HDPE	3.291 ± 0.086^{cb}	$496.796 \pm 23.826^{cdef}$	42.952 ± 10.192^{abc}
	4mm HDPE	3.291 ± 0.086^{cb}	381.700 ± 8.845^{i}	25.942 ± 0.527^{he}
8 weeks	No-liner	3.296 ± 0.115^{cb}	549.433 ± 31.300^{cb}	$34.606 \pm 3.111^{abcdefg}$
+ 5 days	Xtend	3.408 ± 0.056^{ac}	465.370 ± 42.002^{hd}	$32.795 \pm 5.305^{abcdefg}$
	Decco	3.184 ± 0.066^{cbde}	455.550 ± 11.908^{hd}	22.418 ± 2.170^{hg}
	Zoe	3.216 ± 0.313^{cbd}	435.909 ± 21.740^{hif}	$34.459 \pm 2.966^{abcdefg}$
	2mm HDPE	3.573 ± 0.065^{ac}	402.520 ± 15.310^{hi}	27.890 ± 1.717^{hb}
	4mm HDPE	3.331 ± 0.048^{cb}	407.626 ± 16.512^{hig}	29.515 ± 1.971^{hb}
12 weeks	No-liner	3.399 ± 0.463^{ac}	$522.722 \pm 11.732^{cbde}$	28.549 ± 1.578^{hd}
+ 5 days	Xtend	3.195 ± 0.033^{cbde}	521.543 ± 34.400^{cbd}	42.413 ± 4.711^{abcd}
	Decco	2.706 ± 0.069^{f}	461.835 ± 25.720^{hd}	37.592 ± 3.056^{abcde}
	Zoe	2.728 ± 0.042^{f}	459.871 ± 7.338^{gd}	$35.2178 \pm 3.830^{abcdefg}$
	2mm HDPE	3.182 ± 0.006^{cbde}	461.049 ± 26.65^{1hd}	28.879 ± 1.814^{hd}
	4mm HDPE	3.256 ± 0.032^{cb}	497.189 ± 8.249^{cdef}	$32.134 \pm 2.766^{abcdefg}$

The values within a column with different superscript letters are significantly different at $P \leq 0.05$ according to the Duncan's multiple range test.

$^{\#}$Before treatment and storage.

5.3.3.2 Total phenolic content

Total phenolic concentration was 624.9 mg GAE/100ml before storage and generally decreased significantly ($P \leq 0.05$) with storage time and among treatments (Table 5.6). Generally, fruit packed with no-liner had higher TPC compared to all fruit packed with liners. At 12 weeks of cold storage, TPC was significantly higher in fruit packed with no-liner compared to fruit from all other treatments, except for fruit packed with non-perforated 'Decco' liners. A higher moisture loss in fruit packed with no-liner can be responsible for higher TPC. A lower O_2 and increased CO_2 inside liners could be responsible for relatively high TPC in fruit packed with non-perforated 'Decco' liners compared to fruit packed with perforated liners. However, among all liner treatments there was no significant difference in TPC of fruit juice. At the end of 12 weeks of cold storage and subsequent 5 days of shelf life period, fruit packed with no-liner treatment had the highest juice TPC, followed by fruit from perforated liners and lowest in fruit packed with non-perforated liners. However, there was no significant difference in fruit juice TPC among all treatments.

The degradation of total phenolic is related to enzymatic oxidation of polyphenol oxidase and peroxidase with time (Fawole & Opara, 2013c) while as the increase in phenolic concentration can be attributed to cold storage stimulation of certain enzymes that play a role in the synthesis of polyphenols during storage (Hamauzu, 2006). Our results were in agreement with finding by Mphahlele *et al*. (2016) who observed a general decrease in phenolic concentration for 'Wonderful' pomegranate fruit packed in MAP liners and shrink wraps and stored at 7 ^{o} C for 4 months. Arendse *et al*. (2014b) observed similar results on conventionally packed pomegranate (cv. Wonderful) stored for 5 months at 7.5 ^{o} C. Fawole & Opara (2013b) and Sayyari *et al* (2011) also reported a decline in phenolics for other pomegranate cultivars conventionally packed and stored at 2 ^{o} C and 5 ^{o} C. Contrary to our findings, Selcuk & Erkan (2014) reported a general increase in phenolic concentration for 'Hicrannar' pomegranate stored at 6 ^{o} C for 120 days. The authors also reported higher phenolic concentration in no-liner control fruit than in MAP treated fruit. Selcuk & Erkan (2015) reported an initial increase within 120 days and then a decrease to the end of 210 days at 6 ^{o} C for 'Hicaznar' pomegranates.

5.3.3.3 Anti-oxidant capacity (radical scavenging activity)

Ant-oxidant capacity was presented as the ability (%) of antioxidants in fruit juice to inhibit activity of free radicals. Generally, there was a decline in anti-oxidant capacity with storage time. The decline in anti-oxidant activity was lower in fruit packed with no-liner compared to fruit packed with liner (Tables 5.6 and 5.7). However, an increase in percentage inhibition was observed at 8 and 12 weeks of cold storage, generally in all treatments. The variation in anti-oxidant capacity is probably due to variation in total phenolic concentration, which also showed a similar trend. At the end of the 12 weeks of cold storage, percentage inhibition increased from 45.7 to 46.08 % for fruit packed with no-liner and 46.35 % for fruit packed with non-perforated 'Zoe' liners, compared to a decrease in the rest of the treatments. There was no significant difference in fruit juice anti-oxidant capacity among all treatments. However, after 5 additional days of shelf life, fruit packed with no-liner had the lowest percentage inhibition of 28.5 % compared to 37.6 and 35.2 % for fruit packed with non-perforated 'Decco' and 'Zoe,' respectively. Fruit packed with micro-perforated Xtend® had 42.4 % anti-oxidant activity, compared to 28.9 and 32.1 % for fruit packed with 2 mm macro-perforated and 4 mm macro-perforated HDPE liners, respectively. However, there was no significant difference in fruit juice anti-oxidant capacity among all treatments. Similar to our results, Mphahlele *et al*. (2016) observed higher radical scavenging activity (RSA) for no-liner control fruit than 'Wonderful' pomegranate fruit packed in passive MAP liners over a period of 4 months at 7 ° C. The authors also observed a similar trend with a decline in RSA followed by an increase for passive MAP liner treated fruit. Furthermore, D'Aquino *et al*. (2010) observed significant higher decline in antioxidant activity for wrapped fruit compared to un-wrapped fruit when 'Primosole' pomegranates were stored at 8 ^{o}C for 12 weeks and additional 1 week at 20 ^{o}C. Mphahlele *et al*. (2014) reported that the impact of MAP on fruit bioactive compounds is not well established, implying that many factor interactions influence antioxidant activity. The differences in antioxidant results reported in different studies can be attributed to variation in fruit cultivar, maturity and growing region (Mphahlele *et al*., 2014).

5.4 Conclusions

Generally, packaging pomegranate fruit in polyliners did not have significant impact on chemical attributes, phenolic content and anti-oxidant activity of pomegranate fruit. However, fruit packed in non-perforated liners significantly minimized the decrease in titratable acidity. Packing fruit in non-perforated 'ZOE' liners better-preserved fruit juice colour parameters; however, it should be noted that fruit suffer higher weight loss after extended storage period. Overall, this study has shown that using appropriate polyliners to reduce weight loss in pomegranates does not pose risk in retaining the phytochemicals and antioxidant capacity of fruit juice, commonly associated with the health benefits of consuming pomegranate products reported in the literature.

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SECTION IV

Chapter 6. General discussion and conclusion

6 General Summary and Conclusion

6.1 General summary

Currently, global increase in production, promotion and consumption of pomegranate is generally linked to its nutritional and health values, and increasing public health awareness (Holland & Bar-Ya'akov, 2008; Viuda-Martos *et al*., 2010). The pomegranate fruit industry suffers both quantitative and qualitative postharvest losses, however weight loss and decay are the major factors contributing to postharvest losses (Elyatem & Kader, 1984; Caleb *et al*., 2012). Pomegranate is highly prone to moisture loss owing to the relatively high water permeability across the skin through minute openings, despite having a thick rind (Elyatem & Kader, 1984). A combination of cold chain and packaging postharvest technique is important in minimizing quality losses in fresh fruit. Several internal packaging techniques such as thrift bags, bunch carry bags and shrink wrapping of individual fruit have been applied in the fresh fruit industry to minimize moisture loss (D'Aquino *et al*., 2010; Berry, 2013; Ngcobo *et al*.2012b). Plastic liners are a commonly applied internal packaging (IP) to minimize moisture loss for pomegranate and other fruit packaged in ventilated cartons (external packaging). However, the use of liners may give rise to moisture condensation within the bags and around the fruit especially due to temperature fluctuations. Moisture condensation can initiate and or accelerate fruit decay (Wiley *et al*., 1999). Furthermore, liners influence resistance to airflow (RTA), cooling rate and energy consumption during forced-air cooling (FAC) of apples, table grapes, straw berries and pomegranate (Wiley *et al*., 1999; Ngcobo *et al*., 2012a; Berry, 2013; Ngcobo *et al*., 2013; Mukama, 2015). It is therefore important that these liners be comprehensively assessed for suitability of use. Most research involving packing pomegranates in liners has focused on modifying the gaseous atmosphere around the fruit (Selcuk & Erkan, 2014; Selcuk & Erkan, 2015; Mphahlele *et al*., 2016) with less attention given to controlled moisture around the fruit and cooling characteristics during precooling and moisture dynamics around the fruit. This research aimed at assessing the impact of liners on the cooling characteristics and postharvest quality of pomegranate (cv. Wonderful) during cold storage and subsequent shelf life. Furthermore, the research highlighted the influence of perforated liners on pomegranate quality and resistance to air flow during forced air cooling. Fresh fruit suffer quite similar quality deteriorations during postharvest handling; due to limited literature on pomegranates, additional review of research work involving the use of internal packaging on other fruit was relevant.

Chapter 2 The use of internal packaging in postharvest handling and their impact on fruit cooling and postharvest quality – an interpretative review

The aim of the review was to provide an interpretative tool linking the different IP to application and effect in the postharvest fresh fruit industry. It also showed that there is increased application of multi-scale packaging (MSP) in the fresh fruit industry, where in addition to the external packaging (EP), internal packaging (IP) is incorporated inside containers. The review provided relevant information on the different types of IP and their role in offering protection, containment, convenience and communication along the value chain. This information facilitates making choice of IP depending on the type of fruit and target market.

The detailed discussion on the effects of internal packing on cooling characteristics and postharvest quality during storage suggests that critical consideration should be taken in choosing appropriate IP. Generally, IPs had more and clearer impact on fruit cooling characteristics than storage quality, probably because of vast physiological factors affecting the quality of fruit after harvest. Therefore, more research is needed to provide a multidisciplinary understanding of the multifactor interactions influencing fruit quality during storage. From this study of literature, it was identified that most of the IPs applied in the industry are made out of plastic and therefore pose environmental threats if not recycled. Therefore, more environmentally friendly approaches can be investigated.

From this review, we identified that there is very limited work done on the impact of IP of cooling characteristics of pomegranate fruit. It was also noted that liners are the most importantly applied IP in the postharvest storage of fresh fruit. Furthermore, liner perforation was identified as an important technique in solving the challenges associated with the use of polyliners in fruit pre-cooling process and storage quality.

Chapter 3. Effect of internal packaging (liners) on airflow resistance and cooling characteristics of packed pomegranate fruit (cv. Wonderful)

It is commendable that field heat be efficiently removed from the fruit stack as fast as possible to preserve quality even before prolonged storage. The objective of this chapter was to assess the impact of non-perforated and perforated liners on resistance to airflow (RTA), fruit cooling rate, cooling uniformity and energy consumption during the pre-cooling process. The findings in this study have added to the available scientific knowledge that packaging contributes more to RTA during forced air cooling of fresh fruit. Through this study, this knowledge is being extended specifically to the pomegranate fruit industry, where it has been scarce.

This study has pointed out that in pomegranate fruit packaging, IP specifically liners, are the biggest contributor to RTA compared to cartons and fruit. Therefore, more attention should be given to the design of IP (liners) so as to solve industrial problems related to delayed cooling and increased energy consumption. Results from this chapter have showed that perforated liners can be used to solve these challenges. In this study, the macro-perforated 2 mm 'Decco' liner showed the best perforation quality for minimizing RTA. For liners with same percentage ventilation area, the number of macro-perforations was observed to have more influence on RTA compared to size of macro-perforation, probably because of a higher chance of alignment of the liner perforations with the carton ventilation for easy airflow. To avoid blocking of air passages, critical designing to align liner perforations with carton vent holes should be considered. However, this is still a challenge given the diversity in carton designs used in the industry.

Though macro-perforations are important in solving cooling challenges of fruit, they compromise the ability of liners to modify the gaseous atmosphere around the fruit, which is important in the keeping quality during storage. Therefore, there is need to ascertain how the different liners affect the quality of fruit so as to strike a balance between improving cooling and improving keeping quality of the fruit through the use of perforated liners. This was investigated in the following chapters (4 and 5).

Chapter 4 Impact of internal packaging (liners) on moisture dynamics, physical and physiological quality of pomegranate during cold storage

This research chapter aimed at relating liner properties (the ability to modify both gaseous and moisture atmosphere around the fruit) to physical and physiological quality of pomegranate fruit (cv. Wonderful) during prolonged cold storage. The consideration given to different liner properties (water vapour transmission rate and gas composition inside liner bags) will provide integrated understanding of the effects of liners on fruit quality during prolonged storage.

The findings of this research chapter have contributed to available literature that liners significantly minimise weight and lineal size loss which commonly affect pomegranates during prolonged storage. Fruit packed with 2 mm macro-perforated HDPE, 4 mm macro-perforated HDPE and micro-perforated Xtend® liner, minimized fruit weight loss by 84.3 %, 62.5 %, and 73.2 %, respectively, compared to 94.0 % for fruit packed with non-perforated 'Decco' liner. Importantly, the research has contributed to the scarce scientific information about the potential use of perforated liners in preserving the quality of pomegranate fruit during prolonged storage. Non-perforated liners remain superior in minimising fruit weight loss, lineal size loss and associated disorders like shrivelling, in addition to preserving physiological quality through MAP compared to macro-perforated liners. However, using micro-perforated and macro-perforated liners minimised problems of moisture condensation and fruit decay, which were associated with packing fruit in non-perforated liners. A similar situation was observed in kiwifruit (Wiley *et al.*, 1999), and was attributed to the ability of perforated liners improving moisture transmission from around the fruit, avoiding excessive moisture accumulation.

Despite limited and lack of ability to modify the gaseous atmosphere around the fruit by micro-perforated Xtend® and macro-perforated 4 mm HDPE liners, respectively, fruit packed in both liners also retained acceptable quality (peel and aril colour, fruit weight, aril firmness) during prolonged storage. Financial losses due to decay outweigh financial losses due to weight loss. Therefore Using micro-perforated Xtend® and macro-perforated 4 mm HDPE can be considered to minimize postharvest losses instead of using non-perforated liners (it should be noted that 4 mm HDPE liners are over 3 times cheaper than micro-perforated Xtend® liners). Though physical appearance of the fruit is important in influencing marketability, chemical attributes of the fruit may contribute to the nutritional health of the consumers.

Chapter 5 Effect of internal packaging (liners) on chemical and phytochemical properties and anti-oxidant activity of pomegranate fruit during cold and shelf life storage

The internal quality of the fruit remains of uttermost importance, for it is the portion that goes to direct consumption by consumers. Pomegranate fruit is eaten fresh or processed into juice (Opara *et al*., 2009; Wetzstein *et al*., 2011). In this chapter, the impact of packing fruit in liners (MAP) on fruit juice colour, phenolic concentration, antioxidant activity and general chemical quality of pomegranate during prolonged cold storage and shelf life conditions were assessed. Storage time had significantly higher impact on internal fruit quality parameters compared to the influence of internal packaging treatments. In chapter 4, it was shown that non-perforated 'Decco' and 'Zoe' liners reduced O_2 and increased CO_2 concentration around the fruit. Therefore, it was expected that fruit packed with non-perforated liners will significantly retain better juice colour, chemical parameters, phenolic concentration and anti-oxidant activity compared to fruit packed with perforated liners (Drake *et al*., 2004; Selcuk & Erkan, 2014). However, there was no significant difference between the impact of packing fruit with non-perforated and with perforated liners, on most chemical attributes of pomegranate fruit juice. This could be partly attributed to the fact that pomegranate fruit are non-climacteric and therefore do not continue ripening after harvest, and therefore there was minimal alterations in the chemical quality attributes of the fruit.

From this research study, it is observed that the effect of liners on phytochemical and anti-oxidant activity of the fruit is not very clear as compared to physical attributes in Chapter 4. This is probably due to multi-factor interactions that suggest a multi-disciplinary research approach. Overall, this study has shown that using appropriate polyliners to reduce weight loss in pomegranates does not pose risk in retaining the phytochemicals and antioxidant capacity of fruit juice, commonly associated with the health benefits of consuming pomegranate products reported in the literature.

6.2 Conclusion and future prospects

The choice of a particular type of internal packaging material and design is often influenced by a multitude of factors related to market needs, type of product and cost. Bearing these in mind, Table 6.1 provides an interpretative summary of the major findings from this study, including the desirability level of the key attributes of fruit as well as control of moisture and gas composition.

Overall, this research study has shown that the use of perforated liners reduced resistance to airflow, energy consumption and moisture condensation associated with non-perforated liners, and yet retained fruit texture, colour, weight and chemical quality attributes during and after prolonged cold storage. However, future research needs to focus more on optimizing perforation quality in terms of size, number and distribution for better results. Given that plastic liners and other plastic internal packaging are widely applied in the industry, and thus presenting environmental threats, there is therefore a need to investigate the development of more environmentally friendly materials.

Table 6.1 Summary of the effects of liner packaging on fruit quality and control of moisture and gases inside the package

	No-liner	'Decco'	'Zoe'	Xtend®	2mm HDPE	4mm HDPE
Gas & moisture control						
Respiration rate	High	Low	Low	Moderate	Moderate	Moderate
Modifying gas composition inside bags	✗	✓	✓	✓	✗	✗
Water vapour transmission rate	N.A	Poor	Poor	Good	fair	Good
Condensation control	✓	✗	✗	✓	✗	✓
Fruit size loss						
Weight loss	Very high	Very low	Very low	Fair	Low	Fair
Length loss	Very high	Very low	Very low	Fair	Low	Fair
Diameter loss	Very high	Very low	Very low	Fair	Low	Fair
Circumference loss	Very high	Very low	Very low	Fair	Low	Fair
Peel thickness loss	Very high	Very low	Very low	Fair	Low	Fair
Fruit appearance						
Peel colour L*	Poor	Good	Good	Fair	Fair	Fair
a*	Good	Good	Good	Good	Good	Good
C*	Poor	Good	Good	Good	Fair	Fair
Shrivelling	Very high	None	None	Low	Very low	Low
Visible mold & decay	Very high	High	High	Moderate	High	Moderate
Texture properties						
Fruit puncture resistance	low	Good	Good	Moderate	Moderate	Moderate
Aril compression resistance		Moderate	Moderate	Moderate	Moderate	Moderate
Chemical attributes						
TSS retention	Good	Good	Good	Good	Good	Good
TA retention	Moderate	High	High	Moderate	Moderate	Moderate
TSS/TA	High	Moderate	Moderate	Moderate	High	High
Vitamin C retention	High	Moderate	Moderate	High	High	High
Total phenolic concentration	High	Moderate	Moderate	Moderate	Moderate	Moderate
Anti-oxidant activity	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate

🟩 Highly desirable 🟨 Moderately desirable 🟥 Un-desirable

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