RESISTANCE TO AIRFLOW, COOLING CHARACTERISTICS AND QUALITY OF POMEGRANATE FRUIT INSIDE VENTILATED PACKAGING

By

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Declaration

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Abstract

Ventilated packaging has found wide scale industry applications in fresh fruit handling and cooling operations. Given variations in fruit physical and thermal properties, optimal package design for a particular product and supply chain requires a multi-parameter approach incorporating cooling, mechanical and economic performance, as well as resource utilisation efficiency. A wide range of ventilated package designs are used in postharvest handling and marketing of fresh fruit, and several studies have investigated the cooling performance of fruit such as apples, citrus and table grapes; however, very little is known about the performance of pomegranate ventilated packaging. Therefore, the overall aim of this study was to evaluate the cold chain performance of some of frequently used ventilated cartons and internal packages (liners) during forced-air cooling (FAC) and cold storage in the South African pomegranate industry, in terms of resistance to airflow (RTA), cooling characteristics, energy efficiency and fruit quality.

The two studied carton designs, CT1 and CT2 had 5.4% difference in total ventilation. CT2 had relatively higher ventilation in both length and width directions (8.82% and 6.67%, respectively) compared to CT1 (6.52% and 2.86%). In a stack of cartons packed with fresh pomegranate fruit (cv. Wonderful), this resulted into a generally faster fruit cooling rate (29.19%) in CT2. However, the obstruction of vent-holes in the lengthwise orientation of the stack of CT2 resulted in over 50% higher RTA compared to CT1. The results also showed that packaging fruit inside a liner offered up to 50% greater RTA than fruit packaging with no liner. Consequently, the use of liners also delayed fruit cooling and increased energy consumption, with seven-eighths cooling times close to 3 times those of fruit inside packaging with no liner. Packaging fruit with liner required about 3.9 and 8.7 times more energy to cool fruit in CT1 and CT2, respectively, compared with no-liner. Fruit in carton stacks also exhibited a heterogeneous cooling pattern, with fruit in the upstream position to incoming air cooling about 36% faster compared to fruit at back stack position.

During FAC of fruit over a period of 11.6 and 4.5 hours in liner and no liner, respectively, the use of humidification to maintain 95±1% relative humidity (RH) minimised weight loss by about 13.63% compared to precooling fruit inside cold room at 90±1% RH. Fruit packaged without liners also lost about 17.39% more weight during precooling compared to fruit packaged with liners. Fruit in liners and without liners which took longer

to cool to set temperature (7^oC) lost more weight than fruit that got to set storage temperature faster.

A further study into the effects of RH on pomegranate fruit quality during ambient (20^oC) storage showed that storing fruit under high RH (95%) minimised weight loss, maintained fruit colour, firmness and physicochemical quality attributes. Storing fruit under low RH (65%) led to excessive weight loss up to 29.13±1.49% after 30 days (compared to 5.78±0.44% at 95% RH), thereby resulting into an estimated financial loss of ZAR7.78 kg^{-1} and ZAR1.54 kg^{-1} at low and high RH storage conditions, respectively. The onset of visible signs of shrivels occurred when fruit weight loss reached about 5.16%. Linear regression equations developed to estimate weight loss in pomegranates during ambient storage gave a high goodness-of-fit (R^2) of 0.9931 and 0.9368 for low and high RH environments, respectively.

This research has provided an insight into the effects of packaging design used in the pomegranate industry on cooling performance and impacts on fruit quality. Although the use of internal packaging (liners) minimised fruit weight loss, it increased RTA, precooling time, energy consumption and cooling costs. Cold room humidification offered potential remedy to the problem of high moisture loss of pomegranates. Further studies are warranted to optimise the vent design of pomegranate packaging, including the use of perforated liners, to improve cooling performance cost-effectively without compromising structural/mechanical performance in the cold chain.

Opsomming

Geventileerde verpakking het 'n wye skaal bedryfstoepassing in vars vrugte behandeling en verkoelings bedrywighede gevind. Sekere variasies in fisiese en termiese vrug eienskappe, optimale verpakkings ontwerpe vir 'n spesifieke produk en voorsieningsketting vereis 'n multi-parameter benadering wat insluit verkoeling, meganiese en ekonomiese prestasie, sowel as hulpbronbenutting doeltreffendheid.‘n Groot verskeidenheid van geventileerde verpakkings ontwerpe word gebruik in na-oes behandeling en bemarking van vars vrugte. Verskillende studies het die verkoelings uitwerking op vrugte soos appels, sitrus en tafeldruiwe ondersoek; Daar is egter baie min bekend oor die prestasie van granate in geventileerde verpakking. Die oorkoepelende doel van hierdie studie was om die verkoelings prestasie van sommige van die dikwels gebruikte geventileerde kartonne en interne pakkette tydens geforseerde lugverkoeling (GL) en koue storing in die Suid-Afrikaanse granaat bedryf te evalueer in terme van lugvloei weerstand (LW), verkoelings eienskappe, energie-doeltreffendheid en die kwaliteit van vrugte.

Die twee bestudeerde verpakkings ontwerpe, CT1 en CT2 het met 5.4% verskil in die totale ventilasie. CT2 het relatief hoër ventilasie in beide die lengte en breedte rigtings (8.82% en 6.67 % onderskeidelik) getoon in vergelyking met CT1 (6.52% en 2.86%). In 'n stapel van kartonne met vars granate (cv.Wonderful), was die verkoeling vinniger (29.19 %) met die CT2 verpakking. Die obstruksie van ventilasie openinge in die lengte van die stapel van die CT2 verpakking het gelei tot meer as 50% hoër LW in vergelyking met CT1 verpakking. Resultate het ook getoon dat die vrugte verpak in 'n sak, meer as 50% groter as LW vrugte verpakking is sonder ‘n sak. Die gevolg was dat die gebruik van sakke ook verkoeling van die vrugte vertraag en energieverbruik verhoog met sewe-agstes verkoelingtyd; omtrent 3 keer die van vrugte binnekant verpakking met geen sak. Verpakte vrugte in ‘n sak vereis omtrent 3.9 en 8.7 keer meer energie om vrugte af te koel in CT1 en CT2, onderskeidelik, in vergelyking met die sonder sakke. Vrugte in karton stapels toon ook 'n heterogene verkoelings patroon, met vrugte in die stroomop posisie van inkomende verkoeling sowat 36% vinniger in vergelyking met vrugte aan die agterste stapel posisie.

Gedurende GL van vrugte oor 'n tydperk van 11.6 en 4.5 ure met of sonder sakke, onderskeidelik, het die gebruik van bevogtiging om 95±1% relatiewe humiditeit (RH) te behou, gewigsverlies met sowat 13.63% geminimaliseer in vergelyking met vooraf verkoelde vrugte binnekant ‘n koelkamer by 90±1% RH. Vrugte sonder sakke verloor ook oor die 17.39% meer gewig tydens vooraf verkoeling in vergelyking met vrugte verpak in sakke. Vrugte in en of sonder sakke neem langer om af te koel na voorgeskrewe temperature (7°C) verloor meer gewig as vrugte wat vinniger in opgestelde koel stoorgeriewe blootgestel word.

'n Verdere ondersoek na die uitwerking van RH op die vrugte kwaliteit van granate onder omringende (20°C) berging toestande, het getoon dat die vrugte onder hoë RH (95%) lei tot minimale gewigsverlies, behou vrugte kleur, fermheid en fisio-chemiese kwaliteite. Vrugte gestoor onder lae RH (65 %) het gelei tot oormatige gewigsverlies tot 29.13±1.49% na 30 dae (in vergelyking met 5.78±0.44% op 95% RH) en sodoende tot 'n geskatte finansiële verlies van ZAR7.78 kg^{-1} en ZAR1.54 kg^{-1} teen 'n lae en hoë RH bergingstoestande,

onderskeidelik. Die aanvang van sigbare tekens van “shrivels” het plaasgevind toe vrugte gewigsverlies van omtrent 5.16% bereik het. Lineêre regressievergelykings was ontwikkel om te skat wat gewigsverlies in granate tydens berging was; gevolglik was hoë passingstoets (R^2) van 0.9931 en 0.9368 vir lae en hoë RH omgewings.

Hierdie navorsing het 'n insig verskaf in die uitwerking van verpakkings ontwerpe wat gebruik word in die granaatbedryf op verkoelings prestasie en die impak op vrugkwaliteit. Hoewel die gebruik van interne verpakking (sakke) die vrugte gewigsverlies geminimaliseer het, het dit LW verhoog, voorafverkoelings tyd verleng en energie verbruik en verkoeling koste opgestoot. Koelkamer bevogtiging het moontlike oplossings vir die probleem van hoë vog verlies van granate gebied. Verdere studies is gewaarborg om die ventileringsontwerp van granaat verpakking te optimaliseer, asook die gebruik van geperforeerde sakke, om verkoelings prestasie kostedoeltreffend sonder om strukturele/meganiese prestasie prys te gee in die verkoelingsproses.

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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.

Chapter 1 : General introduction

Packaging plays very critical roles of enclosing, containing, protecting, preserving, storage, communicating, sale and distribution of agricultural and other industrial products (Hawkins, 2012; Robertson, 2013). Proper handling, temperature and relative humidity (RH) control as well as packaging favourably preserve horticultural products (Kader, 2006; Fawole & Opara, 2013a; Arendse *et al*., 2014). Preservation of fruits and vegetables is still a challenge due to high respiration rates (Caleb *et al*., 2012) in addition to dehydration, oxidation and microbial decay; yet the demand for raw and fresh-cut fruits and vegetables is on increase (Ladaniya, 2008; Robertson, 2010). Ventilated corrugated fiberboard cartons are widely used packages in the fresh fruit industry (Opara, 2011; Pathare *et al*., 2012; Opara & Mditshwa, 2013). Fresh horticultural cartons are usually provided with openings or vents whose major function is maintaining an air flow between the inside and the surrounding of the container (Zou *et al*., 2006; Ngcobo *et al*., 2012; Pathare *et al*., 2012). Given that fruit and vegetables remain alive (respiring) even after harvest and that marketability is reduced when cooling is delayed (Ngcobo *et al*., 2013), ventilated packaging is essential to ensure that cold air, at the required temperature, is delivered timely and cost-effectively inside the package during precooling and storage (Delele *et al*., 2013; Opara & Mditshwa, 2013).

Precooling, a very important postharvest operation in horticultural produce handling, is applied to remove field heat rapidly in order to minimize the rate of physiological and biological changes affecting quality, which are mainly temperature driven (Brosnan & Sun, 2001; Ravindra & Goswami, 2008). Forced-air cooling (FAC) is among the most widely used horticultural precooling methods (Thompson *et al*., 2008; Dehghannya *et al*., 2010). It involves forcing cold air through vented containers and past individual products along an induced pressure gradient (De Castro *et al*., 2005; Kader, 2006; Ladaniya, 2008; Ravindra & Goswami, 2008; Thompson *et al*., 2008; Ferrua & Singh, 2009; Berry, 2013; Opara & Mshidtwa, 2013). Produce cooling rate during FAC is affected by several factors related to ventilated package design (open area, size, shape, number and position of vents), internal packages (such as liners and trays), carton stacking and stack porosity, operation of the cooling facility (such as airflow rate) and produce physical and thermal properties (Vigneault & Goyette, 2002; De Castro *et al*., 2005; Delele *et al*., 2013; Ngcobo *et al*., 2013). These properties of produce and packaging also affect pressure drop, air distribution and efficiency of precooling (Pathare *et al*., 2012; Berry, 2013; Delele *et al*., 2013). The energy required to maintain airflow during FAC and achieve the desired fruit temperature is mainly a function of pressure drop, which is also affected by carton ventilation and internal packages (Thompson *et al*., 2008; Defraeye *et al*., 2014). Energy consumption is also affected by FAC fan and cooling unit efficiency, product stacking, respiratory heat from produce, external heat infiltration and initial produce field heat (Thompson *et al*., 2010; Defraeye *et al*., 2014).

Fruit storage temperature, RH and time affect the shelf life, marketing, moisture loss characteristics, internal and external quality of fruit. The longer the exposure of fruit to higher temperatures, the higher the deterioration level, each 10^{o}C rise in temperature increases enzymatic and microbial activity by at least two times in the range 0-60^{o}C (Mitchell *et al*., 2008). To achieve products of high quality and a higher value, maintenance of the cold chain is thus essential throughout the whole fruit handling chain right from harvest through to marketing (Thompson *et al*., 2008). The relative humidity of the storage environment mainly has a significant effect on moisture loss and subsequent appearance of fruit. Moisture loss from fruit is normally in water vapour form and it manifests through shrivelling, wilting and weight loss (Arendse *et al*., 2014). Moisture loss is highest in the first two to three weeks after harvest when cold stores are still being filled until when fruit attain the storage temperature (Waelti, 2010). Fruit susceptibility to decay increases with continuous moisture loss from fruit as the plant cells weaken making them easily attacked by pathogens resulting in greater ethylene production and loss of product fresh colour (Mitchell *et al*., 2008). Naturally fruit skins have a cuticle that functions as a barrier against water and gas loss, pathogen attack and sun burn but its structure changes as fruit matures and even after harvest (Montero-Calderon & Cerdas-Araya, 2012). Rapid moisture loss has been reported to be minimised through fruit packaging, precooling and humidification (Delele *et al*., 2009; Waelti, 2010; Montero-Calderon & Cerdas-Araya, 2012). On top of losing sellable weight, shrivelled fruit have a lower visual appeal (Arendse *et al*., 2014).

The pomegranate (Punica granatum L., Punicaceae), native to Central Asia, is a beloved ancient fruit and tree that requires long, hot, and dry season for a good yield of fruit of high quality. Trees are adoptive to wide climatic and soil conditions making growth possible in different regions geographically, for example the Mediterranean basin, Asia and California. In the southern hemisphere, new orchards are being planted in South America, South Africa and Australia (Holland *et al*., 2009). Depending on variety, fruit ripen 5 to 8 months post fruit set. Botanically classified as a berry, pomegranate fruit is commonly consumed fresh with edible portion accounting for about 55-60% total fruit weight (Al-Said *et al*., 2009; Fawole & Opara, 2013b) The edible part (arils) is comprised of juice (75-85%) and seeds/kernels (15-25%). The edible part is also frequently processed into other products such as juice, wine, syrup and jam (Kader, 2006; Opara *et al*., 2009).

Iran and India are the global pomegranate market leaders followed by Turkey and USA (Marriet, 2012; POMASA, 2015). Supply season in the Northern hemisphere is from August to January but March to July in the Southern hemisphere including South Africa (Fawole, 2013; Rymon, 2011). The total area under pomegranate production in South Africa is estimated at 1000 ha (POMASA, 2015) and a recent survey by Mariette (2012) put total number of plantings at 754 ha with ‘Wonderful’ being the most planted cultivar and accounting for over 56% of the cultivated area. Pomegranate exports increased by about 40% during 2014 from the previous year, and it was estimated that the expected production in 2015 would reach 12,000 metric tonnes compared to 2,264 metric tonnes in 2012 (Marriet, 2012; POMASA, 2015). Global consumption and production of pomegranate has grown tremendously in recent years, and this has been mainly attributed to the reported health benefits like decreasing cardiovascular diseases associated with consuming pomegranate products (Vuida-Martos *et al*., 2010). It is currently the 18th most consumed fruit globally and is expected to move to the 10th within the next ten years as information about the health benefits become increasingly known among consumers and the general public(POMASA, 2015).

Pomegranate fruit has low respiration rate and is known to follow a non-climacteric respiration pattern; however, carbon dioxide and ethylene production increases with increase in storage temperature (Elyatem & Kader, 1984; Caleb *et al*., 2012). Pomegranates need proper handling and care during harvesting and postharvest handling to reduce the incidence of physical damage. The leathery skin is highly susceptible to scuffing and abrasion damage and the presence of micro cracks aid water loss (Opara *et al*., 1997; Maguire *et al*., 2001). Other factors affecting fruit appearance quality include decay and presence of physiological disorders (Kader, 2006). Fruit weight loss, mainly through moisture loss, increases during storage especially if stored at high temperature (above the recommended optimum, 5-10^{o}C) (Kader, 2006) for long time, especially at relative humidity lower than 90%. It has been reported that, in general, visible shrivelling begins to occur when weight loss reaches 5% of fruit weight (Kader *et al*., 1984); however, little is known about this phenomenon in pomegranates. During long term cold storage, pomegranates are susceptible to stem-end scald, which is a major physiological disorder that can result in up to 60% brown discoloration of fruit skin. Although the internal tissues of disordered fruit are not affected by scald, deviations from the characteristic red colour of fresh pomegranate fruit is a major limiting factor contributing to downgrading and rejection during marketing (Kader, 2006).

Given the considerable variations in fruit type and thermo-physical properties (such as size, shape, firmness and heat transfer coefficient), the optimisation of package design for a particular product and supply chain requires special consideration (Opara, 2011). What works for one product and/or supply chain may not perform optimally for another. While considerable research has been reported on the cooling performance of multi-scale packaging on other types of fruit such as table grapes (Ngcobo *et al*., 2013), citrus (Defraeye *et al*., 2013) and apples (Delele *et al*., 2013) , there is hardly any literature on cooling performance of packaging types and designs used in the pomegranate industry. Researchers have shown that inadequate cooling and packaging of horticultural produce affects the postharvest quality (Brosnan & Sun, 2001; Opara and Mditshwa, 2013) and may lead to significant economic losses especially after long term storage and shipping. Therefore, the overall aim of this study was to evaluate the cooling performance of some of the frequently used pomegranate ventilated cartons and internal packages in the South African pomegranate industry, in terms of airflow resistance, energy efficiency, cooling characteristics and fruit quality during precooling and cold storage.

This aim was achieved through three specific research objectives by:

(a) Evaluating the resistance to airflow, cooling characteristics and energy consumption of pomegranate fruit inside ventilated cartons during precooling;

(b) Investigating the effects of internal packages, stacking and humidification on pomegranate fruit moisture loss inside ventilated cartons during precooling; and

(c) Investigating the effects of relative humidity (RH) on pomegranate fruit quality under simulated ambient storage conditions.

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Chapter 2 : Literature Review

Resistance to airflow and cooling performance of ventilated horticultural packaging

1. Packaging, precooling and storage of horticultural produce

Packaging is the enclosure of products, and an industrial and marketing technique for containing, protecting, preserving, storage, communicating, identifying, sale and distribution of agricultural and other industrial products (Robertson, 2013). Food packaging is a key development in protection of food and consumers against harmful microorganisms, contamination and extension of food shelf life (Hawkins, 2012). It ensures safe handling and delivery to consumers of all foods from point of production. However, for packaging to meet its functions, choosing the right format is very important. Considerations like structure and form, efficiency as well as disposal after use are equally important (Opara & Mditshwa, 2013).

Packaging may be classified into different levels depending on the stage of introduction onto the food. In primary packages, there is direct contact with the product providing the initial and usually the most significant protective barrier. In the food industry, these vary from metal cans to glass bottles, paper and plastic pouches (Robertson, 2013) and they form a major part of retail businesses. Secondary packages, for example, corrugated cartons contain a number of primary packages while tertiary packages (e.g. a stretch wrapped pallet of corrugated cartons) contain a number of secondary packages (Robertson, 2013). International sea trade uses reefer containers up to 12 m in length holding many pallets. This is classified as a quaternary package, with certain designs having the ability to enable environmental (temperature and relative humidity) and atmospheric gas control (O_2, N_2, CO_2) which are important in handling, movement and maintenance of quality of frozen products as well as fresh fruit and vegetables (Robertson, 2013).

1.1. Generalised functions of packaging

The main functions of packages are protection, containment, convenience and communication (Paine & Paine, 1992; Coles & Kirwan, 2011; Robertson, 2013). Packaging protects products against external factors ranging from gases to moisture, living organisms (macro and micro) and mechanical forces (drops, compressional, vibrational and impact forces) (Pathare & Opara, 2014; Opara & Patahare, 2014). This is important in extending the useful life of food, food safety and quality maintenance (Han, 2005). Protection is also closely linked to preservation; for example, vacuum packaged meat will only achieve its shelf life if the package does not permit gas exchange (Robertson, 2013). Most horticultural products are relatively small in size and thus, to enable movement from place to place, these have to be contained in a package (Robertson, 2013).

Consumer life styles have changed tremendously with the industrialisation and modernisation of most societies. More women are taking on full time careers while some people are living singly and mostly eat on the run. This has created demand for food portions that are easily eaten and convenient. Packaging provides this convenience where foods are apportioned in quantities that are easily consumed and simply reheated preferably in their primary package (Coles & Kirwan, 2011; Robertson, 2013). Shapes and features have been added that ease handling, opening and pouring. In international trade, packaging plays a convenience role through enabling unitisation; primary packs such as ventilated corrugated cartons are stacked onto pallets which are loaded into containers that are then shipped (Coles & Kirwan, 2011; Robertson, 2013). Right from the manufacturing post, through to transportation, sales, consumption up to waste disposal, a package should be convenient to the handler (Han, 2005; Yam *et al*., 2005).

In modern markets such as supermarkets, consumers are only able to recognise products through their brand names, shapes and labels. This is the communication function of packaging. In international trade, due to different languages involved, labels are suited to meet the language market requirements. Product nutritional information which in most cases is mandatory, storage and cooking instructions are all included (Robertson, 2013). New packaging technologies have been designed to function beyond just conventional protection barrier properties to include oxygen and/or moisture scavenging properties, edibility, and atmosphere control in modified atmosphere packaging (Banda *et al*., 2015; Hussein *et al*., 2015). Some of these packages have antimicrobial activity (Gutierrez *et al*., 2009) while others have been designed with eased biodegradability (Han, 2005).

1.2. Effects of packaging on fruit quality

Fruit undergo deteriorative physiological and pathological changes after harvest. These changes are meant to sustain essential biological processes in the harvested fruit. Unlike when fruit is still attached to the tree, harvested fruit must draw energy from its own stored reserves to sustain chemical and physiological activities. These activities are accelerated when handled at high temperatures causing continuous deterioration (Mitchell *et al*., 2008; Caleb *et al*., 2013). These deteriorative changes are mainly qualitative and result in the fruit becoming less palatable or inedible, lose nutritional quality, calorific value and consumer acceptability (Kader & Rolle, 2004; Arendse *et al*., 2014).

According to Kader and Rolle (2004), quality of a product can be defined as the degree of preference of a product. Consumers mainly judge quality based on appearance at time of purchase and subsequent satisfaction, while wholesalers and retailers consider appearance, texture and fruit shelf life. Producers consider yield, appearance, ease of harvest and shelf life as fruit quality parameters (Kader & Rolle, 2004). Fruit quality attributes range from visual to nutritional attributes. Visual attributes are mainly centred on the fruit appearance; like absence of defects, colour, shape, size, and gloss. Appearance is affected at different fruit stages, before harvest, at harvest and postharvest. Before harvest, insect and bird pests or diseases affect fruit; at harvest, appearance defects are mainly due to poor handling that may lead to bruises, scrubs and scars; and postharvest changes in fruit appearance and texture are mainly driven by chemical and biological processes (Fawole & Opara, 2013) in the fruit as well as handling (Kader & Rolle, 2004). Fruit textural properties like firmness and juiciness (Arendse *et al*., 2014) are also important quality attributes that are considered in packaging and fruit handling as some may need to be harvested for shipping before maturity especially soft climacteric fruit (Kader & Rolle, 2004). Nutritionally, fruit are important sources of vitamins, minerals, dietary fibre and antioxidants.

Consumers have different flavour preferences with some preferring sweet, sour, bitter or even fermented fruit and these affect choice and purchase behaviour. Packaging and subsequent handling of fruit is all in the interest of maintaining and/or attaining these quality parameters for the benefit of the ultimate consumer (Kader & Rolle, 2004; Robertson, 2013). Proper handling, temperature monitoring and packaging favourably preserve fruit and vegetables (Caleb *et al*, 2013). Fruit preservation is still a challenge due to high respiration rates in addition to dehydration, oxidation and microbial decay; yet the demand for raw and fresh-cut fruit and vegetables is on increase (Caleb *et al*., 2012; Arendse *et al*., 2014). Pomegranates have a low respiration and a non-climacteric respiration pattern but their carbon dioxide and ethylene production increases with increase in temperature (Elyatem & Kader, 1984; Arendse *et al*., 2014). Packaging in combination with other food preservation methods is expected to preserve and extend the useful life, freshness and quality of products, mitigating unwanted moisture loss, decay and physical damage.

1.2.1. Moisture loss

Moisture loss from fruit is normally in water vapour form and it manifests through shrivelling, wilting and weight loss (Arendse *et al*., 2013). Moisture loss is highest in the first two to three weeks after harvest when cold stores are still being filled until when fruit attain the storage temperature (Waelti, 2010). These changes affect fruit appearance, consumer acceptance and the overall value on the market. Table 1 gives examples of the critical moisture loss levels of some products. Susceptibility to decay increases with continuous moisture loss from a fruit as the plant cells weaken making them easily attacked by pathogens resulting in greater ethylene production and loss of product fresh colour (Mitchell *et al*., 2008). Naturally fruit skins have a cuticle that functions as a barrier against water and gas loss, pathogen attack and sun burn but its structure changes as fruit matures and even after harvest (Montero-Calderon & Cerdas-Araya, 2012).

During water loss, water vapour moves from the saturated intercellular spaces within the product to the outside environment through openings on the fruit that include the stomata, lenticels, directly through the cuticle depending on its thickness, stem scars or even injured areas. This moisture movement depends on the vapour pressure difference (VPD) between the environment in the fruit and the outside with a high VPD causing rapid loss (Mitchell *et al*., 2008; Montero-Calderon & Cerdas-Araya, 2012; Ngcobo *et al*., 2013a). It also depends on the surface area to volume ratio of the produce for example large leafy vegetables with large surface area lose moisture at rates higher than relatively small fruit, variety and maturity stage. While the vapour pressure of the inside of the fruit depends on its temperature; that of its surrounding depends on the environmental temperature and relative humidity (Waelti, 2010). Most products prone to moisture loss are protected by rapid precooling, keeping a high relative humidity in the cold rooms or using polyliner bags during packaging (Mitchell *et al*., 2008; Montero-Calderon & Cerdas-Araya, 2012; Ngcobo *et al*., 2013b). However, polyliner bags have been found to significantly contribute to resistance to airflow during forced-air cooling hence delaying fruit precooling (Ngcobo *et al*., 2012a; Berry 2013).

Pomegranates lose weight during storage especially if stored at a high temperature for a long time at relative humidity lower than 90% (Fawole & Opara, 2013; Arendse *et al*., 2014). This loss of weight is due to moisture loss through transpiration - the loss of moisture from living tissues. To a relatively small extent, some weight loss in horticultural crops is due to carbon loss during respiration (Kader *et al*., 1984; Waelti, 2010). Fruit that lose 5% weight begin shriveling (Kader *et al*., 1984). Arendse *et al*. (2014) in his study on the effects of temperature and storage duration on pomegranates reported that increase in temperature and longer storage duration resulted in increased loss of moisture with the fruit skin being the main route evidenced by significant reduction in peel thickness.

The difference between the vapour pressure in the product interior and that of the surrounding air (VPD) and the commodity transpiration coefficient are used to estimate the rate at which a commodity loses moisture. The assumption is that the air in the product intercellular spaces is saturated (Ladaniya, 2008; Mitchell *et al*., 2008). Vapour pressure is calculated based on equation 1 (Mitchell *et al*., 2008):

$$Vp = \frac{w \times Pa}{0.622} \qquad (1)$$

where Vp – vapour pressure (Pa); w – humidity ratio (kg water vapour/kg dry air; determined from psychometric chart); Pa – atmospheric pressure (Pa); 0.622 – ratio of molecular weight of water to that of air.

Cooling fruit very fast to the required storage temperature reduces the VPD between the fruit and its surrounding thereby minimising water loss. Cold air has low vapour pressure because of its low water vapour holding capacity compared to warm air. Maintaining high relative humidity is very important in fruit storage with most perishables requiring 90-95% relative humidity storage (Mitchell *et al*., 2008). The level of relative humidity in a storage room is mainly affected by evaporator coil design and operation, humidification and the design of the cold room (insulation) (Waelti, 2010). The advantage with high relative humidity is that the corrugated fibreboard cartons may absorb some moisture limiting the cartons uptake of moisture from the product during subsequent handling and storage (Thompson *et al*., 2008a). However, high relative humidity environments have been reported to weaken paperboard packages due to wetting (Ngcobo *et al*., 2013b) and increasing fruit susceptibility to decay (Mitchell *et al*., 2008). Cooling processes like forced-air cooling can augment moisture loss as the air picks with it moisture from the surrounding of the product. This calls for controlled necessary flow rates during precooling and reduction thereafter through storage and transportation (Thompson *et al*., 2008a). Humidity management and use of humidifiers has become part of the modern fruit industry (Delele *et al*., 2009) with presence at most new storages in Europe (Waelti, 2010). Vaporised water in form of a fine mist from high-pressure low-volume nozzles is necessarily added to the circulating cooling air in the cold room depending on detection of fluctuation from modern humidity sensors to keep the cold room at the required relative humidity (Waelti, 2010).

Table 1 Weight loss at which commodities become unsalable, in order of increasing weight loss (Robinson *et al*., 1975; Nelson, 1985; Hardenburg *et al*., 1986; Hruschka, 1997; Thompson, 2008b)

Commodity	**Minimum weight loss (% fresh weight)**	**Manifestation**
Spinach	3	Wilting
Broccoli	4	Taste, wilting
Turnip with leaves	4	Wilting
Tomato	4	Shrivel
Leaf Lettuce	3-5	Wilting, decay
Grapes	5	Berry shrivel
Pear	6	Shrivel
Cabbage	6	Shrivel
Apple	7	Shrivel
Persimmon	7	Shrivel
Carrot	8	Wilting
Brussel sprouts	8	Wilting, rot, yellowing
Green pepper	8	Shrivel
Peach	11	Shrivel
Winter squash	15	Hollow neck

1.2.2. Decay

Pathological decay is estimated to account for over 50% of the total wastage in the citrus fruit industry and while some of the pathogens are air borne (e.g. *Penicillium* spores), others are soil borne (e.g. *Rhizopus*) (Ladaniya, 2008). Decay incidence is normally associated with handling conditions and initial product microbial quality. Contamination occurs in the field, at harvest and marketing (Ladaniya, 2008; Mitchell *et al*., 2008). Organisms that cause fungal rot strive within different conditions, for example, *Rhizopus stolonifera* and

Aspergillus niger do not grow at storage temperatures below 5^{o}C, Aspergillus does not grow at temperatures below 15^{o}C, while some like *Botrytis cinerea* (gray mould) and blue mould (*Penicillium expansum*) continue to grow at temperatures below 0^{o}C, though at reduced rates (Mitchell *et al*., 2008).

Most fungal infections spread very rapidly from one fruit to another. 'Nesting' type fungi like blue mould produce enzymes that soften adjacent fruit to ease entrance while *Rhizopus* infect all neighbouring fruit just as mycelia get into contact with them. *Penicillium* on the other hand causes rapid ethylene production accelerating senescence of adjacent fruit (Ladaniya, 2008). Fungal infection and decay affects wettable packaging materials like corrugated fiberboard cartons leading to loss of mechanical strength as they get wetted by decomposing fruit (Ladaniya, 2008). Decay susceptibility increases with warm conditions especially temperatures between 25-40^{o}C and high relative humidity (Ladaniya, 2008; Mitchell *et al*., 2008; Ngcobo *et al*., 2013b). Fruit contact with the ground at harvest may cause pick up of pathogens like Galactomyces *spp*. (causes sour rot) that live in the soil. Wounds and bruises on fruit surface caused by mechanical damage also serve as pathogenic entry points (Ladaniya, 2008; Mitchell *et al*., 2008; Montero-Calderon & Cerdas-Araya, 2012).

1.2.3. Mechanical damage

As fruit are harvested, transported and stored, they are prone to damage from compressional, impact and or vibrational forces (Mitchell *et al*., 2008; Montero-Calderon & Cerdas-Araya, 2012; Pathare & Opara, 2014). Mechanical damage to fruit is in the form of bruises, cuts, scrapes and abrasions. Bruise damage is the most common, occurring at harvest and during postharvest operations (Opara & Pathare, 2014). In effect, fruit lose moisture through the damaged areas; lose marketability and the damaged areas become easy pathogen entry points. Damaged fruit also have increased respiration and ethylene production, increased susceptibility to decay, and a generally shortened shelf life (Mitchell *et al*., 2008). Cold fruit are mostly susceptible to compression and impact damage while warm fruit are more susceptible to vibrational damage in transit (Mitchell *et al*., 2008). Fruit properties like development stage at harvest, firmness, density, volume, puncture resistance and shape also influence the susceptibility to damage by vibration, compression and impact forces. Firm fruit have greater resistance to these forces compared to soft fruit (Ladaniya, 2008). Effects like browning and discoloration of mechanically damaged fruit arise from the interaction between the polyphenol oxidase enzyme and the polyphenols of the fruit following damage of the internal tissues (Montero-Calderon & Cerdas-Araya, 2012). Proper cushioning in packages, smooth surfaces in machinery and transportation vehicles help reduce mechanical damage to fruit (Ladaniya, 2008).

1.3. Precooling and storage

Temperature and time affect the shelf life and marketing of fruit. The longer the exposure of fruit to higher temperatures, the higher the deterioration level, each 10°C rise in temperature increases enzymatic and microbial activity by at least two times in the range 0-60°C (Mitchell *et al*., 2008). To achieve products of high quality and a higher value, maintenance of the cold chain is essential throughout the whole fruit handling chain right from harvest through marketing. If not possible throughout the chain, at least optimum storage temperatures should be observed in a portion of the product handling as is better than no refrigeration at all (Thompson *et al*., 2008b). According to Kader (2006), pomegranates are harvested into bags, transferred to harvest bins and transported to pack-house for sorting. Scuffing, cuts, bruises, splitting and decay are parameters considered in sorting. Those with severe defects are eliminated; moderate defects are processed into juice, while pomegranates with slight or no defects get to the fresh fruit market after washing, air drying, fungicide treatment, waxing, categorisation and packing in shipping containers. During storage, transport and retail distribution, packed fruit are cooled by forced-air cooling, and then stored at 5 - 10°C, 90-95% relative humidity. Some pack-houses use plastic liners to reduce water loss (Kader, 2006).

Precooling is an important postharvest operation in fruit and should be done as fast as possible because of their perishable nature. It is intended to remove the field heat rapidly postharvest to minimize physiological (respiration, moisture loss and ethylene production) and biological (enzyme and microbial) changes which are mainly temperature driven or dependent (Ravindra & Goswami, 2008). According to Ladaniya (2008), fruit cooling depends on a number of factors that include the fruit's initial and expected final temperature, fruit surface area to volume ratio, temperature, volume and velocity of cooling medium, and the ease of contact between the cooling medium and the fruit. The design of most refrigerated transportation vehicles, some cold storage rooms, ship holds and reefers is to maintain temperature of already precooled produce and not precooling as air circulation may be inefficient to cool loaded cartons. This necessitates that precise temperature and relative humidity management in special fast cooling facilities is employed initially to quickly cool down harvested produce (Ladaniya, 2008; Thompson *et al*., 2008a). Most citrus fruit and pomegranates are precooled after other postharvest treatments and packaging. Relative humidity management is very important in fruit cold chain management (Delele *et al*., 2009; Ngcobo *et al*., 2013b). For cold storage of pomegranates and most other types of fruit, it is recommended that relative humidity should be kept between 90-95% (Kader, 2006) in the precooling and storage room so that the fast moving cold air does not have a drying effect on fruit. However, this prevention of moisture loss only depends on how fast the produce attains the temperature of the cooling medium (Ladaniya, 2008).

Choice of technique for precooling is influenced by nature of product, product packaging requirements, product flow and economic constraints. Some of the methods include hydrocooling, room cooling, vacuum cooling, cryogenic cooling, package icing and forced-air cooling with many alterations (Brosnan & Sun, 2001; Ladaniya, 2008; Thompson *et al*., 2008b). Table 2 gives a comparison of some of the common cooling and precooling methods and their requirements. Hydrocooling involves immersing products in chilled water or showering product with chilled water in batch or continuous flow systems. It is mainly used in leaf vegetables, asparagus, and cherries, and can be easily integrated into a packing line (Thompson, 2008a). Since pomegranates and other citrus fruit are precooled mostly after packaging, hydrocooling would weaken cartons made of wettable material like fibreboard. Hydrocooling also has a disadvantage of predisposing fruit to decay because of the damp environment, and if the water recycled is not properly treated, could act as a carrier of spores and other contaminants. It is thus, not ideal for such products as citrus despite the fact that it is faster than forced-air cooling commonly used (Ladaniya, 2008).

Package icing is a traditional method that involves packing ice flakes or fine ice particles with the product. It is often applied in the flower industry moved in unrefrigerated vehicles or mail deliveries. Icing increases the relative humidity around the product reducing moisture loss. It has limitations of extra transit weights, only applicable in water resistant containers and not suitable in citrus due to chilling injuries at contact sites (Thompson, 2008b). On the contrary, in vacuum cooling, products like lettuce are placed in an air tight chamber, and then the boiling point of the water inside the product is reduced to its field temperature by reduction of the atmospheric pressure in the chamber causing rapid vaporisation of the water and cooling as the product loses latent heat of vaporisation. It is not suitable for large round fruit as cooling will be slow due to a small surface area to volume ratio (Thompson *et al*., 2008b). Cryogenic cooling involves use of cold cryogenic liquids, liquid nitrogen and liquid carbon dioxide (Kondratowicz & Matussevicius, 2002).

Table 2 Comparison of the effects of common horticultural cooling methods on products and costs (Thompson *et al*., 2008b)

	Forced-air	**Hydro**	**Vacuum**	**Ice**	**Room**
Cooling time (hr)	1.0-10.0	0.1-1.0	0.3-2.0	0.1-0.3[a]	20.0-100.0
Moisture loss (%)	0.1-2.0	0.0-0.5	2.0-4.0	No data	0.1-2.0
Water contact with product	No	Yes	No	Yes unless bagged	No
Decay contamination potential	Low	High	None	Low	Low
Capital cost	Low	Low	Medium	High	Low[b]
Energy efficiency	Low	High	High	Low	Low
Need for water resistant packaging	No	Yes	No	Yes	No
Portable	Sometimes	Rarely done	Common	Common	No
Feasibility of in-line cooling	Rarely done	Yes	No	Rarely done	No

[a]Top icing can take much longer
[b]Low if product is also stored in cooler e.g. apples; otherwise long cooling times make it expensive

1.3.1. Forced-air cooling (FAC)

Forced-air cooling is a commonly used method in the initial removal of horticultural products field heat. It is done in batches or as a continuous flow system being technically and economically feasible on commercial scale to tree fruit, cut flowers, berries and melons. It involves forcing cold air through vented containers and past individual products along an induced pressure gradient (De Castro *et al*., 2005a, b; Kader, 2006; Ladaniya, 2008; Ravindra & Goswami, 2008; Thompson *et al*., 2008a; Berry, 2013; Opara & Mshidtwa, 2013). Most small scale operators work with portable forced-air equipment while large systems have these built in the cold room side wall. Systems that combine refrigerated air with a fine mist spray of water forced through cartons are termed hydro-air cooling according to Dincer (1995). The ratio of air to water in hydro-air cooling influences heat transfer capabilities (ASHRAE, 1994). FAC has been reported to augment moisture loss especially if fruit are exposed to unnecessary flow rates for longer times (Thompson *et al*., 2008a). Heat loss from fruit during FAC is through two mechanisms, the first being the convective heat transfer process occurring between the bulk flow of air and the fruit and the second being the removal of latent heat associated with moisture loss from the fruit surfaces in the stack (Ferrua & Singh, 2009a).

Cooling rates during FAC are improved if air passes each fruit rather than carton surfaces, achieving 10-25% faster cooling than room cooling, though slower than the other precooling methods like hydrocooling (Ladaniya, 2008). Ngcobo *et al*. (2013a) studied airflow and cooling rates in different multi-scale packages used in table grapes, they reported lower resistance to airflow and faster table grape cooling rates in packages with higher ventilation (6.13±0.04%) compared to packages with 3.80±1.74% ventilation. They also reported higher resistance to airflow and slower cooling rates in fruit that were packaged with inner packages due to limitations in direct cold air contact with fruit. Important considerations during FAC include: fruit weight and diameter; initial fruit temperature; carton ventilation; internal packages; stack widths and patterns; airflow velocity; and air temperature (Ladaniya, 2008). Though high flow rates of air may allow faster cooling (Table 3), there are cost implications in terms of energy and unnecessary moisture loss from some products. Airflow rates should thus, be regulated depending on the stack volume, type of product, carton ventilation area, number of vent holes, presence of internal packages and stacking arrangements, taking into consideration issues like air leakages in between cartons (Thompson *et al*., 2008a; Berry, 2013).

1.3.1.1. Airflow rate during forced-air cooling

Kumar *et al*. (2008) reported that air velocity affected the cooling rates of food products significantly below dimensionless temperature of 0.6 in their study of thermodynamics during forced-air precooling of oranges and tomatoes at air velocities from 1.2 to 4.4 ms^{-1} at 4-5^{o}C. They also stated limiting velocities of 3.5 ms^{-1} and 2.6 ms^{-1} for orange and tomato fruit respectively. However, their study was only on a single wire mesh rectangular box of fruit (250 mm x 170 mm x 170 mm) in the middle of an air duct. Stacked produce normally have more complex aerodynamics (Berry, 2013; Delele *et al*., 2013a). In determining airflow rates for forced-air cooling of produce, consideration of the respiration rate of produce is very important (De Castro *et al*., 2005a). De Castro *et al*. (2005a) recommended 1.35, 1.56, 1.73

and 2.08 $Ls^{-1}kg^{-1}$ airflow rates for cartons with 2, 4, 8 and 16% ventilation area respectively for high respiration fruit (straw berry, broccoli). The same flow rates recommended for high respiration fruit were also recommended for moderate respiration fruit (lettuce) in container with open area greater than or equal to 4% to minimise energy costs (De Castro *et al*., 2005a). Most coolers are designed to operate within airflow rates 0.5 to 2.0 $Ls^{-1}kg^{-1}$ with flow rates between 0.5 to 3 $Ls^{-1}kg^{-1}$ giving satisfactory cooling results (Ladaniya & Singh, 2000; Ladaniya, 2008; Thompson *et al*., 2008a).

Table 3 Seven-eighths cooling time for selected commodities using forced-air cooling (Thompson *et al*., 1998).

Commodity	Type of package	Vent area (%)	Flow rate (m^3/s)	Average time (hours)
Artichoke	Corrugated container	9.0	1.0	4.0
			1.5	3.0
Grapes	Full telescoping	5.8	0.3	6.0
			0.4	4.0
			1.0	2.0
Nectarines	Corrugated container with plastic trays	6.0	0.5	4.0
			0.8	3.0
Pears	Corrugated container	2.0	0.3	9.0
			1.2	3.0
		5.0	0.4	6.0
			1.0	3.0
Oranges	Bulk bins, slotted bottoms		0.4	6.0
Strawberries	Open crates on pallets		0.5	4.0
			0.8	3.0
			1.4	2.0
Tomatoes	Corrugated container	10.0	0.6	6.0
			1.1	4.0
			1.6	3.0

*The times are only approximates and intended for use as only guides

1.3.2. Room cooling

In room cooling, cold air is allowed to circulate among stacks and loads of produce set out in a cold room. Most cooling rooms have cold air discharge outlets just below the ceiling. The discharged air sweeps past the ceiling to below the produce stacked on the cold room floor. Other systems blow cooled air into a plenum wall onto which is palletised products stacked with 0.09 to 0.13 m spaces for air circulation (Thompson *et al*., 2008b). Room cooling is more suited for less perishable products like potato, onion and some citrus fruit stored at 10-13°C with vented cartons and proper spacing in the room providing faster cooling. Following precooling, say using forced-air cooling, room cooling follows in handy to finish the cooling regime during storage of fruit or transportation in refrigerated marine containers (Thompson *et al*., 2008b). Room cooling is relatively simple to design and operate and can as well function as a store where produce is kept in anticipation for off season periods to hit the market. However, cooling is slow compared to other methods sometimes taking several days (Table 4). This may cause deterioration of fruit quality, moisture loss and decay of some products due to condensation of water being lost from the fruit on the fruit surface (Thompson *et al*., 2008b).

1.3.3. Fruit storage

Given that nearly 67% of the world's fruit are consumed fresh (Ladaniya, 2008), preservation of the fruit freshness during storage for the domestic and international market is of much value (Ladaniya, 2008). Field operations, growth conditions, stage of maturity at harvest, postharvest treatments, packaging, transportation, storage temperature and relative humidity all affect fruit's storage life. Late harvested fruit may be soft, for example, late harvested mandarins and grapes, while early harvested fruit are more prone to chilling injuries during refrigerated storage (Ladaniya, 2008). Pomegranates need proper handling and care during harvesting and postharvest handling because the fruit leathery skin can easily be scuffed by abrasions from physical damage. The skin also has many micro cracks and other openings that aid water loss (Kader, 2006). Pomegranate appearance is also affected by decay (major) and the development of physiological disorders during development like cracking (Kader, 2006). In storage, much emphasis should be placed on avoiding excessive moisture loss to levels beyond 5% for most citrus fruit and pomegranates, at which shrivelling becomes visible (Kader *et al*., 1984), monitoring and minimising any decay predisposition and incidences, as well as fruit flavour and aroma, as these change as the fruit is stored in spite of minimum water loss and no decay. These flavour changes are mainly as a result of continuous biochemical reactions in the fruit (Ladaniya, 2008).

Table 4 Seven-eighths cooling time for selected commodities using room cooling (Thompson *et al*., 1998).

Commodity	**Package type**	**Average 7/8th cooling time (hours)**	**Slowest time to 7/8th cool**
Apples	Wooden box bulk	_	2-3 days
	Wooden box, packed	_	6-8 days
Artichoke	Corrugated container	24	_
Grapes	Wooden lug, solid stacked	_	30 hours
Pears	Telescopic container:-		
	1 inch space between 3.55% ventilation	16	23 hours
	No space between 5% ventilation	24	40 hours
Plums	Corrugated container, tight fill, 28 lb:-		
	1 inch space between, 4% ventilation	_	22 hours
	No space between, no vents	_	84 hours
Oranges	24 inch deep bulk bins, no side vents	33	_
	30 inch deep bulk bins, no side vents	45	_

*The 7/8ths cooling times are approximations and should be used only as guides; (_) indicate no figures given

Storage systems have evolved from simple framed open storage houses of fruit initially used in China and Japan to refrigerated storage (Kader, 2006). Refrigerated storage has allowed long term storage of fruit, with fruit like lemons being stored up to six months, and pomegranates up to four months (Kader, 2006; Ladaniya, 2008; Arendse *et al*., 2014). Storage room relative humidity and temperature are very important aspects in fruit refrigerated storage and greatly influence shelf-life and moisture loss characteristics of fruit (Fawole & Opara, 2013; Arendse *et al*., 2014). The recommended pomegranate storage conditions are between 5^{o}C to 8^{o}C; 90-95% RH depending on variety and area of production (Kader *et al*., 1984). These conditions offer a shelf-life potential of three to four months (Kader, 2006). Arendse *et al*. (2014) in their study on the optimum storage conditions of pomegranate fruit (cv. Wonderful) at different temperatures (5, 7.5, 10 and 21) ^{o}C reported that fruit stored at 5^{o}C for longer than 2 months showed signs of chilling injury, but, the authors recommended storage at 5^{o}C, >92% RH for up to 3 months for maintenance of best internal and external quality attributes. Similarly, Fawole and Opara (2013) in their investigation on storage temperature effect and duration on physiological responses of pomegranate fruit (cv. Bhagwa and Ruby) recommended storage at 5^{o}C, relative humidity >92% for up to 12weeks for best flavor maintenance and low physiological changes.

Chilling injury is one of the shortfalls in refrigerated storage (Mirdehghan *et al*., 2007). It happens when products are handled below their lowest safe temperatures. Internal tissue browning, surface pitting and increased susceptibility to decay are major symptoms of chilling injury in cold stored fruit (Ramezanian & Rahemi, 2011). Susceptibility to chilling injury in pomegranate fruit increases with storage for longer than one month at temperatures between pomegranate freezing point (-3^{o}C to 5^{o}C) or longer than two months at 5^{o}C (Elyatem & Kader, 1984; Kader, 2006; Arendse *et al*., 2014). To minimise chilling injury during cold storage, treatments like fruit coating with wax or vegetable oil, sealing in polythene bags, short time anaerobiosis, jasmonic acid treatment, fungicide treatment, temperature conditioning, foliar sprays and intermittent warming have been used on various fruit, but, most importantly, products should be kept at their lowest safe temperature (Ladaniya, 2008). According to Artes *et al*. (1998), intermittent warming of one day at 20^{o}C every six days for fruit stored for 80 days at 0^{o}C is the best treatment for maintaining pomegranate skin color as at harvest, while 5^{o}C intermittent warming keeps red color of arils better. Ramezanian and Rahemi (2011) reported that spermidine in combination with calcium chloride improved anti-oxidant enzyme activity in pomegranates that is responsible for chilling injury tolerance during cold storage, while Mirdehghan *et al*. (2007) reported that hot water (45^{o}C) dip for four minutes slightly but significantly reduced chilling injury symptoms. They inferred this to increased free putrescene and spermidine in fruit induced by the heat treatment before storage at 2^{o}C for 90 days.

Other storage methods employed with or independent of refrigerated storage in fruit include controlled atmosphere storage (CA), hypobaric storage, evaporative cool storage and ambient temperature storage (Ladaniya, 2006). According to Kader (2006), keeping fresh pomegranates in a controlled atmosphere of 5% oxygen + 15% CO_2 (balance N_2) at 7^{o}C and 90-95% relative humidity keeps them fresh for up to 4 to 6 months. For long term cold pomegranate storage, scald which mainly develops on the stem end of the fruit is a major limiting physiological disorder shown by up to 60% brown discoloration of skin. Though internal tissues are not affected, appearance especially red color is a paramount factor in the marketing of fresh pomegranate fruit (Kader, 2006).

2. Developments in packaging of fresh horticultural produce

Packaging of food has gone through tremendous evolution, from use of leaves, animal skins to wood, paper, plastic, and glass, up to modern, smart and intelligent packaging systems. Most fresh fruit and vegetables are packed in paper and plastic cartons while their juices are packed in plastic bottles, metal cans and glass (Opara & Mditshwa, 2013). In fruit, the package, depending on its mass transfer properties, in addition to containment, may avoid water loss, reduce respiration, slow down ripening and/or microbial decay (Robertson, 2010).

2.1. Types of packaging

The packages for horticultural produce are in two main types, the first are those meant for the transportation and shipment of produce to storage houses and markets and the second are those meant for retailers and consumers (Ladaniya, 2008). The other type is the ones meant for bulk handling that include baskets used in collection of fruit in the field and pallet bins (Ladaniya, 2008). Before final packaging for marketing, the bulk handling containers serve the purpose of collecting fruit in the field, to initial storage in the pack house. They range in size from 275 kg to 499 kg of fruit and are easily handled by fork lift trucks. Materials range from wood to metal to high density polyethylene bins. India's fruit growers commonly use plastic crates handling 20-21 kg of fresh fruit (Ladaniya, 2008).

Container designs for storage, shipment and transportation of horticultural fruit have to meet requirements of: palletisation; be adoptable to the machinery used in bulk handling especially fork lifts and cranes; have mechanical strength to withstand compression, vibration and impacts to a reasonable degree; have moisture loss barrier properties; and strength in high relative humidity environments. Most of the fresh fruit containers are made of corrugated paperboard material making them susceptible to direct water wetting. Other materials used include wood, bamboo, sacks and jute, especially in developing countries, moulded pulp and foamed polystyrene (Ladaniya, 2008). Packages employed in retail markets are normally small, holding one to a dozen pieces of fruit and they range from polyethylene (PE) bags, paper bags and cartons, to plastic trays and meshes. Choice depends on the market requirements in terms of the economics and availability.

2.1.1. Common materials of fresh fruit packages

1. *Wood*: - Wood (mostly local grown species) is made into boxes and crates of varying sizes and ventilation that are used in fresh fruit handling. Wood is cheap and in most cases readily available but, it has the following disadvantages: its abrasive to the fruit especially if the finishing is poor; it may be irregular causing packing non-uniformity on the trucks; most weigh 4 to 5 kg causing additional transport costs in terms of gross weight; moisture absorption both from the atmosphere and fruit; and sometimes the nails let go during fruit transportation (Ladaniya, 2008). Farmers especially in India line wood with dry paddy straw and newspapers to avoid abrasive action on fruit skin and tie ropes around fully packed wooden boxes for reinforcement. Gaps of 0.5 to 1.0 cm are left in between adjacent wood boards for ventilation. Wooden boxes are common for mandarin export in India (Ladaniya, 2008).
2. *Plastic*: - Plastic crates are reusable helping cut down packaging costs, and have good mechanical strength compared to wood and paper based packages. The common plastic packages are made from polypropylene (PP) and High Density Polyethylene (HDPE) through injection moulding. There are also collapsible plastic cartons that have a great advantage of occupying about one fourth of the initially occupied space on the return journey after unloading the fruit (Ladaniya, 2008).
3. *Jute, sisal and bamboo*: - These were used in the early times and are still used in developing countries like India (especially conical woven bamboo baskets) to weave gunny bags and baskets used to package fresh fruit. Some are also reusable due to sturdy character (Ladaniya, 2008).
4. *Paper*: - The most common paper based packages of fresh fruit are corrugated fibreboard (CFB) packages with ventilations (Ladaniya, 2008; Opara & Mditshwa, 2013). Water absorption in high humidity environment especially cold storage conditions affect the mechanical strength of the paper based cartons with chances of collapse in extreme cases (Ladaniya, 2008).

2.1.2. Corrugated fibreboard (CFB) cartons

The most widely used packaging material for the horticultural industry is the corrugated fibreboard carton (Opara, 2011; Pathare & Opara, 2014). CFB cartons have the advantage of being recyclable and of relatively low cost compared to other packages and may be single or multi-layer (Opara & Mditshwa, 2013). These cartons are used worldwide for packaging and trade of fresh fruit replacing wooden boxes that were mainly used initially. CFB cartons light weight and size uniformity compared to wooden boxes saves on transportation costs and space (Ladaniya, 2008). Some of the fibreboard cartons are telescopic; folded in two pieces which are individually stapled or taped with open tops and can be placed over each other or filled in separation. The other type is the “regular slotted corrugated board box” usually folded into a single piece with closer flaps that are stapled or taped (Ladaniya, 2008). CFB cartons normally have prints on the sides and can be transported in stacks or individual units (Ladaniya, 2008). To minimise CFB carton wetting, especially in high humidity environments (Ngcobo *et al*., 2013b) in refrigerated storage, wax coating, polypropylene film paper lamination, use of bitumen paper and resin coating are used as water vapour barriers subject to country rules and regulations. In some cases, shipping containers may be smeared with waterproof adhesives to minimise possible ingress of moisture into the container which predisposes the cartons to reduced structural integrity (Ladaniya, 2008).

Fruit in CFB cartons are place or jumble packed in single or multilayers, with some separated by polyvinyl chloride (PVC) or paper trays, air bubble entrapped PVC films, corrugated pads, with even some having vertical separations (Ladaniya, 2008). Certain packaging modes involve use of internal packages, most especially polyliners to minimise water loss and quality degradation (Ngcobo *et al*., 2012b). Fruit packaged in non-ventilated polyliners with poor water vapour transmission have been reported to have water condensed within that predisposes them to fungal decay (Ladaniya & Singh, 2001; Opara & Mditshwa, 2013). Polyliners have also been reported to delay fruit cooling (Ngcobo *et al*., 2012a; Berry, 2013). CFB cartons commonly have to be stacked during transportation and cold storage; hence, all carton designs should undergo compression tests to determine individual carton strength (Pathare & Opara, 2014). However, there are limitations to the stacking limit for each design. Drop, impact and burst tests to test carton sustainability to such incidences, water absorption property (Cobb value) are also considered in the design process (Pathare & Opara, 2014).

South African pomegranates are normally graded according to weight and packaged into open top cartons in single layers. The cartons with fruit normally weigh 3.5 to 5 kg (Citrogold, 2011). Such horticultural cartons are usually provided with openings or vents whose major function is maintaining airflow between the inside and the surrounding of the carton. These normally vary in shape, size, location on carton and area depending on manufacturer, product type, shape and cooling requirements (Pathare *et al*., 2012).

2.2. Developments in packaging vent design

Ventilated packaging is essential to ensure that cold air at the required temperature is delivered inside the package during the precooling and storage, as well as ensuring out flow of the heat of respiration of the products (Zou *et al*., 2006a, b; Tutar *et al*., 2009; Opara, 2011; Pathare *et al*., 2012; Opara & Mditshwa, 2013). Hand holes on large and heavy produce cartons used to aid handling also contribute to ventilation (Opara, 2011; Singh *et al*., 2008). When designing ventilated cartons for handling horticultural products, uniform airflow distribution is very important to ensure uniform cooling of the packaged products (Delele *et al*., 2013a). The open area, size and position of vents on the package play an important effect on air distribution, pressure drop, and the efficiency of cooling (Ngcobo *et al*., 2012a; Pathare *et al*., 2012; Berry, 2013; Delele *et al*., 2013a). Table 5 shows the effects of different carton vent configurations and total open area (TOA) on cooling rate, cooling heterogeneity and pressure drop during forced-air cooling. One of the biggest design challenges is maintaining the mechanical strength of the package with produce (Pathare & Opara, 2014) while ensuring optimum airflow requirements in the cold chain (Zou *et al*., 2006b). While little venting does not affect the mechanical strength of the carton, it restricts airflow and causes cooling heterogeneity in the products (De Castro *et al*., 2005b). On the other hand, too many vents weaken the carton (Opara & Mditshwa, 2013).

2.2.1. Ventilation effects on strength

While providing optimal ventilation, ventilated cartons are also meant to withstand especially compressional, shock and vibrational forces encountered during produce stacking, during cooling and shipping (Pathare & Opara, 2014). This calls for a compromise between mechanical strength and achieving optimal ventilation (Pathare *et al*., 2012; Defraeye *et al*., 2013). Best cooling efficiency is obtained with an open ventilation area of between 8 to 16% of the carton walls (De Castro *et al*., 2005a), while Mitchell (1992) found a reasonable compromise of ventilation area and mechanical strength at 5 to 6% venting of the cardboard end or side walls. He also went further to recommend fewer large vents instead of numerous small openings. For plastic containers, the open area can go to 25% of the container face (Vigneault & Goyette, 2002). At least 5% is the recommended open area on each face of corrugated cartons meant for the South African pome fruit industry (Hotgro, 2015).

To maintain mechanical strength, vent position is also crucial, with Thompson *et al*. (2008a) recommending a distance of 4 to 7 cm of vents from all carton corners. Singh *et al*.

(2008) in their study on effects of ventilation and hand holes in the loss of corrugated carton compression strength reported that rectangular and parallelogram hole designs offer better compressional strength compared to circular holes. They also observed that loss of strength in shipping paperboard cartons varied linearly with the total area of the ventilation holes, reporting up to 20 to 50% loss in strength in ventilated corrugated single wall cartons due to presence of vents and hand holes.

2.2.2. Ventilation configuration effects on airflow and cooling

Inadequate ventilation on cartons based on design, misalignment of ventilation holes during stacking on pallets due to variations or poor package design significantly reduces the airflow distribution in ventilated packaging (Tutar *et al*., 2009; Ngcobo *et al*., 2012a; Berry, 2013). Dehghannya *et al*. (2008), in their study on air velocities and heterogeneity index for different configurations of package openings observed that at an airflow rate of 0.022 m^3s^{-1}, packages with a ventilation area of 2.4% had the highest cooling heterogeneity index (108%) whereas 12.1% vent area had the lowest (0%). Similar observations were made by De Castro *et al*. (2005b) for cartons with vent area 8% compared to 4% and 2%. Higher carton ventilation coupled with proper vent distribution on carton wall and alignment on stacking improves the efficiency of the forced-air cooling process and quickens produce cooling (De Castro *et al*., 2005b; Dehghannya *et al*., 2012).

2.2.2.1. Vent position

The position of vents on the carton walls has effects on the structural strength, and airflow through the carton. To minimise loss in the mechanical strength of cartons, vents should be 4 to 7 cm away from all carton corners (Thompson *et al*., 2008a). While Delele *et al*. (2013a) observed a 14.6% decrease in pressure drop on placing vents to the top and bottom of the carton compared to the centre, De Castro *et al*. (2005a) observed that vent position had no effect on pressure drop and air velocity. Top and bottom positioned vents increase the airflow uniformity compared to centre and corner positioned vents (De Castro *et al*., 2005a). Carton vents should not be positioned in corners as this affects airflow uniformity and increases energy requirements during forced-air cooling (De Castro *et al*., 2005a). Improper vent distribution on cartons increases the cooling heterogeneity even with higher percentage ventilation (Dehghannya *et al*., 2012).

2.2.2.2. Vent area

The total opening area and size show a significant impact in reducing the pressure of the air during forced-air cooling (Pathare *et al*., 2012; Ngcobo *et al*., 2013a). Thompson *et al*. (2008a) recommended a vent area of the carton side walls of at least 5% for minimum airflow restriction during forced-air cooling. Ngcobo *et al*. (2013a) in their study on the cooling performance of multi-packaged table grapes during forced-air cooling found that 5 kg grape punnet boxes reduced the air pressure loss compared to the 4.5 kg boxes because the latter had a higher vent ratio (6.13 ± 0.04%) compared to 3.80 ± 1.74% of the former. Cooling rates of the grapes were also reported to be higher in the 5 kg punnets compared to the 4.5 kg punnets. However, in terms of quality, the 5 kg punnet boxes caused a higher weight loss (2.01–3.12%) and more stem dehydration compared to the 4.5 kg box (1.08%). Uniformity of cooling has also been reported to increase with increase in vent area due to reduction in air velocity variance (De Castro *et al*., 2005b; Dehghannya *et al*., 2011, 2012; Delele *et al*., 2013a). Although increasing vent area has been reported to reduce pressure drop and increase cooling rates and uniformity, this is only to certain limits beyond which mechanical properties of the carton are compromised. Delele *et al*. (2013a) observed a 6.56% and 5.44% decrease in 7/8ths cooling time following an increase in vent area from 7-9% and 7-11%, respectively, and Singh *et al*. (2008) observed a 0.56-1.08% reduction in structural strength following a 1% increase in vent area of corrugated carton. Increase in vent area beyond 8% does not significantly increase the cooling rate (De Castro *et al*., 2004) while Delele *et al*. (2013a) observed a lower percentage vent area increase of 7% beyond which there is no reasonable increase in cooling rate.

2.2.2.3. Vent shape

Shape is crucial in design of vents on cartons, as fruit packaged in the container may block the vents increasing airflow resistance and delaying cooling. For example round fruit are more likely to block the vent holes if placed in cartons with round vent holes (Thompson *et al*., 2008a). Delele *et al*. (2013a) observed that rectangular vents generated 8.4% more pressure drop compared to circular vents but the shape did not affect the uniformity of airflow and the cooling characteristics (rate and uniformity) of the produce.

2.2.2.4. Vent size and number

At a constant superficial airflow velocity of 0.5 ms^{-1} and the same vent area 7%, Delele *et al*. (2013a) observed that changing the size and number of vent-holes affected the uniformity of airflow and thus cooling as well as changes in the pressure drop. The observed reduction in pressure drop was 12.52%, 21.87%, 33.33% and 36.26% for two, four, six and nine vents relative to a single vent for the same ventilation area of 7%. There is also more uniform airflow with increase in the number of vents which is necessary to ensure uniform cooling of produce as well as reducing half cooling times (Dehghannya *et al.*, 2011; Delele *et al.*, 2013a). Analysing heterogeneity indexes at different positions of ventilated cartons, Dehghannya *et al*. (2011) reported 61.5%, 6.7% and 5.6% heterogeneity indexes for products in cartons with one, three and five vents respectively after 180 minutes of cooling. Vents need to be 10 mm wide or more because chances of blockage of vents smaller than 10 mm by the produce are higher (Thompson *et al.*, 1998).

Table 5 Effect of total opening area and vent configuration of cartons on air velocity, half-cooling time (HCT), coefficient of heterogeneity (*Vi*), and air pressure drop (APD) (De Castro *et al*., 2005b)

TOA (%)	**Vent number**	**Vent area (%)**	**Vent position**	**Air Velocity (ms^{-1})**	**HCT (minutes)**	***Vi***	**APD (Pa)**
2	3	0.67	Centre	0.195^{b}	58.04^{c}	0.609^{f}	363^{f}
	4	0.50	Corners	0.188^{ab}	65.36^{d}	0.750^{g}	347^{f}
4	8	0.50	Bottom and top	0.175^{a}	60.19^{c}	0.487^{c}	85.2^{d}
	4	1.00	Centre	0.221^{c}	49.11^{b}	0.541^{d}	112^{e}
	4	1.00	Corners	0.217^{c}	48.37^{b}	0.567^{de}	115^{e}
8	8	1.00	Bottom and top	0.219^{c}	45.55^{a}	0.377^{b}	29.4^{b}
	4	2.00	Centre	0.241^{d}	45.61^{a}	0.582^{ef}	59.8^{c}
100	Fully open			0.187^{ab}	47.90^{ab}	0.094^{a}	0.0^{a}

"Means in the same column and the same group of number followed by the same letter (a–f) are not significantly different based on t-test using $\alpha = 0.05$. Since the airflow range was not the same for all opening configurations tested, the statistical analyses showed on this table were performed only with the results obtained at 0.125–2 L s^{-1} kg^{-1}."

2.3. Multi-scale packaging and stacking

The use of a number of successive layers during packaging of a commodity is multi-scale packaging (Ngcobo *et al*., 2012a; Berry, 2013). Fruit are packaged in multi-scale package combinations for protection against mechanical damage, foreign matter and moisture loss.

The components used in multi-scale packaging are required to perform optimally in the cooling of fruit (Ngcobo *et al*., 2012a, 2013a).

There is hardly any literature on ventilated packaging of pomegranates; however, Berry (2013) in his survey on the use of ventilated packaging in the South African pome industry found that the ventilation of cartons varied between less than 1 to 11%, and that stacking led to the blocking of some ventilation holes from adjacent cartons rendering many ineffective. He also noted the importance of air velocity and distribution in the effectiveness of the cooling process of multi-scale packaged fruit, and that internal packages like thrift bags, polyliner bags contributed highly to resistance to airflow, 89% and 66% respectively. Similarly, Ngcobo *et al*. (2012a) in their study on resistance to airflow in multi-scale packaged table grapes noted a low pressure drop through the grape bulk ranging from 1.4±0.01% to 9.41±1.23% compared to 40.33±1.15% for the micro-perforated polyliner and 83.34±2.31% for the non-perforated liner film. These two studies detail the contribution of internal packaging to pressure drop during forced-air cooling.

Palletisation in the logistical handling of corrugated cartons in industry is widely used, easing handling, movement and stacking (Chen *et al*., 2011). The pallet materials range from wood, to metal, plastic up to paper (Chen *et al*., 2011). Stacking orientation has an influence on airflow patterns and hence cooling rates of individual fruit in boxes within the stack due to heterogeneity of airflow in misaligned vent holes (Berry, 2013; Ngcobo *et al*., 2013a). Container and stack total ventilation, fluid properties like velocity of air, product size, shape, texture, confinement, stack porosity, stack alignment all contribute to resistance to airflow during forced-air cooling (Vigneault & Goyette, 2002; De Castro *et al*., 2005a; Berry, 2013). Stacking arrangements of ventilated cartons with low porosity at a given airflow produce a high pressure drop compared to arrangements with high porosity regardless of fruit size (Chau *et al*., 1985). Vigneault *et al*. (2004) however, mentioned that geometry of produce also plays a significant role in pressure drop during forced-air cooling. Large total open areas in stacked produce achieved through proper alignment of ventilation holes in ventilated packaging during forced-air cooling effectively reduces pressure drop. Therefore, configuration of ventilation holes in ventilated cartons should facilitate more alignment in the stacks to improve air flow circulation and cooling efficiency (Berry, 2013).

3. Techniques for analysing airflow and cooling performance of horticultural packaging

Several methods have been used to analyse cooling performance of ventilated packages. These include numerical modelling techniques, analytical modelling and experimental analysis (Deghannya *et al*., 2008; Tutar *et al*., 2009; Ngcobo *et al*., 2012a, 2013a; Delele *et al*., 2013a, b). However, numerical and analytical models don't give the required accuracy unless experimentally validated (Tutar *et al*., 2009; Zou *et al*., 2006a, b). On the other hand, they are good design tools (Defraeye *et al*., 2013). Compared to numerical techniques, experimental techniques are tedious, costly, time consuming and work with already established facilities, but give a validation of models (Hoeng *et al*., 2000).

3.1. Experimental analysis

3.1.1. Resistance to airflow

Fast and efficient cooling rates during forced-air cooling have been reported to be impeded by airflow resistance from the packages mainly as a function of carton vent area, fruit properties (like shape, roughness, size, confinement and porosity) and multi-scale packaging (Vigneault & Goyette, 2002; Delele *et al*., 2008; Ferrua & Singh, 2011; Ngcobo *et al*., 2012; Berry *et al*., 2013; Ngcobo *et al*., 2013; Opara & Mditshwa, 2013).

Ramsin (Chau *et al*., 1985) and Darcy-Forchheimer (Forchheimer, 1901) equations (2) and (3), respectively, have been used to estimate airflow resistance in ventilated packs of fruits and vegetables (Chau *et al*., 1985; Vigneault *et al*., 2004; Delele *et al*., 2008, Ngcobo *et al*., 2012a, Berry, 2013):

$$\nabla P = -au^{b} \qquad (2)$$

$$\nabla P = -\frac{\mu}{K}u - \beta\rho|u|u \qquad (3)$$

where ∇P – pressure loss (Pam^{-1}); u – fluid velocity (ms^{-1}); a - Ramsin equation coefficient ($kg^{(b-2)}m^{-(b+2)}$); b – Ramsin equation exponent; μ - fluid viscosity (Pas); ρ – density (kgm^{-3}); 1/K - Darcy permeability of porous matrix (m^{-2}); β - Forchheimer drag constant (m^{-1}).

a and b depend on porosity, diameter of product and stacking pattern of the cartons, and are determined experimentally (Vigneault *et al*., 2004; Delele *et al*., 2008). The β and 1/K also depend on product diameter, stack porosity, cartons stacking pattern, vent-hole ratio, confinement ratio, fluid property, product shape and roughness (Vigneault *et al*., 2004; Delele *et al*., 2008).

The Ergun equation, which is considered "a special case of Darcy-Forchheimer-Brinkman equation", that considers fruit diameter has also been used to characterise airflow properties through porous media (Smale, 2004):

$$\frac{P}{L} = K_1 \frac{(1-\varepsilon)}{\varepsilon^3} \frac{\mu u}{D^2} + K_2 \frac{(1-\varepsilon)}{\varepsilon} \frac{\rho u^2}{D} \qquad (4)$$

where P – pressure loss (Pa); L – distance (m); μ - fluid viscosity (Pas); u – superficial velocity (ms^{-1}); ε – bed porosity; D – fruit diameter (m); K_1 & K_2 – Ergun equation constants.

A number of studies have characterised resistance to airflow through cartons and carton stacks based on the coefficients a, b, β, and 1/K reported in equations 2 to 4 above (Chau *et al*., 1985; Van der sman, 2002; Vigneault & Goyette, 2002; Vigneault *et al*., 2004; Smale, 2004; Delele *et al*., 2008; Delele *et al*., 2012; Ngcobo *et al*., 2012a; Berry, 2013). Ngcobo *et al*. (2012a) used a and b in Ramsin equation (2) and 1/k and β in the Darcy-Forcheimer equation (3) to express the pressure drop through multi-scale packages of grapes. The authors and others (Vigneault & Goyette, 2002; Vigneault *et al*., 2004, Delele *et al*., 2008) found that packaging systems with higher resistance to airflow were also characterised by higher values of these coefficients, thus highlighting the relevance as potential design criteria in optimising in-package airflow patterns and cooling performance.

3.1.2. Airflow patterns

Airflow distribution systems are complex and not easily measured in slow processes which are often prone to giving erroneous results (Cheong, 2001). This is because air flows non-uniformly during laminar flow and turbulent eddies develop, especially at low flow velocities that is common in cold storage of fresh horticultural produce (Smale, 2004). Airflow rate and distribution are very important design factors in refrigeration systems contributing significantly to system efficiencies since they have a direct effect on heat exchange (Opara, 2011; O'Sullivan *et al*., 2014) Airflow patterns also affect the cooling uniformity of products in refrigerated storage (Smale *et al*., 2006). The instruments traditionally used to measure the rates of airflow are vane anemometers and pitot tubes (Cheong, 2001). While vane anemometers measure airflow velocities at supply diffusers, pitot tubes measure velocities in ducts. Cross-sectional area of the duct is thus necessary in calculating the airflow rates when using pitot tubes (Cheong, 2001). With continuous research and development, novel air measurement methods are being used (Table 6) with some being invasive while others are non-invasive.

3.1.2.1. Non-invasive methods

Non-invasive airflow measurement methods involve non-interference in the flow path of air while measuring its velocity. They provide for detailed qualitative and quantitative airflow studies in horticultural refrigerated systems (O'Sullivan *et al*., 2014). The laser doppler anemometry (LDA) is an accurate but expensive non-invasive technique for air velocity measurement. It uses laser beams emitted by diodes that penetrate a cold room and the light scattered by the air particles produce doppler signals converted into velocity and time (Hoang *et al*., 2000; Moureh & Flick, 2004). Moureh and Flick (2004) while measuring the airflow pattern in a typical pallet loaded refrigerated truck made walls of their wooden scale model with one lateral wall in glass and used closed glass boxes as a representation of the pallets to be able to measure the velocity of the air inside with laser doppler velocimetry with the anemometer outside the model to avoid airflow interference. The results showed that use of air-ducts in the container system improved airflow homogeneity, minimising low velocity and airflow stagnant zones in the container. The LDA can give accurate velocities from a few mms^{-1} to hundreds of air velocity readings (ms^{-1}), and is useful in turbulence; however, it requires optically transparent measuring fields, and the equipment can be bulky (Smale, 2004). In the other non-invasive method similar to LDA, cylindrical and spherical lenses expand a laser beam forming a sheet of laser light whose motion in fluid, say air is recorded with a digital camera and the particle displacements are used to calculate air velocity using Fourier transformations. It's called particle image velocimetry (PIV) (Smale, 2004). Ferrua and Singh (2009b) used PIV to validate a mathematical model on airflow behaviour within individual straw berry packages during forced-air cooling. PIV provided quantitative and qualitative description of local airflow behaviour within packages and a good fit of the model.

3.1.2.2. Direct invasive methods

Direct invasive methods involve placement of measuring devices in the flow field measuring point values in the field (O'Sullivan *et al*., 2014). Techniques include use of vane anemometry, sonic anemometry, pitot tubes and thermal anemometry (Hoang *et al*., 2000; O'Sullivan *et al*., 2014). Sonic anemometers use speed of sound to measure airflow velocity.

Sound is moved in a medium, thus, its speed depends on the speed of the medium. Sonic anemometers are accurate and have a high sampling frequency, but, are bulky and expensive. Vane anemometers on the other hand use propellers whose rotation speed depends on the speed of air. Optical or magnetic sensors convert the signal from propeller rotation into a velocity measurement (O'Sullivan *et al*., 2014). They can be bulky, unresponsive but relatively inexpensive and viable in large spaces (Smale, 2004). Nagle *et al*. (2010) used a hand held vane anemometer to measure the air velocity in fixed-bed longan dryer plenum in a study to improve its performance by thermodynamic modifications. Inverted mesh modification of the dryer was found to increase airflow, reduce energy demand and increased efficiency of the drier by 1.51%.

The Pitot-static tube is an example of a differential flowmeter pressure device (O'Sullivan *et al*., 2014). It is one of the most widely used U-tube manometers for airflow velocity measurements. It works on the principal of pressure differential to measure airflow rates. Depending on the size and shape of the ducts, air velocity measurements are made across the duct and averages taken (Cheong, 2001). It has a disadvantage in turbulent airflow cases where the manometer reading keeps fluctuating requiring a fully developed flow profile to give a more accurate reading. In addition, velocities below 1.0 ms^{-1} are not easily detected with precision (Cheong, 2001). De Castro *et al*. (2004) used a pitot tube attached to the fan outlet to measure the airflow during the determination of the cooling efficiency of different container designs for horticultural produce. They found that airflow rate was the most significant variable that affected the cooling rate of the fruit as determined by the half cooling time. The other type of pressure differential flowmeters is the pressure transducers. These convert the pressure difference to an electrical signal recorded on data acquisition device giving them more accuracy in turbulent flow systems compared to U-tube manometers (O'Sullivan *et al*., 2014).

Hot wire anemometry is an intrusive technique that measures instantaneous velocity and temperature at point of flow. The principle of operation is that heat losses by convection from a surface relate to velocity of air (Smale, 2004). Initially the temperature of the hot wire (thermal) anemometer sensor is kept above that of the air (O'Sullivan *et al*., 2014). It measures air magnitude and direction with a wide velocity range. It is however affected by high turbulence in airflow and air impurities affect the sensor; altering the calibration characteristics and reducing the frequency of response (O'Sullivan *et al*., 2014). The fine wire is generally made of tungsten or platinum. Constant temperature hot-wire anemometers have a constant resistance with the variable being the voltage while constant current hotwire anemometers have a constant current with resistance as the variable ((Fingerson & Freymuth, 1996; O'Sullivan *et al*., 2014). Hot wire anemometers are relatively cheap, available and small and have been used widely in horticultural and refrigeration studies (Cheong, 2001; Smale, 2004). Berry (2013) used a hotwire anemometer to measure the velocity of air escaping through the top of the extender tunnel of the forced-air equipment while studying resistance to airflow in multi-scale packaging of pome fruit. Lower velocities were observed for carton stacks with lower ventilation and internal packages. Other horticultural studies involving use of hot wire anemometers to measure airflow include Alvarez and Flick (1999), Delele *et al*. (2008; 2009a, b), and Ngcobo *et al*. (2013a, b).

Hot film anemometers have the same working principal as the hot-wire anemometers and are typically constructed of platinum and nickel deposits on Pyrex glass. They are mechanically stronger compared to hot wire anemometers and are not well suited for measurement in turbulent situations (Smale, 2004). Smale (2004) used thermistor anemometers to measure airflow velocity in refrigerated marine transport containers, reporting large variations in air circulation rate during evaporator defrosting. Hot film anemometers operate on the same principal as the hot wire anemometers relating rate of heat transfer from a heated sensing element to fluid velocity.

3.1.2.3. Indirect invasive methods

The tracer-gas technique is a fast and simple indirect intrusive method used to measure airflow rates. It generally involves instrumental monitoring of concentration changes of a tracer-gas injected into the air flow path at a number of sample points which is then related to the airflow velocity and patterns (Smale, 2004; O'Sullivan *et al*., 2014). Carbon dioxide is the commonly used gas though carbon monoxide becomes the better option for cases involving natural convection (Smale, 2004). Other gases used include nitrous oxide, sulphur hexafluoride (SF6) and perfluorocarbon tracers (PFT) (Cheong, 2001). The tracer-gas technique compensates for the non-uniform flow nature of air that makes for example pitot-tube measurements slow and erroneous as it requires only a single point measurement in say a duct cross-section (Cheong, 2001). It also has added advantages that include: no need for a fully developed airflow profile like most direct intrusive methods; there is no need to determine the cross-sectional area of say a duct; it is suitable even in turbulent flow; and it measures airflow over a wide range (Cheong, 2001). Tracer-gas measurement techniques used include: decay, where drop in gas concentration across a flow system is related to flow rate; constant injection that involves injection of uniform concentration of gas into flow path and determining velocity by measuring the gas concentration at particular points within the system; and constant concentration, where the concentration of the gas is kept constant at particular point and velocity of air is calculated from required flow rate of gas divided by concentration of gas (Sherman, 1990; O'Sullivan *et al*., 2014). This method was used by Tumambing *et al*. (2001) to measure velocities and pattern of airflow in a commercial apple cold store using carbon monoxide as the tracer-gas. Amos (2005) also used carbon monoxide tracer-gas technique to characterise airflow in a commercial cool store, reporting heterogeneous flow within store and very little airflow in centrally located bins.

Table 6 Methods used for airflow rates and patterns measurements in experiments

Category	**Method/instrument**	**Mechanism**	**Reference/used by**
Non-invasive	Laser doppler anemometry (LDA)	Laser beam emitted by diodes produces Doppler signals	Moureh & Flick, 2004; O'Sullivan *et al*., 2014
	Particle image velocimetry (PIV)	Cylindrical and spherical lenses expand a laser beam forming a sheet of laser light	Smale, 2004; Ferrua & Singh, 2009b; O'Sullivan *et al*., 2014
Direct invasive	Vane anemometry	Propeller rotation	Smale, 2004
	Sonic anemometry	Speed of sound	Hoang *et al*., 2000
	Pitot tubes	Pressure differential	De Casro *et al*., 2004
	Hot wire anemometry	Heat losses by convection from surface	Berry, 2013; Cheong, 2001; Zou *et al*., 2006b
	Hot- film anemometry	Heat losses by convection from surface	Smale, 2004
Indirect invasive	Tracer gas technique	Concentration changes of a tracer gas injected into the air flow path	Tumambing *et al*., 2001; Amos, 2005; O'Sullivan *et al*., 2014; Tanner *et al*., 2000

3.1.3. Cooling performance of packaging

3.1.3.1. Fruit cooling rate

Cooling products follow a typical pattern shown in Fig. 1. The rates at which products are cooled depend on the temperature difference between the product and the cooling medium, with rates being rapid at the beginning, but slowing down towards product final temperature (Thompson e*t al*., 2008a). Horticultural products need very fast cooling to slow down physiological changes, chemical and enzymatic processes which all lead to deterioration in quality (Brosnan & Sun, 2001).

The half cooling time and seven-eighths cooling time, the required time for the product temperature to reach half and seven-eighths respectively, the difference between its initial temperature and the temperature of the cooling air, are used to determine the cooling rate of produce. Three half cooling periods make up the seven-eighths cooling time (Fig 1). This is the time most precooling processes of most products are stopped, since the products will have cooled close to required storage and transport temperatures (Brosnan & Sun, 2001). Temperature fluctuations of the cooling medium should be avoided especially towards the end of the cooling process (Brosnan & Sun, 2001; Thompson *et al*., 2008a).

The rate at which air flows and diameter of produce affects the total time it takes for produce to cool with larger fruit taking relatively longer compared to the small produce. Large produce for example water melons take significantly longer to cool compared to products with small diameters like table grapes because the large products have a small surface area to volume ratio (Thompson *et al*., 2008a; Berry, 2013). On the effect of airflow rates, Dincer (1995) reported a decrease in half cooling time and seven eighths cooling time of individual grapes in 5 kg batches by 21.8% and 23.6% respectively by just an increase in airflow velocity from 1.0 to 2.0 m/s meaning that the cooling rates increased by that magnitude. Delele *et al*. (2012) reported 61.09% and 97.34% increase in half and seven-eighths cooling times respectively on addition of carry bag in grape packaging compared to cooling individual bunches with no bag, while investigating the effects of table grape package components on heat transfer.

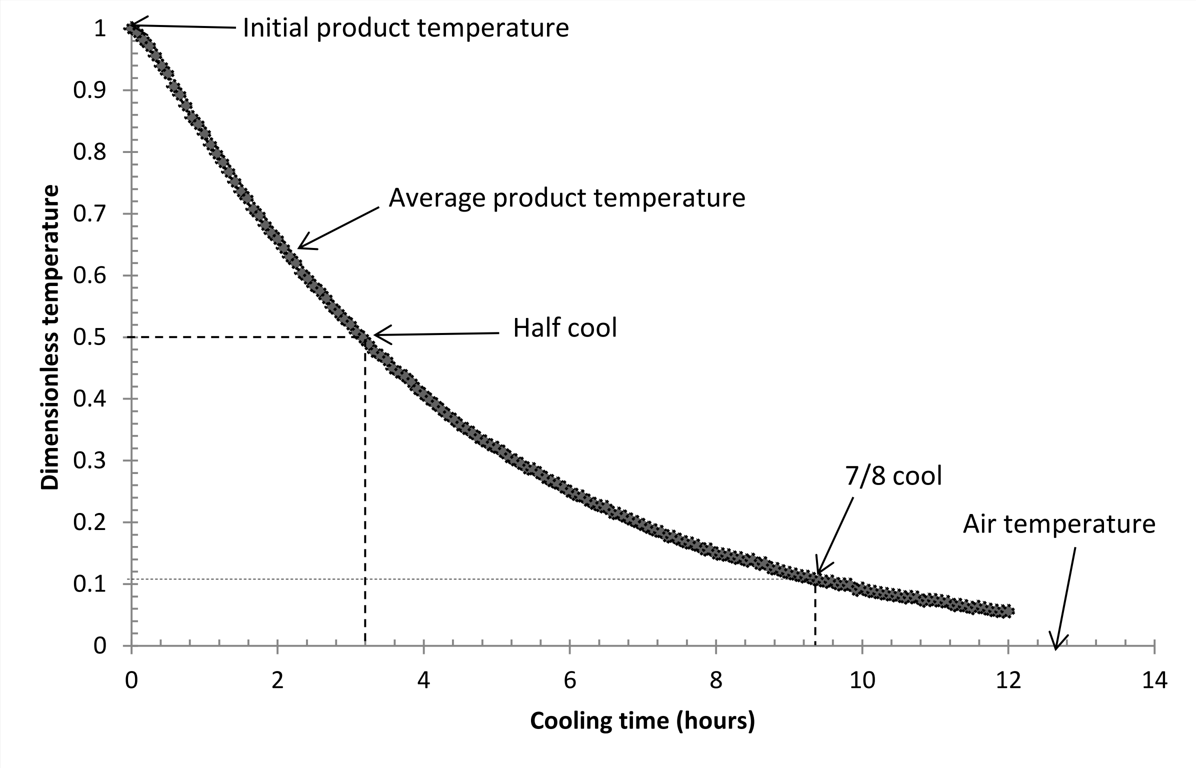

Figure 1 Typical temperature pattern in produce cooling. The dimensionless temperature is the fraction obtained by division of the difference between product and air temperature in cooler by the difference between initial product and air temperature.

According to Dincer (1995), dimensionless temperature is defined as shown in equation 5:

$$\theta = \frac{(T - T_a)}{(T_i - T_a)} \qquad (5)$$

where, θ – dimensionless temperature; T – product temperature at any time (°C); T_i – initial product temperature (°C); and T_a – temperature of cooling medium (°C).

The rate of change of the dimensionless temperature is defined by equation 6 (Dincer, 1995):

$$\theta = J \exp(-Ct) \qquad (6)$$

where, θ – dimensionless temperature; J – lag factor (function of thermal properties, size and shape of produce; Dincer, 1995); C – cooling coefficient (s^{-1}) (change in produce temperature per unit time for each degree of temperature difference between product and coolant; Dincer, 1995); t – cooling time (s).

The half cooling time (H), equation (7), is derived by substitution of 0.5 for θ in equation 6 (Dincer, 1995):

$$H = [\ln(2J)]/C \qquad (7)$$

where, H – half cooling time; J – lag factor; and C – cooling coefficient.

The seven-eighths cooling time (S), equation (8), derives from the substitution of 0.125 for θ in equation 6 (Dincer, 1995):

$$S = [\ln(8J)]/C \qquad (8)$$

where, S – seven-eighths cooling time; J – lag factor; and C – cooling coefficient. Half cooling time and seven-eighths cooling time both indicate the rate of produce cooling, however, in forced convection and most precooling systems, the seven-eighths cooling time is the parameter at which precooling processes of most products are stopped since the products will have attained temperatures close to those required in storage and transport (Brosnan & Sun, 2001; Thompson *et al*., 2008a).

3.1.3.2. Cooling heterogeneity and homogeneity

Heterogeneous cooling is where products cool down at different rates, with some being still warm while others are already at storage temperature. On the other hand, in homogeneous cooling, products cool down to the storage temperature at almost the same rate. Heterogeneous cooling is caused by increase in air temperature as it moves across a stack causing local variations in heat loss in the stacked products. Air velocity is also not homogeneous inside stacks characterised by turbulence, worsened by poor ventilation causing varying heat transfer coefficients (Alvarez & Flick, 1999; Berry, 2013). This temperature difference also influences moisture loss patterns from the fruit (Delele *et al*., 2009).

Cooling uniformity is generally improved by increase in carton ventilation and stack porosity (Ferrua & Singh, 2011; Defraeye *et al*., 2013, 2014; Patahare & Opara, 2014). The heterogeneity of cooling also decreases with increase in cooling time (Dehghannya *et al*., 2011). Additionally, Dehghannya *et al*. (2011) observed that products near inlet vents generally cooled faster, in their study on heat transfer in cartons with various vent areas during forced-air cooling. They also reported that produce in cartons with 7.25% vent area cooled homogeneously compared to produce packaged in cartons with 2.4% vent area, and went ahead to suggest that the homogeneous cooling phenomenon begins from middle of cartons outwards. Delele *et al*. (2013a) also reported increase in cooling uniformity with increase in vent area in their three dimensional computational fluid dynamics study on heat transfer characteristics of fruit horticultural packaging systems. Ferrua and Sigh (2009a) studied forced-air cooling process of fresh straw berry packages. They reported that the structure and design of the individual clamshell packages and trays influenced cooling heterogeneity, with differences of up to 2.4°C to 8.3°C due to about 75% airflow bypass of the clamshells.

High airflow rates improve cooling homogeneity (De Castro *et al*., 2005a,b). Alvarez and Flick (1999) while analysing heterogeneous cooling of products inside bins reported that the "dead zones", mainly corners and non-perforated zones, had the highest turbulence up to 50% and airflow velocity up to four times lower compared to the perforated zones. The heterogeneity index (HI) can be calculated by comparing the average temperature inside the package and the instantaneous temperature at a particular position by the equation 9:

$$HI = \frac{\sqrt{(t_p - T_p)2}}{T_P} \times 100 \qquad (9)$$

where, t_p is the sample temperature and T_P is the in-package mean temperature (Deghannya *et al*., 2011).

Barbin *et al*. (2012) while evaluating a portable air tunnel for forced-air cooling of products reported that heterogeneity within temperature of the products being cooled was low for container areas with no airflow obstruction and large temperature variations were observed in areas with no proper air circulation. Equation10 was used to estimate the cooling heterogeneity (Barbin *et al*., 2012):

$$\phi = \frac{\sqrt{\sum(\Delta T_c)^2}}{n} / \check{T}_c \qquad (10)$$

where, ϕ - dimensionless heterogeneity factor; ΔT_c – variation in temperature at each monitored point in layer or stack (°C); n – number of monitored samples; $\check{T}_c$ – product average temperature in layer or pallet (°C). The product average temperature for a specific mass of products at a given moment, $\check{T}_c$ was derived from equation 11 (Barbin *et al*., 2012):

$$\check{T}_c = \frac{\sum(m_i T_i)}{m_t} \qquad (11)$$

where, m_i – local mass of infinitesimal part of product (kg); m_t – total mass of product in pallet or layer (kg); and T_i - temperature of the mass of products (°C). ΔT_c (variation in temperature at each monitored point in layer or stack) was derived from equation 12 or 13

(Barbin *et al.*, 2012) for the variation in minimum (Tmin) and maximum (Tmax) temperatures of products, respectively:

$$\Delta T_c = \check{T}_c - T_{min} \qquad (12)$$

$$\Delta T_c = \check{T}_c - T_{max} \qquad (13)$$

3.1.3.3. Energy efficiency

Energy efficiency of a horticultural cooling system is dependent on a number of factors including airflow rate, carton ventilation and stack porosity, cold room insulation, refrigeration components efficiency and product thermal properties (Thompson *et al.*, 2008a, 2010; Defraeye *et al.*, 2014). Increasing the airflow may reduce the cooling time and uniformity (De Castro *et al.*, 2005b) but this requires more power and may require increased fan motor size and hence higher energy costs. Large product stacks will also need more fan power to achieve an appropriate velocity to effect cooling (Thompson *et al.*, 2008a). To minimise energy costs some fans are constructed to reduce airflow as the set product temperature nears being attained (Thompson *et al.*, 2008a). Harvesting produce at the coolest time of the day, reducing fans, lights and air infiltration especially through doors into the refrigeration space and refrigerant pipe insulation all contribute towards energy saving (Thompson *et al.*, 2010). Pressure drop in forced-air cooling is affected by carton ventilation, stacking porosity and internal packaging liners, these affect cooling rates and hence cooling efficiency. Well vented boxes and stacks with well aligned vents reduce energy needs from the fan (Thompson *et al.*, 2008a; Ngcobo *et al*, 2012a; Berry, 2013). Carton designs and arrangements that allow air infiltration between the cartons rather than the products, personnel and any equipment like fork lifts used during the forced-air cooling process also affect the refrigeration capacity during forced-air cooling, hence, energy needs and cooling efficiency (Brosnan & Sun, 2001; Thompson *et al.*, 2008a). Defraeye *et al.* (2014) reported energy consumption in relation to citrus fruit package design during forced-air cooling. The authors found lower energy costs and reduced seven-eighths cooling time of cooling fruit using "Ecopack" and "Supervent" cartons compared to "Standard carton" due to low aero-dynamic resistance of the two carton designs as a result of relatively higher ventilation.

The fan power required for a particular refrigeration application can be given by equation 14 below (Thompson *et al.*, 2008a):

$$Pf = \frac{q \times p}{\varepsilon \times 1000} \qquad (14)$$

where, Pf – fan power (kW); q – airflow (m^3s^{-1}); p – pressure (Pa), ε - fan efficiency (based on their studies on commercial cooling of fruits, vegetables and flowers, Thompson *et al*. (2008) reported that the efficiency of properly selected cooling fans ranges from 0.4 to 0.7).

Thompson *et al*. (2010) in their study on energy use in commercial forced-air coolers found that much of the electricity demand during forced-air cooling of fruit was towards fan operation to remove fruit heat and the heat fans produce during their operation, followed by electricity for cooling and light operation, cooling cold room walls and lastly electricity for operation and cooling of lift trucks. The authors also found that high throughputs in a cooling facility result in high energy efficiency and that only 36% of total electricity use catered for fruit cooling. Thompson *et al*. (2010) divided the amount of cooling work accomplished by a commercial forced-air fruit cooling facility by the amount of electricity purchased, referred to as energy coefficient, EC as a measure of the efficiency of electricity use (equation 15):

$$EC = M\,C_P\,(T_i - T_f)/(E\,c) \qquad (15)$$

where, EC – energy coefficient (kJ heat energy removed/ kJ electricity consumed); M – mass of product cooled per month (kg); Cp – specific heat of product ($kJkg^{-1}{}^{o}C^{-1}$); T_i – initial product temperature (^{o}C); T_f – final product temperature (^{o}C); E – electricity consumption per month (kWh); c – 3600 $kJkWh^{-1}$. The average EC was found to be 0.4, which is the same as reported earlier by Thompson and Chen (1988). Using less/no internal packages, liner perforations and produce containers with adequate ventilation will reduce electricity costs, making forced-air cooling process more energy efficient (Thompson *et al*., 2010; Ngcobo *et al*., 2012a; Berry, 2013). However, these internal packages may be part of the market specification for particular supply chains such as table grapes, apples and pomegranates, where they are commonly used to minimise fruit weight loss and contamination.

4. Conclusions and future prospects

Packaging plays a very critical role in the postharvest handling of horticultural produce especially given the fact that most of them are perishable. Right from the primary package to the tertiary packages, the designers' aim is to provide the best protection possible while at the same time ensuring preservation of the food, and at the end of it communicating adequately to the final consumer. Most fresh produce cartons have vents; these are meant to ease handling especially for bulky cartons but most importantly to allow for easy air circulation during forced-air cooling which is the most common precooling method for horticultural produce.

Precooling and cold storage reduce rates of chemical, biological and physiological changes in fruit and vegetables and have been widely reported as effective mechanisms for prolonging the useful life of fruit and vegetables. While room cooling may attain the produce intended storage temperature, this may take a very long time and by that time, most perishable products would have deteriorated to a great magnitude. Hence precooling is important to rapidly remove field heat of fruit and vegetables after harvest and significantly slow down physiological and biological changes which are deteriorative in nature. Carton vents may allow for air passage during forced-air cooling but may have negative impacts on carton strength, causing ventilation limitation in their design. Internal packages have also been reported to have a negative effect on rapid fresh produce precooling during forced-air cooling by significantly contributing to the pressure drop; however, they have been found to minimise weight loss and contamination of fruit.

Pomegranates have been widely reported as very nutritive fruit especially for their richness in micronutrients. The fruit, however, is prone to moisture loss, decay, mechanical damage and other physiological and biological deteriorative changes postharvest just like many other fruits. Forced-air cooling involves forcing refrigerated air through produce cartons or produce mass with the aim of getting air past every fruit surface such that heat is transferred by convection between the fruit and the cooling medium. The easier it is for chilled air to get to the fruit, the faster the cooling rate. This is mainly a function of the carton ventilation including vent shape, vent position, vent area, number of vent holes and airflow rate. The intention is also such that the fruit cool down at a homogeneous rate as large variations in temperature of produce cause inconsistencies, and the improperly cooled fruit quality may be adversely affected. The faster fruit are cooled, the greater the energy saved in terms of electricity because forced-air cooling is quite expensive in terms of energy consumption compared to other precooling techniques.

Given variation in fruit size, shape, texture and thermal properties, optimal package design for a particular product is very specific. What works for one product may not perform optimally for another. While considerable research has been reported on the cooling performance of multi-scale packaging on table grapes and citrus packaging, there is hardly any literature on cooling performance of packaging types and designs used in the pomegranate industry which inspired this study.

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Chapter 3

Resistance to airflow, cooling characteristics and energy consumption of pomegranate fruit inside ventilated cartons during precooling

Abstract

The performance of two ventilated corrugated fibreboard carton designs (referred to as CT1 and CT2 in this study) with fruit bulk inside liner versus no liner was studied during forced-air cooling (FAC). Resistance to airflow (RTA), energy consumption and fruit cooling characteristics of stacked cartons were investigated. The study entailed air being forced through the 1.2 m side of stack (lengthwise orientation) and through the 1.0 m side of stack (widthwise orientation). The two studied carton designs had 5.4% difference in total ventilation (CT1 – 23% and CT2 – 28.4%). CT2 had relatively higher ventilation lengthwise and widthwise, 8.82% and 6.67%, respectively, compared to that of CT1 (6.52% and 2.86%). This resulted into a generally faster cooling rate (29.19%) for fruit packaged in CT2, but, over 3 times higher RTA in CT2 compared to CT1 stacks due to vent-hole obstruction during stacking of CT2 in the lengthwise orientation of stack. The results also showed that liner packaged fruit (reference) in CT1 and CT2 on average offered 53.00% and 50.23% greater RTA than fruit packaged with no liner, respectively. In comparison to empty CT1 cartons, liner packaging (reference) resulted in 62.81% and 72.64% higher RTA compared to 23.76% and 39.84% of no-liner packaging (reference) in the lengthwise and widthwise orientations of stack, respectively. The lengthwise orientation of CT1 stack had a surface total vent area of 6.35% compared to 4.24% for the widthwise orientation which may be the reason for the comparatively lower RTA lengthwise. On the contrary, CT2 stack had a larger ventilation of 8.57% in the widthwise orientation compared to 2.35% lengthwise. The low stack ventilation lengthwise was due to vent-hole obstruction during stacking. Fruit packaged with no liner in CT1 stack cooled 61.21% faster than liner packaged fruit (reference) with average seven-eighths cooling times (SECT) of 4.5 hours and 11.6 hours, respectively. Liner packaging and stack orientation significantly affected cooling of fruit in CT2 stack, resulting in about 64.29% faster cooling rate with no liners, and 10% faster cooling in the widthwise stack orientation. Fruit in liner upstream the stack (at the entrance of cold air) cooled about 16.67% and 23.08% faster than the fruit in the middle and at the back layers within the same stack level, respectively, for both carton designs. Cooling heterogeneity was even higher in

no-liner packaged fruit, with fruit in front position inside the stack cooling 40.35% faster compared to back layer fruit (reference). Stack ventilation and packaging design also affected the energy requirements for cooling fruit. CT2 stack, with liner packaging in the lengthwise orientation of stack, had the highest energy consumption (3806.11±6.85 kJ) during precooling while widthwise orientation with no-liner packaging of the same carton design (which had the highest ventilation) resulted in lower energy requirement (54.09±0.15 kJ) to precool fruit. The energy requirement to precool fruit in the CT2 stack in the lengthwise orientation was over 7 times higher than the widthwise orientation due to vent-hole obstruction in the stack lengthwise. Furthermore, precooling fruit in liners inside CT2 required over 2 times more refrigeration energy compared to CT1 carton design.

1. Introduction

The most widely used packaging in the horticultural industry for postharvest handling and marketing are corrugated fibreboard cartons (Pathare & Opara, 2014). Compared to other types of materials used to handle fresh fruit, such as wood, fibreboard cartons have the advantage of being recyclable and of relatively low cost (Opara & Mditshwa, 2013). Fresh horticultural fibreboard cartons are usually provided with openings or vents whose major function is maintaining airflow between the inside and the surrounding of the container (Opara, 2011; Pathare *et al*., 2012). During design of ventilated cartons, mechanical strength and uniform airflow distribution are very important to ensure uniform cooling and protection of the packaged products (Zou *et al*., 2006; Pathare & Opara, 2014). The open area, size and position of vents on the cartons play an important effect on pressure drop, air distribution and the efficiency of cooling (Ngcobo *et al*., 2012; Pathare *et al*., 2012; Delele *et al*., 2013a). South African pomegranates are normally graded according to weight and packaged into open-top/semi-closed cartons in single layers. These are normally 3.5 to 5 kg when full (Citrogold, 2011). Polyethylene liners are used in most cases during packaging. The use of a number of successive sub-units such as trays, liner bags and thrift bags inside packaging of a commodity has led to the use of the term multi-scale packaging (Berry, 2013; Ngcobo *et al*., 2012; 2013). The increasing use of multi-scale packaging has resulted in a number of issues related to resistance to airflow and cooling performance of produce, energy consumption during cooling and potential impacts on product quality, especially weight loss.

Forced-air cooling is a common method in the initial removal of field heat from horticultural products (Dehghannya *et al*., 2010). It involves forcing cold air through vented containers and past individual products along an induced pressure gradient (De Castro *et al*., 2005; Kader, 2006; Ladaniya, 2008; Thompson *et al*., 2008). Fast and efficient cooling rates during forced-air cooling are impeded by airflow resistance (pressure drop) from the packages mainly as a function of carton ventilation, fruit properties (shape, thermal properties and size) and multi-scale packaging (Vigneault & Goyette, 2002; Delele *et al*., 2008; Ngcobo *et al*., 2012, 2013; Berry, 2013). Delele *et al*. (2013a) reported reasonable increase in fruit cooling rate with increase in carton vent area up to 7% with further vent area increase recording a reduced cooling rate increase. Airflow rate has also been reported to affect cooling rate and patterns during forced-air cooling (Berry, 2013). Most FAC cooling operations are at airflow rates 0.5 to 2.0 $Ls^{-1}kg^{-1}$ (Thompson *et al*., 2008). De Castro *et al*. (2005) recommended 1.35,1.56,1.73 and 2.08 $Ls^{-1}kg^{-1}$ airflow rates for cartons with 2,4,8 and 16% ventilation area respectively for high respiration fruit (strawberry, broccoli) and also for moderate respiration fruit (lettuce) in container with open area greater than or equal to 4%. Air velocity is also not homogeneous inside stacks characterised by turbulence worsened by poor ventilation and multi-scale packaging, causing varying heat transfer coefficients thus, heterogeneous cooling (Alvarez & Flick, 1999; Delele *et al*., 2013b). Delele *et al*. (2013b) reported higher air velocities and more turbulence in stack regions near air entrance vents.

The amount of energy required to achieve desired fruit temperature and maintain airflow during FAC is mainly a function of pressure drop, which in turn is affected by carton ventilation and internal packages (Thompson *et al*., 2008; Defraeye *et al*., 2014). Energy consumption during cooling is also affected by factors such as FAC fan and cooling unit efficiency, product stacking, respiratory heat from produce, external heat infiltration and initial produce field heat (Thompson *et al*., 2010; Defraeye *et al*., 2014). Defraeye *et al*. (2014) investigated energy consumption during FAC in relation to citrus fruit package design and reported reduced energy costs in “Ecopack” and “Supervent” cartons compared to “Standard carton” due to lower aero-dynamic resistance of the “Ecopack” and “Supervent” designs. The lower resistance to airflow of both package designs was attributed to the relatively higher ventilation, which in turn contributed to reduced seven-eighths cooling time of fruit.

The influence of multi-scale packaging of fresh table grape and apples to resistance to airflow and fruit cooling rates were studied by Ngcobo *et al*. (2012 and 2013) and Berry (2013), respectively. Both researches highlighted the need for effective airflow distribution for faster and homogeneous cooling of packaged produce. Ngcobo *et al*. (2012) in their study of resistance to airflow inside multi-scale packaged table grapes reported a low pressure drop through the grape bulk ranging from 1.4±0.01% to 9.41±1.23% compared to 40.33±1.15% for the micro-perforated polyliner and 83.34±2.31% for the non-perforated liner film. This study also demonstrated the critical contribution of the presence of internal packaging to higher pressure drop during FAC in multi-scale packaging. Stacking arrangements with low fruit packing porosity inside ventilated cartons at a given airflow produce higher pressure drop compared to arrangements with high porosity regardless of fruit size (Chau *et al*., 1985). Detailed knowledge on the cooling performance of ventilated packaging used for handling pomegranates is lacking. Therefore, the aim of this study was to investigate the effects of two ventilated carton designs and internal packaging (liners) used for pomegranate handling on airflow resistance, energy consumption and fruit cooling rate during precooling. The influence of stack orientation and fruit position inside a stack on fruit cooling rate was also studied.

2. Materials and methods

2.1. Fruit supply

Pomegranate fruit (cv. Wonderful) were harvested at commercial maturity from Merwespont farm in Bonnievale (33°58'12.02"S, 20°09'21.03"E), Western Cape, South Africa and transported in an air-conditioned vehicle to Postharvest Technology Research Laboratory at Stellenbosch University. Fruit were medium in size (diameter 8.15±0.20 cm and mass 440±10 g).

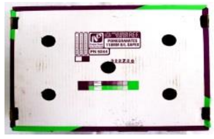
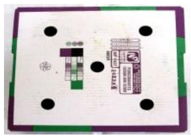
2.2. Package materials

Two pomegranate packaging carton designs were studied, CT1 and CT2 (Table 1). CT1 had 6 vent-holes lengthwise, at positions top and bottom of face, and 2 widthwise (top), while CT2 had 1 vent-hole lengthwise (top) and 1 widthwise (bottom). In CT1, fruit were placed on a fiberboard tray at the bottom (Fig.1B) while in CT2 no tray was used. Each carton was packed with 12 fruit with an average fruit weight of 4.32±0.39 kg per carton. In one multi-scale packaging system, the fruit (and tray for CT1) was enveloped in a polyliner bag (ZOE PAC; referred to as liner packaging in this study; Fig. 1F) while in the other, no liner was used (no-liner packaging; Fig. 1E). The dimensions and ventilation area of the cartons are shown in Table 1, and Table 2 shows the different ventilation configurations of each of the studied carton orientations.

Table 1 Studied pomegranate cartons used in the South African pomegranate industry and their ventilations

Carton	Carton orientation	Wall area (m^2)	Vent area (m^2)	Ventilation (%)
 CT1	Lengthwise	0.046	0.003	6.52
	Widthwise	0.035	0.001	2.86
	Top	0.116	0.064	55.17
	Bottom	0.116	0.004	3.45
	Total	0.313	0.072	23.00
 CT2	Lengthwise	0.034	0.003	8.82
	Widthwise	0.030	0.002	6.67
	Top	0.093	0.064	68.82
	Bottom	0.093	0.002	2.15
	Total	0.25	0.071	28.4

Table 2 Photographs of studied cartons showing ventilation of all carton orientations

Carton	Orientation			
	Widthwise	Lengthwise	Top	Bottom
CT1				
CT2				

2.3. Experimental set up

The cartons were stacked onto a pallet of dimensions 1.2 x 1.0 m (Fig. 1G). For CT1, this set up comprised of 70 cartons in 7 layers with each layer containing 10 cartons, height 0.826 m while CT2 comprised of 96 cartons in 8 layers with each layer containing 12 cartons, height 0.84 m (Fig. 2). The stacks were tightly connected to portable FAC equipment and sealed with air tight plastic along the sides, top and bottom so that air being forced through the stack only entered from the stack face opposite the FAC equipment, and exited the stack along the stack face on the pressure drop tunnel of the FAC equipment (Fig. 1H). Vertical slots between two perpendicular cartons were also sealed with LDPE plastic to minimize chances of carton by-passing by the air. The study entailed air being forced through the 1.2 m side of stack (lengthwise orientation) and through the 1.0 m side of stack (widthwise orientation; Fig. 2). Table 3 shows the ventilation configuration of each of the studied carton stacks.

2.4. Resistance to airflow (RTA) studies

For RTA measurements, pressure drop resulting from forcing air through the stack at airflow rates ranging from zero to 25.0 ms^{-1} measured at the extender tunnel (area: 0.018 m^2) of the portable FAC equipment (Fig. 1H) was noted. Measurements were taken with airflow in the lengthwise and widthwise orientations of the stacks, respectively (Fig. 2). For each carton design, this was performed in triplicate for (a) stack of empty cartons, (b) stack of cartons with fruit inside liners and (c) stack of cartons of fruit with no liners. FAC equipment (Fig. 1H; Defraeye *et al*., 2013; Delele *et al*., 2013b) was used to generate airflow across the stack using centrifugal fan model (KDD 10/10 750W 4P-1 3SY, AMS supplies, Sandton, South Africa). Manometer positioned in the pressure drop tunnel, a 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) were used to record pressure drop across the stack. A hotwire anemometry air velocity meter was used to measure the flow rate of air escaping the top of the FAC equipment at the extender tunnel (Alnomar velometer AVM440, TSI Incorporated, Shoreview MN 55126, USA). The Darcy-Forchheimer equation was used to estimate airflow resistance in the ventilated packs (Forchheimer, 1901; Ngcobo *et al*., 2012; Berry, 2013; Defraeye *et al*., 2014):

$$\nabla P = -\frac{\mu}{K} u - \beta\rho|u|u \qquad (1)$$

where ∇P – pressure drop (Pam^{-1}); u – fluid velocity (ms^{-1}); μ - fluid viscosity (1.77E-05 Pas at 7^{o}C) and ρ – air density (1.2613 kgm^{-3} at 7^{o}C); 1/K - Darcy permeability of a porous matrix (m^{-2}); β - Forchheimer drag constant (m^{-1}).

2.5. Fruit cooling characteristics

To determine fruit cooling rate and homogeneity inside stacks, stacked fruit were precooled from 17±3.0^{o}C to 7±1.2^{o}C. Fruit temperature at the thermo-centre was monitored using T-type thermocouples connected to a Data Acquisition/Data Logger Switch Unit (Model 34970a, Agilet Technologies, Santa Clara CA 95051, USA) and recorded at 5-minute intervals. Fruit in positions 1 to 5 in stack levels 2, 4 and 6 (Fig. 2) were instrumented with temperature data loggers positioned at fruit's thermo-center (fruit central position). Stack and

FAC equipment was aligned in the cold room with dimensions; 3.05 m (length), 2.4 m (width), 2.83 m (height) with three cooling fans of diameter 30 cm each (1290 m^3h^{-1} airflow capacity; Fig. 3). Similar to the RTA studies, stacks were oriented lengthwise and widthwise, measurements were also done in triplicates. The FAC equipment was used to generate a spectrum of controlled airflow rate across the stack. A constant airflow rate of 0.5 $Ls^{-1}kg^{-1}$ was used in this study (De Castro *et al*., 2005; Vigneault *et al*., 2006) since pomegranates are low respiring fruit. The temperature of the room for the cooling experiments was set to 7^oC. Tinytag sensors (Tinytag TV-4500, Hastings Data Loggers Australia) were used to monitor the temperature and humidity in the cold room. Total pressure drop and air velocity were continually monitored.

2.6. Energy consumption estimation during FAC of fruit

The energy required to cool fruit during forced-air cooling in both CT1 and CT2 was estimated using two equations. In equation 2, the power required to force air through the stacks was calculated as the product of the pressure drop over the stack and the volumetric airflow rate through the stack. This was then multiplied by the seven-eighths cooling time to get the energy (Defraeye *et al*., 2014):

$$\text{Energy (J)} = \Delta P * G * SECT \qquad (2)$$

where ΔP - pressure drop (Pam^{-1}), G – volumetric flow rate (m^3s^{-1}), SECT – seven-eighths cooling time (s).

Equation 3 puts into consideration the fan efficiency. Based on their studies on commercial cooling of fruits, vegetables and flowers, Thompson *et al*. (2008) reported that the efficiency of properly selected cooling fans ranges from 0.4 to 0.7. In this present study, we assumed the efficiency of the centrifugal fan to be 0.6 (average). To estimate the energy requirement during the cooling cycle in the different package types, orientations and carton design, the power required to run the centrifugal fan was multiplied by the seven-eighths cooling time (Defraeye *et al*., 2014):

$$\text{Energy (kJ)} = \frac{G \text{ x } \Delta P}{\varepsilon \text{ x } 1000} \text{ x SECT} \qquad (3)$$

where ΔP – pressure drop (Pa), G – volumetric flow rate (m^3s^{-1}), ε – efficiency of centrifugal fan, SECT – seven-eighths cooling time (s).

2.7. Statistical analysis

Statistical analysis was done using Statistica software (Statistica version 12, StatSoft Inc., Tulsa, USA). Mixed model repeated measures analysis of variance (ANOVA) was done using the VEPAC module of Statistica 12 at 95% confidence interval. Variations were compared between the package designs, stack orientations and fruit position within a stack level.

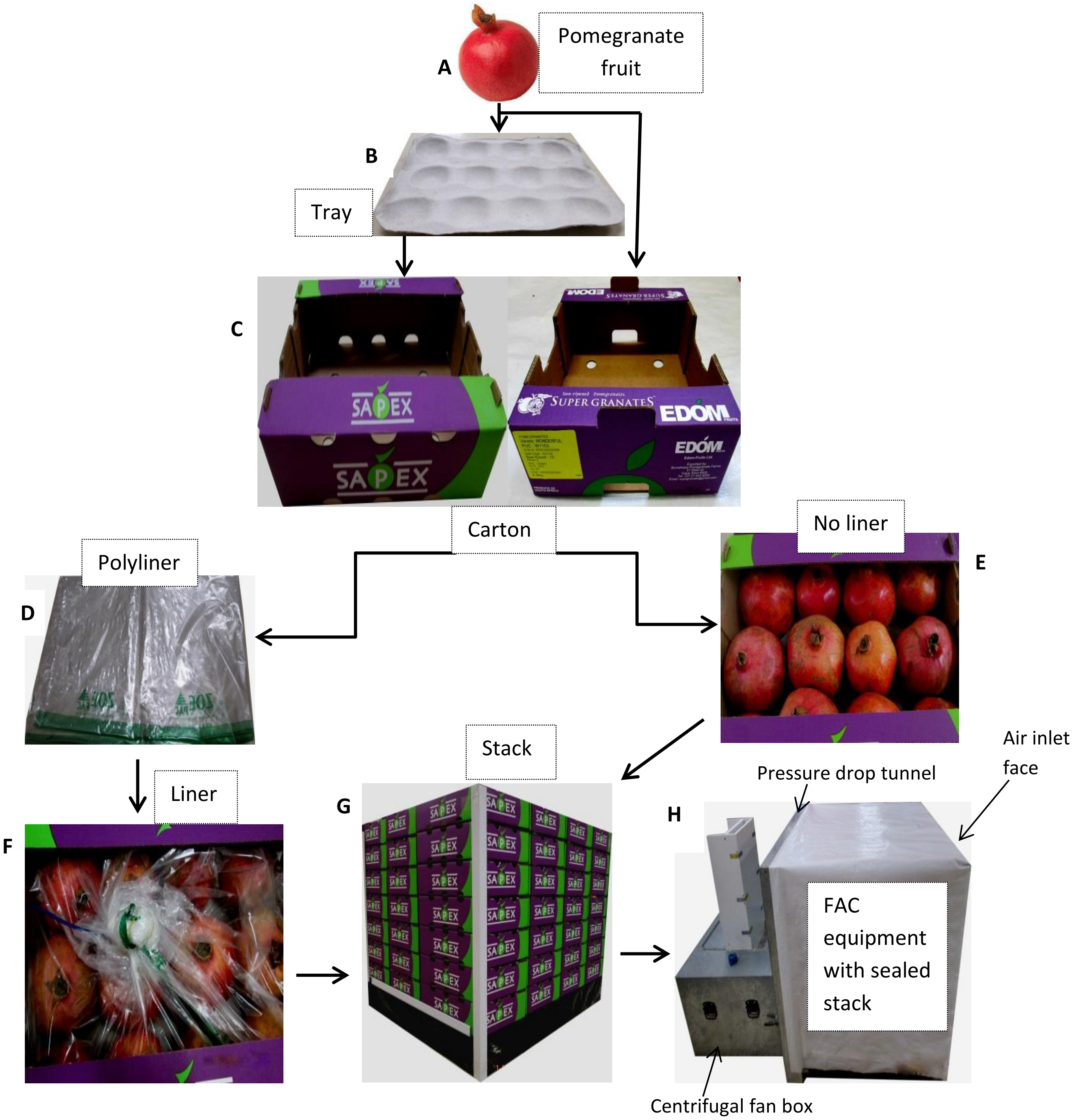


Figure 1 Diagram of packaging combinations and stages of the pomegranate fruit for RTA, energy consumption and cooling experiments. No-liner packaging **E** has fruit sitting (on tray for CT1) at the bottom of the carton; liner packaging **F** has a liner enclosing the fruit (and tray); and stack **G** is sitting on a standard pallet of dimensions 1.2 x 1.0 m.

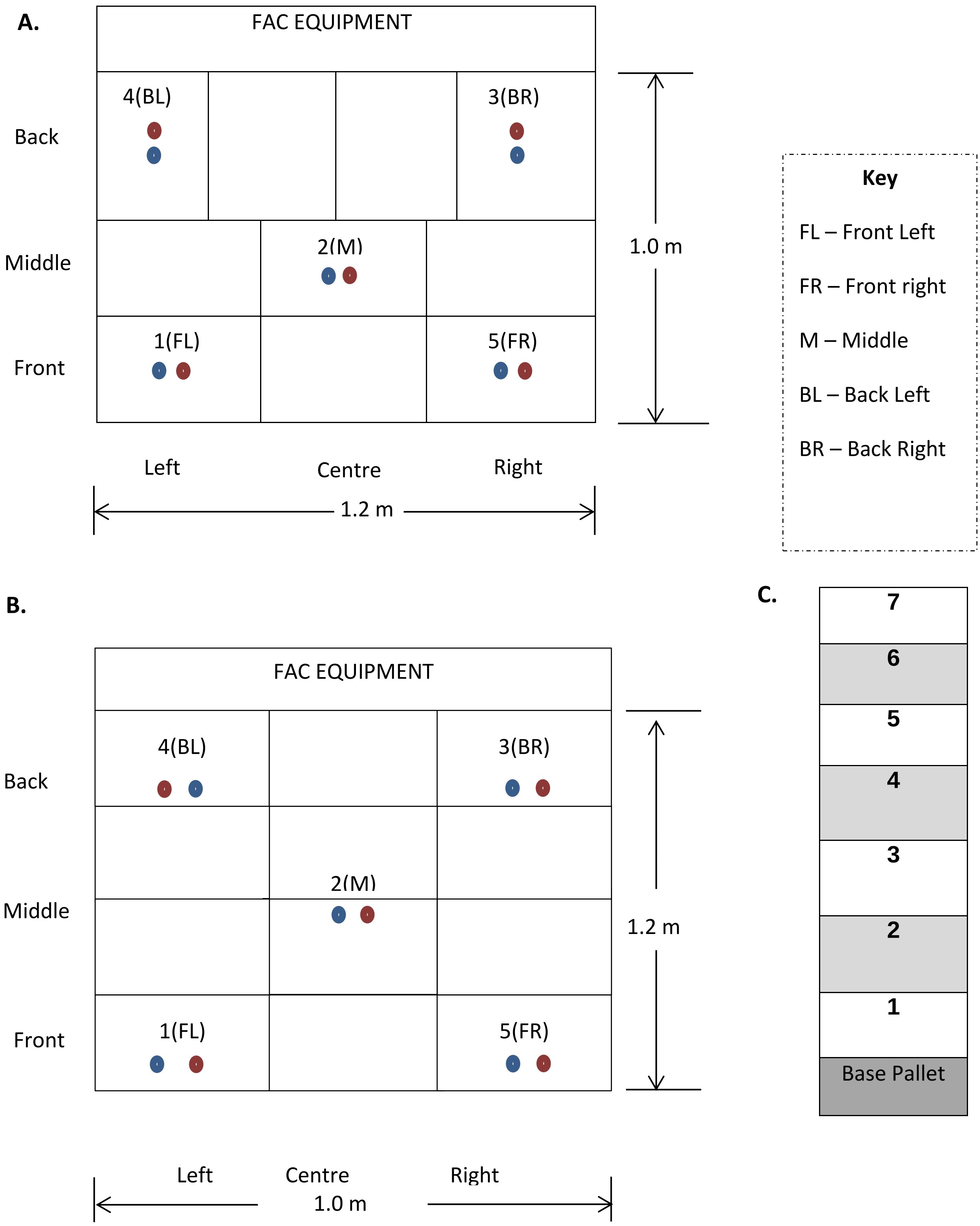
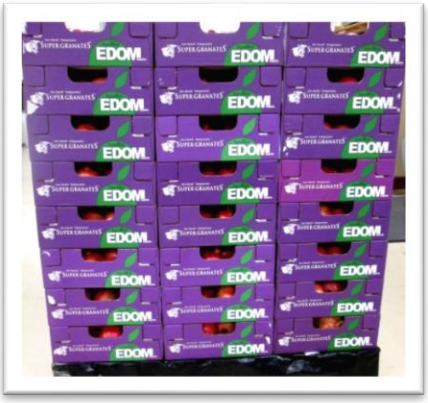


Figure 2 Lay-out of the stacking pattern of studied cartons in each layer, temperature logged pomegranate fruit positions, and position of fruit monitored for moisture loss. **A** = CT1 **B** = CT2; **C** = stack layers (levels); blue circle = temperature logged fruit; and red circle = moisture loss fruit. Layers 2, 4, and 6 in **C** were used for monitoring temperature and moisture loss.

Table 3 Pallet stacks of studied carton designs showing the stack orientations and total stack ventilation (TSV)

Stack	Stack orientation: Lengthwise	Stack orientation: Widthwise
CT1	 TSV = 6.35%	 TSV = 4.24%
CT2	 TSV = 2.35%	 TSV = 8.57%

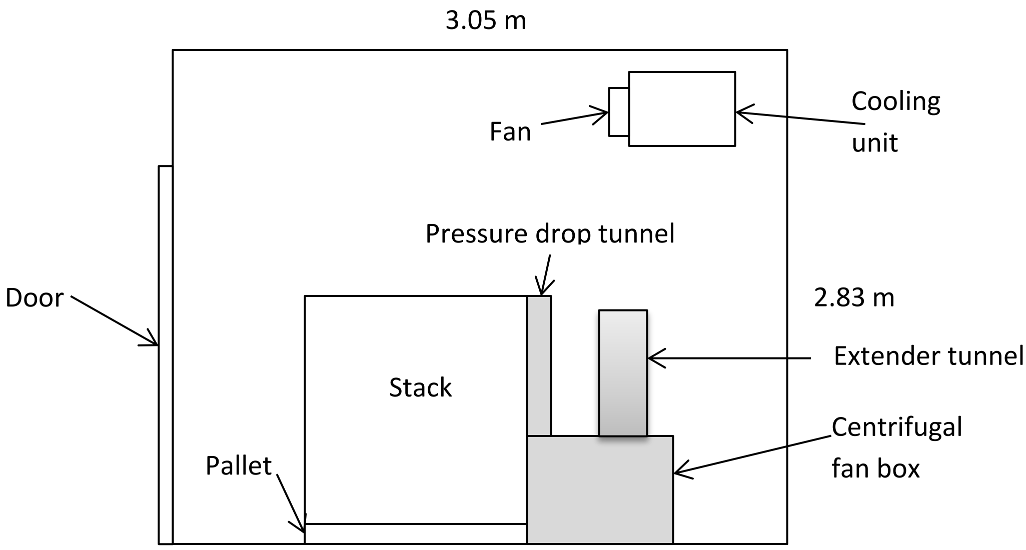


Figure 3 Side view of experimental set up inside cold room

3. Results and discussions

3.1. Effect of package design on resistance to airflow

The two studied carton designs had 5.4% difference in individual carton total ventilation (CT1 – 23% and CT2 – 28.4%, Table 1). CT2 had relatively higher ventilation lengthwise and widthwise, 8.82% and 6.67% respectively compared to that of CT1 (6.52% and 2.86%). However, on stacking CT2, vent-holes were greatly obstructed in the lengthwise orientation of the stack resulting into a total stack ventilation of 2.35% from individual carton ventilation of 6.67% (Table 3). This caused up to about 5 times more airflow resistance in the lengthwise orientation of CT2 compared to the same orientation of CT1 stack based on the β coefficient from the Darcy-Forchheimer equation (Table 4). The widthwise orientation of CT2 stack had a higher ventilation (8.57%) compared to CT1 stack (4.24%, Table 3) resulting in about 2 times higher RTA in the CT1 stack. Overall, the CT2 stack had about 3 times more resistance to airflow than the CT1 stack. This result highlights the effect of carton ventilation and stacking on resistance to airflow during forced-air cooling. Studies have shown that the higher the ventilation area, the easier it is for air (cooling medium) to penetrate the stack (Vigneault & Goyette, 2002; Delele *et al*., 2008; Ngcobo *et al*., 2012, 2013; Opara & Mditshwa, 2013).

Resistance to airflow also increased with addition of different components to the cartons including: tray, fruit, and polyliner (Fig. 4A and B). Based on the Forchheimer drag constant (β) in equation 1 (Table 4), CT1, liner packaging (reference) generally had 53.00% higher RTA compared to no-liner. Similar trends were observed for CT2, with liner packaging offering 50.23% higher RTA compared to no-liner packaging. This observation is in agreement with observations made in multi-scale ventilated packaging of apples by Berry (2013) and Ngcobo *et al*. (2013) in grape packaging where the polyliner films were also the greatest contributors to pressure drop during FAC of those fruit.

Empty cartons had the lowest RTA detailing the contribution of both the fruit and package components to airflow resistance experienced during the precooling of fruit. The β coefficient from the Darcy-Forchheimer equation varied linearly with the graphical representation of airflow resistance. CT1 stack with liners in the widthwise orientation had the highest value (2485.45 m^{-1}) and the empty cartons stack in the widthwise orientation had the lowest value (679.8 m^{-1}), while the CT2 stack with liners lengthwise had the highest value of 8878.93 m^{-1} compared to 312.1 m^{-1} of the empty carton widthwise (Table 4).

CT1 had ventilation area along the width (2.86%) (Table 1) below the recommendation of 8-16% by De Castro *et al*. (2005) for optimum energy use, but, the length face 6.52% ventilation was within the recommended ventilation (5-6%) by Thompson *et al*. (2008) for minimum airflow restriction (Table 1). Baird *et al*. (1988) and Mitchell (1992) also recommended a face ventilation of 5-6% for a compromise between ventilation area and carton mechanical strength. According to Hortgro (2015), the South African pome fruit industry corrugated cartons should have at least 5% open area on each face. Ladaniya and Singh (2002) recommended 6% ventilation for citrus cartons, 4-5% for Nangpur mandarin cartons (Ladaniya, 2008), 5-6% for Nectarine cartons (Mitchell *et al*., 1971), and 5% for table grape cartons (Aswaney, 2007). It was also observed that the tray put at the bottom of CT2 physically blocked the lower holes along the length of the carton. This could also have contributed to airflow resistance since the effective open area was further reduced. CT2 had ventilation above 5% on its length and width faces (Table 1). However, the vent along the width of the carton got about 80% blocked by the preceding carton during stacking making the lengthwise orientation of stack during forced-air cooling unsuitable as air inlet is largely restricted. The bottom and top ventilation areas (Table 1) were not useful in this study after stacking since air was sucked horizontally through the stack.

Table 4 The β coefficient as affected by internal packaging and stack orientations using the Darcy-Forchheimer equation

	β(m^{-1})		**R^2**	
Internal packaging and stack orientation	**CT1**	**CT2**	**CT1**	**CT2**
Liner: widthwise	2485.45	1861.41	0.9991	0.9999
Liner: lengthwise	2151.83	8878.93	0.9993	0.9998
No liner: widthwise	1130.03	335.62	0.9993	0.9999
No liner: lengthwise	1049.47	5009.36	0.9999	0.9992
Empty carton: widthwise	679.80	312.10	0.9999	0.9997
Empty carton: lengthwise	800.13	7585.67	0.9995	0.9995

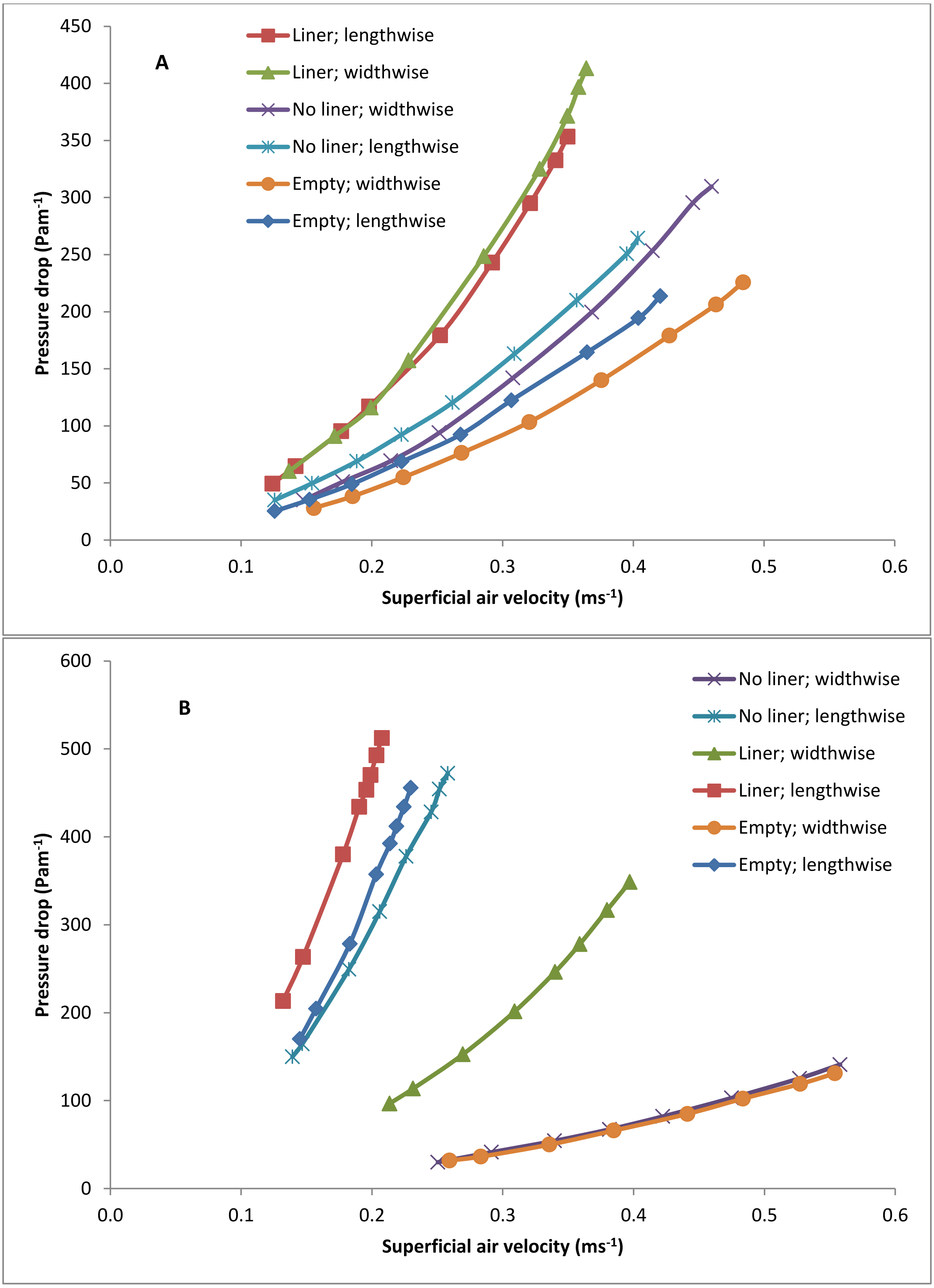


Figure 4 Pressure drop as a function of packaging components and orientation of stack during forced-air cooling of pomegranates: **A** = CT1 stack and **B** = CT2 stack.

3.2. Fruit cooling characteristics

The results show that fruit packaged in CT1 with no liner cooled 61.21% faster than fruit packaged with liner (reference) with average seven-eighths cooling time of 4.5 hours and 11.6 hours respectively (Fig. 5). A similar trend was observed in CT2 with no liner packaging achieving 64.28% faster cooling compared to liner packaging (reference) with seven-eighths cooling time averages of 3.00 hours and 8.39 hours respectively (Fig. 6). This was attributed to fruit packaged with no liner coming into direct contact with cold air on entering the carton through the vent holes facilitating quicker heat transfer between the air and fruit through convection and conduction compared to the liner design where the polyliner envelopes the fruit limiting the surface area for heat exchange. These results are also in agreement with the resistance to airflow results discussed in section 3.1 where liners offered greater resistance to airflow compared to no-liner packaging. The half cooling times also followed a similar trend. Similar observations of polyliners delaying the cooling process were made in multi-scale packaging of grapes by Ngcobo *et al*. (2013) and apples by Berry (2013). The relatively lower seven-eighths cooling times (29.19%) of the CT2 compared to CT1 fruit (reference) could be due to CT2 having a 19.01% higher total ventilation (Table 1) allowing in more cold air hence faster heat exchange between the fruit and the air.

Fruit in CT2 stack, in liners cooled significantly faster in the widthwise orientation (SECT, 7.67 hours) compared to the lengthwise orientation (9.13 hours) (Fig. 6). This may have been as a result of a larger ventilation of stack in the widthwise orientation of stack (8.57%) and almost 80% obstruction of the vent-holes by preceding cartons during stacking in the lengthwise orientation of stack (individual carton ventilation along width (that becomes lengthwise orientation upon stacking, Table 3) was 6.67%, Table 1) leading to a larger pressure drop hence lesser heat exchange. Significant heterogeneous cooling was observed within the same layer of stack with upstream fruit in cartons at the entrance of the air stream cooling faster than fruit downstream in both carton designs (Fig. 7 and 8). In liner packaging, fruit in the same stack level (Fig. 2) at front left position (FP1) and front right (FP5) cooled on average 16.67% faster than fruit in middle cartons (FP2; reference), which also cooled about 7.69% faster than fruit in the back cartons back left (FP4) and back right (FP3) of a layer (reference). The cooling heterogeneity was even larger in the no-liner packaging for both CT2 and CT1 stacks (Fig. 7 and 8) with front fruit cooling by about 40.35% in CT1 and 44.41% in CT2 faster rates compared to the back fruit (reference) in same layer. This may be as a result of air warm up as it flows from the front to the back of the layer carrying heat from the fruit it has already contacted (Baird *et al*., 1988). It was also observed that the bottom layer (SL2) in CT1 stack cooled significantly faster than layer 4 and 6 along the stack (Fig. 5). Cold rooms designed with fans just below the ceiling operate in a way that the discharged air flows past the ceiling to opposite wall then to the floor before rising through the room (Thompson *et al*., 2008). This could be the reason the lower layer cooled faster as it receives a higher velocity of cold air compared to upper stack layers. Delele *et al*. (2009) also reported high air velocity at the bottom region of stack in cold room with cooling fans at the back of room just below the ceiling. The portable FAC equipment also had the sucking centrifugal fan at its bottom.

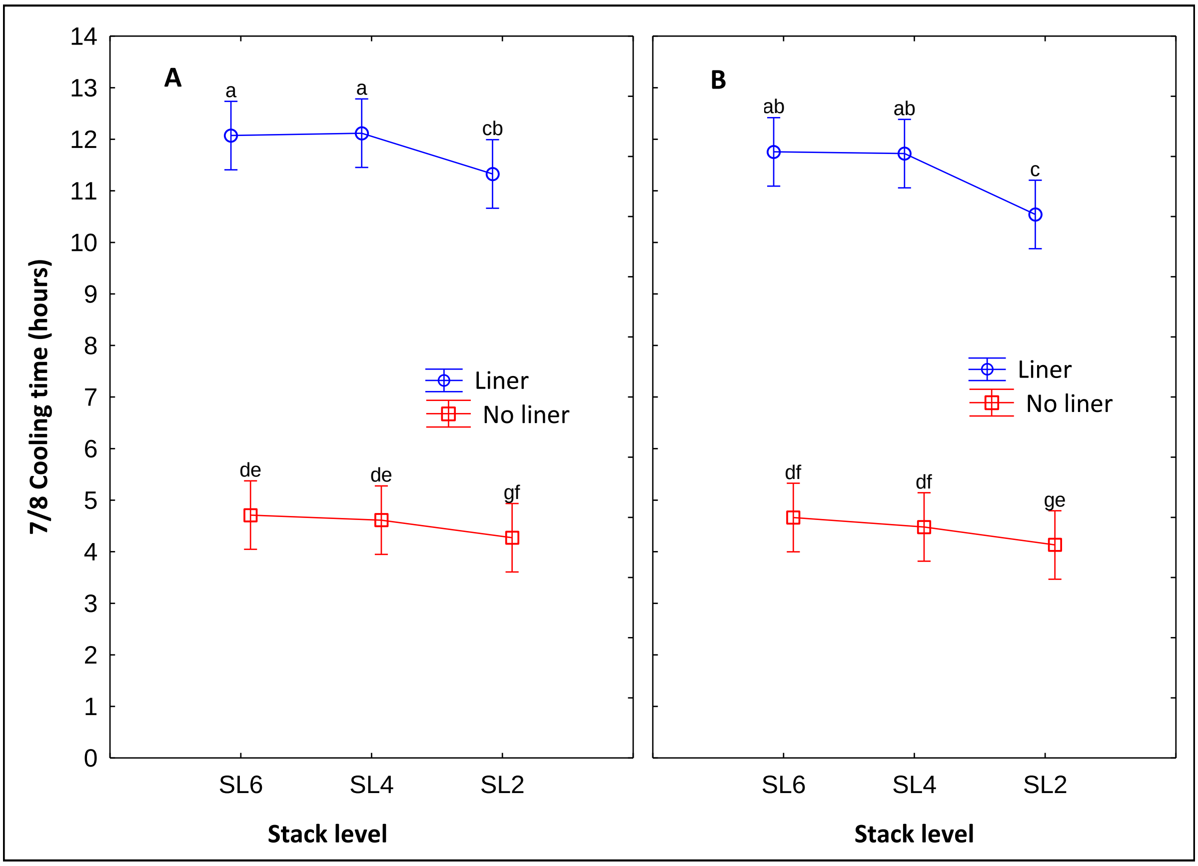


Figure 5 CT1 stack seven-eighths cooling time as a function of the package components, stack level and stack orientation: **A** = Lengthwise orientation; and **B** = widthwise orientation. Different letters indicate significance difference (p<0.05).

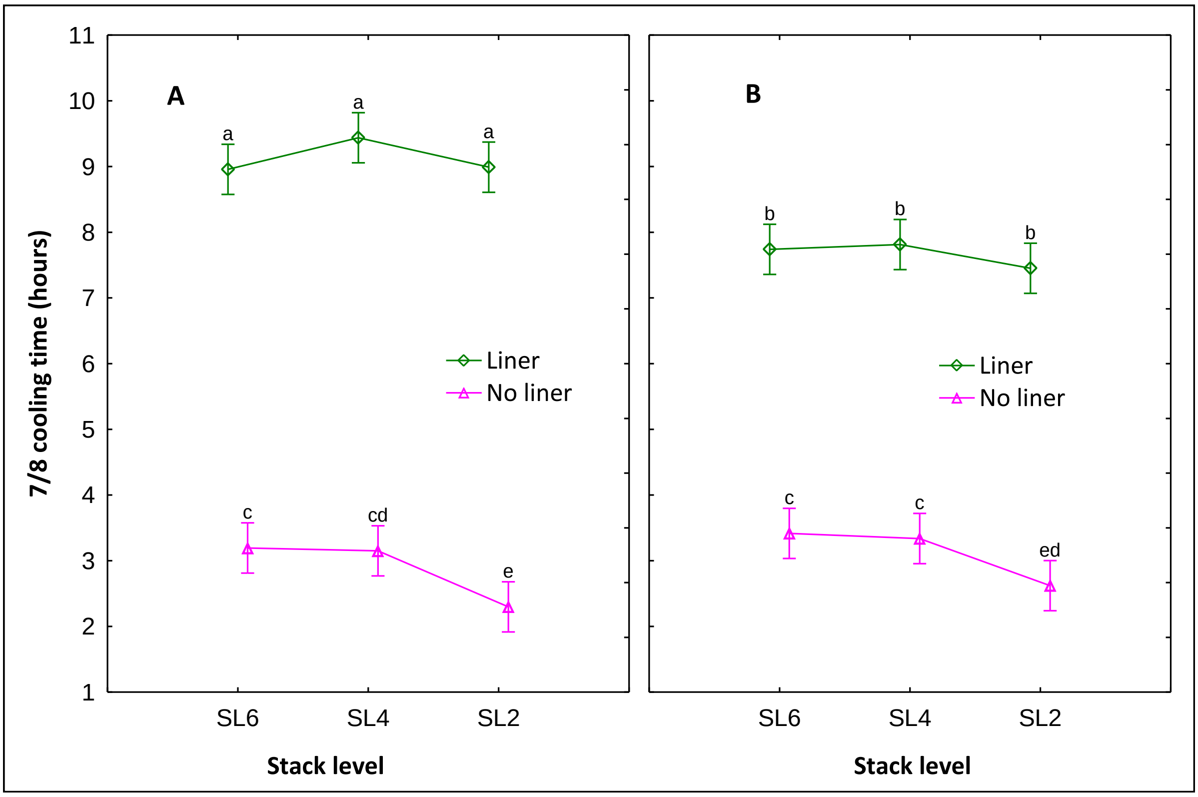


Figure 6 CT2 stack seven-eighths cooling time as a function of the package components, stack level and stack orientation: **A** = Lengthwise orientation; and **B** = widthwise orientation. Different letters indicate significance difference (p<0.05).

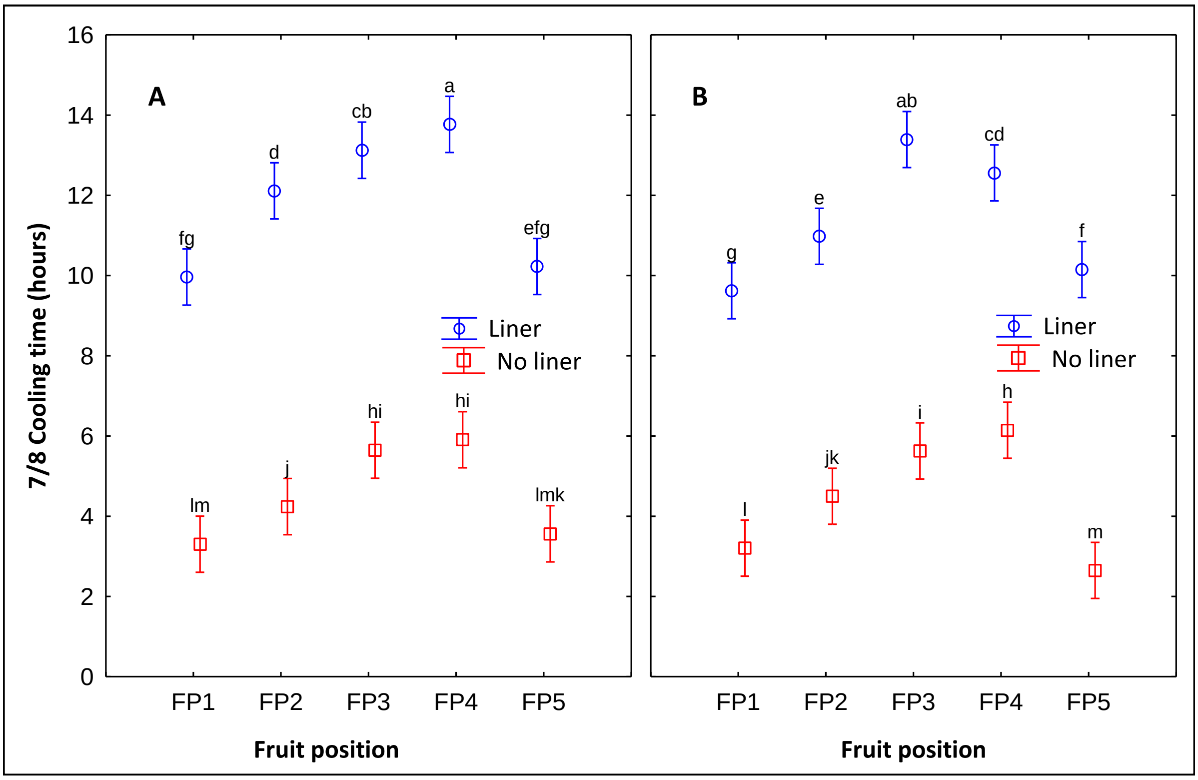


Figure 7 CT1 stack seven-eighths cooling time as a function of package components, fruit position in a stack level and stack orientation: **A** = Lengthwise orientation; and **B** = Widthwise orientation. Different letters indicate significance difference (p<0.05).

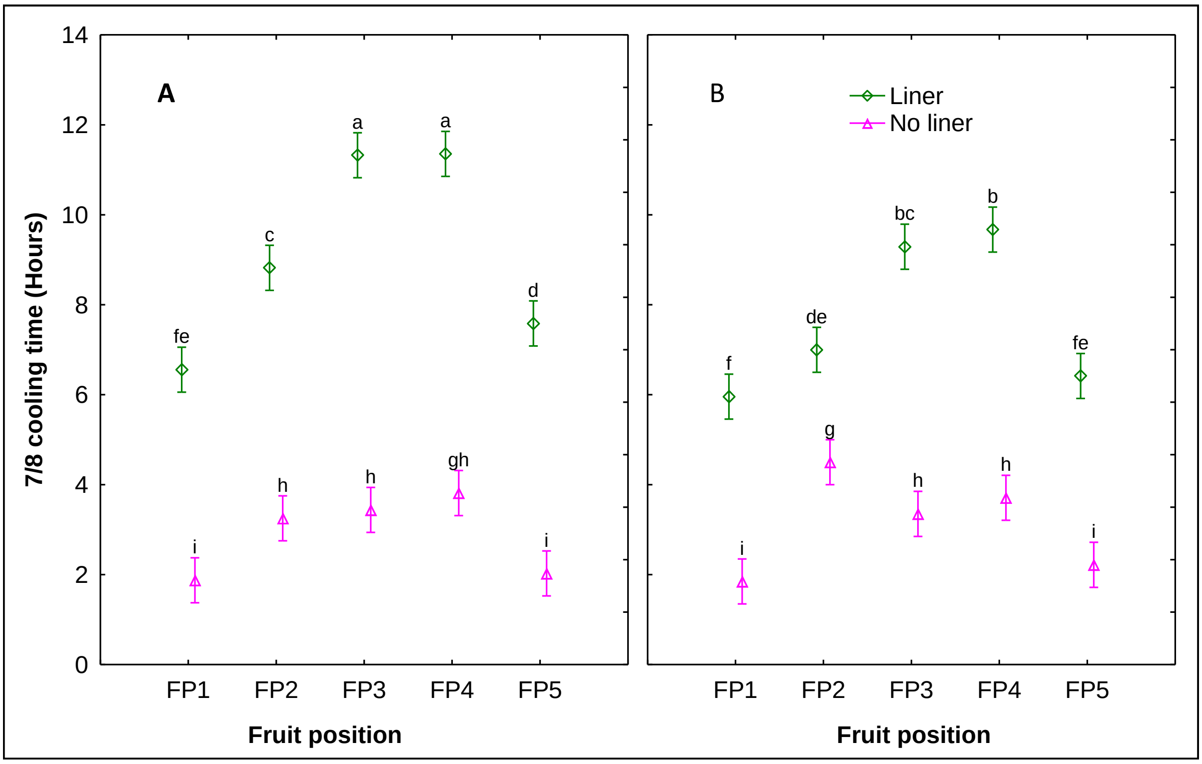


Figure 8 CT2 stack seven-eighths cooling time as a function of package components, fruit position in a stack level and stack orientation: **A** = Lengthwise orientation and **B** = widthwise orientation. Different letters indicate significance difference ($p<0.05$).

3.3. Estimating energy consumption during FAC

Using equation 2 in section 2.6, Fig. 9 shows the energy estimates needed to cool pomegranate fruit to seven-eighths cooling time as a function of volumetric airflow rate in the two stacks of CT1 and CT2 designs. Packaging fruit with no liner during forced-air cooling clearly shows potential of reducing energy costs compared to liner packaging during FAC in both CT1 and CT2 designs (Fig. 9). Taking energy requirements at volumetric flowrate 0.2 m^3/s, liner packaging (reference) used 76.00% and 81.08% more energy compared to no-liner packaging in CT1 (Fig. 9A) and CT2 (Fig. 9B), respectively. This is consistent with the observed large pressure drop and longer cooling times discussed in sections 3.1 and 3.2 in liner packaged fruit. The orientation of CT1 stack lengthwise, liner and no-liner packaging which had a larger total ventilation (6.35%) was observed to require 21.43% and 33.3% less energy, respectively, compared to the widthwise orientation (reference) with 4.24% total ventilation area (Fig. 9A). This observation was similar in CT2 where the widthwise orientation of stack with a higher total vent area of stack, 8.57% required 76.67% and 83.33% less energy for liner and no-liner packaging, respectively, compared to the lengthwise orientation (reference) with only 2.35% total stack ventilation as a result of vent-hole obstruction during stacking. These observations are also consistent with the pressure drop and cooling times results discussed earlier. Defraeye *et al*. (2014) used the same equation (2) to estimate energy consumption during forced-air cooling of oranges in commercial cartons used in the South African citrus industry. They found that the "Ecopack" and "Supervent" cartons with higher ventilation and shorter seven-eighths cooling times had much lower fan energy requirements compared to the "Standard" container. This observation is consistent with those in this study. They however recommended further integration of their findings with a study on optimal airflow rates for each container.

Combining the energy estimations for CT1 and CT2 in Fig. 9C clearly shows the effects of carton ventilation and liner packaging on energy consumption. Vent obstruction during stacking of the CT2 in the lengthwise orientation that left the whole stack with a ventilation of 2.35% required the highest energy (3000 kJ) due to a relatively larger pressure drop and longer cooling time. This energy estimate was for liner packaged fruit. The widthwise CT2 stack orientation that had the highest ventilation (8.57%) and packaged in no liner had the lowest fan energy requirements (100 kJ) (Fig. 9C). Increase in carton vent size to a minimum of 5% reduces the fan energy costs during forced-air cooling of produce (Thompson *et al*., 2008). Paper wraps occupy spaces between products restricting airflow, slowing cooling and ultimately requiring more energy (Thompson *et al*., 2008; Ngcobo *et al*, 2012). Thompson *et al*. (2008) recommended a taller carton for liner packaged fruit in order to allow airflow over the top of the liner in each carton so as to improve heat exchange.

The energy estimations using equation 3 that considers the efficiency of the fan are given in Table 5. The energy estimations follow a similar trend as observed using equation 2 for stack orientation and packaging type. CT2, liner packaging in the lengthwise orientation of stack had the highest energy consumption (3806.11 kJ) while widthwise orientation, no-liner packaging of the same carton which had the highest ventilation had the least energy requirement (54.09 kJ). In addition, liner packaging in CT1 and CT2 was found to require 4 times and 9 times more energy, respectively, compared to no-liner packaging (Table 5). These trends are similar to the graphical trends in Fig. 9C and still highlight the need for effective FAC carton ventilation, and the effect of internal packages on energy requirements during FAC.

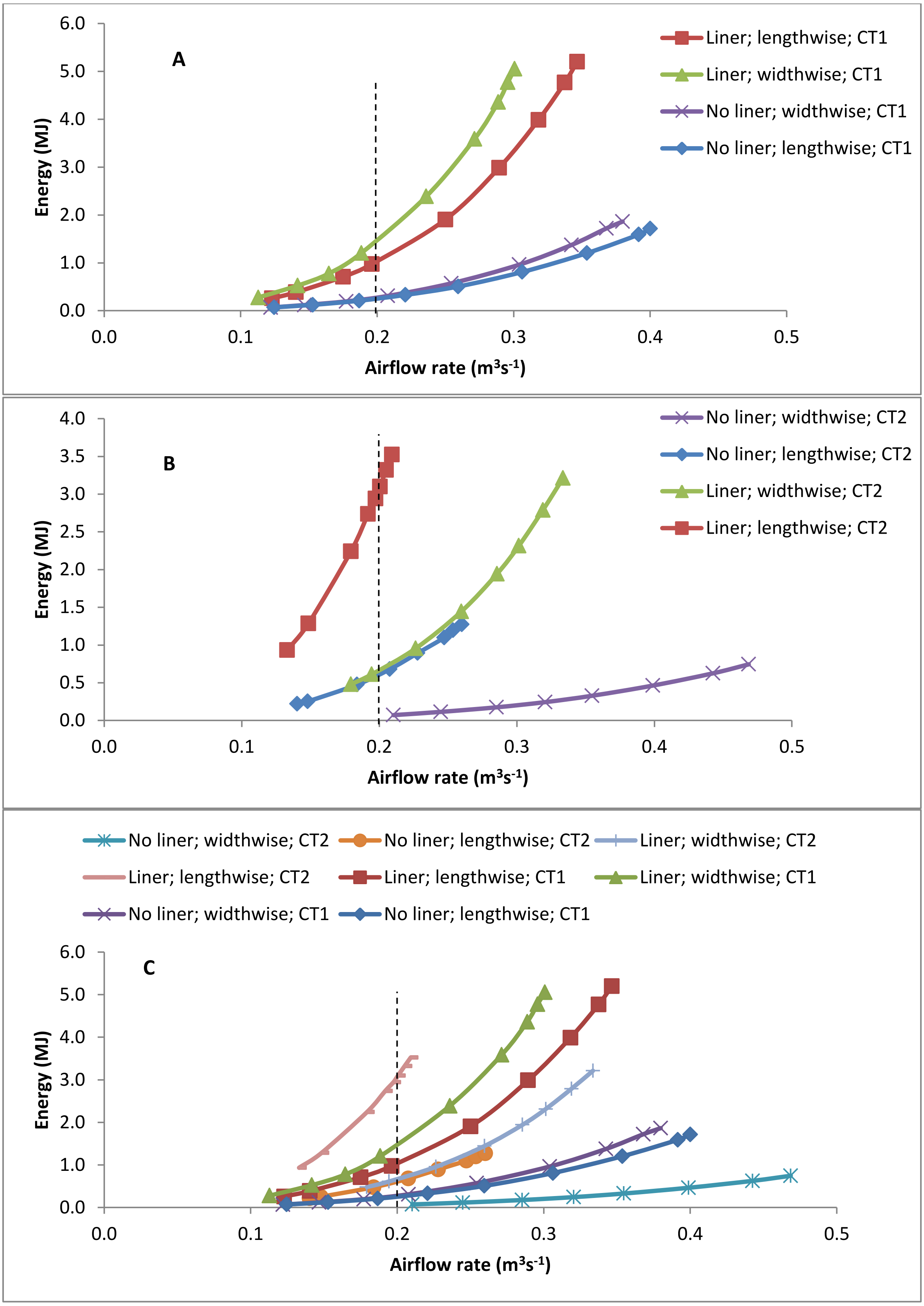


Figure 9 Fan energy requirement to achieve seven-eighths cooling time as a function of internal packaging, stack orientation and volumetric flow rate through CT1 stack, **A**; CT2 carton **B**; and **C** = combination of CT1 and CT2 graphs.

Table 5 Approximate energy consumption during FAC of pomegranates inside stack CT1 and CT2.

		Energy (kJ)	
Internal Packaging	**Orientation**	**CT1**	**CT2**
Liner	Widthwise	1509.28±0.11	521.87±0.63
	Lengthwise	1121.47±1.13	3806.11±6.85
No-liner	Widthwise	361.15±0.56	54.09±0.15
	Lengthwise	312.66±0.37	443.75±1.06

4. Conclusion

The results obtained from the designs used in this study for pomegranate packaging showed that the CT2 performed better in terms of cooling rates and energy consumption than the CT1, but, only when the stack was oriented widthwise where vent holes were not obstructed. Stacking CT2 obstructed the vents along the width of the carton increasing pressure drop in the lengthwise orientation of stack. Liner packaging offered the greatest resistance to airflow and also significantly delayed precooling of the pomegranate fruit in the forced-air cooling operations. Liner packaging and poor ventilation due to carton design and stacking also increased energy requirement during FAC. The tray at the bottom of CT1 was found to obstruct the lower holes along the length of the carton which reduced the effective ventilation along that face. This could be avoided by redesigning the carton with the lower vent holes along the length at least 2 cm from the bottom of the carton to create space for the tray and avoid vent-hole obstruction. Heterogeneous cooling of fruit in different positions in stack was also observed showing the influence stacking has on airflow patterns. To improve cooling homogeneity, stack widths and height during forced-air cooling of pomegranate fruit should be put into consideration for specific airflow rates and fan capacity. Limited carton ventilation reduced cooling rates and increased energy costs due to a higher pressure drop and longer cooling times. CT1 ventilation along the width face (2.86%) was also found to be low compared to the industry minimum carton face recommendation of 5%.

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Chapter 4

Effect of internal packaging, stacking and humidification on pomegranate fruit moisture loss inside ventilated cartons during precooling

Abstract

The effect of packaging liners, carton stacking and cold room humidification on moisture loss in pomegranate fruit during forced-air precooling was studied. The study entailed air being forced through the 1.2 m side of stack (lengthwise orientation) and through the 1.0 m side of stack (widthwise orientation). Fruit packaged without liners had short seven-eighths (SECT) of 4.5 hours and lost more weight (0.23±0.003%) compared to fruit packaged with liners (0.19±0.003%) which also required longer to precool (SECT = 11.6 hours). Cold room humidification caused 0.19±0.003% weight loss compared to 0.22±0.003% weight loss observed in precooled fruit under no humidification. The average relative humidity (RH) in the humidified room was 95.00±1.0% while under no humidification, RH was 90.88±1.15%. Fruit at the front (upwind) and sides of the stack lost 13.6% less moisture than the fruit at the back positions sides (reference) of the stack. This was attributed to the slower cooling of the fruit at the back. The orientation of the stacks widthwise or lengthwise had no effect on the moisture loss from the fruit packaged in liners while fruit packaged with no liner experienced 17.39% more weight loss in the lengthwise (reference) than widthwise orientation of stack. This was attributed to a higher average stack ventilation (6.35%) in the lengthwise orientation than (4.24%) in the widthwise orientation allowing more airflow past the fruit in which case fruit lost more moisture than fruit enveloped in liners. Liner packaged precooled fruit lost weight in equal magnitude to fruit under humidified precooling (0.19±0.003%).

1. Introduction

Rapid moisture loss characterised by shrivelling is among the main quality problems affecting postharvest life of pomegranate fruit (Fawole & Opara, 2013; Arendse *et al*., 2014). Moisture loss in fruit is highest in the first two to three weeks after harvest when cold stores are still being packed, after which fruit attain the storage temperature (Waelti, 2010). However, this loss can be reduced through fruit packaging, precooling and humidification (Delele *et al*., 2009a; Paul, 2009; Waelti, 2010; Montero-Calderon & Cerdas-Araya, 2012). Most weight loss in fruit is due to moisture loss by transpiration and to a relatively small extent carbon loss due to continuous fruit respiratory activity (Waelti, 2010). Pomegranate fruit that lose 5% weight and above begin shrivelling (Kader *et al*., 1984; Fawole & Opara, 2013). On top of losing sellable weight, shrivelled fruit have a lower visual appeal and thus reduced commercial value. Cooling pomegranate fruit preserves quality, but weight loss still remains a challenge in cold storage (Arendse *et al*., 2014). Humidification of cold rooms is an emerging practice to minimise moisture loss and quality degradation of cold stored products (Delele *et al*., 2009a, 2009b; Paul, 2009; Waelti, 2010). It increases the RH and cooling rate of stacked produce lowering the water vapour pressure deficit (VPD) between the fruit and the surrounding air (Delele *et al*., 2009a). Large VPD between fruit surfaces and cooling air during initial fruit cooling normally leads to high moisture loss rates (Xu & Burfoot, 1999; Hamdami *et al*., 2009). After fruit attain storage temperature, interval humidification can maintain the RH of the room (Delele *et al*., 2009a). Literature has shown that humidification has limitations of wetting packages (Ngcobo *et al*., 2013a) which compromises structural integrity of paperboard cartons (Hung *et al*., 2010), and could lead to produce microbial proliferation due to foggy environment (Brown *et al*., 2004). However, nano-mists generate droplets that easily and quickly evaporate without causing wetting, while achieving intended humidity (Hung *et al*., 2010, 2011). High pressure low volume nozzles are preferred for humidification and use very little water (Waelti, 2010). Ngcobo *et al*. (2013a) investigated the potential of humidification on control of moisture loss and quality in table grapes. Humidification increased RH inside "5 kg clamshell" and "5 kg open-top punnets multi-scale packages" to 7.5% and 9%, respectively, but had no effect on RH inside "4.5 kg carry-bag multi-packaging". They also reported that humidification reduced weight loss (0.97±0.34%; 1.08±0.27% and 2.00±0.57% under humidification compared to 1.45±0.32%, 1.62±0.21% and 2.01±0.57% under no-humidification for "carry-bag", "clamshell punnet" and "open-top punnet" multi-packages respectively), reduced stem dehydration and browning, but increased SO_2 injury, and package wetting after 35 days in cold storage. They inferred reduced weight loss to increased RH achieved through humidification which lowered the VPD.

Packaging has been reported to affect the quality and shelf-life of fresh fruit (Ngcobo *et al*., 2012, 2013b). Use of polyethylene, polypropylene and polyvinyl chloride films in fresh produce packaging has been reported to lower transpiration rates by lowering VPD between the fruit and surrounding air, and creating near saturation conditions in the fruit microenvironment that helps check water loss (Mahajan *et al*., 2008; Ngcobo *et al*., 2013b).

However, water condensation inside some liner packaged fruit due to temperature fluctuations and poor package water vapour transmission may predispose them to decay (Mahajan *et al*., 2008). Ventilation of fresh produce cartons has also been reported to affect fruit cooling, moisture loss, package mechanical strength, cooling time, energy costs and general fruit quality (Ngcobo *et al*., 2012; Pathare *et al*., 2012; Opara & Mditshwa, 2013). Ngcobo *et al*. (2013b) reported the effects of multi-scale packages on quality of table grapes. The authors found that weight loss (2.01-3.12%) was higher in "5 kg punnet multi-packages (open-top and clamshell)" than in "4.5 kg carry-bag multi-packages" (1.08%). This was attributed to differences in measured RH inside the packages: 85.31±2.45% (open-top punnets); 84.11±1.04% (clamshell punnets) and 93.52±0.23% (carry bag) resulting in VPD of 92.97 Pa in open-top punnets, 100.71 Pa in clamshell punnets and 40.95 Pa in carry-bag multi-packages. There is a possibility that liner packaging of fruit and humidification of cold storage room may help mitigate weight loss problems and enhance the shelf-life of pomegranates.

Therefore, the aim of this study was to investigate the effects of internal packaging, carton stacking and the use of cold room humidification on the moisture loss of pomegranate fruit during forced-air precooling. The effects of internal packaging components, humidification, stack orientation and fruit position in stack level were analysed.

2. Materials and methods

2.1. Pomegranate fruit

Pomegranate fruit (cv. Wonderful) were harvested at commercial maturity from Merwespont farm in Bonnievale (33^{o}58'12.02"S, 20^{o}09'21.03"E), Western Cape, South Africa and transported in an air-conditioned vehicle to Stellenbosch University Postharvest Technology Research Lab. The fruit were medium sized (diameter of 8.29±0.25 cm).

2.2. Package materials

Fruit were packaged in the CT1 carton (Sapex, Stellenbosch; Fig. 1C) of dimensions 0.39 m (length) x 0.30 m (width) x 0.118 m (height) with a fiberboard tray (Fig. 1B) at the bottom of each box. Each carton was packed with 12 fruit, with an average fruit weight of 5.09±0.39 kg per carton. In one packaging mode, the fruit and tray was enveloped in a polyliner bag (ZOE PAC; liner packaging; Fig. 1F) while in the other, no liner was used (no-liner packaging; Fig. 1E).

2.3. Experimental set-up

The cartons were stacked onto a pallet of dimensions 1.2 x 1.0 m (Fig. 1G). This set up comprised of 70 cartons in 7 layers with each layer containing 10 cartons, height 0.826 m (Fig. 4). The stack was tightly connected to a portable forced-air cooling (FAC) equipment and sealed with air tight plastic along the sides, top and bottom so that air being forced through the stack only entered from the stack face opposite the FAC equipment, and exited the stack along the stack face on the pressure drop tunnel of the FAC equipment (Fig. 1H). Vertical slots between two perpendicular cartons were also sealed with LDPE plastic to minimize chances of carton by-passing by the air. The study entailed air being forced through the 1.2 m side of stack (lengthwise orientation) and through the 1.0 m side of stack (widthwise orientation; Fig. 2 A and B) in a humidified and a non-humidified experimental cold room with dimensions; 3.05 m (length), 2.4 m (width), and 2.83 m (height) with three cooling fans of diameter 30 cm each (1290 m^3h^{-1} capacity; Fig. 3).

2.4. Fruit precooling and humidification

After stacking, fruit were precooled from 17±3.0°C to 7±1.2°C. Temperature of the fruit pulp at the thermo-centre was monitored using T-type thermocouples and a 34970a Data Acquisition/Data Logger Switch Unit (Agilet Technologies, Santa Clara CA 95051, USA) at 5 minutes intervals. Fruit monitored for weight loss were positioned next to temperature data logger instrumented fruit in positions 1 to 5; stack levels 2, 4 and 6 (Fig. 2). Stack and FAC equipment was aligned in the experimental cold room (Fig. 3) with stack oriented lengthwise and widthwise as described in section 2.3, measurements were done in triplicates. The FAC equipment was used to generate a spectrum of controlled airflow rate across the stack. The sucking action of the FAC was effected by a centrifugal fan model (KDD 10/10 750W 4P-1 3SY, AMS supplies, Sandton, South Africa). A constant airflow rate of 0.5 $Ls^{-1}kg^{-1}$ was used in this study (De Castro *et al.*, 2005) since pomegranates are low respiring fruit. The temperature of the cold room was set to 7±1.2 °C.

In one set of experiments, the cold room was humidified using air-assisted Aqua Room-2 humidifier (Miatec inc. 9480SE, Lawnfield Road, Chackamas OR 97105 USA) with 1.4-2.1 bars pressure capacity, 2 Lh^{-1} liquid capacity, 10 µm droplet size and digital hygrotransmitter sensor (0-100% RH). It was set to RH 95%. Kader (2006) recommended storage of pomegranate (cv. Wonderful) at 90–95% RH. Tinytag sensors (Tinytag TV-4500, Hastings Data Loggers Australia) were used to monitor the temperature and humidity in the cold room. In the non-humidified precooling cold room, the RH was 90.88%.

2.5. Weight loss measurements

Fruit monitored for weight loss at the various positions (1, 2, 3, 4 and 5; Fig. 2) in each stack level at the three levels 2, 4 and 6 were each weighed at the start and at the end of the precooling period using an electronic weighing scale (Mettler Toledo, Model ML 3002E, Switzerland with 0.0001 g accuracy). The fruit weight loss was calculated as:

$$W = \left(\frac{W_o - W_1}{W_o}\right) x100 \qquad (1)$$

where W = fruit weight loss percentage; W_0 = initial fruit weight at start of experiment and W_1 = fruit weight at end of precooling cycle. Values were presented as mean weight loss ±Standard error (SE).

2.6. Statistical analysis

Statistical analysis was done using Statistica software (Statistica version 12, StatSoft Inc., Tulsa, USA). Mixed model repeated measures analysis of variance (ANOVA) was done using the VEPAC module of Statistica 12 at 95% confidence interval. Variations in weight loss were compared between the package designs, stack levels, stack orientations and fruit position within a stack level.

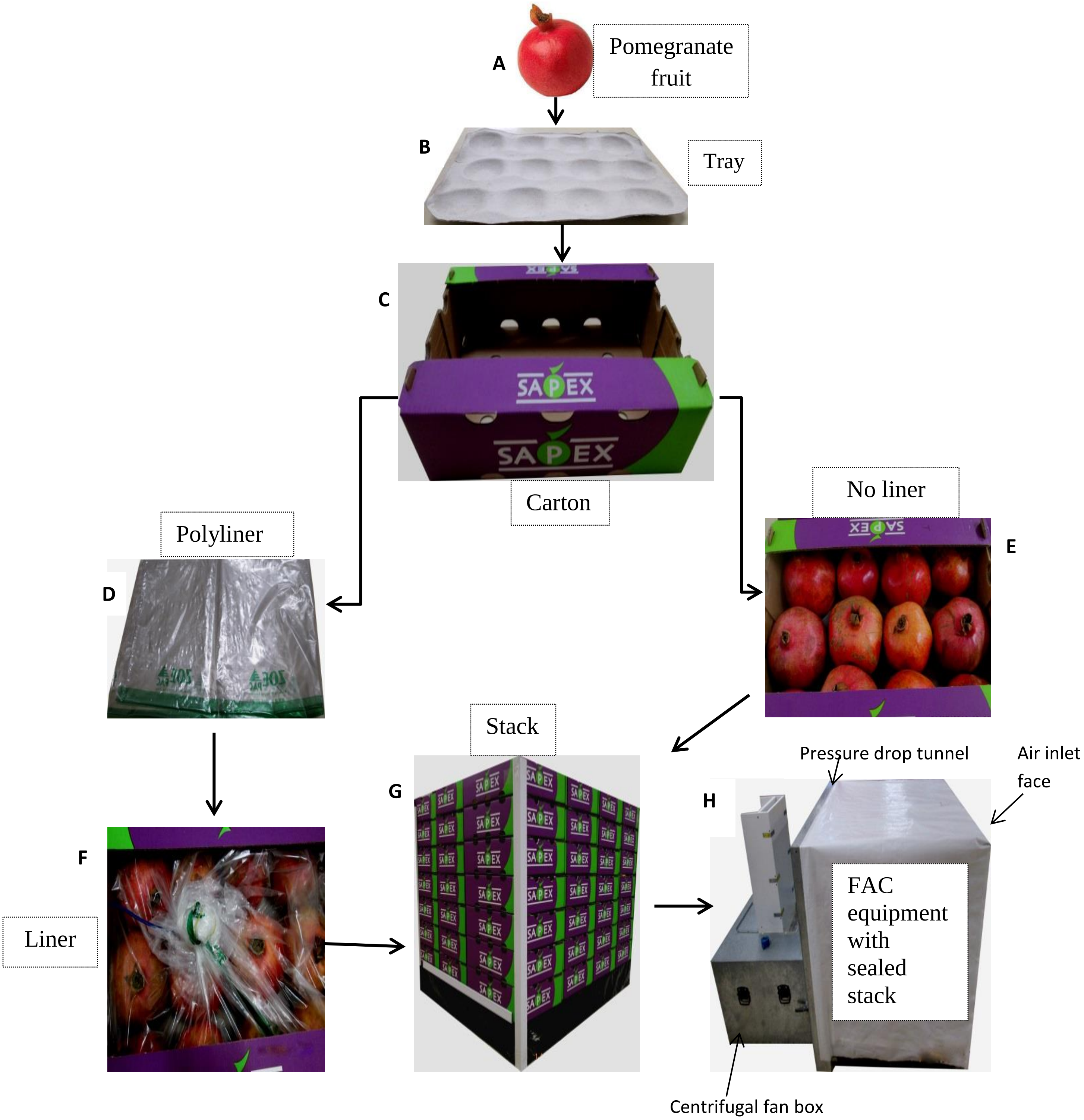

Figure 1 Diagram of packaging combinations and stages of the pomegranate fruit for weight loss measurements. No-liner packaging **E** has fruit sitting on the tray at the bottom of the carton; liner packaging **F** has a liner enclosing the fruit and tray; and stack **G** is sitting on a standard pallet of dimensions 1.2 x 1.0 m.

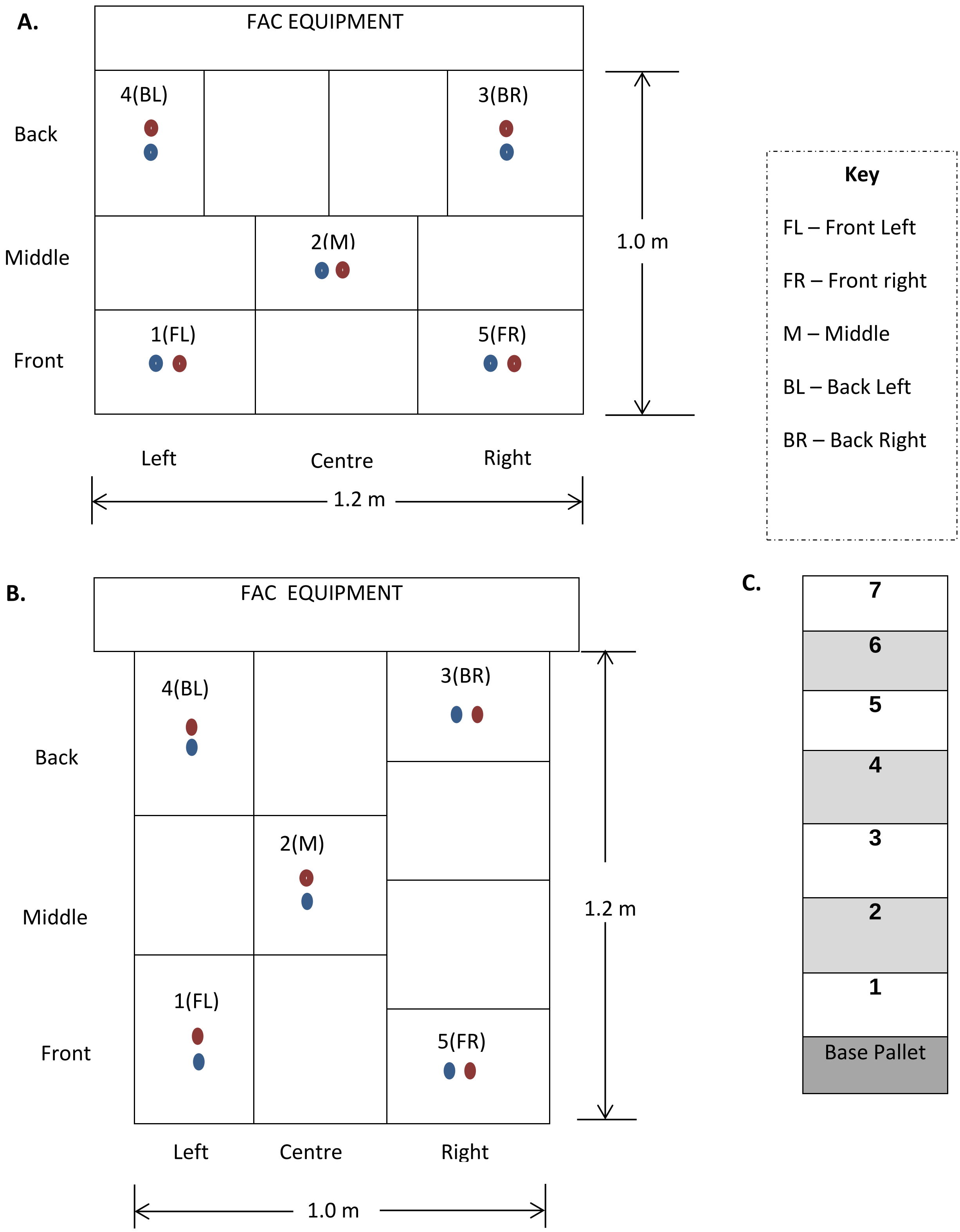

Figure 2 Lay-out of the stacking pattern of the fruit cartons in each layer, temperature logged pomegranate fruit positions, and position of fruit monitored for moisture loss. **A** = lengthwise orientation; **B** = widthwise orientation; **C** = stack layers (levels); blue circle = temperature logged fruit; and red circle = moisture loss fruit. Layers 2, 4, and 6 in **C** were used for monitoring temp and moisture loss.

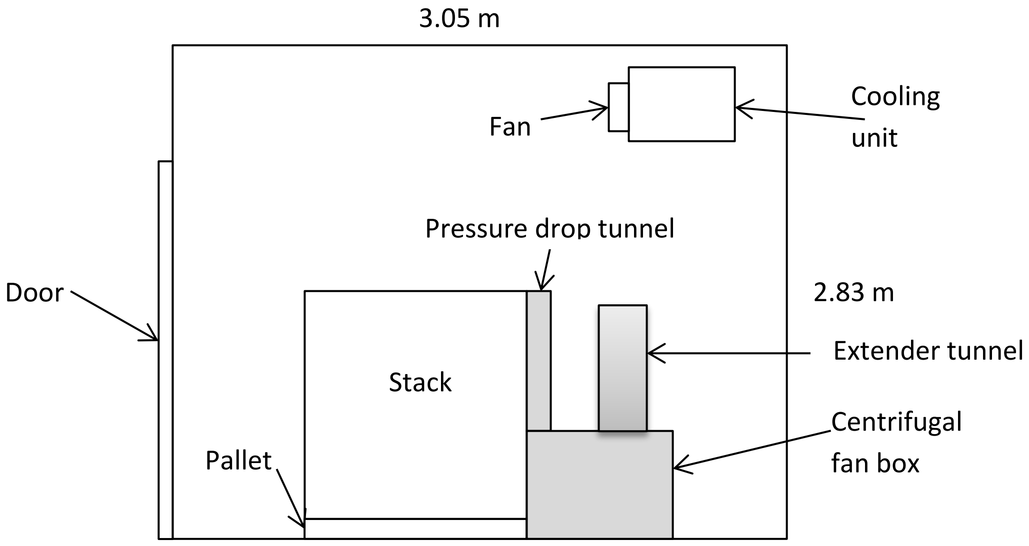

Figure 3 Side view of experimental set up inside cold room

3. Results and discussions

3.1. Effect of internal packaging and stacking on fruit weight (moisture) loss

Fruit packaged without liners had short seven-eighths cooling time (SECT) of 4.5 hours and lost more weight (0.23±0.003%) compared to fruit packaged with liners (0.19±0.003%; values are mean weight loss irrespective of humidification; Fig. 4), which also required longer to precool (SECT = 11.6 hours). This transforms to an estimated moisture evaporative rate of 2.4 x 10^{-4} kgh^{-1} and 8.1 x 10^{-5} kgh^{-1} in no-liner and liner packaged fruit, respectively. This could be attributed to fruit releasing moisture through transpiration that eventually saturates the microenvironment around the fruit within the liner, which lowers the VPD and thus reduces the fruit transpiration rate (Mahajan *et al.*, 2008). Higher VPD causes high transpiration rates thus higher moisture loss from fruit (Mitchell *et al.*, 2008; Ngcobo *et al.*, 2013a, 2013b). Fruit packaged with no liner at the front positions of the stack (Fig. 2), front left (FP1) and front right (FP5) lost less weight (0.19±0.005%) than the fruit at the back positions, back left (BL4) and back right (BL3) (0.22±0.005%). No significant weight loss differences with position in stack level were seen in liner packaged fruit except for fruit at fruit position (FP1) with 0.17±0.007% weight loss (Fig. 4). This may be attributed to the slower cooling of the fruit at the back of stack in which process more weight is lost compared to the upstream fruit that get to the storage temperature faster. Increase in air temperature as it moves across a stack causes local variations in heat loss in the stacked products (Baird *et al.*, 1988) and holding pomegranate fruit at higher temperatures for longer periods causes higher moisture loss rates (Arendse *et al*., 2014; Berry, 2013). Delele *et al*. (2009a) reported lowest percentage RH in the hottest fruit stack regions during fruit cooling which can lead to more moisture loss in those regions. Consistent with the observations in this study, Ngcobo *et al*. (2013b) reported a higher weight loss (2.01-3.12%) in grape bunches packaged in "5 kg punnet multi-packages (open top and clamshell)" than those in "4.5 kg carry-bag multi-packages"(1.08%) stored at -0.5°C and at 95% humidity for 35 days. The authors attributed this effect largely to differences in VPD inside the packages where the 4.5 kg carry-bag multi-packaging had a VPD of 40.95 Pa compared to 92.97 Pa and 100.71 Pa in open-top and clamshell packaging, respectively as a result of different %RH inside each of the packages; 93.52±0.23% (carry-bag); 85.31±2.45% (open-top); and 84.11±1.04% (clamshell).

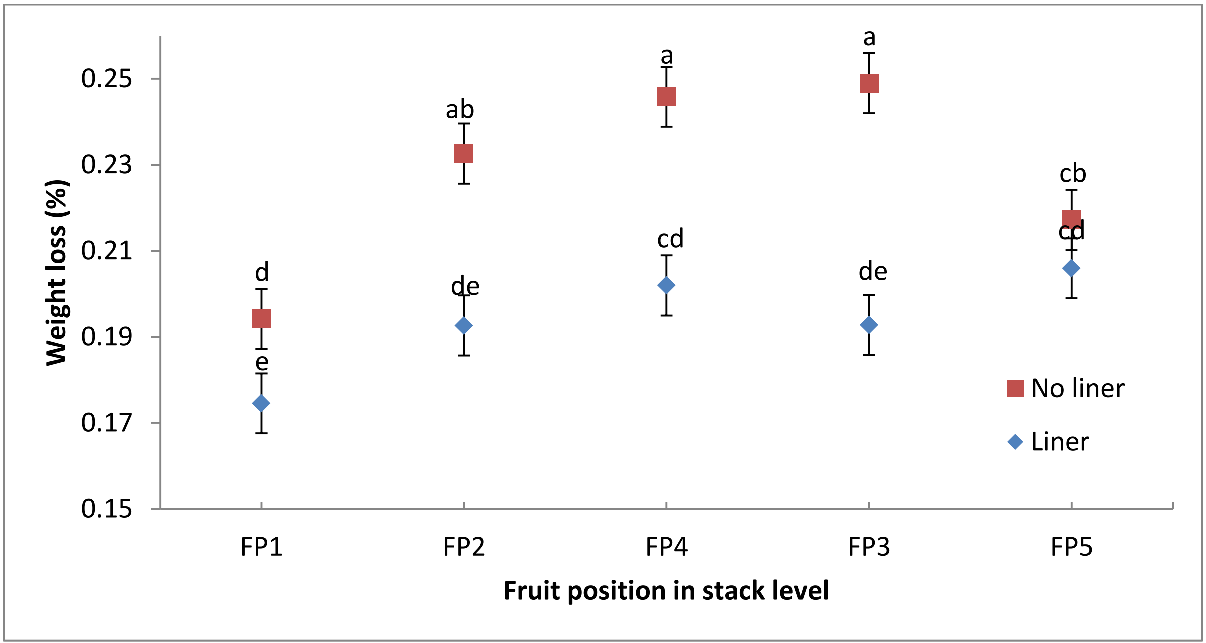

Figure 4 Pomegranate fruit weight loss as a function of internal packaging and fruit position in a stack level. Vertical bars denote the standard error of the mean. Different letter(s) indicate significance difference ($p<0.05$).

The orientation of the stacks widthwise or lengthwise had no effect on the moisture loss from the fruit packaged in liners while fruit packaged with no liner experienced more weight loss in the lengthwise (0.25±0.004%) than widthwise (0.21±0.004%) orientation of stack (Fig. 5B). This could be attributed to a higher average stack ventilation (6.35%) in the lengthwise orientation than 4.24% in the widthwise orientation allowing more air to flow past the fruit in which case fruit lose more weight than when the fruit is enveloped in liners or, with more resistance to airflow in the lower ventilation case. Stack level 6 was also observed to have 7.14% lower weight loss than stack level 4 and 2 (reference) in the liner and no liner packaging (Fig. 5). This could be due to differences in airflow velocity through the stack levels with stack level 2 and 4 experiencing a higher velocity due to cold room and portable FAC equipment design. Cold rooms designed with fans just below the ceiling operate in a way that the discharged air flows past the ceiling to opposite wall then to the floor before rising through the room (Thompson *et al*., 2008). Delele *et al*. (2009a) also reported high air velocity at the bottom region of stack in cold room with cooling fans at the back of room just below the ceiling. The portable FAC equipment also had the sucking centrifugal fan at its bottom. This can increase weight loss as the air picks up moisture from the surrounding of the product. This calls for controlled flow rates during precooling and reduction thereafter through storage and transportation (Thompson *et al*., 2008).

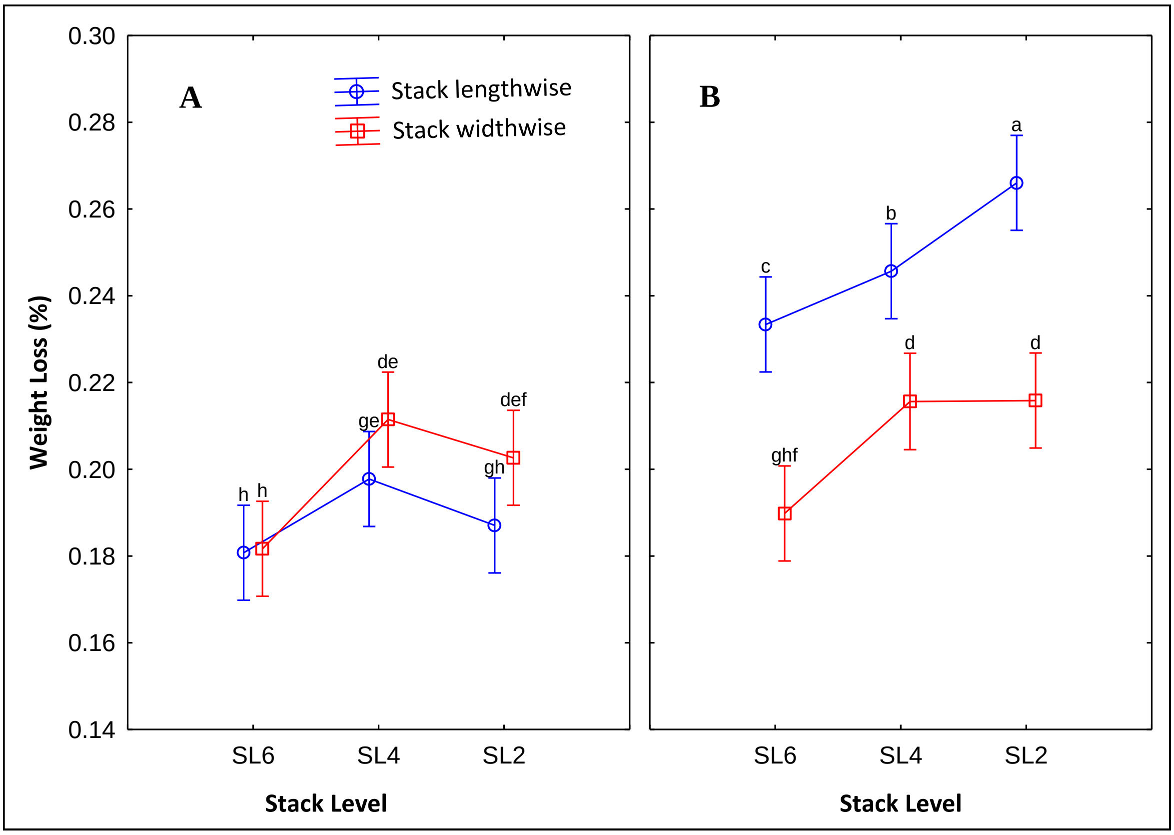

Figure 5 Pomegranate fruit weight loss as a function of stack orientation, stack level and fruit packaging: **A** = liner and **B** = no liner. Vertical bars denote 0.95 confidence intervals. Different letter(s) indicate significance difference ($p<0.05$).

3.2. Effect of humidification on fruit weight loss

Fruit precooled under humidification generally lost 0.19±0.003% weight compared to 0.22±0.003% weight loss observed in precooled fruit with no humidification (Values are mean weight loss irrespective of internal packaging, Fig. 6). Humidification of the cold room during forced-air cooling and storage of fruit increases the relative humidity within the room thus reducing the VPD that results into reduced moisture loss from the fruit (Delele *et al*., 2009a; Waelti, 2010). A higher VPD results in high transpiration rates and thus higher water loss from fruit (Ladaniya, 2008; Mitchell *et al*., 2008; Ngcobo *et al*., 2013a). In a computational fluid dynamics model study on optimisation of humidification of cold stores, Delele *et al*. (2009a) reported a decrease in weight loss of pears (cv. Conference) from 4.22% to 3.09% due to humidification (from 83.6% RH to 96.3% RH) of the cooling room after 21.05 hours and a reduction in weight loss rate from 1.02%/month to 0.61%/month. This was consistent with our findings. Kirchoff (1990) recommended the use of humidifiers in fruit storage for the first two weeks because storage air often has undesirably low relative humidity levels which increase weight loss. Similar to observations made in section 3.1 above, it was also observed that fruit in the front position of the stack perpendicular to the incoming air, front left (FP1) and front right (FP5), lost about 7.14% less weight compared to the fruit at the back positions (reference) of the stack, back left (FP4) and back right (FP3), in both the humidified and the non-humidified rooms. However, this was only significant for FP1 (Fig. 6), which can be attributed to a faster cooling rate of the fruit that come into contact with cold air first (Ngcobo *et al*., 2013b; Berry, 2013), thus, achieving the set storage temperature faster than fruit at the back of the stack. The hottest stack regions have been reported to have the lowest RH which causes relatively more weight loss of stacked fruit (Delele *et al*., 2009a). It is also known that fruit moisture loss increases with storage time and temperature (Paul, 2009; Arendse *et al*., 2014); hence, it would be expected that the magnitude of weight loss found during precooling in this study would increase substantially with increasing duration of static cooling during long-term refrigerated storage.

Weight loss of fruit in stack level six (SL6) in the non-humidified precooling cold room (0.21±0.006%) was significantly lower than those in stack level four (SL4) (0.23±0.006%) and two (SL2, 0.24±0.006%, Fig. 7A). These differences in weight loss could be attributed to differences in local airflow. Cold rooms designed with fans just below the ceiling operate in a way that the discharged air flows past the ceiling to opposite wall then to the floor before rising through the room (Thompson *et al*., 2008). Delele *et al*. (2009a) also reported high air velocity at the bottom region of stack in cold room with cooling fans at the back of room just below the ceiling.

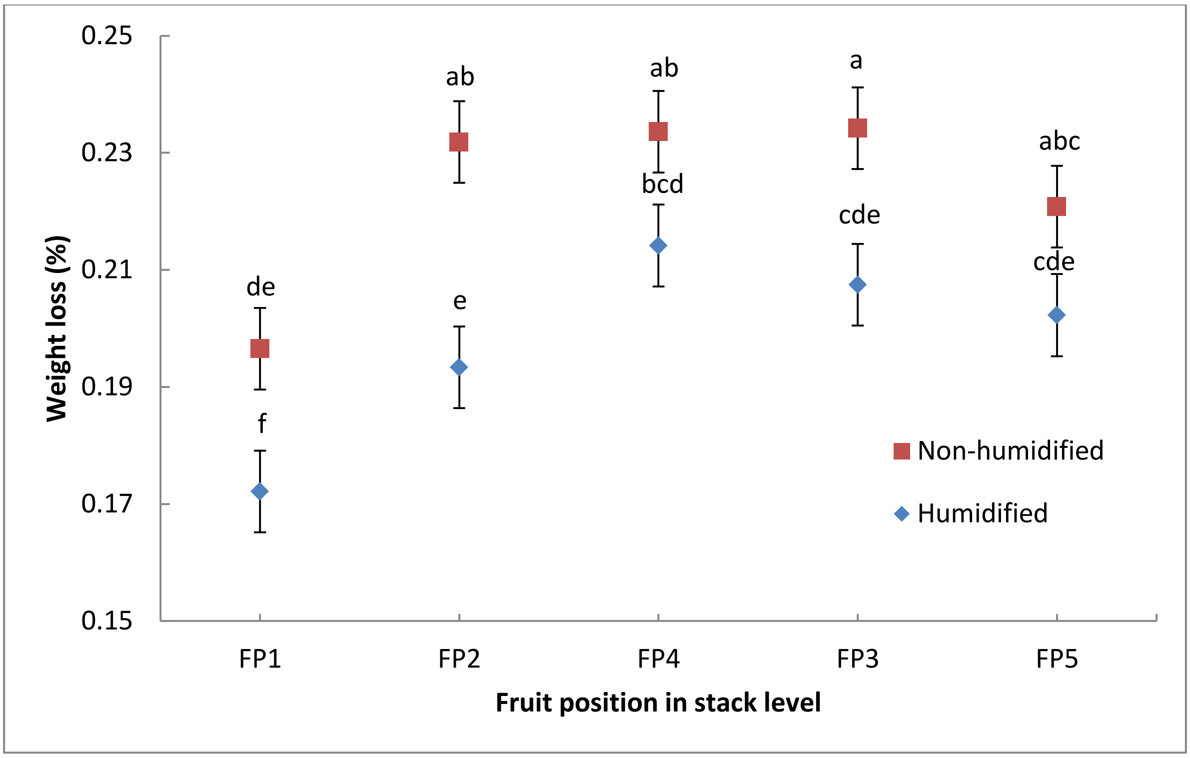

Figure 6 Pomegranate fruit weight loss as a function of cold room humidification during precooling and fruit position in a stack level. Vertical bars denote the standard error of the mean. Different letters indicate significance difference (p = 0.01155).

The orientation of the stack lengthwise or widthwise did not affect weight loss of fruit in the non-humidified precooling cold room (Fig. 7A); however, fruit in stacks oriented lengthwise lost 0.21±0.004% weight compared to 0.18±0.004% in widthwise oriented stacks in humidified cold room (Fig. 7B). This could be due to the higher stack ventilation in the lengthwise (6.35%) compared to the widthwise (4.24%) orientation allowing in more cold airflow past the fruit that possibly picks up moisture from the fruit surrounding.

Fig. 8 shows the interaction between packaging and humidification and it can be seen that fruit mean weight loss in liner packaged fruit (with and without humidification) was similar to fruit weight loss in humidified storage (with and without internal packaging). Similarly, mean fruit weight loss was similar inside no-liner packaging (with and without humidification) and cold store with no humidification (with and without internal packaging). This shows that packaging fruit in liners or using humidification represent practical options to maintain high RH around the fruit as part of the postharvest management to minimise fruit weight loss of pomegranates during precooling.

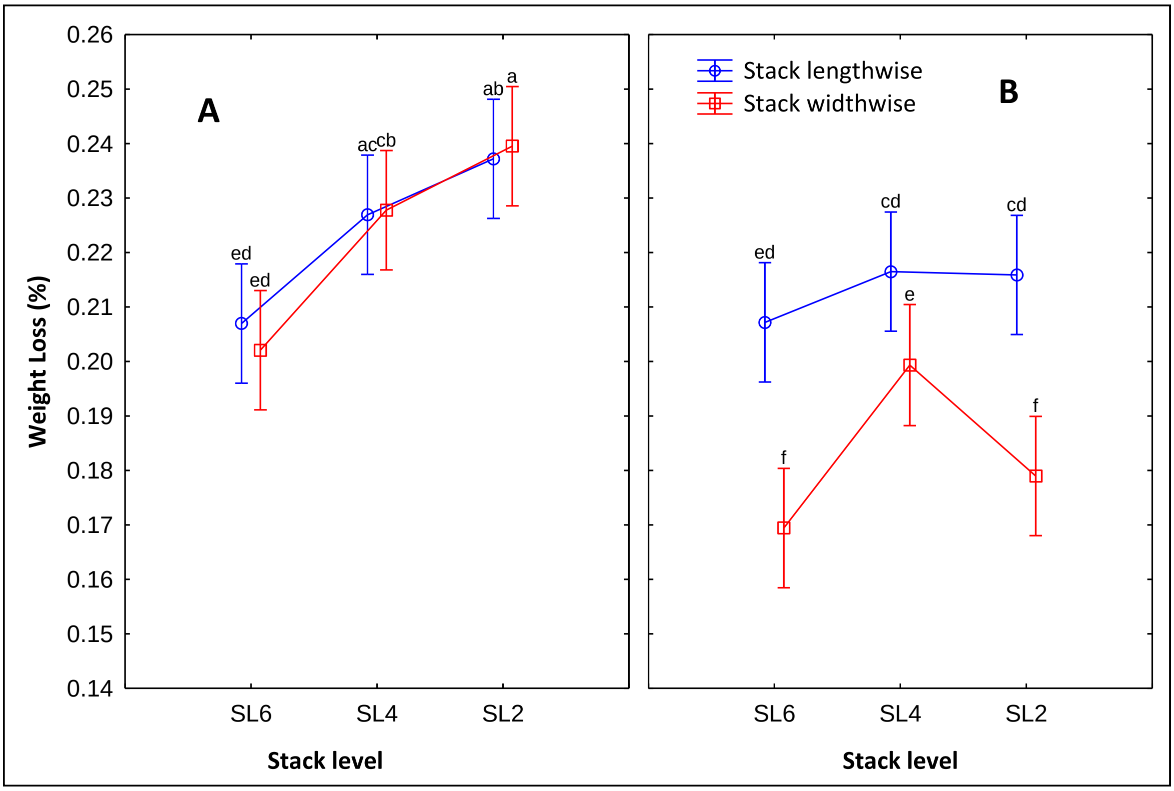

Figure 7 Pomegranate fruit weight loss as a function of stack orientation, stack level and cold room humidification: **A** = non-humidified cold room and **B** = humidified cold room. Vertical bars denote 0.95 confidence intervals. Different letter(s) indicate significance difference ($p<0.05$).

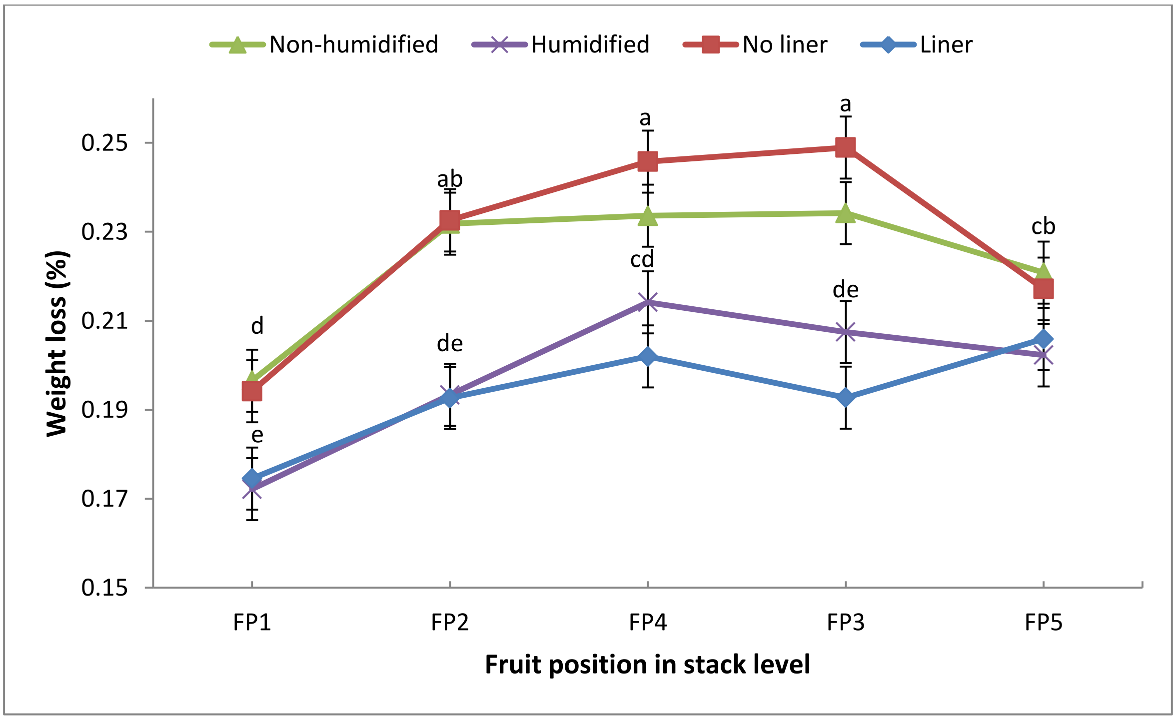

Figure 8 Pomegranate fruit weight loss as a function of cold room humidification, packaging and fruit position in a stack level during precooling. Vertical bars denote the standard error of the mean. Different letters indicate significance difference ($p>0.05$).

4. Conclusion

This study showed that the use of liner packaging and cold room humidification alone or in combination has the potential of reducing moisture loss in pomegranates, perhaps, supporting the popularity of liners in the South African pomegranate industry. However, liners have been reported to delay fruit precooling. Comparatively, humidification and liner packaging reduced fruit moisture loss in equal measure during precooling. Fruit that cool down in a shorter time and fruit exposed to a lower air velocity within the stack were also observed to lose less weight compared to fruit in the hottest stack regions and fruit exposed to high velocity air. The magnitude of weight loss (0.22%) in such a short time (precooling) of pomegranate fruit in this study prompted a further study into the effects of RH on the physical and chemical properties of pomegranate fruit in the next chapter.

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Chapter 5

Effect of relative humidity on pomegranate quality under simulated ambient storage conditions

Abstract

The effects of relative humidity (RH) on the quality of pomegranate fruit (cv. Wonderful) stored in ambient temperature (20°C) under low RH (65±6.79%) and a high RH (95±1.23%) conditions were studied. Significantly high weight loss up to 29.13±1.49% at day 30 was observed in fruit stored at low RH compared to 5.78±0.44% at high RH. At the end of a 30 day storage period, this magnitude of fruit weight loss was estimated to be worth about ZAR7.78 kg^{-1} and ZAR1.54 kg^{-1} under low and high RH conditions, respectively. Fruit stored under low RH were also severely shriveled and reduced in size. The high RH environment better maintained fruit colour, texture and chemical quality attributes. Regression equations were developed to estimate weight loss in pomegranates at 65% and 95% RH ambient storage conditions. The equations had a high goodness-of-fit with R-squared values of 0.9931 and 0.9368 for low and high RH, respectively. These findings show that pomegranate fruit should preferably be stored at RH conditions ≥ 95% to maintain appearance, sensory quality and reduce weight loss.

1. Introduction

Relative humidity affects the behaviour, marketability and consumer choices of fruit on retailer shelves (Tu *et al*., 2000; Nunes, 2008). Compromises of fruit handling conditions of temperature and RH are common in the distribution chain due to inadequacy of facilities for ideal handling of each commodity leading to quality loss, physiological stress and reduced shelf life (Paull, 1999; Nunes, 2008). The effects of different storage temperatures and RH on physico-chemical and antioxidant properties of different cultivars of pomegranates have been previously studied; both arils and whole fruit (Kader, 2006; Caleb *et al*., 2012; Fawole & Opara, 2013; Arendse *et al*., 2014), however, much emphasis has been put on the effect of temperature with less insight on the relative humidity and conditions outside cold storage and on local open market shelves. Landrigen *et al*. (1996) in their study on the influences of RH on postharvest browning of Rambutan at 20°C reported increased browning in fruit stored at low RH (65%) in comparison to fruit stored at high RH (95%) inferring this to non-enzymatic changes associated with desiccation at low RH. Similarly, Tu *et al*. (2000) reported the effects of RH on apple quality under simulated shelf temperature storage at 20^{o}C with 30%, 65% and 95% RH. They reported faster weight loss, firmness loss, juice content loss, increase in dry matter and increase in soluble solids content at low RH (30% and 65%), while at 95% RH, the apples developed a mealy texture after 2-3 weeks, though firmness and weight were maintained better. They also observed a faster weight loss on decreasing RH from 95% to 65% than from 65% to 30% attributing this to a larger vapour pressure deficit (VPD). Increasing the relative humidity and lowering storage temperature lowers the VPD of a storage environment (Paull, 1999). A higher VPD of 92.97 Pa and 100.71 Pa caused a weight loss of 2.01-3.12% in "open top and clamshell" packaged table grapes respectively compared to 1.08% weight loss in "4.5 kg multi-packaging" with a lower VPD of 40.95 Pa (Ngcobo *et al*., 2013a).

Quality loss in pomegranate fruit has been reported to be high at high temperatures (above 10^{o}C) and low RH (below 90%) leading to loss of weight, shrivelling, changes in the chemical composition (total soluble solids - TSS, pH, and titratable acidity - TA) and antioxidant properties of pomegranates postharvest (Fawole & Opara, 2013; Arendse *et al*., 2014). These changes are affected by storage duration and storage conditions of temperature and RH, and affect fruit appearance, flavour and consumer acceptance. Weight loss is due to moisture loss through transpiration and to a relatively small extent, some weight loss in horticultural crops is due to carbon loss during respiration (Kader *et al*., 1984; Waelti, 2010). Arendse *et al*. (2014) in their study on the effects of temperature and storage duration on pomegranates reported that increase in temperature and longer storage duration resulted in increased loss of moisture, loss of fruit firmness, and changes in pomegranate (cv. Wonderful) fruit chemical composition. Similarly, Fawole and Opara (2013) reported loss of color of pomegranate fruit with increase in storage temperature and duration due to anthocyanin breakdown. TSS and TA in pomegranate fruit have also been reported to decrease with storage duration (Turfan *et al*., 2011). Kader (2006) recommended storage of pomegranate (cv. Wonderful) at 5^{o}C and 90–95% to achieve a shelf-life of up to 2 months. In a study on effects of humidification on control of moisture loss and quality of crimson seedless table grapes during cold storage, Ngcobo *et al*. (2013b) reported higher moisture loss, rapid stem dehydration and browning for grapes stored under low (90.3%) RH, and attributed this to high transpiration due to a higher VPD at low RH (no humidification) while humidification (high RH (95%)) increased incidences of SO_2 injury in the grapes and package wetting.

Limitations in the handling chain and retail market call for a better understanding of the effects of RH and temperature on fruit quality and shelf life from all participants in the fruit distribution chain (Paull, 1999; Nunes, 2008). In this study, physico-chemical changes of pomegranate fruit (cv. Wonderful) at 20^{o}C under two RH conditions were monitored. The objective of the study was to investigate the effects of RH on pomegranates at room temperature. Weight loss, firmness, size and chemical properties of pomegranate fruit were studied.

2. Materials and methods

2.1. Pomegranate fruit and storage conditions

Fresh pomegranate fruit (cv. Wonderful) were obtained at commercial maturity from Sonlia Pack-house (33^{o}34'851"S, 19^{o}00'360"E), Western Cape, South Africa (fruit diameter 8.0±0.15 cm) and transported in an air-conditioned vehicle to Stellenbosch University Postharvest Technology Research Lab. These were in ventilated cartons of dimensions 0.32 m length, 0.29 m with and 0.105 m height. After equilibration to room temperature (20±2^{o}C 65±5.55% RH), fruit were randomly divided into two groups containing 200 fruit each. One group was placed in a simulated shelf storage condition of 65±6.79% RH at 20±0.36^{o}C (low RH environment) while the other was placed under 95±1.23% RH at 20±0.31^{o}C (high RH environment). High humidity was achieved using an air-assisted Aqua Room-2 humidifier (Miatec inc. 9480SE, Lawnfield Road, Chackamas OR 97105 USA) with 1.4-2.1 bars pressure capacity, 2 Lh^{-1} liquid capacity, 10 µm droplet size and digital hygrotransmitter sensor (0-100% RH). It was set to RH 95%. Tiny Tag TV-4500 data loggers (Gemini Data Logger, Sussex, UK) were used to monitor and record the temperature and RH in the two study environments. Physico-chemical quality attributes of 10 pomegranates in each of the two environments were monitored for 30 days at 3 day intervals.

2.2. Measurement of physical properties

2.2.1 Weight loss

In each environment, 10 fruit were randomly selected and marked. The marked fruit were weighed at 3 day intervals for 30 days using an electronic weighing scale (Mettler Toledo, Model ML 3002E, Switzerland with 0.0001 g accuracy). The cumulative fruit weight loss was calculated as:

$$W = \left(\frac{W_o - W_1}{W_o}\right) x100 \qquad (1)$$

where W = cumulative fruit weight loss percentage; W_o = initial fruit weight at start of experiment and W_1 = fruit weight on each sampling day during storage. Values were presented as mean weight loss for the 10 fruit in each environment ±Standard error (SE).

Developments of fruit shrivel and any decay incidences were also monitored throughout the 30 day storage period in the two environments.

2.2.2 Fruit colour

The 10 fruit in each environment marked for cumulative weight measurement were also marked for colour measurements. Using a calibrated Minolta Chroma Meter (Model CR-400/410, Minolta Corp, Osaka, Japan), the colour change of the pomegranate skin was measured on each sampling day on two marked spots on each fruit surface. The International Commission on Illumination (CIE) L*, a*, b* coordinates were measured, Chroma (C*) was calculated according the following equation (Pathare *et al*., 2013):

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

2.2.3 Fruit puncture resistance and size

Fruit puncture resistance was measured using the Fruit Texture Analyser (GUSS-FTA, Model GS, South Africa). With the calyx of fruit parallel to the platform, a 5 mm cylindrical probe was used to puncture 8.9 mm into the fruit at penetration speed of 10 mm/s. This was done on two opposite sides of 10 fruit from each environment. Fruit size was measured using the Electronic Fruit Size Measure (EFM) connected to Fruit Texture Analyser. Measurements were done on 10 fruit from each test environment.

2.3. Measurement of chemical properties

2.3.1 Titratable acidity, total soluble solids and pH

On each sampling day 10 fruit from each storage environment were hand peeled and juiced separately using Liquafresh juice extractor (Mellerware, South Africa) without crushing the seeds. Titratable acidity, total soluble solids and pH measures were taken for each fruit juice at room temperature. For titratable acidity (TA), 2 ml of fresh juice was diluted with 70 ml of distilled water and titrated with 0.1 M NaOH solution to an endpoint pH 8.2 using Metrohm AG 862 compact titrosampler (CH-9101 Herisau, Switzerland). Results were expressed as % citric acid. The total soluble solids measure was taken using a digital refractometer (Atago, Tokyo,Japan). pH was measured using calibrated pH meter (Crison, Model 924, Barcelona, Spain). TSS/TA ratio was also calculated for further exploration of TSS/TA relationship.

2.4. Statistical analysis

Analysis of variance (ANOVA) was carried out using STATISTICA 12 (StatSoft, Inc. Oklahoma, USA) according to Duncan's multiple range tests. All the data was analysed in a 2-way ANOVA (Factor A: Humidity; Factor B: Storage Time). The results were presented as mean (±S.E) values.

3. Results and discussion

3.1. Physical properties

3.1.1 Weight loss and fruit shrivel

Throughout the storage period, pomegranate fruit continuously lost weight (moisture). There were no significant fruit weight loss differences from the two RH environments from day 0 to day 6 (Fig. 1). However, the weight loss from the low RH environment was significantly higher compared to the high RH environment from day 9 until day 30 ($p<0.05$) with losses up to 29.13±1.49% in the low RH environment compared to 5.78±0.44% in the high RH environment by day 30 (Fig. 1). Elyatem and Kader (1984) reported that the pomegranate fruit peel is highly porous thus enabling free movement of water vapour. High RH has been reported to reduce the vapour pressure deficit (VPD) between the fruit and the environment resulting into reduced moisture loss from the fruit (Ladaniya, 2008; Waelti, 2010 Ngcobo *et al*., 2013a). Similar weight loss observations were made by Fawole and Opara (2013) for fruit stored at conditions of 22^{o}C 65±5.5% RH where Bhagwa and Ruby pomegranate cultivars lost between 20-25% weight at the end of 4 weeks storage. Arendse *et al*. (2014) also reported 20% weight loss for pomegranate (cv. Wonderful) stored at 21^{o}C, 65±6% RH for 4 weeks. In a similar study on apples, Tu *et al*. (2000) reported more rapid weight loss in apples stored at 30% RH (up to 6% by day 18) and 65% RH (about 4.5% by day 30) compared to only about 1.0% weight loss by day 30 at 95% RH conditions at 20^{o}C.

Commencement of fruit shrivel was observed in the low humidity environment on day 6 after fruit had lost up to 5.28±0.32% weight (Fig. 2B) and by day 9, the indents had grown bigger while in the high humidity environment, slight signs of shrivelling were only seen on day 24 after fruit had lost 5.04±0.33% weight (Fig. 2I). This observation was similar to one of Kader *et al*. (1984) where pomegranate fruit (cv. Wonderful) that lost weight up to 5% and above begun shrivelling but contrary to Fawole and Opara (2013) that reported no sign of shrivelling in Bhagwa and Ruby until 12% weight loss. The observed differences may be attributed to the different cultivar types studied. By day 30, fruit in the low RH environment was severely shrivelled and deformed with less visual appeal (Fig. 2J). Shrivel is due to loss of turgor pressure in the fruit cell walls as they continuously lose moisture (Paull, 1999). On hand peeling, it was also observed that fruit's leathery skin at low RH continuously became thinner (Fig. 2L) with storage duration compared to high RH where there was no visible change in fruit leathery skin thickness even at day 30 (Fig 2M). This observation could suggest that the fruit loses moisture from the skin first before the arils probably protected by the aril sac.

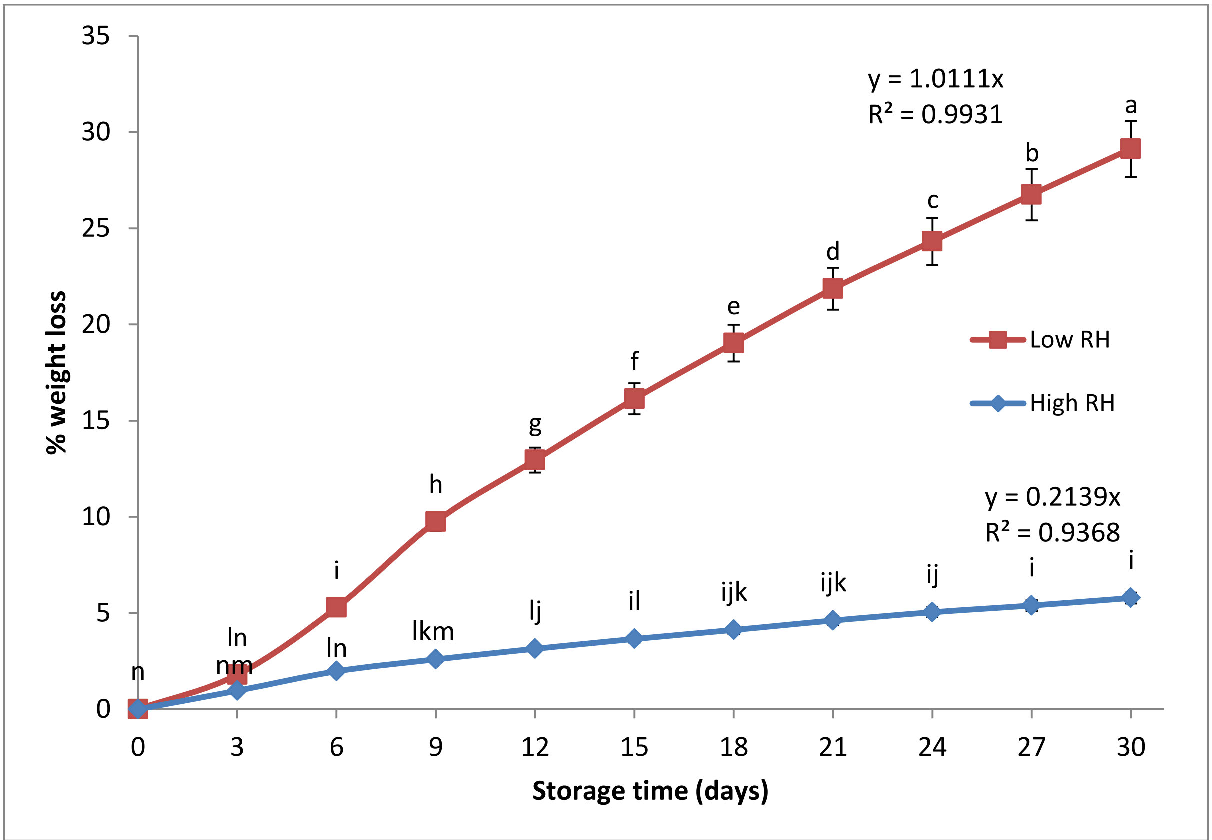

Figure 1 Weight loss of pomegranate fruit at 20^{o}C and different RH (Low = 65±6.79%; High = 95±1.23%). Vertical bars denote the standard error of the mean and different letter(s) indicate significant difference ($p<0.05$).

Fig. 1 shows the regression equations that can be used to predict weight loss of pomegranate fruit stored in two RH environments of 65% and 95%, equations 3 and 4 respectively:

$$y = 1.0111x \qquad (3)$$

$$y = 0.2139x \qquad (4)$$

where y = predicted weight loss and x = storage time in days. The linear regression equations have high goodness-of-fit given high coefficients of determination; R-squared (R^2) values of 0.9931 and 0.9368 for low and high RH weight loss predictions respectively.

At a market price of ZAR26.7 per kg of pomegranate (price at which experimental fruit used in this study was purchased), at the end of one month storage, the estimated cost of weight loss at 65% and 95% RH was ZAR7.78 kg^{-1} and ZAR1.54 kg^{-1}, respectively.

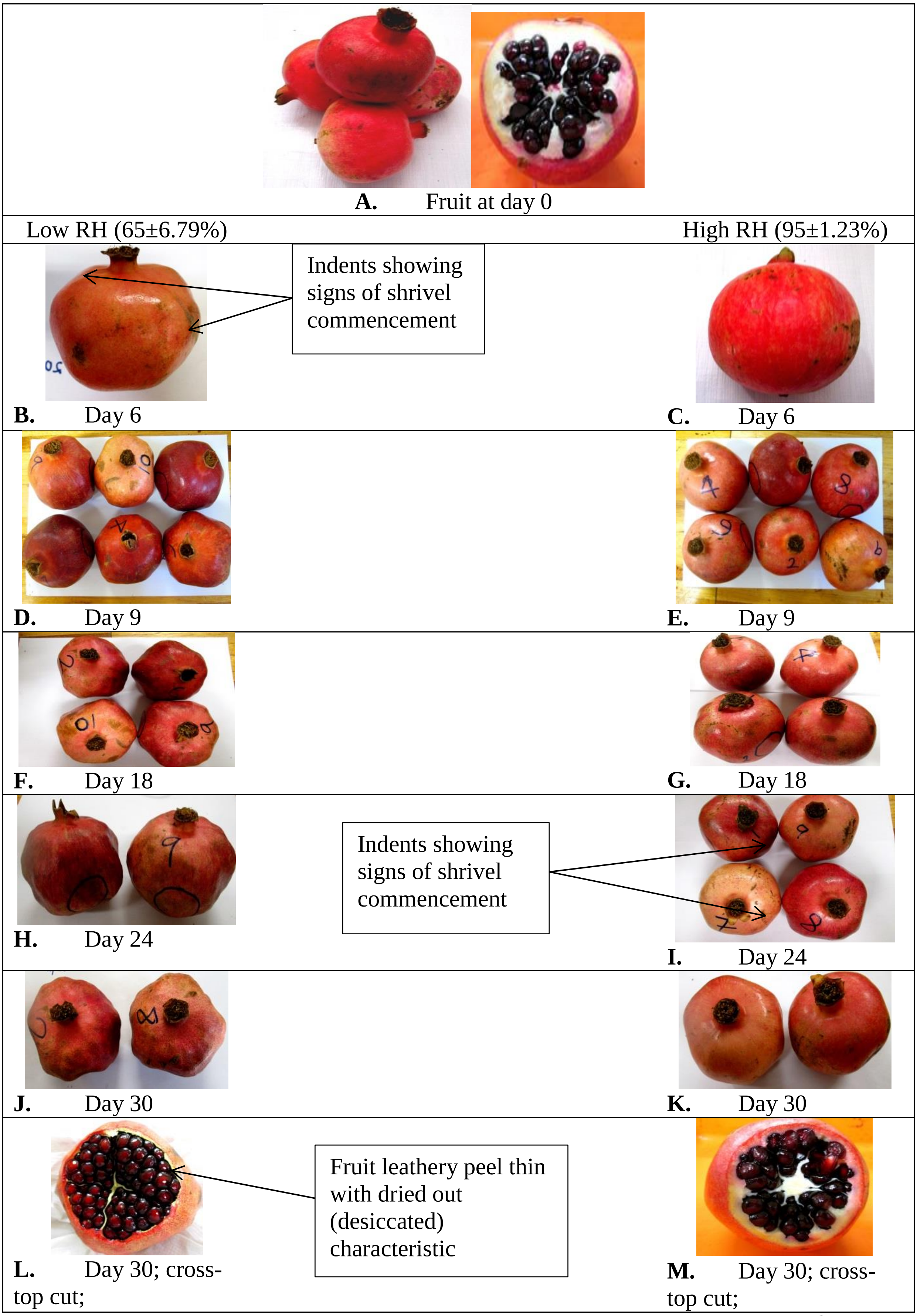

Figure 2 Pictorial presentation of the changes in appearance of pomegranate at 20°C at the studied RH conditions (Low = 65±6.79%; High = 95±1.23%).

3.1.2 Fruit colour

There was continuous reduction in CIE value a* (redness) of the fruit in both RH storage environments throughout the storage period (Fig. 3). Significant reduction in redness of the fruit was only observed after day 12 in the low RH environment while the reduction in the high humidity environment was not significant throughout the storage period. The colour intensity of the fruit (C*) followed a similar trend as the fruit redness (a*) with no significant, though slight reduction for fruit in high RH environment while in the low RH environment, significant reduction in colour intensity compared to day 0 was observed from day 12 onwards (Fig. 3).

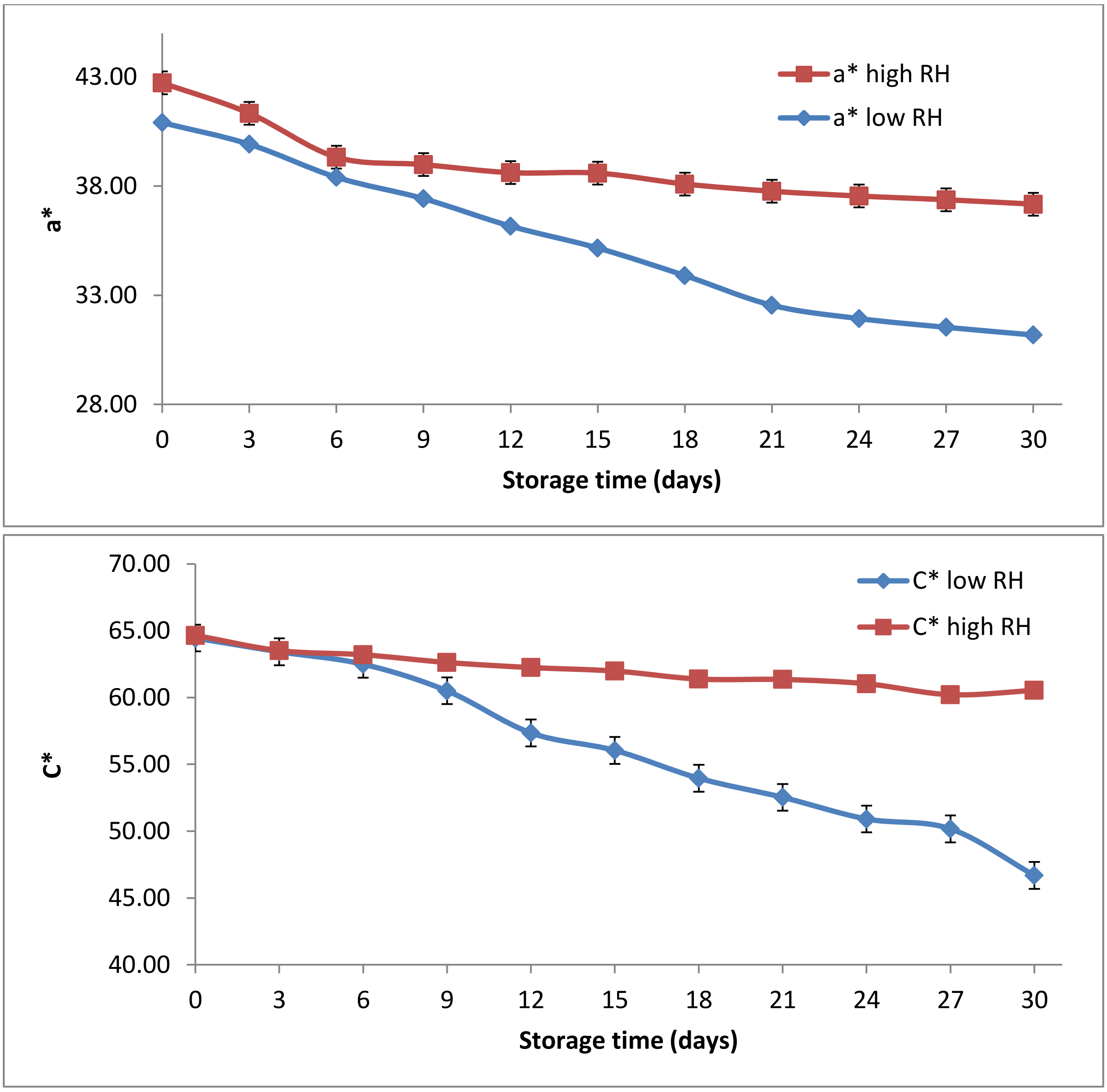

Figure 3 Changes in a* (redness) and C* (colour intensity) of pomegranate fruit surface (peel) at low (65±6.79%) and high (95±1.23%) RH. Vertical bars denote standard error of mean.

This may be attributed to breakdown of pigments in the fruit peel due to water stress and also the desiccation of the peel as observed in Fig. 2. Similar reduction in fruit peel redness and colour intensity was observed by Fawole & Opara (2013) for Bhagwa and Ruby pomegranate fruit cultivars. However, their study was at temperatures 8^{o}C, 15^{o}C, 92±3% RH and 25^{o}C, 65±5.5% RH. On the contrary, Arendse *et al*. (2014) reported and initial increase in a* and C* values of the fruit (cv. Wonderful) peel at 5^{o}C, 7.5^{o}C and 10^{o}C, 92% RH for the first 3 months before reduction until the end of the 5th month of storage attributing the initial increase to anthocyanin biosynthesis in the fruit peel.

3.1.3 Fruit size and puncture resistance

There was a general reduction in fruit size throughout the storage period. The loss in size was however bigger in the low RH environment with up to 13.03% loss compared to about 2.47% loss in the high RH storage environment (reference) at the end of the 30 day storage period (Table 1). This could be attributed to a higher moisture loss from fruit in the low RH environment. There was no significant change in the fruit puncture resistance in the two environments with only a slight increase from 99.59 N at day 0 to 103.74±4.45 N and 101.36±3.77 N at low and high RH, respectively, at the end of the 30 days storage period (Table 1). This could have been as a result of the drying out of the pomegranate peel as observed in Fig. 2L. This observation is in agreement with one made by Arendse *et al*. (2014) who found an increase in puncture resistance for fruit stored at 5°C, 7.5°C, and 10°C with 92% RH from 127.94±1.19 N to 130.29±1.36 N, 133.52±1.45 N and 138.64±1.29 N, respectively, at the end of the one month before a decrease until the end of the 5 months. The authors attributed initial increase to moisture loss then the subsequent decrease to fruit and aril softening with storage period.

3.2. Chemical properties

By the end of the 30 day storage period in the two RH environments, there was no significant change in the TSS, pH, TA, and TSS/TA ratio of the pomegranate fruit juices in the high RH environment stored fruit, however, some significant changes were observed in the fruit stored in the low RH environment (Table 2). The TSS increased slightly from 15.24 ^{o}Brix at day 0 to 15.71 ^{o}Brix at high RH while at low RH, a significant increase to 16.72 ^{o}Brix was observed at the end of the 30 day storage period. This increase may be attributed to concentration of sugars as the fruit lost moisture. Similar observations of increase in TSS with storage were made by Ghafir *et al*. (2010) and Koksal (1989). Ghafir studied response of pomegranate fruit (cv. Shlefy) to packaging and cold storage while, Koksal studied different environments storage of pomegranate (cv. Gok Bahce).

Table 1 Changes in size and puncture resistance (firmness) of pomegranate fruit (cv. Wonderful) stored at low (65±6.79%) and high (95±1.23%) RH at 20°C for 30 days

Storage duration (days)	RH	Size (mm)	Firmness (N)
0		86.70±0.67^{a}	99.59±4.54^{c-e}
9	Low	84.52±0.59^{b-d}	99.89±5.22^{c-e}
	High	85.55±0.41^{ab}	99.75±7.22^{c-e}
21	Low	82.10±0.46^{e-g}	101.43±9.72^{b-e}
	High	84.60±0.61^{b-d}	100.58±7.78^{b-e}
30	Low	75.40±0.61^{i}	103.74±4.45^{a-e}
	High	84.55±0.31^{b-d}	101.36±3.77^{b-e}

Values are presented as mean±SE. Values in the same column followed by different letter(s) indicate significant difference ($p < 0.05$).

TA also increased significantly from 1.76% to 2.33% (%Citric Acid) in the low RH environment at the end of storage compared to the slight change to 1.78% in high RH at the end of storage (Table 2). This could also be attributed to the concentration of the acids as fruit lose moisture. pH slightly reduced at the end of storage in the two environments. This could be due to the observed concentration of acids as the fruit lose moisture. At the end of the 30 day storage period, the TSS/TA values were 7.79 in the low RH environment and 9.40 in the high RH environment. These were lower than the value of 14.75±0.32 reported by Arendse *et al*. (2014) for fruit (cv. Wonderful) stored at 21°C 65% RH for one month. Fawole and Opara (2013) also reported TSS/TA ratios of 45.57 and 49.69 for Bhagwa and Ruby pomegranate cultivars respectively at the end of four weeks storage at 22°C 65±5.5% RH.

In a similar study of apples by Tu *et al*. (2000), at 30%, 65% and 95% RH at 20°C, there was a slight increase in soluble solids content of the apples from 13.1±0.2% to 13.5±0.2%, 13.2±0.2% and 13.7±0.2%, respectively, at the end of the 30 day storage period. Arendse *et al*. (2014) also reported an increase in TSS from 13 °Brix to 14.35 °Brix of pomegranate fruit (cv. Wonderful) stored at 21°C 65% RH for one month. However, they observed a decline in TA at similar conditions and attributed it to rapid breakdown of organic acids. Fawole and Opara (2013) reported a significant decrease in pH of Bhagwa pomegranate cultivar from 3.35 to 3.19 but an increase in Ruby from 3.18 to 3.61; a very slight decrease in TA for both cultivars, Bhagwa (0.34% to 0.33%), Ruby (0.33% to 0.32%); and significant decrease in TSS for both cultivars, contrary to our findings, for pomegranates stored at 22^{o}C 65±5.5% RH at the end of 4 weeks storage and this was attributed to breakdown of sugars and acids with storage.

Table 2 Changes chemical attributes of pomegranate fruit (cv. Wonderful) stored at low (65±6.79%) and high (95±1.23%) RH at 20^{o}C for 30 days

Storage duration (days)	RH	TSS (^{o}Brix)	TA (% Citric Acid)	pH	TSS:TA
0		15.24±0.50^{g}	1.76±0.13^{bc}	3.65±0.06^{a}	9.36±1.12^{a-e}
9	Low	16.50±0.28^{ab}	1.91±0.13^{a-c}	3.32±0.03^{bc}	8.94±0.56^{b-e}
	High	15.40±0.17^{e-g}	1.78±0.15^{bc}	3.32±0.04^{bc}	9.65±1.12^{a}
21	Low	16.54±0.25^{ab}	2.30±0.16^{a}	3.16±0.04^{b-d}	7.36±0.45^{a-d}
	High	15.67±0.38^{b-g}	1.78±0.13^{bc}	3.36±0.04^{bc}	9.33±0.71^{a-e}
30	Low	16.72±0.24^{a-c}	2.33±0.22^{a}	3.08±0.04^{ef}	7.80±0.78^{c-e}
	High	15.71±0.24^{d-g}	1.78±0.14^{bc}	3.25±0.05^{b-d}	9.40±0.86^{a-e}

Values are presented as mean±SE. Values in the same column followed by different letter(s) indicate significant difference ($p<0.05$).

4. Conclusion

The results from this study showed that the postharvest life of pomegranate fruit is affected by relative humidity during ambient storage. Storing fruit under 95% RH treatment maintained the fruit colour best, minimised weight loss, and hence, associated cost, maintained firmness, fruit size and the chemical quality attributes of pomegranates. Storing fruit under low RH ambient conditions led to excessive weight loss, reducing visual quality of fruit due to the shrivelled and deformed appearance. These findings can be applied in efforts to establish the best storage conditions of pomegranates to maintain quality and reduce incidence of postharvest losses along the value chain from harvest to consumers.

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Chapter 6 : General discussion and conclusion

Introduction

Food packaging is a very vital sector in the food industry contributing to food safety, preservation and marketing functions (Hawkins, 2012, Robertson, 2013). The fresh horticultural produce market is an ever growing one due to increased awareness of health benefits that come with the consumption of fruits and vegetables (Ladaniya, 2008). Fresh horticultural packages are usually provided with vents whose major function is maintaining an airflow between the inside and the surrounding of the container (Zou *et al*., 2006; Ngcobo *et al*., 2012; Pathare *et al*., 2012). Fruit cooling and relative humidity management is important in reducing quality deteriorative changes once fruit is detached from the mother plant (Brosnan & Sun, 2001). Forced-air cooling (FAC) is one the most widely used precooling methods in the fruit industry (Dehghannya *et al*., 2010; Opara, 2011). The South African pomegranate fruit industry is a fast growing one with about 40% increase in export volumes in 2014, and expected production of about 12,000 metric tonnes for the year 2015 (POMASA, 2015). Fruit cooling and moisture loss characteristics; airflow resistance; and energy consumption during FAC have been reported to be affected by: the open area, size, shape, number and position of vents on the carton, carton stacking and stack porosity, internal packages, airflow rate and product properties like shape, size and thermal properties (Vigneault & Goyette, 2002; De Castro *et al*., 2005; Ngcobo *et al*., 2013; Delele *et al*., 2013). Inadequate cooling of horticultural produce affects the postharvest quality leading to significant economic losses. Therefore, this study evaluated some of the frequently used pomegranate ventilated cartons and internal packages in the South African pomegranate industry, in terms of airflow resistance, cooling characteristics, and energy efficiency. Furthermore, the study investigated the effects of packaging, carton stacking and humidification on the moisture loss of pomegranate fruit inside ventilated packages during precooling. The study went further to investigate the effects of relative humidity on pomegranate quality under simulated shelf storage conditions.

Chapter 2 Literature review on resistance to airflow and cooling performance of ventilated horticultural packaging

The review highlighted the different forms of packaging and packaging significance in the fruit industry. Ventilated corrugated fibreboard cartons were found to be the most commonly used packages for fresh fruit handling. While providing optimal ventilation, ventilated cartons are also meant to withstand especially compressional, shock and vibrational forces encountered during produce stacking, cooling and shipping (Pathare & Opara, 2014). On that basis, the review highlighted developments in horticultural produce carton designs and ventilation configurations; multiscale packaging and carton stacking. Horticultural packages were found to differ depending on market and economies, for example, wooden boxes used in developing countries like India, different ventilation configurations of cartons used in international trade and some markets were found to use different combinations of packages on same product, for example, a combination of punnets, liners and carton to package grapes. The review further explored different precooling and cooling methods with emphasis on forced-air cooling and the critical significance of fruit cooling to quality maintenance. The review then highlighted the need for individual product carton design optimisation given variation in fruit thermal and respiratory properties.

Chapter 3 Resistance to airflow, energy consumption and cooling characteristics of pomegranate fruit inside ventilated cartons during precooling

In this chapter, the performance of two ventilated corrugated fibreboard carton designs (CT1 and CT2) with pomegranate fruit bulk in liner versus no liner was studied during FAC. Between the two carton designs studied, individual carton vent area was 5.4% higher in CT2 (28.4%) than CT1 (23%), while stack vent area (SVA) was 0.17% higher in CT2 (5.46%) than CT1 (5.29%). This difference in SVA contributed to higher cooling time of fruit packed in CT1 cartons using liners (27.6%) and without liners (33.3%), respectively. The results also showed that liner packaged fruit offered up to 50% greater resistance to airflow than fruit packaged with no liner in both the studied cartons. The liners were also observed to delay cooling with seven-eighths cooling times close to three times those of no-liner packaging. Same trend was observed for energy consumption estimates as a function of a larger pressure drop and longer cooling times. Liners in grape and pome packaging have been however reported to minimise moisture loss from fruit, though similar higher resistances to airflow and delayed cooling were reported (Berry, 2013; Ngcobo *et al.*, 2013). This delayed cooling and increased energy costs yet minimal moisture loss could open up a possibility of forced-air cooling of fruit before being packaged in liners. However, fruit at low temperature have been reported to be more susceptible to bruise damage reducing quality and income (Opara &

Pathare, 2014). Increased bruise susceptibility would call for closer supervision and training of workers at the pack-house, which could be an added cost. Packaging after precooling would also call for workers at pack-houses to package fruit in environments between 5-8^{o}C to avoid fruit re-heat in warmer environments which is quite uncomfortable with time. Therefore a cost ratio analysis is needed to compare time, labour and energy costs of precooling liner packaged fruit; and bruise, training and labour costs of liner packaging after fruit precooling to come up with an economically beneficial decision.

The study also entailed air being forced through the 1.2 m side of stack (lengthwise orientation) and through the 1.0 m side of stack (widthwise orientation). Differences in design of the studied pomegranate cartons led to differences in observed total ventilation areas with orientation of stacks. While the CT2 stack had a high total ventilation area in the widthwise orientation, the lengthwise orientation in CT1 stack had the higher ventilation. This higher total ventilation with stack orientation is critical during carton stacking and alignment of stacks for forced-air cooling since it was observed to offer lesser resistance to airflow, shorter cooling time and comparatively lower energy consumption. The results in this study also reaffirmed the need for adequate carton ventilation. Hortgro (2015) recommended minimum carton face ventilation of 5%. Faster cooling rates, about 29.19%, was observed in CT2 packaged fruit with comparatively higher face ventilation. Additionally, this study highlighted the heterogeneous cooling pattern of pomegranate fruit during forced-air cooling which highlighted the need to consider stack widths set up for forced-air cooling, based on the ventilation of cartons, airflow velocities, fan capacity and packaging types. In conclusion, this study has highlighted the need for adequate carton ventilation and the need to consider the effect of internal pomegranate package liners on fruit cooling performance. Future research should focus on the possibility of liner perforations in reduction of resistance to airflow and cooling time while also minimising moisture loss from fruit.

Chapter 4 Effect of packaging and humidification on the moisture loss of pomegranate fruit inside ventilated cartons during precooling

In this chapter, the effect of packaging liners, stacking and cold room humidification on moisture loss in pomegranate fruit during forced-air precooling was studied. The results from this study showed that cold room humidification during forced-air cooling was able to maintain 95% RH that is recommended for pomegranate storage to minimise moisture loss from fruit (Kader, 2006). Furthermore, we also observed that fruit packaged without liners lost about 17.49% more weight compared to fruit packaged with polyethylene liners. This observation was in spite of the longer cooling time (close to thrice) of liner packaged fruit as explained in the chapter three discussion above. This observation reaffirms the ability of liners to maintain a high VPD in the fruit microenvironment minimising moisture loss (Ngcobo *et al*., 2013) though they increased cooling times. Additionally, cold room humidification was also observed to minimise weight loss, with about 13.63% less weight loss compared to the non-humidified room within the precooling time. The magnitude of weight loss from fruit in humidified cold room was similar to liner packaged fruit showing that both environments maintained similar VPD in the fruit environment. This means room humidification could provide an alternative to liner packaging, achieving faster cooling while minimising moisture loss too.

Results from this study also showed that pomegranate fruit that took longer to cool lost more weight than fruit that got to storage temperature faster. This observation emphasizes the significance of bringing down pomegranate temperature faster after harvest to minimise weight loss costs. The study also showed that fruit that are exposed to higher airflow rates in the stack have a possibility of losing comparatively more moisture. Summarily, use of liners and cold room humidification has shown potential of reduction of moisture loss. However, liners delay fruit cooling during forced-air precooling. Differences in fruit weight loss were also small compared to no-humidification and no-liner packaging during the forced-air cooling process, however, these findings provide new insights on magnitude and mechanism of pomegranate fruit weight loss during storage which was further explored in chapter five.

Chapter 5 Effect of relative humidity (RH) on pomegranate quality under ambient storage conditions

This study investigated the effects of RH on the quality of pomegranate fruit (cv. Wonderful) stored at 20^{o}C under low RH (65±6.79%) and a high RH (95±1.23%) conditions. The results showed significantly high weight loss up to 29.13% in fruit stored at low RH compared to 5.78% at high RH at the end of the 30 day storage period. Based on prevailing unit market price of pomegranates, the estimated cost of fruit weight loss was 5 times higher under low than high humidity ambient storage conditions. This magnitude of weight loss at the end of one month storage indicates the susceptibility of pomegranate fruit to moisture loss when stored under unsuitable RH environments and thus validates the porous nature of the fruit’s leathery skin (Kader, 2006). In addition cross-sectional cuts revealed that most of the moisture loss may be attributed to losses from the fruit peel as evidenced by the thin appearance yet the arils remained fully turgid. This finding could be an adaptation of the fruit to harsh dry climates where some of its agronomy is done, for example, the Middle East. Fruit at low RH also severely shrivelled and reduced in size. Shrivel signs started at about 5.16% weight loss compared with 3%, 6%, 7%, and 15% for spinach, cabbage, apples and winter squash, respectively. This has negative marketing impact as shrivelled fruit are less acceptable despite the fact that the arils may be still fresh as observed in this study.

The high RH environment better maintained the colour, texture and chemical quality attributes of the fruit. The significant physical and chemical changes in the low RH environment were inferred to high moisture loss. Additionally, regression equations developed to estimate weight loss in pomegranates at 65% and 95% RH storage conditions had a high goodness-of-fit with R-squared values of 0.9931 and 0.9368 for low and high RH, respectively. These findings show that pomegranate fruit should preferably be stored at RH conditions ≥ 95% or at least 90% and above. The nearly fresh appearance of the fruit kept at high RH at the end of the 30 day storage in spite of the storage temperature (20^{o}C) highlighted how much effect the relative humidity has on pomegranate fruit quality.

Recommendation and future prospects

This research has provided an insight into the cooling performance and impacts on fruit quality using some of the packaging designs used in industry for commercial handling of pomegranates. This information is of help in making package design decisions and handling at pack-houses. Additionally, an insight into moisture loss properties of pomegranate fruit and how this relates to the prevailing RH was generated. Cold room humidification was observed to be a potential remedy to extreme moisture loss and maintenance of fruit quality while achieving faster cooling. Given the predominant use of liners inside ventilated cartons as part of the strategy to reduce weight loss and contamination, future research should focus on the possibility of perforating polyethylene liners to improve airflow penetration into ventilated cartons during forced-air cooling and long term cold storage to achieve cost-effective, efficient and uniform cooling of fruit inside the stack. Given the high cost of energy for precooling fruit, improved understanding of the effects of delay in precooling on fruit quality after long term cold storage is warranted. There is also need for analysing the effect of humidification on the mechanical integrity of the fiberboard cartons.

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