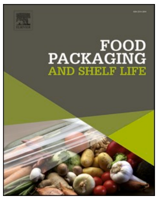
Food Packaging and Shelf Life 26 (2020) 100585

Contents lists available at ScienceDirect

Food Packaging and Shelf Life

journal homepage: www.elsevier.com/locate/fpsl



Evaluation of the airflow characteristics, cooling kinetics and quality keeping performances of various internal plastic liners in pomegranate fruit packaging

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ARTICLE INFO

Keywords:
Plastic-free packaging
Micro-perforated liners
Macro-perforated liners
Cold chain management
Cooling rate
Energy usage
Postharvest loss
Cold storage
Cold transport

ABSTRACT

There is a trade-off to be optimised carefully as plastic liners deal with postharvest cooling processes as well as the produce quality and sustainability requirements. Understanding the implementation of plastic liners in the fresh fruit cold chain is required to reconcile the opposing roles. In this paper, the performances of four types of internal packaging plastic liners were studied. The airflow characteristics, cooling rate, cooling uniformity and quality keeping performances were measured. Cases: no liner, non-perforated liner, micro-perforated liner, macro perforated liner with 2 mm diameter holes, macro perforated liner 4 mm diameter holes were investigated. Generally, the liners delayed the cooling rate significantly. Non-perforated and micro-perforated liners are similar in terms of airflow resistance and cooling rate, both delayed the optimum cooling time by 5 h compared to the plastic-free case. On the other hand, macro-perforated liners cause a delay of only 3 h.

1. Introduction

Packaging prevents food from spoiling under normal conditions and therefore allows it to be consumed safely over a long period of time (Opara & Mditshwa, 2013). Packaging also helps extend the marketing period by offering a layer of additional protection to keep the items safe for consumption and providing a barrier against pathogens and infestations, thus helping distributors and retailers reduce food loss and waste. In the fresh fruit supply chain, packages also play a key role in the postharvest cooling, humidity control and gas treatment processes (the rate and uniformity of mass and heat distributions) during storage and transit (Belay, Caleb, & Linus, 2019; Lufu, Berry, Ambaw, & Opara, 2018; Mukama, Ambaw, Berry, & Opara, 2019).

Cooling of fresh produce after harvest and keeping these products cool throughout the cold chain is paramount for maximising shelf life. Forced-air cooling (FAC) is commonly used to rapidly remove heat from freshly harvested produce (Brosnan & Sun, 2001; de Castro, Vigneault, & Cortez, 2005; Kader, 2013). The technique involves forcing chilled air through a pallet of packed produce. This process is affected by the design of the packaging cartons (box dimension, vent proportion, vent shapes and vent positions) (Berry, Defraeye, Nicolaï, & Opara, 2016; Pathare, Opara, Vigneault, Delele, & Al-Said, 2012). The importance of carton vent hole design on the airflow and the produce cooling kinetics are well known (Ambaw, Mukama, & Opara, 2017; Getahun, Ambaw, Delele, Meyer, & Opara, 2017; Pathare et al., 2012). The energy required to operate the air circulation fans during cooling of stacked produce is a function of several parameters, such as produce stacking, the vent hole proportion of the packaging carton and the nature and characteristics of internal packaging materials like plastic liners. Understanding the relative importance of the different factors is vital in the design and choice of packaging technology (Delele et al., 2013a, 2013b; Getahun, Ambaw, Delele, Meyer, & Opara, 2017; Ngcobo, Delele, Opara, Zietsman, & Meyer, 2012; Ngcobo, Opara, & Thiart, 2012).

The analysis of two pomegranate packaging modalities: packaging with internal plastic liner and plastic-free packaging, demonstrated the negative effect of internal plastic liner on the cooling rate and energy usage of typical precooling operation (Ambaw et al., 2017; Mukama, Ambaw, Berry, & Opara, 2017). The previous studies investigated the

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https://doi.org/10.1016/j.fpsl.2020.100585
Received 13 May 2020; Received in revised form 2 August 2020; Accepted 7 October 2020

effect of carton vent design and internal packaging liner on the performance of produce cooling operation and fruit quality keeping. Box dimension and vent hole design (position and proportion of vent-holes) affected the cooling kinetics significantly that a cooling rate difference of 30 % was observed between two different package designs. Apart from the individual box design, the orientation of boxes during stacking on pallets also played a significant role as a part of the vent holes are blocked. However, the internal liner was highlighted as the most significant factor in the produce cooling rate. Presence of internal liner increased the seven-eighth cooling time by more than 2-fold (from 4.0 and 2.5 h to 9.5 and 8.0 h for the tested pomegranate carton 1 and 2, respectively). Correspondingly, the energy usages of the precooling processes were increased by up to 3-fold compared to stacks with no liners.

The plastic liner is crucial to control moisture loss from fruit and on the overall fruit quality keeping. On the other hand, plastic liners may cause water condensation on the surface of fruit and vegetables causing defects on the external appearance, promote both the forming of spores and the growth of micro-organisms, and thus accelerating deterioration (Kumar, Babu, Bhagwan, & Kumar, 2013; Lufu et al., 2018). Hence, there is a trade-off to be optimised carefully as plastic liners deal with postharvest cooling processes as well as the produce quality and sustainability requirements. Understanding the implementation of plastic liners in the fresh fruit cold chain is required to reconcile the opposing roles.

In the packaging industry, “perforation” is often done mechanically by puncturing holes in the plastic liner to avoid excessive moisture condensation on fruit surfaces inside the liner. This should be performed carefully so that fruit weight loss is still controlled during prolonged storage. However, there is still very limited literature on the effect of perforation on the cooling dynamics and produce quality keeping. Specifically, perforated liners have not been properly studied and yet have the potential to reduce energy costs during precooling and quality losses during prolonged fruit storage. By using pomegranate fruit as a test case, perforation of the liner will be demonstrated reducing fruit decay while still reducing fruit weight loss during prolonged storage.

The present study aimed to understand the influence of different types of plastic liners on the cooling performance and postharvest quality keeping of pomegranate fruit. Hence, the objectives of this study were (1) to investigate and compare the effects of micro and macro perforated liner on the airflow and the accompanying fruit cooling characteristics, and (2) to study the effect of the different liners on the postharvest fruit quality during extended storage. To achieve the objectives, three separate experiments were performed: experiment one (described in Section 2.4.1) was conducted to study the airflow resistance characteristics using a wind tunnel setup, experiment two (described in Section 2.4.2) was conducted in a separate forced air cooling (FAC) system to study the cooling kinetics of the different packages. After finishing the precooling of the fruit in the FAC system (which took about 9 h) fruit were placed in pilot cold storage room (experiment three as discussed in Section 2.4.3) to monitor fruit quality during prolonged storage. The fruit used in the wind tunnel setup (experiment one) were discarded (not taken to the subsequent tests). The wind tunnel allows testing the airflow characteristics over a wide range of air velocities with high precision.

2. Materials and methods

2.1. Fruit supply

Pomegranate fruit (*Punica granatum* L., cv. Wonderful) of uniform diameter 81.8 ± 2.5 mm and mass 286 ± 15 g were harvested at commercial maturity from Merwespont farm in Bonnievale, Western Cape, South Africa (33°58′12.02″ S, 20°09′21.03″ E). The fruit were delivered by an air-conditioned refrigerated truck to the Postharvest Technology Research Laboratory, Stellenbosch University.

2.2. Internal plastic liners

Four different types of plastic liners: non-perforated (Non-perf), micro-perforated (Micro-perf), macro perforated with 2 mm diameter holes (Macro-perf 2 mm) and macro perforated with 4 mm diameter holes (Macro-perf 4 mm)) were measured. The Non-perf liner was a 15 μm thick high-density polyethene (HDPE) plastic film.

Macro-perforated liners were manufactured from the 15 μm thick HDPE Non-perf liners using 2- and 4-mm drill punchers. The total proportion of perforation was kept at 0.05 % for both Macro-perf liners. The choice of the 0.05 % perforation area was based on observations in commercial plastic bags used on pomegranates (Artés, Villaescusa, & Tudela, 2000) and table grapes (Ngcobo, Opara et al., 2012). Hence, 160 and 40 holes per square meter of the liner for the Macro-perf 2 mm and Macro-perf 4 mm, respectively. The Micro-perf was the 20 μm thick Xtend® liner (StePac Co., Antalya, Turkey) liner.

2.3. Packaging carton

One of the many commercially used pomegranate packaging cartons in South Africa was used in this study. The carton has an external dimension of Length/Width/Depth of 0.33 m × 0.29 m × 0.10 m. The sides of the carton have vent-hole proportions of 8.8, 6.7, and 2.2 % on the long side, short side and bottom side, respectively. Each carton was packed with 12 fruit, in a single layer. The individual carton in the stacking has an average weight of 3.5 ± 0.41 kg. Liner-in-box packaging was done by first placing the liner in the box, then the pomegranate fruit were placed in 3 × 4 in the plastic film. The surplus part of the liner was then twisted and tightly knotted using rubber bands to completely wrap the fruit (Fig. 1).

2.4. Experimental setup

2.4.1. Wind tunnel

The wind tunnel, in which the various stacks were placed to determine their airflow resistance characteristics, was constructed from a wooden rectangular cylinder with dimensions adjustable to fit different carton box configuration (Fig. 2). The air was drawn from the outside and forced through the stack by the centrifugal fan (Fig. 2). Ranges of flow velocities were generated through the stack and the corresponding pressure differential, across the stack, were measured using digitalised pressure transducers (PMD70-AAA7D22AAU, ENDRESS + HAUSER, Weil am Rhein, Germany). The prevailing atmospheric conditions (temperature, relative humidity and pressure) were recorded. Using this setup, the pressure drop vs. airflow data of the different stacks (2 × 2 × 4 cartons) were obtained. Test cases included stacks of empty carton boxes (without pomegranate fruit), fruit in cartons with and without liners. The different liners used are described in Section 2.2 above. Measurements were done in triplicates.

2.4.2. Forced air cooling

All cooling experiments were done for a standard pallet. Eight layers of 12 cartons on a standard ISO industrial pallet (1.2 × 1.0 m × 0.1 m) (Fig. 3(a)) form a pallet. The lateral sides and top of the pallet were completely enclosed with a plastic sheet and coupled to the forced air cooling system (Fig. 3(b)). The stack and FAC assembly were placed inside a 20 m^3 cold storeroom (Fig. 4). The air circulation rate in the room was 1290 $m^3 h^{-1}$. The compressor/condenser unit (CR36K6-TF6-121 model, Emerson Climate Technologies) was placed in another room outside the cool room. The centrifugal fan (Kruger KDD 10/10 750 W 4P-1 3SY) draws cold air through the stack (Fig. 4).

Temperature and relative humidity (RH) of the storeroom were set at 6 ± 1.0 °C and 91.4 ± 5.3 %, respectively. The velocity of air leaving the FAC equipment was measured using a hotwire anemometer (Alnomar velometer AVM440, TSI Incorporated, Shoreview MN 55126, USA).

The core temperatures of the sample pomegranate fruit were

Fig. 1. Individual carton as loaded with pomegranate fruit: (a) without a liner (No-liner), (b) as packaged with a non-perforated liner (Non-perf) and (c) packaged with a macro perforated liner (Macro-perf; visible perforations are highlighted with blue dots).

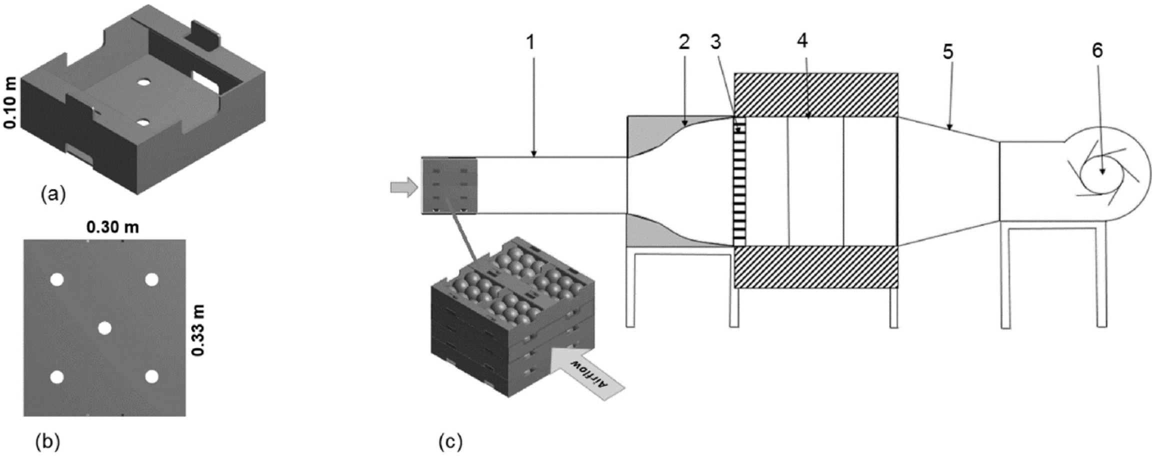

Fig. 2. Schematic diagram of the wind tunnel setup to measure the airflow resistance of stacked pomegranate fruit: (a) dimension and vent hole design of the carton, (b) bottom view of the carton and (c) the wind tunnel with (1) test chamber, (2) contractor (3) honeycomb, (4) settling chamber, (5) diffuser and (6) centrifugal fan.

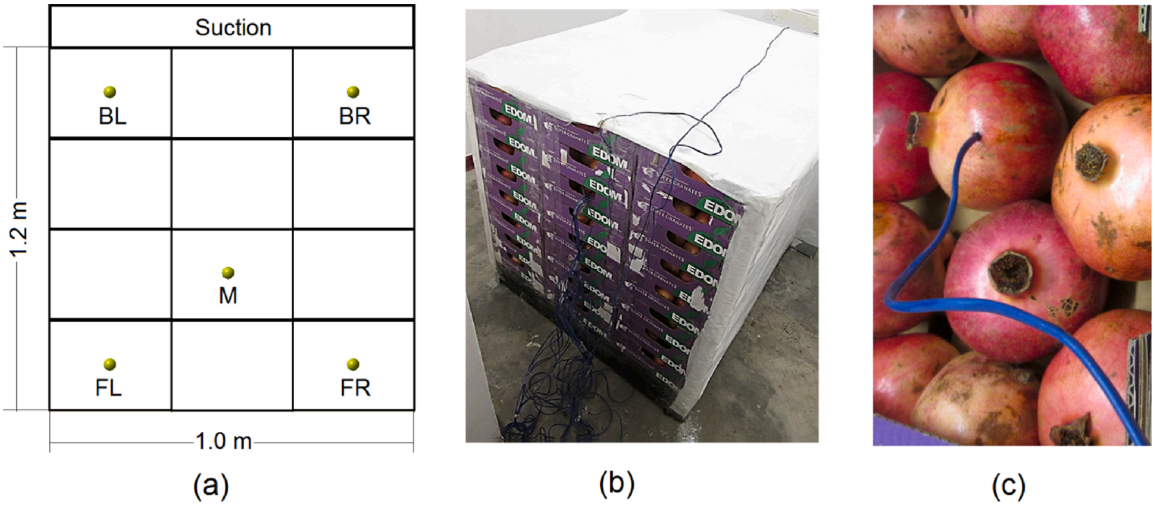

Fig. 3. Schematics showing the package arrangement in a layer (a). Dots (FL = front left, FR = front right, M = middle, BL = back left, BR = back right) are the positions of temperature sampling fruit as illustrated in (b). Temperature measurements were from the 2nd, 4th and 6th layers of the stack (c).

monitored during the cooling process using the T-type thermocouples (Fig. 3(c)) (Thermocouple products Ltd, Edenvale, South Africa. Range −30 to 100 °C and ± 0.025 % precision). The interference due to the physical presence of a thermocouple inside the fruit (due to their heat capacity and density) was assumed negligible as the thermocouples were small compared to the fruit. The relative positions of the temperature sampling positions in a layer are shown in Fig. 3(a). Temperature sampling was from the 2nd, 4th and 6th layers from the floor. This way pulp temperature data was collected every 300 s.

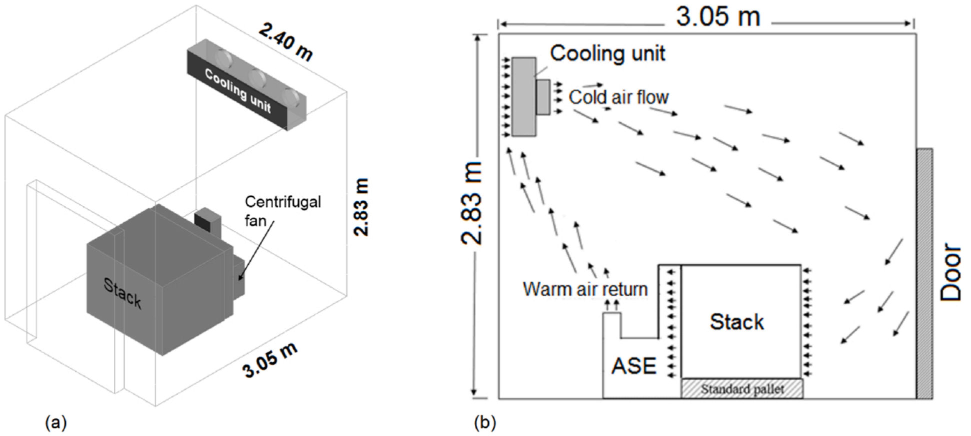

Fig. 4. Illustration of the forced air-cooling (FAC) experimental setup. The FAC as positioned in a cool storeroom (a) and side view of the setup illustrating the airflow streamlines (b). Temperature and relative humidity (RH) of the cold storeroom were 6 ± 1.0 °C and 91.4 ± 5.3 %, respectively.

2.4.3. *Measuring the fruit storability*

In this study, weight loss and decay incidences were used to measure and characterise the fruit quality preservation capacity of the different packaging liners. The fruit were portioned into six treatments: No-liner (control); Non-perf; Micro-perf; Macro-perf 2 mm and Macro-perf 4 mm liners. For each treatment, 11 cartons, each loaded with 12 fruit were stored in cold rooms at 5° C and 90–95 % RH for 84 days. For each treatment, 12 fruit were randomly selected from the stack and the initial quality (visually) and weights were registered. Afterwards, the quality and weights of the same samples were assessed at 28, 42, 56 and 84 d of cold storage. Fruit weight was monitored using a digital scientific scale (Mettler Toledo, model ML3002E, Switzerland, 0.0001 g accuracy).

The decay was assessed by using a hedonic scale method by ratting the severity of decay visually on a scale of 6: 0 = none; 1 = trace; 2 = slight; 3 = moderate; 4 = severe; 5 = extremely severe. Then the decay indices were calculated by multiplying the scores of severities by the number of affected fruit and dividing by the total number of fruit (Artés, Tudela, & Gil, 1998; Fawole & Opara, 2013b).

2.5. *Calculations*

2.5.1. *Resistance to airflow*

The airflow resistance is the pressure drop of the flowing air experienced while flowing through the stack. This characteristic directly affects the rate and uniformity of the cooling process. The energy usage of the cooling process is then directly affected by the resistance.

2.5.2. *Fruit cooling rate*

Cooling curves are used for evaluating the cooling characteristics of produce stacks. The temperature-time history of the fruit core is used to quantify the fruit cooling rate. In this study, the measured core temperature data was converted into dimensionless form by Eq. (1).

$$T_d = \frac{(T - T_a)}{(T_i - T_a)} \tag{1}$$

where T_d is the dimensionless temperature and T, T_a and T_i are fruit core temperature (°C), cooling air temperature (°C) and initial fruit core temperature (°C), respectively (Dincer, 1995). Curve-fitting, to the dimensionless temperature data set, in the form of Eq. (2) gives the cooling parameters (coefficient (C), and lag factor (J)). Eq. (2) is called Newton's Law of Cooling, an approximate description of experimentally observed cooling behaviour.

$$T_d = J\exp(-Ct) \tag{2}$$

where t is the cooling time (s). The lag factor J is a function of fruit shape, size and thermal properties; cooling coefficient C (s^{-1}) is the rate of change in fruit temperature for every degree of the difference in temperature between fruit and cooling medium (Dincer, 1995). The time required to reduce the difference in temperature between T_i and T_a by seven-eighths is called the seven-eighths cooling time (SECT) (Brosnan & Sun, 2001). The SECT is a useful parameter to characterise the cooling behaviour of the fruit in each stack. Hence, by drawing a horizontal line at $T_d = 0.125$ the 7/8th cooling times (SECTs) of the different stack were read from the cooling curves.

2.5.3. *Fruit cooling uniformity*

The cooling uniformity is quantified based on the fruit core temperature of each sampled fruit in the stack and the average of these temperatures at a given time. This means, at the instant of time during the precooling operation, the fruit core temperature of all the sample fruit (N = 15) were taken to give the T in Eq. (3). Correspondingly, the average temperature at the instant gives the T_{avg} in Eq. (3). The temperature sampling fruit are shown in Fig. 3 above. The relative standard deviation (coefficient of variation) of fruit core temperatures was then computed using Eq. (3) and plotted against time. The higher the coefficient of variation, the more the spread of the data around its mean. Hence, a smaller relative standard deviation (RSD) indicates better cooling uniformity.

$$RSD = \frac{\sqrt{\frac{\sum\left(T - T_{avg}\right)^2}{N-1}}}{T_{avg}} \times 100 \tag{3}$$

2.5.4. *Statistical analysis*

Analysis of variance was carried out using Statistica software (Statistica version 13, StatSoft Inc., Tulsa, USA). Means were separated using Duncan's multiple range test and the significant difference between means was considered at $P < 0.05$. Variations were compared between treatments, stack faces, stack layers and different fruit positions within layers.

3. Results and discussion

3.1. *Resistance to airflow*

The experimental results of tests performed to determine the resistance to airflow through the various stacks are given in Fig. 5. The effect of internal packaging liner is illustrated. Clearly, the airflow resistance across the stack of empty carton boxes was the lowest. When the fruit were added to the carton (No-liner) the airflow resistance increased by 13.5 %. Enveloping the pomegranate fruit with liner further increased the airflow resistance in an amount dependent on the type of

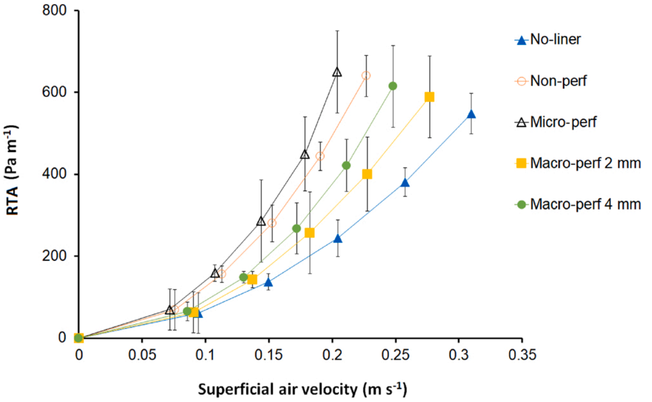

Fig. 5. Stack resistance to airflow (RTA) versus superficial air velocity data of the various stacks. The curves represent mean values and the vertical lines correspond to the standard deviation of three repeated measurements.

perforation. The maximum increase in resistance was observed for the stack with non-perforated and micro-perforated liners, which were almost a 3-fold increase compared to the No-liner. This indicates that micro-perforation has no beneficial effect on airflow resistance. However, macro perforation of the liner significantly reduced the airflow resistance.

The resistance of the stack of empty carton boxes was the lowest followed by stack with fruit only (No-liner). The wrapping of the fruit with plastic liner considerably increased the resistance compared to the empty carton with the Non-perf and Micro-perf liners scoring high resistances. The Micro-perf has almost identical flow resistance characteristics as the liner with no perforation. Macro perforation (Macro-4 mm and Macro-2 mm) reduced the airflow resistance significantly. This demonstrates the beneficial effect of macro perforation in improving the ventilation effect.

The 4 mm diameter perforation allowed air into the wrapping which caused inflation of the plastic wrapping inside the carton, this phenomenon blocked the airflow path compared to the 2 mm. Such incidence was visually observed during the experiment.

Fig. 6 summarises the relative contributions of the package components (carton, plastic liner and the fruit mass) to the total flow resistance. The relative contribution was computed based on the airflow resistance across the stack of empty cartons. The resistance induced by the fruit mass is considerably small compared to the resistance induced by the packaging carton (see the result for No-liner in Fig. 6). The contribution of the Non-perf and Micro-perf liners were more than 60 %. Macro-perf liners have contributed less than 45 % to the total RTA.

For the studied packaging modalities, the carton itself contributes significantly to the airflow resistance. The resistance due to the product inside the box is relatively small. In packaging oranges, pear and apple fruit, the contribution of the fruit to the overall resistance could be substantial. For these commodities, the amount of fruit per box (stacking density) is high (Verboven, Flick, Nicolaï, & Alvarez, 2006). Pomegranates fruit are stacked in a single layer inside the carton, loose and with low stacking density. This translated into poor space usage during storage and transit.

3.2. *Cooling characteristics*

3.2.1. *Influence of the different liners on the cooling kinetics*

Measurements correspond to cooling airflow rate, temperature and relative humidity (RH) of the cold storeroom of 0.5 L kg^{-1} s^{-1}, 6 ± 1.0 °C and 91.4 ± 5.3 %, respectively. Fig. 7 depicts the cooling curve obtained by fitting the dimensionless temperature data set in the form of Eq. (2). The corresponding cooling parameters (coefficient (C (s^{-1})), and lag factor (*J* (-))) are summarised in Table 1.

The lag factors (*J*) which are functions of the physical and thermal properties of the stack are larger than 1 indicating the added internal resistance to the heat transfer. The cooling coefficient decreases when adding plastic liners. As expected, pomegranates in the stack with No-liner cooled the fastest with an average SECT of 3.5 ± 0.2 h (Table 1). The effect of plastic liner on the cooling rate depended on the type of perforation. Stacks with the Non-perf and Micro-perf liners cooled the slowest with SECT of 8.1 ± 0.2 and 8.4 ± 0.3 h, respectively. There was no significant difference in the SECT for fruit packed with Non-perf and Micro-perf liners. On the other hand, the stacks with Macro-perf 2 mm and Macro-perf 4 mm liners have a SECT of 6.5 ± 0.7 and 6.9 ± 0.6 h, respectively (Table 1). Also, there was no significant difference ($P > 0.05$) in the SECT for fruit packed with Macro-perf 2 mm and Macro-perf 4 mm. In a similar study, liners were reported to create delays during forced-air cooling of seedless table grapes (Ngcobo, Opara et al., 2012). Provision of macro-perforation reduces the barrier effect of the liners and resulted in relatively faster cooling.

3.2.2. *Effect of liners on fruit cooling homogeneity*

In all the experiments, there was no significant difference in cooling rate between pomegranates in the three different layers in the stack. Hence, the average SECT per fruit position is given in Fig. 8. For all

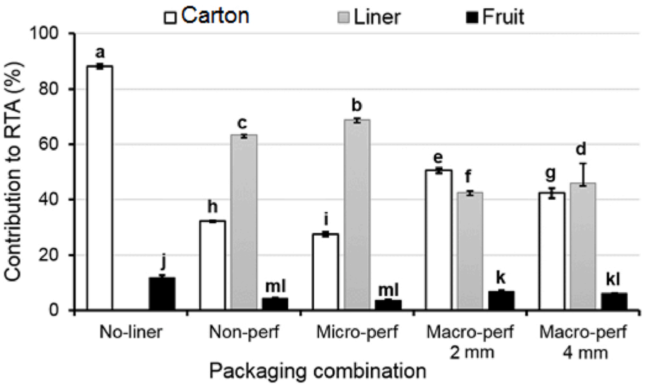

Fig. 6. Contribution of individual components (carton, fruit and liner) to the total resistance to airflow (RTA) across fruit stacks of different packaging combinations. The bars represent mean values and the vertical lines correspond to the standard deviation of three repeated measurements. The bars (means) with different letters are significantly different while similarities in one or all of the letters show no significant difference ($P < 0.05$).

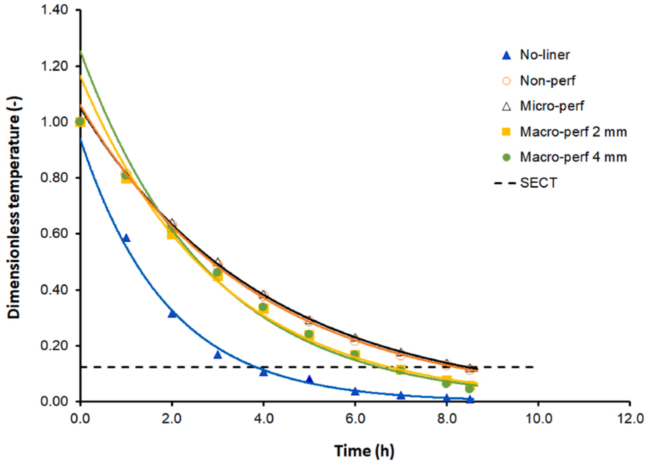

Fig. 7. Cooling kinetics of pomegranate fruit stack at a cooling airflow rate of 0.5 L kg^{-1} s$^{-1.}$ The cooling experiments were inside a cool storeroom at temperature and relative humidity (RH) of 6 ± 1.0 °C and 91.4 ± 5.3 %, respectively. The dotted line represents the seven-eighths cooling time (SECT).

Table 1
Parameters of precooling of different packages of pomegranate fruit with air.

	r^2	*J*	*C*	SECT (h)
No-liner	0.9823	0.9417	0.528	3.82
Non-perf	0.9995	1.0597	0.262	8.16
Micro-perf	0.9987	1.0517	0.253	8.42
Macro-perf 2 mm	0.9933	1.1647	0.332	6.72
Macro-perf 4 mm	0.9819	1.2543	0.355	6.50

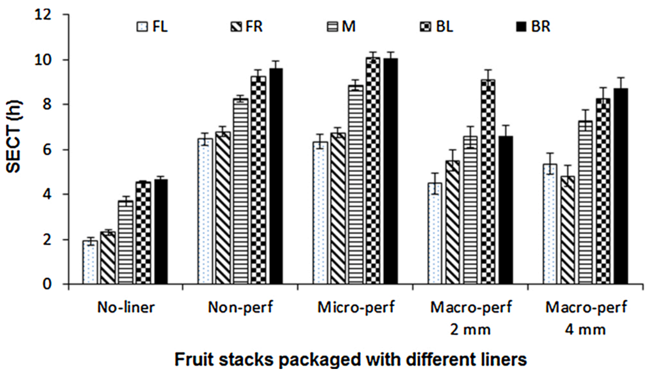

Fig. 8. Seven-eighth cooling time (SECT) per fruit positions in a layer of stacked pomegranate. See Fig. 3 for the specific positions (FL = front left, FR = front right, M = middle, BL = back left, BR = back right). The bars represent mean values and the vertical lines correspond to the standard deviation of three repeated measurements.

treatments, fruit at the front of the stack (position FL and FR) cooled fastest, followed by fruit at mid stack (position M) and then fruit at the back of the stack (position BL and BR). Fruit at the front of the stack cooled 1.65, 1.16, 1.29, 1.31 and 1.43 times faster than fruit in the middle and 2.03, 1.38, 1.45, 1.57 and 1.67 times faster than fruit in the back, for fruit packed with No-liner, Non-perf, Micro-perf, Macro-perf 2 mm and Macro-perf 4 mm liners, respectively.

Fig. 9 shows that, generally, cooling heterogeneity increases for the first few hours and then decreases gradually. Clearly, due to the absence of the insulation effect of liners, the stack without plastic liner (No-liner) was quick to respond to the cooling action. For this case, the cooling heterogeneity reached its maximum during the first 2 h of cooling and then rapidly decreased. On the other hand, stacks with plastic liners respond slowly and have a more uniform cooling pattern.

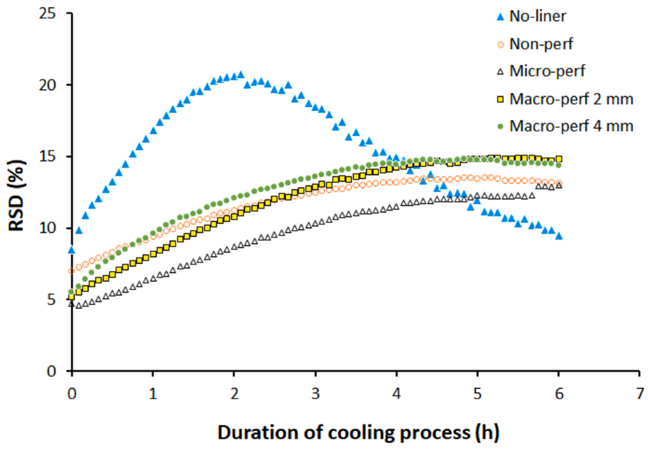

Fig. 9. The time history of cooling heterogeneities during cooling of stacked pomegranate fruit at cooling airflow rate of 0.5 L kg^{-1} s^{-1} air at temperature and relative humidity (RH) of 6 ± 1.0 °C and 91.4 ± 5.3 %, respectively. RSD is the relative standard deviation.

3.3. *Moisture loss control capabilities of the various liners*

The cumulative weight losses during the cold storage (5 °C and 90 % RH) of the different stacks are shown in Fig.10. Clearly, weight loss was dependent on the type of liner. Pomegranates packed with No-liner lost more weight than the rest. The plastic liner reduces weight loss in an amount dependent on the type. At the end of 84 d of cold storage, the No-liner packed fruit lost 15.6 ± 0.3 % of initial weight (Fig. 10). On the other hand, fruit packed in Non-perf liner lost only 0.8 %. Fruit packed in Micro-perf, Macro-perf 2 mm and Macro-perf 4 mm liners lost 4.2, 5.0 and 7.2 % of initial weight, respectively. Shrivelling did not appear until the fruit had lost 4.0 % of initial harvest weight. This is attributable to high moisture loss (Fawole & Opara, 2013a). Shrivelling (data not shown) were observed in fruit packed without liner (No-liner) and in the Macro-perf 2 mm and Macro-perf 4 mm liners. A weight loss exceeding 5 % of the initial weight causes shrivelling of the peel (Fawole & Opara, 2013a), while excessive water loss results in browning of the peel, aril browning and peel hardening (Artés et al., 2000; Caleb, Mahajan, Opara, & Witthuhn, 2012). However, the limiting moisture loss at which pomegranates becomes unsaleable still needs to be established.

3.4. *Efficiency of various liners in the control of decay*

Decay incidence changed with storage time in all treatments (Fig. 11). The levels of reductions of the decay incidences were dissimilar and depended on the type of liner used. There was no sign of decay till 28 d of storage for all treatments. Decay was observed in day 42 in amounts 9.4, 2.1, 8.3 and 2.1 % for No-liner, Non-perf, Macro-perf 2 mm and Macro-perf 4 mm, respectively. On the other hand, no decay was observed in the Micro-perf at day 42. At day 84 of cold storage, 35.4, 24.0 and 18.5 % for No-liner, Macro-perf 2 mm and Macro-perf 4 mm, respectively. Fruit in the Non-perf liner had a decay incidence of 25 %. The Macro-perf 2 mm was not significantly different from the Non-perf liner with respect to decay incidence ($P > 0.05$). Yet, significantly lower decay incidence (17.7 %) was observed for the Micro-perf liners. This may be attributed to the nature of the Xtend liner in modifying the atmosphere inside the bags. High incidence of fruit decay is expected in the package with the internal liner than without liner, especially in the package with non-perforated liners as this causes moisture condensation on fruit surfaces, leading to a high incidence of decay (Mphahlele, Fawole, & Opara, 2016). This is more pronounced and is crucial if the fresh fruit is already infected with microorganisms. On the other hand, the plastic liner can prevent decay for its ability (especially the non-perforated and micro-perforated liners) to passively modify the atmosphere surrounding the fruit in a way that the oxygen composition is reduced to a level that mould growth is reduced. In addition, the internal plastic liner isolates the fruit from the outside environment

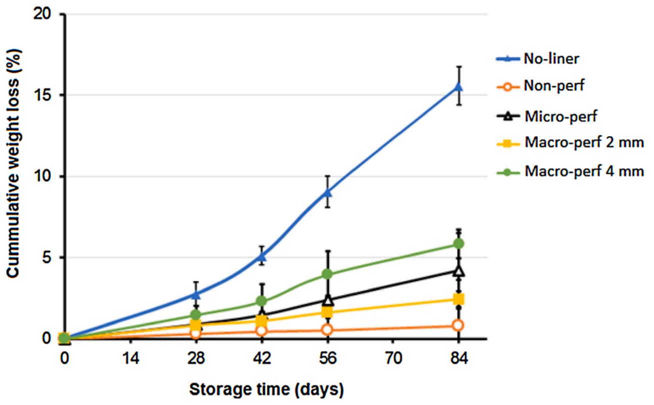

Fig. 10. Profile of the weight loss during prolonged storage of pomegranate fruit (cv. Wonderful) at 5 °C and 90 % RH. Vertical lines correspond to standard errors of n = 12 replicates.

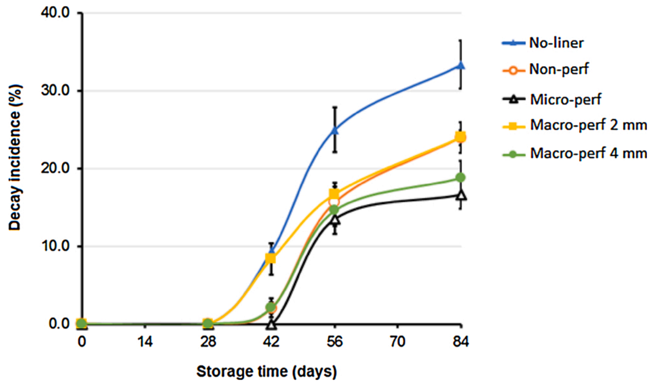

Fig. 11. Profile of the decay incidence during storage of pomegranate fruit (cv. Wonderful) at 5 °C and 90 % RH. Vertical lines correspond to standard errors of n = 12 replicates.

preventing spore contamination and fruit-to-fruit cross-contamination. In the current test, in addition to reducing weight loss, the various types of plastic liners also reduced the decay incidence. Similar observations have been made by Selcuk and Erkan (2014) on 'Hicrannar' cultivar that showed 40 % decay while in no-liner packaging compared to 13 and 27 % in liner-based packaging after 120 d at 6 °C.

4. Conclusions

The incorporation of the liner in the package increased the airflow resistance and delayed the cooling time significantly. The study demonstrated the beneficial effect of macro perforation in reducing the resistance to airflow and cooling time. The resistance and cooling behaviour of the non-perforated and micro-perforated liners were similar, they both delayed the SECT by 5 h compared to the stack with no liner. On the other hand, the macro-perforated liners caused a delay of only 3 h. All types of plastic liners reduced decay incidence compared to the no-liner. This could be attributed to the ability of liners to modify the gaseous atmosphere around the fruit and provide a barrier effect against possible external spore contamination. In addition, the high decay in the no-liner treatment could have been aggravated as a result of high spore contamination susceptibility from the environment, suggesting regular disinfection of storerooms before fruit storage. The micro-perforated liner performed significantly better in decay control.

A more comprehensive study by including additional perforation styles (number and size) is recommended to attain a much-improved cooling rate (compared to non-perforated and micro-perforated liners) with acceptable fruit quality preservation.

CRediT authorship contribution statement

Robert Lufu: Investigation, Writing - original draft. **A. Ambaw:** Supervision, Writing - review & editing. **Tarl M. Berry:** Supervision. **Umezuruike Linus Opara:** Conceptualization, Supervision, Writing - review & editing, Funding acquisition.

Acknowledgements

This work is based on research supported by the South African Research Chairs Initiative of the Department of Science and Technology and National Research Foundation. We acknowledge the award of postgraduate scholarship to Mr. R. Lufu by the Intra-ACP Sharing Capacity to Build Capacity for Quality Graduate Training in Agriculture in African Universities (SHARE), and the Regional Universities' Forum for Capacity Building in Agriculture (RUFORUM) for support. This work is based on the research supported wholly or in part by the National Research Foundation of South Africa (Grant Numbers: 64813). Research reported in this publication was supported in part by the Foundation for Food and Agriculture Research under award number – Grant ID: DFs-18-0000000008.

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