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Advances in design and performance evaluation of fresh fruit ventilated distribution packaging: A review

Matia Mukama[a], Alemayehu Ambaw[b], Umezuruike Linus Opara[a,b,*]

[a] Postharvest Technology Research Laboratory, South African Research Chair in Postharvest Technology, Department of Food Science, Faculty of AgriSciences, Stellenbosch University, South Africa
[b] Postharvest Technology Research Laboratory, South African Research Chair in Postharvest Technology, Department of Horticultural Science, Faculty of AgriSciences, Stellenbosch University, South Africa

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ABSTRACT

This review was initiated to realise the state-of-the art in optimising the ventilation and structural requirements of corrugated packaging carton design. Researchers have been using computational methods: computational fluid dynamics, particularly, the finite volume method, to analyse the airflow and heat transfer performances, and computational structural dynamics, particularly, the finite element method, to analyse the loss of compression strength due to vent-holes. Models are validated using actual testing: wind tunnel based forced air cooling system to study the produce cooling kinetics and box compression test machine for the package industry to study the structural dynamics. Studies on the rate and uniformity of produce cooling and the loss of structural strength in corrugated cartons as a function of size, shape, and location of vent-holes are reviewed. Based on experimental data, results show that the loss in strength can range between 10–40 % on addition of vent and hand holes on cartons, and reasonable increase in cooling rates is only achieved with increase in carton face ventilation area only up to 7–8 %. With regards to internal packaging components, increasing awareness of consumers to the environmental degradation of especially disposable plastic packaging means packers and suppliers must devise means to cut back and eventually eliminate plastic packaging from fruit and vegetables.

1. Introduction

Fruit consumption is on an ever-increasing trend due to the scientifically acclaimed health benefits of fresh fruit consumption (Steinmetz & Potter, 1996). Globally, over 67 % of the volume of fruit production is consumed fresh (Ladaniya, 2008). The challenge of meeting this globally increasing fresh fruit demand is the rapid loss of quality due to increased respiration rate, weight loss, loss of firmness, colour changes, and microbial spoilage. Following harvest, fruit continue to respire, breaking down stored sugars which negatively affects their quality as the replenishment from the parent plant is cut off. These deteriorative metabolic processes are temperature driven and thus quality deterioration is high when fruit are handled at non-optimal temperatures (Caleb, Opara, & Witthuhn, 2012). The fresh produce market is characterised by strict quality requirements entailing substantial logistical challenges. Particularly, maintaining the integrity of the cold chain along the whole supply chain is the most important factor to meet the requirements. This strict control of the temperature along the whole supply chain is compulsory.

Packaging is a key food processing unit operation serving functions of containment, protection, preservation, storage and distribution of food (Robertson, 2013). The fresh fruit market employs different package designs including punnets, corrugated fibreboard cartons (CFC), plastic crates, plastic and woven nets. These are made from different materials, including wood, jute, plastic, metal and paper (Ladaniya, 2008). However, corrugated fibreboard cartons are the most widely used in fresh fruit markets (Berry, Delele, Griessel, & Opara, 2015; Opara & Mditshwa, 2013).

The CFC handles the fruit in a single layer or multiple layers (multi-layered). Normally, in a multi-layer arrangement, a layer of fruit is not placed directly on top of another layer below it, rather, layers are separated with trays, or air-bubble entrapped films to reduce mechanical damage. (Opara & Mditshwa, 2013; Opara, 2011; Pathare, Opara, Vigneault, Delele, & Al-Said, 2012). Fresh fruit packages are designed with vent-holes that enhance the rate of removal of field and respiration heat from the produce (Berry, Fadiji, Defraeye, & Opara, 2017; Opara &

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* Corresponding author at: Postharvest Technology Research Laboratory, South African Research Chair in Postharvest Technology, Department of Horticultural Science, Faculty of AgriSciences, Stellenbosch University, South Africa.

E-mail addresses: opara@sun.ac.za, umunam@yahoo.co.uk (U.L. Opara).

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Table 1
Summary of mechanical forces, their occurrence and the injury they cause on the fruit.

Mechanical force	Occurrences	Injury	References
Impact	● dropping the product onto a hard surface; ● dropping the product into the back of a car; ● excessive drops during loading and unloading; ● suddenly stopping or accelerating a vehicle.	Bruises, puncture	Holt and Schoorl (1977); Schoorl and Holt (1980); Peleg (1981); Jarimopas et al. (2007); Jarimopas, Manor, and Sarig (1984); Chen and Yazdani (1991); Pang et al. (1992); Bajema and Hyde (1998); Ragni and Berardinelli (2001); Fadiji, Coetzee, Chen, Chukwu, and Opara (2016); Ahmadi (2012); Ahmadi, Ghassemzadeh, Sadeghi, Moghaddam, and Neshat (2010)
Vibration or abrasion	● vehicles with small wheels and bad shock-absorbers; ● weak crates; ● bad roads; ● transmission vibration.	Abrasion, bruises	Darmawati and Yulianti (2009); Vursavuş and Özgüven (2004); Chonhenchob and Singh (2005); Jarimopas et al. (2007); Chonhenchob et al. (2009); Park et al. (2011); Eissa, Gamaa, Gomaa, and Azam (2012); Fadiji, Coetzee, Pathare, & Opara, 2016
Compression	● over-packing of crates and boxes; ● too high stacking of crates; ● weak packaging.	Puncture, bruises	Urbanik (2001); Han and Park (2007); Navaranjan et al. (2013); Fadiji, Coetzee, Opara et al. (2016); Fadiji, Ambaw et al., 2018); Berry et al. (2017)
Puncturing	● nails or splinters from the crate or box; ● fingers or nails of a person; ● other crates, fork-lifts, etc. ● hard and sharp stalks of fruit.	Cuts, puncture	Timm et al. (1996); Spotts, Sanderson, Lennox, Sugar, and Cervantes (1998); Rudra, Singh, Jyoti, and Shivhare (2013)

Mditshwa, 2013; Zou, Opara, & McKibbin, 2006, 2006b). Poorly designed CFC with inadequate ventilation, vent-holes misaligned and blocked on pallet stacks, internal packaging materials like plastic liners, plastic bags, trays, etc., can significantly reduce the airflow distribution and negatively impacts the fruit cooling operation (Ngcobo, Delele, Chen, & Opara, 2013; O'Sullivan et al., 2016; Mukama, Ambaw, Berry, & Opara, 2017). However, internal plastic liners and plastic bags are vital to minimise moisture loss and the associated wilting and shrivelling of fresh fruit (Mphahlele, Fawole, & Opara, 2016). Shrivelled fruit loses commercial value due to reduced sellable weight and visual appeal. The environmental impact of plastics in the food supply chains and the accompanying negative news in developed countries prompts the opening of grocery stores that renounce the use of disposable plastic packaging (Beitzen-Heineke, Balta-Ozkan, & Reefke, 2017). In some countries, regulations are in place to minimise use of plastic packaging, though implementation of the regulations is still lacking (Jayaraman, Haron, Sung, & Lin, 2011). Following this, studies to reduce or remove plastic from the fruit and vegetables supply chain are on the increase (Ma, Aranda-Jan, & Moultrie, 2018).

Design of vent-holes on the walls of the CFC must also be in cognisance of the reduction of the structural integrity of the carton (Berry et al., 2017; Fadiji, Coetzee, & Opara, 2016; Han, Zhao, Yang, Qian, & Fan, 2015). Fresh fruit packages handling involves palletisation and stacking for storage and transportation. This eases the handling and movement of the packaged fruit (Chen, Zhang, & Sun, 2011). It is thus necessary that compression tests are undertaken on all new designs to determine suitability to this practice (Berry et al., 2017). In addition, drop, impact and burst tests, as well as the effect of CFC moisture absorption give further information on the mechanical integrity of the designed cartons (Pathare & Opara, 2014).

Packaging science and technologies in the fruit industry have been discussed by a number of authors; structural design of CFC (Pathare & Opara, 2014), fresh produce package performance evaluation (Defraeye, Cronjé, Berry et al., 2015), use of computational fluid dynamics (CFD) in fruit storage facilities (Ambaw, Delele et al., 2013), airflow measurement techniques in fruit forced air cooling (O'Sullivan et al., 2014), mechanical design and performance testing of CFC (Fadiji, Ambaw, Coetzee, Berry, & Opara, 2018; Fadiji, Berry, Coetzee, & Opara, 2018). Package design is a complex problem that requires a multilevel and multidisciplinary approach.

In a recent review on performance evaluation of future packaging for fresh produce in the cold chain, (Defraeye, Cronjé, Berry et al., 2015) summarised recent research on fresh fruit package functionalities in terms of cooling rate, box ventilation, product quality, mechanical strength and energy consumption and how they are quantified. This review provides the design considerations of packaging used in the fresh fruit industry, with emphasis on corrugated fibreboard cartons, including some of the latest findings in this field. A description of fruit cold chain is provided and the multiparameter evaluation process of the designed cartons is emphasised. This review further puts consideration on cargo density requirements and how this is affected by package design as well as a description of the contribution of packaging technologies to fresh fruit quality. The review was initiated to realise the state-of-the art in optimising the ventilation and structural requirements of corrugated packaging carton design. Studies on the rate and uniformity of produce cooling and the loss of structural strength in corrugated containers as a function of size, shape, and location of vent-holes are reviewed.

2. Packaging in the fresh fruit industry

2.1. The function of packaging

Fruit vary in physical, mechanical, thermal, and metabolic properties, thus, require different postharvest handling requirements. The precooling, cold storage, cold transportation processes and the ultimate fruit quality are considerably affected by the packaging practice. Packages must protect fruits from mechanical damage, reduce the moisture loss from the fruit and prevent the proliferation and spread of decay-causing microorganisms.

In the various stages of cold chain management and distribution, fruit endure different types and combinations of mechanical loads. These loads may cause injuries like cuts, bruises, abrasions and punctures. The level and severity of these losses depend on the energy inputs to the package during transport and handling, and the way in which the energy is dissipated within the package. Table 1 summarises the different mechanical forces, their occurrence and the injury they cause on the fruit. Among the various mechanical forces, impact has been recognised as the most crucial cause of damage (bruising) in fruits (Pang, Studman, & Ward, 1992). Severity of damage to the fruit is primarily related to height of fall; initial velocity; number of impacts; type of impact surface and size and physical properties of the fruit, related or not to maturity. Excessive compression also causes bruising, as do repeated impacts. Bruising appears as a result of vibration, impacts, and compressions of the fruits against other fruits, containers, parts of any grading and treatment machinery, and on any un-cushioned surfaces. Produce cartons must completely contain the produce in convenient units for handling and distribution and protect the produce from mechanical damage.

2.2. Types of packaging for produce handling

A fresh fruit package can be made from different materials – wood, paper, plastic or glass. In the global fruit trade, corrugated fibreboard cartons (CFC) and reusable plastic containers (RPC) are frequently used as shipping packages. Comparatively, the use of CFCs surpasses RPC (Berry et al., 2015; Defraeye, Cronjé, Berry et al., 2015; Opara & Mditshwa, 2013) due to their lightweight, completely recyclable, biodegradable, and more cost-effective characteristics (Pathare & Opara, 2014). Corrugated fibreboard materials are also good in damping mechanical impacts and vibration, which are sources of damage on fruit. In the South African pome fruit industry, CFCs are the most commonly used cartons (Berry et al., 2015), and over 90 % of fresh fruit packaging in the USA use CFC (Little & Holmes, 2000). RPC are made from recyclable plastic material, mostly polyethylene that is moulded to the desired shape, size and ventilation (McGrath, 1993). RPC for fresh produce movement is ideal in close and local markets where the logistics of return will be easily managed but may be difficult in international trade where fruit are shipped for weeks to the destination markets.

The stage of fruit handling governs the size of container to use. Bulk packages moved by forklifts are handled using wooden bins (Fig. 1(a) and (b)) or plastic (Fig. 1(c) and (d)). These packages weigh as much as 550 kg (Timm, Brown, & Armstrong, 1996). Depending on the size and physiology of the fruit, bins can be designed open type (high venting) (Fig. 1(a) and (c)) or closed type (low venting) (Fig. 1(b) and (d)). Packages of produce commonly handled by hand are usually limited to 25 kg in wooden, plastic or corrugated fibreboard cartons (Fig. 2(a)–(d)). Packaging footprints need to conform to the dimensions of the pallet standard to be used (Fig. 3). The dimensions of the pallet depend on the standard used in the market. For instance, the ISO2 standard, (W × L) (1.0 × 1.2) m (Fig. 3(a)–(c)) and the ISO1 standard, (0.8 × 1.2) m (Fig. 3(d)) standards are frequently used in Europe and Asia as presented in ISO Standard 6780: Flat pallets for intercontinental materials handling-principle dimensions and tolerances.

Fruit packaging involves the use of more than a single material to package fruit for the market. This is referred to as multiscale packaging (Fig. 4) (Berry et al., 2015; Ngcobo et al., 2013). Trays, plastic bags, liners and clamshells are frequently used internally for positioning fruits in place and for the purpose of moisture control. However, the increasing awareness of consumers to the environmental and social externalities of the food supply chains in developed countries prompts the opening of grocery stores that renounce the use of disposable plastic packaging. In a bid to cut down on packaging waste, retailers worldwide are currently moving toward removing plastic from fruit and vegetables. Hence, packers and suppliers must, therefore, look for ways to reduce packaging plastics. (Ansorena & Ponce, 2019; Convery, McDonnell, & Ferreira, 2007; Flores-López, Cerqueira, de Rodríguez, & Vicente, 2016; Jalil, Mian, & Rahman, 2013).

3. Vent-hole design

3.1. Carton-vents for effective cooling of produce

Carton vents play a critical role in the fresh fruit industry. A vent-hole facilitates the airflow during a produce cooling process, remove the heat of respiration, and avoid the heat build-up during fruit storage (Pathare et al., 2012). The vents are the “access gates” for the cooling air to the fruit as illustrated in Fig. 5. The total vent area, the position of the vent holes, and their shape determines the produce cooling rate and the cooling uniformity and thus, the energy, material usage, and the carbon footprint of the industry (Ambaw, Mukama, & Opara, 2017; Opara & Mditshwa, 2013).

Precooling is the quick removal of the field heat shortly after the harvest of a crop. Adequate ventilation is crucial to ensure that fruit is effectively pre-cooled rapidly and uniformly. The tunnel horizontal airflow system (Fig. 6(a)) is the most common precooling arrangement (Aswaney, 2007; Boyette, 1996). In this arrangement, the top and back sides of the tunnel are covered by an air-tight sheet. At the front end of the tunnel, a fan is mounted to pull chilly air through the stack. According to the industry requirement, the precooling process continues till 88 % of the initial difference in temperature between the produce and the cooling air is removed, called 7/8th cooling time (Thompson, Rumsey, & Mitchell, 2008). The magnitude and distribution of the horizontal airflow is crucial for the fast cooling of the produce in this system as demonstrated in Fig. 6(b) by comparing the cooling curves of

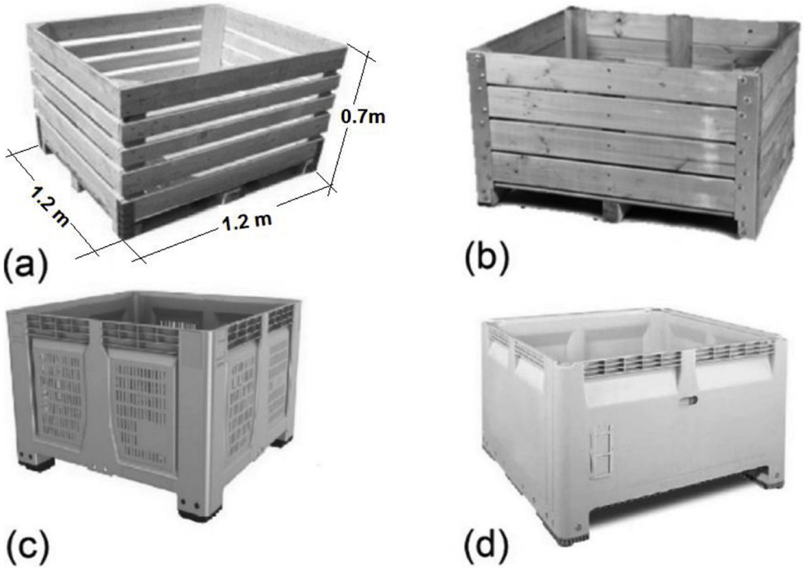

Fig. 1. Harvest bins: (a) wooden bulk bin with high vented sides, (b) wooden bulk bin with closed sides, (c) reusable vented plastic bulk bins, (d) reusable closed plastic bulk bin. Notice (a) gives typical dimensions of harvest bins.

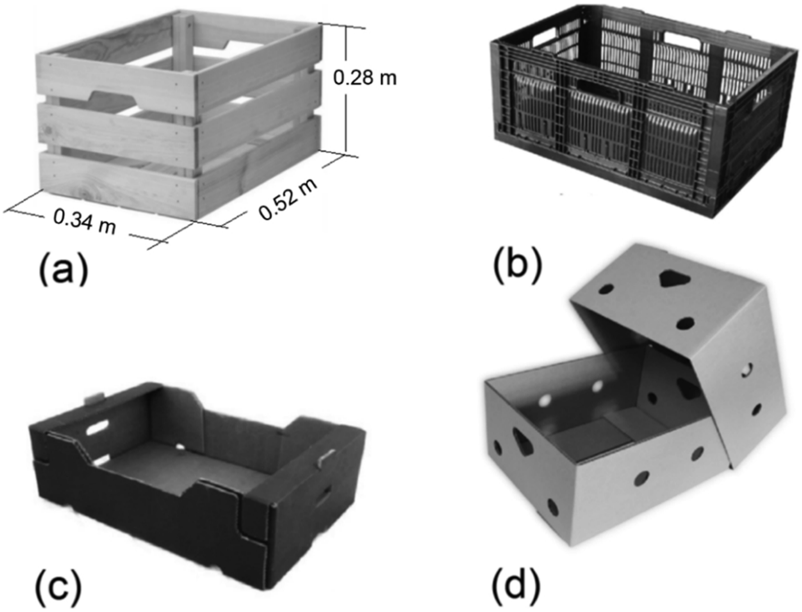

Fig. 2. Fresh fruit packaging boxes commonly handled by hand: (a) wooden crates, (b) reusable plastic container, (c) display corrugated fibreboard cartons and (d) telescopic corrugated fibreboard cartons. Notice (a) gives typical dimensions of packaging cartons.

blueberry stacks at different airflow rates ($m^3\ kg^{-1}\ s^{-1}$), 0.0011, 0.0015, and 0.0022 (Boyette, 1996). Hence, vent-holes perpendicular to the direction of the cooling airflow path (horizontal in a precooling operation) are vital.

In integral containers (reefers) the air flow is vertically directed (Fig. 7) and is in a much lower rate (0.02 to 0.06 $L\ s^{-1}\ kg^{-1}$) compared to the forced air-cooling ($\approx 1\ L\ s^{-1}\ kg^{-1}$) and therefore box design and selection should aim to maximise the vertical airflow. Hence, vent-holes at the bottom of the carton are important in reefers (Getahun, Ambaw, Delele, Meyer, & Opara, 2017). The amount and spacing of these vent-holes are a function of many factors: paper combination, presence of internal packaging materials like liners, trays, fruit bags, and the type of pallet used which determine the carton orientation on the pallet as, if not aligned, vent holes are blocked during stacking. It is recommended that at least 5 % of the surface area on each surface be open for air flow and vent-hole misalignment and blockage should be avoided as much as possible during stacking on pallets.

3.2. Carton structural integrity

Fruit loaded cartons need to withstand compressional, shock and vibrational forces in the handling chain (Berry et al., 2017; Fadiji, Coetzee, Opara et al., 2016; Pathare & Opara, 2014). Any packaging box (particularly the boxes at the bottom most in a pallet) in the stack must have sufficient structural strength to avoid buckling under the weight of the fruit. This is assessed based on the total load that the carton in the bottommost layer of the stack experiences (the maximum compression force). This load depends on the number of packages above it, the weight of individual packages, and the appropriate safety factor to account for other dynamic loads, for instance, impact forced during loading and unloading and vibration during transit (Beldie, Sandberg, & Sandberg, 2001).

The stacking strength of the carton is a function of the edgewise compression resistance and bending stiffness of the CFC (Navaranjan, Dickson, Paltakari, & Ilmonen, 2013; Urbanik, 2001). Maximum stress of stacked cartons is concentrated at the corners of the cartons (Fadiji,

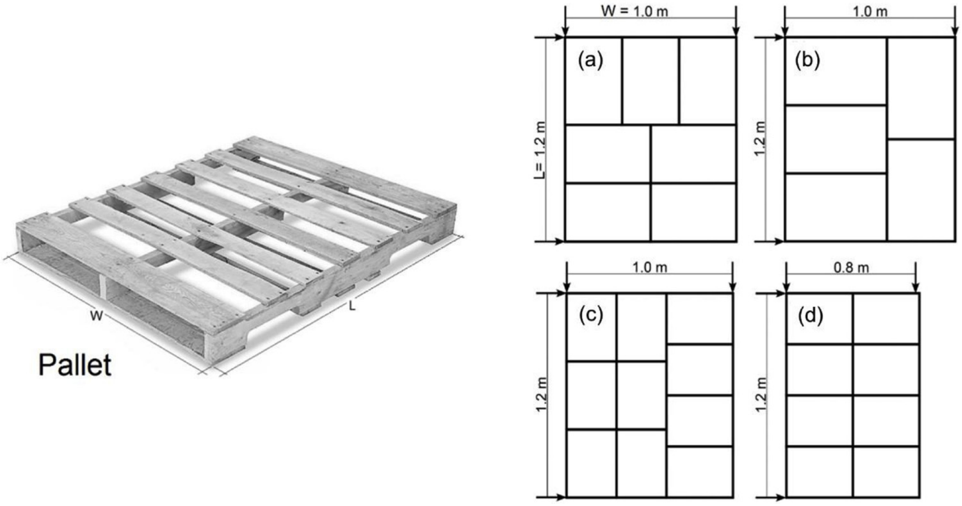

Fig. 3. Wooden pallet (left), the value of width (W) and length (L) specifications depends on pallet standards as shown in the schematic of stacking patterns on the ISO2 standard ((a) to (c)) and ISO1 standard (d).

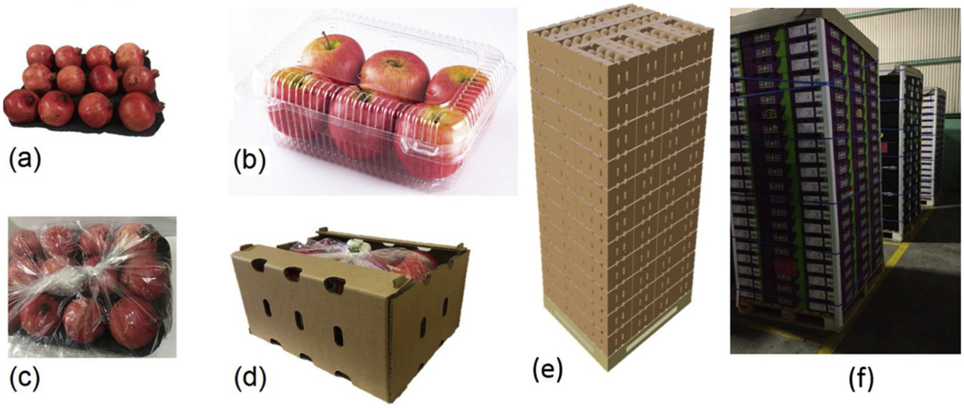

Fig. 4. Schematic showing hierarchical packaging levels in a fruit multiscale packaging perspective: (a) fruits on pulp or polystyrene trays, (b) fruit internal clamshell packaging (c) internal plastic liners, (d) unitised package, ready for stacking into pallet (e) palletised stacked fruit, (f) stacking in cold storage room.

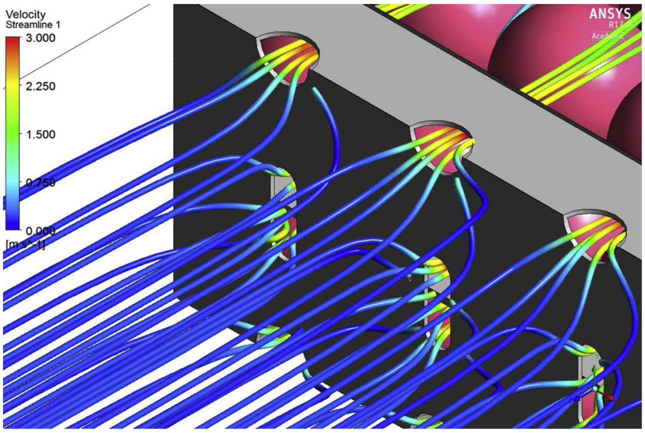

Fig. 5. Closer look of airflow through vent-holes of a typical fresh fruit corrugated fibreboard carton. Visualisation of the airflow path using computational fluid dynamics.

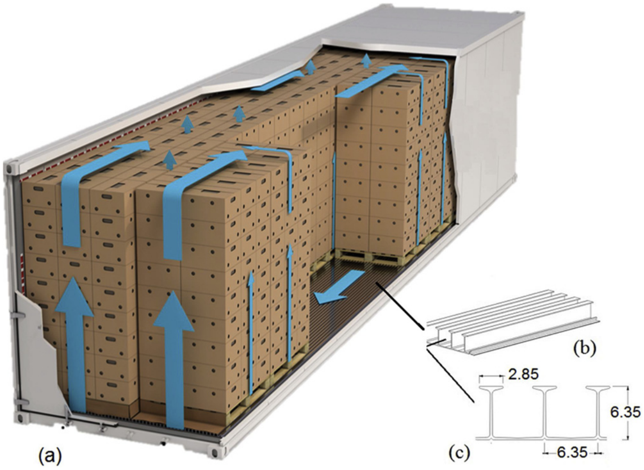

Fig. 7. Schematic showing the major airflow path (vertical) in a fully loaded refrigerated container (a), closer view of the T-bar floor structure (b) and the section view showing the dimensions of the T-bar (c) (Opara, Ambaw, & Berry, 2018).

Coetzee, Berry, & Opara, 2019). The presence of both vent-holes and hand-holes cause a loss of material in two or more faces of the carton. As a result, the compression strength required for shipping and stacking is compromised. The magnitude and severity of the loss of compression strength, due to holes, has been investigated by many researchers. Singh, Olsen, Singh, Manley, & Walace (2008) reported the presence of hand and vent holes on a carton can cause a reduction of compression strength between 20–50 %. The authors also reported a linear relationship between the loss of strength and the total area of the holes made for venting or handling. Similar results have been observed by Berry et al. (2017).

Fadiji, Coetzee, Opara et al. (2016) found 8–12 % reduction in

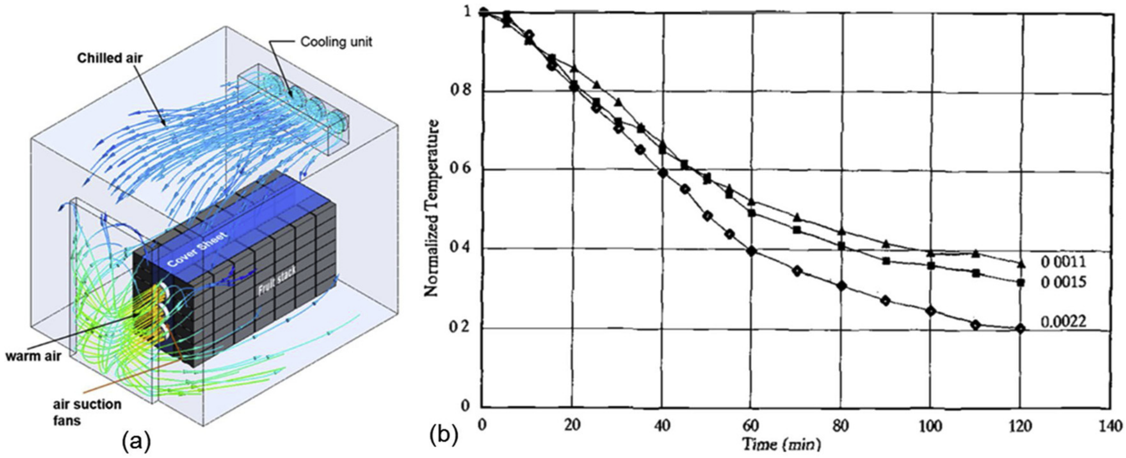

Fig. 6. Forced air-cooling (a) (FAC) tunnel and (b) cooling curves of packaged blueberries as a function of airflow rates (0.0011,0.0015, and 0.0022 $m^3 kg^{-1} s^{-1}$) (Boyette, 1996).

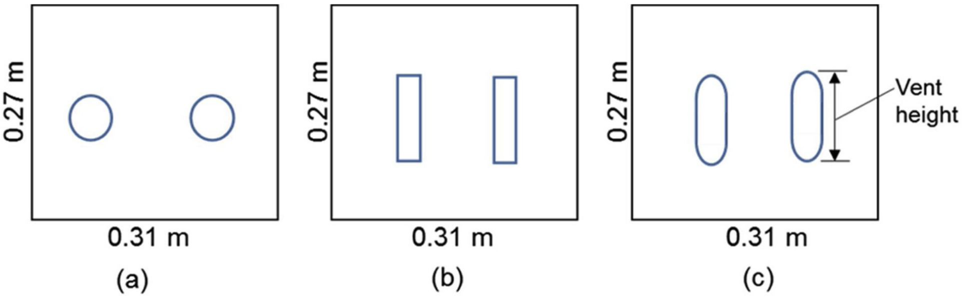

Fig. 8. Schematic showing different vent shapes typical on corrugated fibreboard cartons for horticultural packaging (a) circular (b) rectangular (c) oblong.

buckling load following a 2–7 % increase in ventilation of the CFC. Mitchell (1992) observed a significant reduction in the mechanical strength of a fibreboard at 5–6 % venting of the side walls. The thickness of the linerboards used in carton manufacture and the quality of input cellulose fibres also have a bearing on the mechanical integrity of manufactured cartons. Fadiji, Ambaw et al. (2018) found a linear relationship between liner thickness and compression strength of “standard vent” apple cartons.

In addition to the ventilation area, ventilation number, orientation, and shape can affect the structural strength of CFC. Fadiji, Coetzee, Opara et al. (2016) reported better retention of mechanical strength by rectangular vent-holes compared to circular ones (Fig. 8) and found a linear correlation between vent height and carton buckling load. Similarly, Jinkarn, Boonchu, and Bao-Ban (2006) reported that circular vent-holes at carton centre reduced carton mechanical integrity less compared to oblong vent-holes. On the contrary, Han and Park (2007) found that circular vents reduced the compression strength more compared to vertical oblong vents.

With regards to position on the carton, vents need to be far-off from the vertical corners of the cartons (Vigneault, Thompson, & Wu, 2009). Table 2 lists some additional vent-hole design characteristics on CFC face and their effects on the fruit carton strength. Therefore, design considerations of new cartons ought to take into consideration the fruit weights, handling conditions (especially temperature and relative humidity) and stacking requirements in designing sturdy cartons that will deliver fruit without mechanical damages like bruises, dents, and cuts, to the ultimate consumer.

3.3. Space utilisation and cooling process throughput

The storage capacity of cool rooms and reefers is critical in the produce peak season. Therefore, optimal usage of space in the cold chain in storage and transit is important. Given that pallets are standardised worldwide, package design, including the number of fruit per unit package and package dimensions, which affects the number of packages on the pallets plays a significant role in space utilisation and packaging density. In addition to the inventory, optimising space utilisation should consider the expected level of activity in the storage room like movement of forklifts and personnel in the storage room. Cooling process throughput mainly relates to precooling capacity, majorly forced air cooling in fruits, which depends on fans and cooling unit capacity. It is also affected by package design; package with high vent-hole proportion and perfect vent-hole alignment during stacking, cool fruit faster (Mukama et al., 2017). The faster the produce is precooled to the required storage temperature, the faster it is moved to the storage rooms or to the reefers. Hence, the frequency of using the precooling facility to handle fresh produce from the field increases.

Packaging designs are affected by the intended market destinations (domestic or international), cooling requirements, fruit properties, package properties, retailer specifications, etc. leading to cartons of different geometrical configurations and size in the fresh fruit industry (Berry et al., 2015; Opara & Zou, 2007). Fruit shape and dimension determines the design of individual carton (Berry et al., 2015; Singh, Saha, & Singh, 2013). The objective here is to achieve closest packing of fruit inside individual carton. However, fruit are living things, they are not stable and coherent physiologically and mechanically. Therefore, package design considerations have to be made to prevent abrasion of the fruit against each other. The design will have to allow space for the tray to hold fruit in place and space above the package such that the package stacked on top of each other do not touch the fruit underneath. Given that current carton designs are mainly based on empirical knowledge and market requirements, scientific investigation to improve space utilisation and cooling process throughput are paramount.

For cartons with the same base dimensions (footprint), tray designs are made to suit different sizes of fruit through staggering or uniform alignments, for example, tray designs used in the pomegranate industry (Fig. 9). Staggered tray design (Fig. 9a, c, d) and uniform alignment (Fig. 9b) are all designed in consideration of the fruit diameter and this will eventually influence the carton height and weight. Pomegranate cartons packaged with lower fruit count (6–8) (larger diameter fruit

Table 2
Effect of vent-hole characteristics on corrugated fibreboard carton mechanical strength.

Vent-hole characteristic	Main finding(s)	Reference(s)
Vent shape	Ventilation holes with a vertical oblong shape produce smaller stress level, the least surface area of stress concentration, and have the highest structural stability against compression	Han and Park (2007)
Vent area	Increase in vent area of CFC beyond 8 % does not significantly increase the cooling rate	De Castro, Vigneault, and Cortez (2004)
Vent area	There is no reasonable increase in cooling rate with vent area of CFC increase beyond 7 %	Delele, Ngcobo, Getahun et al. (2013a)
Vent position	To minimise loss in the mechanical strength of cartons, vents should be 40–70 mm away from all carton corners	Thompson et al. (2008)
Vent area	Cartons with vent area above 5 % require careful design to achieve mechanical integrity of CFC	Mitchell (1992)
Vent area	There is 0.56–1.08 % reduction in structural strength following a 1% increase in vent area of corrugated carton	Singh, Olsen, Singh, Manley, and Wallace (2008)
Vent shape	Rectangular and parallelogram vent-holes have higher compressional strength than circular vent-holes	Singh et al. (2008)
Presence/absence	There is 20–50 % loss in strength of single wall CFC due to presence of vent and hand holes	Singh et al. (2008)
Vent area	Loss in carton strength varies linearly with total vent area	Singh et al. (2008)

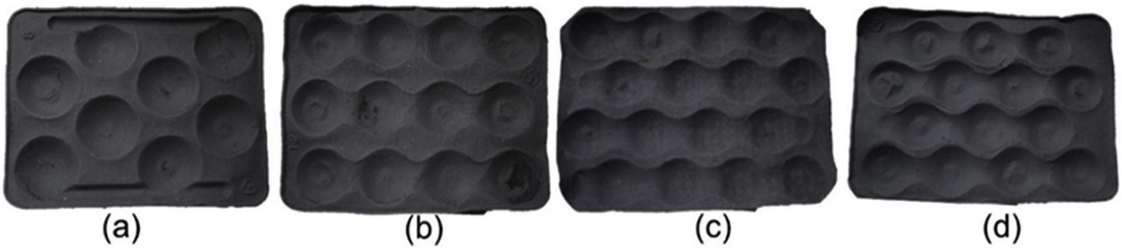

Fig. 9. Schematic showing the different tray designs used in the pomegranate industry. Tray to accommodate 8 fruit in a staggered arrangement (a), regularly arranged 12 fruit (b), 16 fruit in a staggered arrangement (c) and 14 fruit in staggered arrangement (d). All the trays shown are for a carton with a footprint of 0.39 × 0.29 m.

above 80 mm) are 118 mm high, yielding a gross weight over 4.5 kg, while higher counts (10–16) (smaller fruit diameter – 80 mm and below) are packaged in cartons with 104 mm height, gross weight 3.8 kg (Muller, J.C., 2019, General manager, Sonlia Pack house, Wellington, South Africa, personal communication, 10 May). Additionally, the number of layers of fruit in one carton is primarily dependent on the fruit weight with heavier fruit packaged in one or two layers while lighter fruit, for example, apples and pears are packaged in up to 4 or more layers within as single carton. (Berry, Defraeye, Nicolai, & Opara, 2016; Berry et al., 2015; Fadiji, Coetzee, Opara et al., 2016, b, Fadiji, Berry, Coetzee, & Opara, 2017; Singh et al., 2013).

Most fruit handling is done on standard ISO2 pallet (1.0 × 1.2) m (Fig. 3) and thus depending on the carton footprint, the cartons are arranged in different numbers to fill up the base of the pallet. For example, in a study on packaging cartons used in the pomegranate industry, Mukama et al. (2017) found two stack configurations where one carton footprint required 10 cartons to fill up the pallet base while the other required 12 cartons. Berry et al. (2015) identified four different configurations (5, 7, 8, and 10) for cartons used in the pome industry. A standard 40 ft refrigerated truck takes 20 standard ISO pallets when fully loaded (Defraeye, Cronjé, Berry et al., 2015). These are loaded to a height of about 2.2 m leaving the top space for airflow circulation (Fig. 7). Thus, depending on the carton height and weight of each carton, a fully loaded container will take a particular number of cartons which will further determine the tonnage.

3.4. *Effect of humidity on the CFCs*

Packaged fruit are often predisposed to low temperature and high humidity environments to preserve quality during storage and transportation. This causes moisture uptake by the CFC material leading to considerable loss of structural strength through weakening of bonds between cellulose fibres (Allaoui, Aboura, & Benzeggagh, 2009; Ngcobo et al., 2013). This phenomenon is called mechano-sorptive creep, where the CFC permanently deforms under mechanical loads (Berry, Ambaw, Defraeye, Coetzee, & Opara, 2019).

Fadiji, Coetzee, Opara et al. (2016), for example, reported between 11–16 % loss in compression strength of apple cartons under low temperatures and high humidity condition (0 °C; 90 % RH) compared to standard atmospheric condition (23 °C; 50 % RH). Pathare, Berry, & Opara (2016), demonstrated a reduction of the maximum carton (apple carton, ‘MK4’) compressive strength by 618 N per 1 % increase in the moisture content of the CFC at −0.5 °C, 90 % RH over a period of 43 days. The moisture content increased from 5.1 % dry basis (g water/g dry matter) to about 11 % after 4 days in cold storage and remained almost constant for the rest of the storage days until day 43 (Pathare, Berry, & Opara, 2016). It is thus paramount to design cartons that will remain strong under humid and cold conditions, specific mechanical loads as a function of fruit weight and stack heights through the long-haul refrigerated transport and refrigerated storage.

Berry et al. (2019) developed a CFD model to predict the spatio-temporal moisture distribution within CFC under refrigerated shipping conditions and convective airflow conditions. The authors found relatively low moisture content gradients within the stacked CFC cartons under optimal shipping conditions but noted accelerated moisture content gradients at the initial activation of the refrigerated container. They further attributed heat conduction from the outside throughout the container wall to be the most influential factor in the spatial moisture gradients within the CFC stacks. The developed model could be used to guide refrigerated shipping package design and predict changes in moisture content as well as mechano-sorptive creep during shipping of packaged produce (Berry et al., 2019).

3.5. *Keeping fruit quality*

The ultimate measure of the performance of every packaging design is keeping fruit quality. The design, selection, redesign/change may be initiated to save electricity cost, space usage, process throughput or to meet commercial requirements, but ultimately should be measured and evaluated on the keeping of fruit quality achieved. Keeping the moisture and gas composition at optimum condition requires the use of internal packaging materials like plastic liners and plastic bags. These added packaging components however impair the cooling air circulation leading to improper temperature management (Ambaw et al., 2017), high respiration of the produce and quality degradation. These opposing requirements make the packaging design a complex task. For example, in the pomegranate industry, the fruit are packaged in polyliner bags (Fig. 4d) that minimise moisture loss from these fruit by creating a moisture saturated environment around the fruit after some time that minimises further loss of moisture from the fruit (Mukama, Ambaw, Berry, & Opara, 2019). However, Mukama et al. (2017) and Ambaw et al. (2017) in their studies on energy usage, cooling rate, and uniformity of cooling of packaging in the pomegranate fruit industry found that the polyliners increased the energy demand of the precooling process up to 3-fold compared to carton stacks with no liners, and increased the precooling time by 5 h.

Polyliner bags destined to modify the levels of O_2/CO_2 in the bag atmosphere to control the metabolic processes may affect the moisture distribution in the treatment atmosphere. The problem here is that, in case of temperature fluctuations, moisture condenses on fruit surfaces creating favourable conditions for fungal growth and proliferation, hence decay (Ngcobo et al., 2013).

Bruising of fruit caused by the breakage of fruit surface cell membranes due to excessive impact, compression or abrasion of fruit is also one of the main mechanical problems in the fruit industry (Hussein, Fawole, & Opara, 2019). Bruised fruit eventually discolour and decay. To minimise this, fruit are packaged in trays (Fig. 4a) to minimise their movement during transit (Berry et al., 2015; Mukama et al., 2017), others are packaged with cushions (bubble pack sheets, sponge sheets, riffled paper) between layers or around individual fruit to minimise abrasion against each other during handling and transportation (Chonhenchob & Singh, 2005), and others are sandwiched with foam balls that help absorb mechanical shocks (Jarimopas, Singh, Sayasoonthorn, & Singh, 2007). However, trays in poorly designed cartons block the vent-holes interfering with free airflow and ultimately fruit cooling rates (Mukama et al., 2017).

To this end, most of the CFCs employed in the fresh fruit industry are based on trial and error procedure instead of a rigorous performance and design evaluation process, hindered by the practical difficulties and cost associated with pallet scale investigations (Berry et al., 2015). This possibly disposes the fruit industry to go through costly testing and evaluation process. A more holistic package design process that considers the space usage, energy usage, process throughput, the environment and ultimately the produce quality, throughout the value chain, is important. Computer simulation models are a potential solution for overcoming some of these difficulties. Despite their common use in postharvest research, there is a lack of design guidelines for such simulators in the literature which in some case has led to their inappropriate use. Subsequent sections of this review examine aspects of computational models in produce cold-chain management studies.

4. CFD (computational fluid dynamics) in vented carton design and analysis

4.1. CFD modelling in postharvest applications

The complexity of air movement inside stacks of cartons and around individual fruit makes experimental measurements and information of local airflow, heat and mass transfer very difficult, time consuming and challenging. Package design and evaluation should employ a multiparameter approach giving a holistic assessment of all functionalities and parameters to help avoid contradictions in the design requirements. For example, increasing the ventilation area to improve cooling rates without consideration of the carton strength may result in a carton lacking in mechanical integrity, increasing chances of fruit mechanical damage.

Mathematical models are important in reducing time and saving costs that would have gone into experimental studies (Delele, Verboven, Ho, & Nicolaï, 2010; Ambaw, Delele et al., 2013, b; Fadiji et al., 2019). The models allow exact control of operating parameters while providing vital information like the airflow, mechanical stress, mechanical strain and temperature patterns within the stack of fruit under refrigeration conditions; providing mechanisms and performance details of the processes (Berry et al., 2019; Fadiji, Ambaw et al., 2018, b, Fadiji, Coetzee, Berry, Ambaw, & Opara, 2018; O'Sullivan et al., 2016; Wu & Defraeye, 2018; Wu, Beretta, Cronje, Hellweg, & Defraeye, 2019; Wu, Cronjé, Verboven, & Defraeye, 2019; Wu et al., 2018). The finite volume method (FVM) is the most frequently used modality of CFD in the fresh fruit packaging design (Delele, Ngcobo, Getahun et al., 2013a, b; Defraeye et al., 2014; Delele, Ngcobo, Opara, & Meyer, 2013; Norton & Sun, 2006; Ambaw et al., 2014, 2017; Getahun, Ambaw, Delele, Meyer, & Opara, 2017, 2017b, 2018; O'Sullivan et al., 2016; 2017). The basic steps of applying this method is described below.

4.1.1. Model geometry

The geometry of the horticultural system to be studied is created using computer-aided drawing (CAD) software like ANSYS DesignModeler, AUTOCAD, Solidworks, etc. The complexity of the geometry increases from where a single fruit is considered to fully loaded cold store or reefer. This increases the computation costs and time (Defraeye, Cronje, Verboven, Opara & Nicolai, 2015). Therefore to reduce costs and time, simplifying assumptions are used, for example, assuming even airflow profile and temperature distribution across each layer of the stack under a precooling process, hence analysing a single layer out of the stack in a cold room (Ambaw et al., 2017), or taking one row of cartons on a pallet instead of the entire pallet or container (Defraeye, Cronjé, Verboven, Opara, & Nicolai, 2015).

For the purpose of analysing a fully loaded cold storage room or reefer, which is highly complex, the porous medium approach is used. This approach assumes individual palletised stacks as a porous medium. This procedure transforms the stacked fruit and air spaces into a continuous and homogeneous medium, characterised by properties such as porosity, tortuosity, and interface transfer coefficients (Ambaw, Verboven et al., 2013, 2014; Getahun et al., 2017a, 2017b).

4.1.2. Discretisation

This step involves formation of a computational grid from the partitioning of the spatially continuous computational domain into several nonoverlapping subdomains, a process called discretisation (Zhao, Han, Yang, Qian, & Fan, 2016). The grid shapes can be pyramidal, tetrahedral, triangular prism, or hexahedral. The accuracy and reliability of the solution is dependent on the size of the grid. Smaller elements are more accurate, though take a longer time to process and require more memory (Ambaw, Delele et al., 2013; Norton & Sun, 2006; Zhao et al., 2016). Grids can be: structured, where the geometry shape is relatively even and thus the cells connect regularly, unstructured, where the cell elements do not connect regularly or a mixture of the two (hybrid). Hybrid grids are common in horticultural cold chain CFD models given the complexity of the geometry of packed produce (Ambaw et al., 2014; Defraeye et al., 2014; Delele, Ngcobo, Getahun et al., 2013a; O'Sullivan et al., 2016). After meshing, properties of fluids and solids, interface boundary conditions and initial conditions in the simulation must be specified (Smale, Moureh, & Cortella, 2006). The next step is transforming the governing partial differential equations over the mesh. The governing equations are discretised over the mesh and time is discretised for transient problem. (Zhao et al., 2016).

4.1.3. Governing equations to model carton-vents for effective cooling

Computational fluid dynamics employs mathematical equations that are statements of conservation of mass, momentum and energy laws (Zhao et al., 2016). Airflow and heat transfer in horticultural cooling systems is modelled using the three-dimensional Reynolds-averaged Navier-Stokes equations. These include:

$$\nabla\cdot\ \mathrm{U}=0 \tag{1}$$

$$\frac{\partial \mathrm{U}}{\partial t}+\nabla\cdot(U\otimes\ U)-\nabla\cdot\left(\left(\frac{\mu+\mu_t}{\rho_a}\right)\nabla\mathrm{U}\right)-S_U+\frac{1}{\rho_a}\nabla p=0 \tag{2}$$

$$\rho_a C_{pa}\left(\frac{\partial T_a}{\partial t}+\mathrm{U}\cdot\nabla T_a\right)-\nabla\cdot((k_a+k_t)\nabla T_a)-Q=0 \tag{3}$$

where U is the vector of the velocity (m s^{-1}), t is time(s), μ is the dynamic viscosity of air (kg $m^{-1}s^{-1}$), μ_t is the turbulent eddy viscosity (kg $m^{-1}s^{-1}$), p is pressure (Pa) causing the fluid flow and S_u (m s^{-2}) is any momentum source inside the fluid domain, C_{pa} (J kg^{-1} K^{-1}) is the heat capacity of air, ρ_a (kg m^{-3}) is the density of air, T_a (K) is the air temperature, k_a (W m^{-1} K^{-1}) is the thermal conductivity of air, k_t (W m^{-1} K^{-1}) is the turbulent thermal conductivity, Q is volumetric heat generation (W m^{-3}).

To model airflow coupled with moisture transport, the basic heat transfer model (Eq. (3)) incorporates respiration and transpiration of produce and heat gain/loss from evaporation/condensation of water on the produce surface (Eqs. (4) and (5))

$$(\rho_a C_{pa})\left(\frac{\partial T_a}{\partial t}+\mathrm{U}\cdot\nabla T_a\right)=\nabla\cdot((k_a+k_t)\nabla T_a)+h_{pa}(T_p-T_a) \tag{4}$$

$$(\rho_p C_{pp})\frac{\partial T_p}{\partial t}=\nabla\cdot(k_p\nabla T_p)+h_{pa}(T_a-T_p)+Q_r-Q_v \tag{5}$$

where $h_{pa}(T_p-T_a)$is the heat exchange across the interface between the produce and the cool store atmosphere, $h_{pa}$is interfacial heat transfer coefficient (W m^{-2} K^{1}), T_p is the temperature of the produce (K), Q_r is respiration heat generation and Q_v is heat loss due to evaporation of water from the surface of the produce. Modelling the moisture distribution requires Eq. (6) to be coupled to the basic Navier-Stokes equations.

$$\rho_a \frac{\partial G}{\partial t} + \nabla \cdot (G\mathrm{U}\text{-}(D_a + D_t)\nabla G) = m \quad (6)$$

where G is moisture concentration in cold room, D_a is diffusivity of moisture in air, D_t is turbulent diffusion coefficient and m is rate of evaporation of moisture from produce surface.

Wu and Defraeye (2018) incorporated generic models (Eqs. (7) and (8)) into the basic CFD models based on kinetic rate-law (Wu et al., 2018) to model the change in quality of fruit attributes like colour, texture, etc.

$$-\frac{dA}{dt} = \gamma A^n \quad (7)$$

where t is the time (s), γ is the rate constant (s^{-1}), n is the order of the reaction. The temperature driven quality changes can be described by an Arrhenius relationship (Eq. (8))

$$k(T) = k_0 e \frac{-E_a}{RT} \quad (8)$$

where k is a constant (d^{-1}), E_a is the activation energy ($\mathrm{J\ mol}^{-1}$), R is the ideal gas constant (8.314 $\mathrm{J\ mol}^{-1}\ \mathrm{K}^{-1}$), T is the absolute temperature (K). The constants k_o and E_a can be inferred from quality decay data.

4.1.4. Simulation techniques

Different numerical techniques are used to discretise the computational domains, the most important include finite elements, finite differences and finite volumes techniques (Ambaw, Delele et al., 2013; Zhao et al., 2016). Of all the techniques, the finite volume techniques are easily programmed, understandable, have high computation efficiency, and have become the method of choice for CFD numerical studies (Delele, Ngcobo, Getahun et al., 2013a, b, Norton & Sun, 2006; Delele, Ngcobo, Opara et al., 2013; Ambaw et al., 2014, 2017; Defraeye et al., 2014; Getahun et al., 2017a, 2017b; Getahun, Ambaw, Delele, Meyer, & Opara, 2018; O'Sullivan et al., 2016, 2017). The finite element method (FEM) has a lower resolving speed and is not widely used in commercial packages, while the finite difference technique is rarely used in engineering fields because it requires extremely fine meshes that are difficult to process (Zhao et al., 2016).

The most common commercial software applied in the CFD in the horticultural chain studies is ANSYS®. This includes, ANSYS® DesignModeller™, ANSYS® Meshing™, ANSYS® CFX™ (Ambaw, Verboven et al., 2013, 2014; Berry et al., 2017, 2019), and ANSYS Fluent™ (Berry et al., 2016, 2017; Defraeye et al., 2013, 2015b; Getahun et al., 2017a, 2017b; O'Sullivan et al., 2016, 2017). This software has up-to-date physical models including multiphase flow, porous media, laminar and turbulent transition, heat transfer as well as other functional models. The software is also easily compatible with most CAD software (Norton & Sun, 2006).

4.1.5. Model validation

CFD models must be validated experimentally to prove their accuracy before making any decisions. Quantitative data, for example, temperature distribution or fluid velocity in the horticultural systems require high accuracy levels, thus comparison with experimental or highly accurate numerical results will help determine the error of the simulation. Table 3 gives a summary of validation data from some studies that validated data from computational fluid dynamics experimentally. Most studies represent the validation data graphically or as calculated coefficients of deviation between the values. Temperature history of the fruit thermal centre was measured with T-type thermocouples to validate numerical results in CFD model on cooling of pomegranate fruit in different carton designs (Ambaw et al., 2017). Getahun et al. (2017a, 2017b) measured air velocity in different sampling points, including free region between the two stack rows and between the stacks and roof in a fully loaded refrigerated container with TVS 1100 data logger with candle stick sensors (Fig. 10). The average prediction error between the experimentally measured and model captured the velocity profiles was 26 ± 2 %.

4.2. Notable findings

Recent studies and key findings from different studies that used CFD are summarised in Table 4. The studies applied CFD to packaging and cooling systems for various fruits ranging from apples, pomegranates, citrus, straw berries to kiwifruit. These investigated different problems in the fruit cold chain, for example: effect of vent-hole design on fruit cooling (Ambaw et al., 2017; Berry et al., 2017; Defraeye et al., 2013; Delele, Ngcobo, Getahun et al., 2013a, b), mass loss in fruit (Han, Zhao, Qian, Ruiz-Garcia, & Zhang, 2018), effect of refrigerated container floor design on air circulation (Getahun et al., 2018), effect of multiscale packaging on fruit cooling (Ambaw et al., 2017; Berry et al., 2016), effect of internal packages on fruit cooling, airflow and energy needs of fruit precooling (Ambaw et al., 2017; Berry et al., 2016; O'Sullivan et al., 2017), modelling of airflow velocities within stacks of currently used commercial pomegranate fruit packages (Fig. 11), cooling and airflow performance of new package designs and modes (Defraeye et al., 2013), optimal airflow velocities (Han, Qian, Zhao, Yang, & Fan, 2017) etc. (Table 3). Accuracy of the findings (numerical vs experimental) varied between 10–25 %.

5. Computational structural dynamics (CSD) in vented carton design

5.1. Aspects of CSD application in vented carton design

In the fresh fruit industry, packages are mainly constructed from Kraft corrugated fibreboard. This corrugated board consists of three components namely liner sheets, corrugated sheet (fluting) and adhesive (Fig. 12). The combination and properties of these components determine the strength of the carton. Packaging aims to increase the cushioning and damping of impact, compression and vibration forces. Proper design and implementation of package involves measuring and modelling of mechanical forces and the response of the packaging material and the biological tissues to loading. This problem is basically in the field of structural mechanics that studies the behaviour of solid materials, especially their motion and deformation under the action of forces, temperature changes, and other external or internal agents. Simultaneously, the effect of package design on the produce cooling rate and cooling uniformity and the accompanying energy requirements are also important performance requirements.

A packaging carton should have enough vent-holes to facilitate the thermal exchange between the produce and the cooling air. On the other hand, vent-holes cause reduction in the mechanical strength of the package. In a recent study by Han and Park (2007) finite element analysis (PEA) was used to predict the loss of compression strength due to vent and hand holes. The basic steps of applying this method is described below.

5.1.1. Basic concepts of FEA

FEA analysis basically follows a similar procedure as the CFD where the geometry for the structural analysis is first created with CAD programs, this is then discretised to several subdomains (finite elements) connected at nodes, called the mesh. After meshing, the constraints, loads, boundary condition and the material properties of the structure are defined.

5.1.2. Governing equations

The FEA process involves piecewise polynomial interpolation at each node of the structure generating a set of simultaneous algebraic equations that are associated with the elements in the mesh (Eq. (9)). The functions of all the elements are then assembled to form the governing algebraic equation that defines and represents the entire

Table 3
Summary of experimental validation data from some studies that used computational fluid dynamics.

Measured variable	Model	Experimental	Reference(s)
Seven-eighths cooling time of pomegranate fruit precooled with polyliner	11.5 h	9.5 h	Ambaw et al. (2017)
Seven-eighths cooling time of pomegranate fruit precooled without polyliner	4.2 h	3.5 h	Ambaw et al. (2017)
Airflow rate through palletised apple; fitted polynomial coefficients A and B in $\Delta P = AV^2 + BV$	A = 792.83, B = 7.5488	A = 791.39, B = 10.725	Han et al. (2018)
Temperature in the centre of the oranges in row 3 of stacked "Supervent" containers after 2 hours of cooling	14 °C	13 °C	Defraeye et al. (2013)
Moisture content of corrugated fibreboard stored at 1 °C after 29 hours	18 g $100g^{-1}$	17 g $100g^{-1}$	Berry et al. (2019)
Pressure loss coefficient μ/k during forced air cooling of polyliner pomegranate fruit in carton	30.88 Pa s m^{-2}	36.88 Pa s m^{-2}	Ambaw et al. (2017)
Airflow rate through palletised apple; fitted polynomial coefficients ξ_1 and ξ_2 in $\Delta P = \xi_1 G^2 + \xi_2 G$	ξ_1 = 12.310, ξ_2 = 29.277	ξ_1 = 12.286, ξ_2 = 42.258	Han et al. (2018)

structure (global matrix equation) (Eq. (10) (Fadiji, Coetzee et al., 2018).

$$[K]_e\{u\}_e = \{f\}_e \tag{9}$$

$$[K]\{u\} = \{f\} \tag{10}$$

where, *[K]$_e$* is the elementary stiffness matrix, dependent on and determined by the geometry, element and material properties, *{u}$_e$* is the elementary displacement vector which defines the nodes motion under loading, *{f}$_e$* is the elementary force vector which defines the applied force on the element, *[K]* is the global stiffness matrix, *{u}* is the vector of the unknown nodal displacements (or temperature in thermal analysis) and *{f}* is the vector of the applied nodal forces (or heat flux in thermal analysis). An account of the commercial software packages used in previous food packaging was discussed by Fadiji, Coetzee et al. (2018), including ANSYS® (Fadiji, Ambaw et al., 2018, 2019; Han & Park, 2007), ABAQUS® (Hammou, Duong, Abbès, Makhlouf, & Guo, 2012), MS-NASTRAN® (Biancolini & Brutti, 2003; Fadiji et al., 2017) and MSC MARC® (Beex & Peerlings, 2009; Fadiji, Coetzee, Opara et al., 2016).

5.1.3. Model validation

Validation of the FEA results just like in CFD has to be performed experimentally, for example, performing box compression tests (Fadiji, Coetzee, Opara et al., 2016, 2019). The strength of the cartons is measured using the box compression test (BCT), in accordance with the ASTM D642 standard (ASTM, 2010). The cartons are preconditioned to the test environment and then compressed by a continuous motion platen until failure. Fig. 13 shows an illustration of the box compression tester.

Fadiji et al. (2019) found a good agreement (10 %) between the experimental and numerical compression strength results of apple cartons with different vent area (2 %, 4 %, and 8 %) and corrugated fibreboard grades (B, C, and BC flute boards). The authors reported a negative and almost linear relationship between strength and vent area of the cartons, and that this depended largely on the board grade, with BC-flute being the strongest board. Results were validated experimentally using box compression tester (M500-25CT, Testomatic, Rochdale, United Kingdom) (Fig. 13).

5.2. Notable findings

The use of FEA to study corrugated fibreboard cartons can be traced back as early as 1983 when Peterson (1983) studied the stress generated under 3-point loading of corrugated fibreboard where they found that the flute part of the corrugated fibreboard was the most critical component controlling the applied stress. Fadiji, Ambaw et al. (2018) used an experimentally validated FEA model to study the structural behaviour of corrugated fibreboard cartons with different vent-hole percentages subjected to a compression load. They found that the compression strength of the fibreboard was linearly affected by the fibreboard thickness and ventilation area of the corrugated fibreboard cartons. Table 5 summarises recent studies that used FEA and their key findings. For all these studies, model results were experimentally

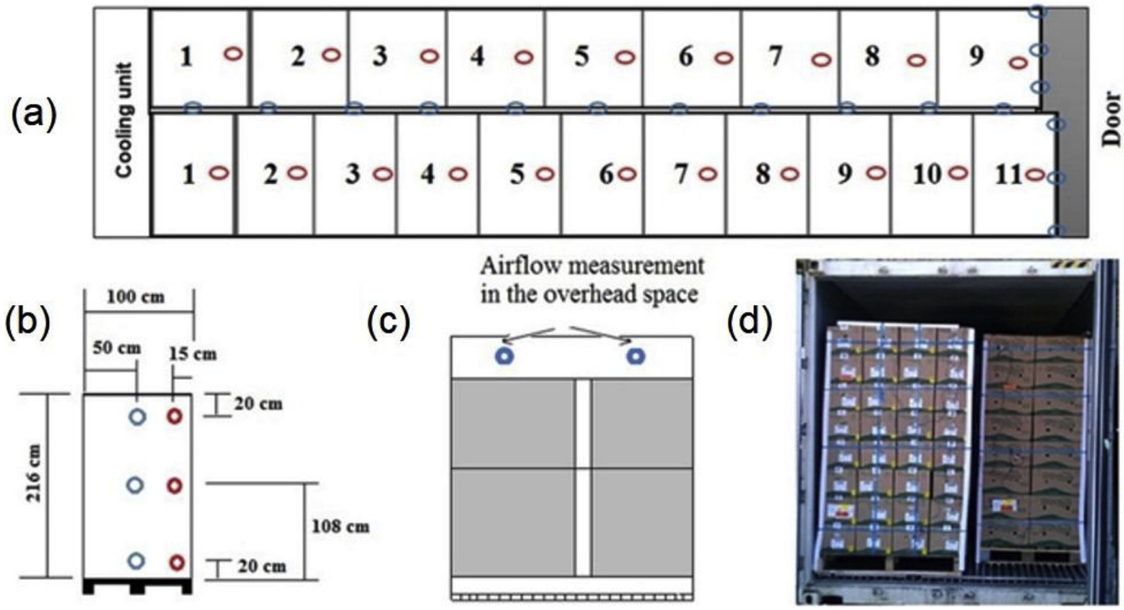

Fig. 10. Schematics of the position of pulp temperature sensors (red circle) and air velocity sensors (blue circle) in a fully packed reefer container: (a) top view, (b) side view of a pallet in a row, (c) overhead space, and (d) snapshot of a fully packed reefer with sensors (Getahun et al., 2017a).

Table 4
Examples of recent studies applying computational fluid dynamics (CFD) in analysis of corrugated fibreboard cartons used in the fruit industry.

Study	Fruit	Key findings	Reference
Airflow and heat transfer inside horticultural packaging system using 3-D CFD model	Citrus	Heterogeneous airflow and temperature distribution; reasonable increase in cooling rate was only recorded for increase in vent area up to 7 %	Delele, Ngcobo, Getahun et al., 2013a, b
Effect of table grape packaging and stacking on heat and mass transfer	Table grapes	Presence of carry bag increased 7/8 cooling time by 97.3 %, non-perforated liners reduced moisture loss but caused condensation in packages, stacking affected airflow, cooling and moisture transfer	Delele, Ngcobo, Opara et al. (2013)
Cooling performance of existing and new corrugated fibreboard cartons for citrus fruit	Citrus	New container designs showed significant improvement in cooling	Defraeye et al. (2013)
Cooling of citrus fruit during the long-haul marine transport	Citrus	Low airflow rates in reefers induced slower fruit cooling and caused heterogeneous cooling, gaps between pallets lead to airflow short circuiting lowering cooling rates	Defraeye, Cronjé, Verboven et al. (2015)
Multiparameter analysis of impact of vent-hole design and internal packages on apple cooling and airflow characteristics	Apples	Addition trays to existing commercial design increased ventilated energy consumption by 31 %, airflow was better distributed between fruit layers in two new proposed carton designs	Berry et al. (2016)
New parallel airflow system to improve cooling uniformity of forced-air precooled packaged strawberries	Strawberry	The new airflow system resulted in better cooling uniformity with average fruit temperature difference of 0.8 °C after 3 hours of cooling	Nalbandi, Seiiedlou, Ghasemzadeh, & Rangbar (2016)
Integral approach to evaluate cooling rate, cooling uniformity, energy efficiency and apple fruit quality in different ventilated package designs	Apples	Optimal cooling velocity for the studied packaging designs was $0.4-1\ \mathrm{m\ s^{-1}}$	Han et al. (2017)
Effect of package design on airflow and cooling characteristics of pomegranate fruit in corrugated fibreboard cartons	Pomegranates	Stacking orientation affected airflow, cooling rates and uniformity, plastic lining increased the cooling time by > 5 h	Ambaw et al. (2017)
Effect of vent-hole design on cooling and carton mechanical strength	Apples	Multi-vent carton design used 58 % less cooling energy and significantly improved cooling uniformity compared to commercial design	Berry et al. (2017)
Optimal cooling conditions and package design for forced air-cooling (FAC) of polylined produce	Kiwifruit	Package design that channelled air to slowest cooling packages reduced pressure drop and energy requirement of FAC process by 24 % and achieved better cooling uniformity	O'Sullivan et al. (2017)
Evaluate the cooling characteristics, moisture loss, and energy consumption during precooling of palletized apples	Apples	Mass loss in fruit is primarily influenced by cooling time rather than airflow rate, reasonable increase in cooling rate and uniformity was obtained with increase in airflow rate up to $2.3\ \mathrm{l\ s^{-1}\ kg^{-1}}$	Han et al. (2018)
Airflow inside T-bar and flat floor refrigerated shipping containers	Apples	The air exchange rate in the rear part of the reefers was $0.2\ \mathrm{m^3\ h^{-1}}$ and $0.6\ \mathrm{m^3\ h^{-1}}$ for the flat floor and T-bar floor, respectively, T-bar exhibited noticeable reduction in air recirculation and enhanced uniform vertical airflow	Getahun et al. (2018)
Absorption of moisture by corrugated fibreboard cartons during shipping	–	There is relatively low moisture content gradients in fibreboards through the stacked cartons under optimal shipping conditions, heat conduction from outside through the container wall significantly influenced spatial moisture gradients through the cartons	Berry et al. (2019)

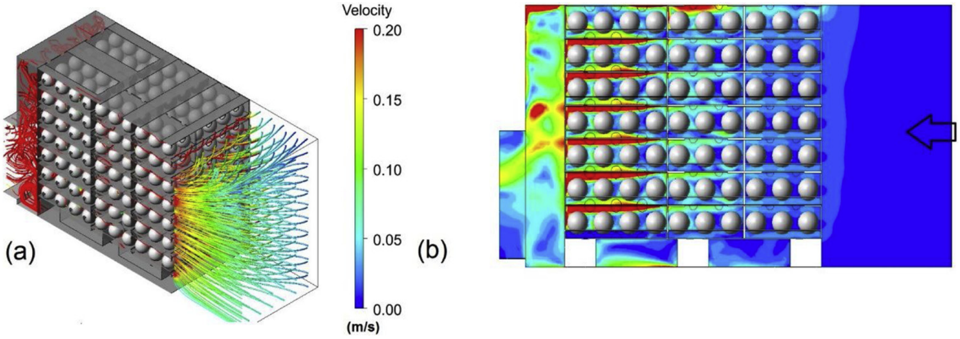

Fig. 11. Simulated streamlines of air velocity in stack of fruit (a), and (b) contours of velocity on vertical plane sectioning the fruit stacks (Ambaw et al., 2017).

validated before using the FEA models to simulate scenarios. However, FEA designers in the field of corrugated packaging have to cope with several inaccuracies due to a number of assumptions and approximations made owing to the complex structure and mechanical behaviour of corrugated fibreboard, as well as the complex linearity of paper material (Cheon & Kim, 2015; Fadiji, Coetzee et al., 2018). In more recent simulations, therefore, an equivalent orthotropic plate has been adopted in place of the complex corrugated fibreboard (Cheon & Kim, 2015). Combining numerical models like FEA and CFD in corrugated fibreboard studies coupled with experimental validation provides a more integrated investigation of the packaging and cold chain process of the fruit industry geared towards reduction of loses and energy efficiency.

6. Conclusion

Research studies on the design and performance evaluation of fresh fruit packaging has been steadily increasing in the last several decades. Specifically, the application of mathematical modelling technique is important in reducing time and saving costs that would have gone into

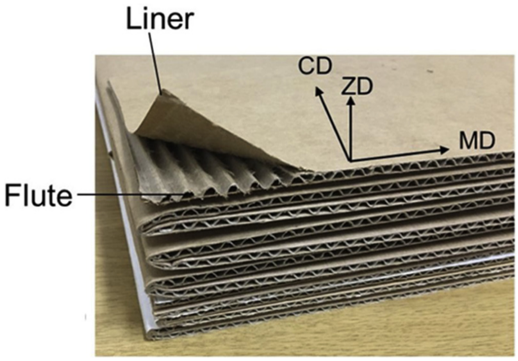

Fig. 12. Schematic showing the basic geometric structure of corrugated fibreboard (co-ordinates: ZD is the thickness direction, CD is the cross direction and MD is the machine direction.

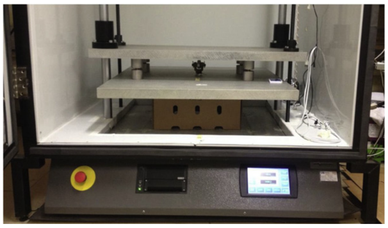

Fig. 13. Compression testing of the cartons with box compression tester.

experimental studies. Numerical modelling approaches closely follow the steadily growing power of computers which has eased the simulation and analysis of complex scenarios, for example, airflow and cooling patterns in stacked fruit in cold rooms or transit reefers.

The vent-holes on cartons are very important design aspects that is highlighted by many researchers. The focus was primarily on the number, shape or position of vent-holes and the total open area on the packaging walls and the effect of these design factors on the cooling rate and cooling uniformity of produce cold handling processes. Packaging should aim for maximum ventilation without compromising the mechanical integrity of the stacked produce during storage and transport.

Further, the merits and demerits of internal packages were emphasised by many researchers. The importance of a multiparameter approach that tests packaging with respect to all processes (airflow, cooling characteristics, strength, effect on fruit quality, and stacking requirements) was suggested by many researchers. The environmental impact of plastics in the food supply chains and the accompanying negative news in developed countries prompts the opening of grocery stores that renounce the use of disposable plastic packaging. Following this, studies to reduce or remove plastic from the fruit and vegetables supply chain is increasing.

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Table 5
Examples of recent studies applying finite element analysis in analysis of corrugated fibreboard cartons used in the fruit industry.

Study	Key findings	Reference
Buckling of corrugated fibreboard carton	Stiffness was low at the top and bottom corners of the package, stiffness was governed by the creases on the package, box compression strength prediction was 7.4 % lower than the experimental value for high quality Kraft corrugated fibreboard	Biancolini and Brutti (2003)
Modelling folding carton erection failure	The model predicted pattern of deformation of the carton during buckling, model could be used to study the effects of variation in material properties, pack properties and machine settings	Sirkett, Hicks, Berry, Mullineux, and Medland (2007)
Stress levels and distribution on corrugated fibreboard cartons with different vent-hole/hand-hole designs	Appropriate location and pattern of the hand holes were a short distance from the centre to the top of the boxes, vertical oblong-shaped vent-holes symmetrically positioned within a certain extent of distance to the right and left of the centre was most appropriate for vent-holes	Han and Park (2007)
Drop tests of corrugated fibreboard packaging containing different foam cushions	Corrugated fibreboard package with the corner foam cushions had more damping effect to the shock response of the packed product	Hammou et al. (2012)
Model stress and strain distribution on corrugated fibreboard boxes made with three types of waveform corrugated fluted medium	Boxes made with V-shaped and U-shaped corrugated fluted medium had good rigidity and good cushioning properties, respectively	Yuan, Xu, Zhang, & Xie (2013)
Compression strength of the corrugated fibreboard cartons with different vent-hole designs	There was a linear correlation between vent height and buckling load, rectangular vent-holes better retained package strength in comparison to circular vent holes, vent number, location and shape affected buckling load of corrugated fibreboard cartons	Fadiji, Coetzee, Opara et al. (2016)
Apple susceptibility to bruising during simulated transport in ventilated corrugated packaging	Bruise incidence and severity was affected by package design and vibration frequency, top layer fruit were more susceptible to bruising	Fadiji, Coetzee, Chen et al. (2016)
Mechanical properties of corrugated fibreboard under different environmental conditions	Modulus of elasticity reduced by 20–53 % at 0 °C 90 % RH compared to 23 °C 50 % RH for all studied paper grammages, modulus of elasticity was higher in the machine direction (MD) than other directions for all the paper grammages	Fadiji et al. (2017)
Behaviour of corrugated fibreboard cartons subjected to shocks	Drop height of the packed product was strongly related to the velocity change that products experience in transportation and handling	Luong et al. (2017)
Compression strength of different corrugated fibreboard carton designs with different vent-holes designs and fibreboard grades	There was a negative and almost linear relationship between compression strength and vent area, Packages with BC-flute and B-flute board grade had the highest and lowest compression strength, respectively, functionality of package vent-hole design is tied strongly to the properties of the chosen board grade, short side of corrugated fibreboard cartons is more resistant to buckling	Fadiji et al. (2019)

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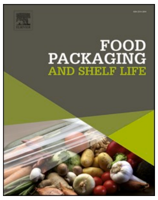

Erratum regarding missing Conflict of Interest statements in previously published articles

Declaration of Competing Interest statements were not included in published version of the following articles that appeared in previous issues of *Food Packaging and Shelf Life*. Hence, the authors of the below articles were contacted after publication to request a Declaration of Interest statement:

"Poly(vinyl) alcohol crosslinked composite packaging film containing gold nanoparticles on shelf life extension of banana: 24 (2020) 100463] https://doi.org/10.1016/j.fpsl.2020.100463.

"Novel ABTS-dot-blot method for the assessment of antioxidant properties of food packaging" [Food Packaging and Shelf Life: 24 (2020) 100478] https://doi.org/10.1016/j.fpsl.2019.100478.

"Production and characterization of chitosan-gelatin nanofibers by nozzle-less electrospinning and their application to enhance edible film's properties" [Food Packaging and Shelf Life: 22 (2019) 284] https://doi.org/10.1016/j.fpsl.2018.11.01.

"Advances in design and performance evaluation of fresh fruit ventilated distribution packaging: A review" [Food Packaging and Shelf Life: 24 (2020) 100472] https://doi.org/10.1016/j.fpsl.2020.100472.

"The effects of varying gas concentrations and exposure times on colour stability and shelf-life of vacuum packaged beef steaks subjected to carbon monoxide pretreatment" [Food Packaging and Shelf Life: 18 (2018) 230–237] https://doi.org/10.1016/j.fpsl.2018.10.010.

"Characterization of antioxidant properties of soy bean protein-based films with Cortex Phellodendri extract in extending the shelf life of lipid" [Food Packaging and Shelf Life: 22 (2020) 100413] https://doi.org/10.1016/j.fpsl.2019.100413.

"Comparison of water vapour transmission rates of monolayer films determined by water vapour sorption and permeation experiments" [Food Packaging and Shelf Life: 17 (2018) 80–84] https://doi.org/10.1016/j.fpsl.2018.06.004.

"Development of food packaging materials containing calcium hydroxide and porous medium with carbon dioxide-adsorptive function" [Food Packaging and Shelf Life: 21 (2019) 100352] https://doi.org/10.1016/j.fpsl.2019.100352.

"Ready-to-eat cherry tomatoes: Passive modified atmosphere packaging conditions for shelf life extension" [Food Packaging and Shelf Life: 22 (2019) 100407] https://doi.org/10.1016/j.fpsl.2019.100407.

"In situ synthesis of multi-functional gelatin/resorcinol/silver nanoparticles composite films" [Food Packaging and Shelf Life: 22 (2019) 100399] https://doi.org/10.1016/j.fpsl.2019.100399.

"Development of antimicrobial LDPE/Cu nanocomposite food packaging film for extended shelf life of peda:" [Food Packaging and Shelf Life 16 (2018) 211–219] https://doi.org/10.1016/j.fpsl.2018.04.001.

"The effect of fat contents and conditions of contact in actual use on styrene monomer migrated from general-purpose polystyrene into selected fatty dishes and beverage" [Food Packaging and Shelf Life: 21 (2019) 100363] https://doi.org/10.1016/j.fpsl.2019.100363.

"Enhanced properties of silver carp surimi-based edible films incorporated with pomegranate peel and grape seed extracts under acidic condition" [Food Packaging and Shelf Life 19 (2019) 114–120] https://doi.org/10.1016/j.fpsl.2018.12.001.

"Cinnamon nanophytosomes embedded electrospun nanofiber: Its effects on microbial quality and shelf-life of shrimp as a novel packaging" [Food Packaging and Shelf Life: 21 (2019) 100349] https://doi.org/10.1016/j.fpsl.2019.100349.

"Tough aliphatic-aromatic copolyester and chicken egg white flexible biopolymer blend with bacteriostatic effects" [Food Packaging and Shelf Life 15 (2018) 9–16] https://doi.org/10.1016/j.fpsl.2018.12.001.

DOIs of original article: https://doi.org/10.1016/j.fpsl.2020.100472, https://doi.org/10.1016/j.fpsl.2018.10.010, https://doi.org/10.1016/j.fpsl.2019.100352, https://doi.org/10.1016/j.fpsl.2019.100363, https://doi.org/10.1016/j.fpsl.2020.100463, https://doi.org/10.1016/j.fpsl.2018.04.001, https://doi.org/10.1016/j.fpsl.2020.100478, https://doi.org/10.1016/j.fpsl.2019.100461, https://doi.org/10.1016/j.fpsl.2019.100413, https://doi.org/10.1016/j.fpsl.2019.100399, https://doi.org/10.1016/j.fpsl.2018.06.004, https://doi.org/10.1016/j.fpsl.2019.100407, https://doi.org/10.1016/j.fpsl.2018.12.001, https://doi.org/10.1016/j.fpsl.2019.100349, https://doi.org/10.1016/j.fpsl.2018.01.001, https://doi.org/10.1016/j.fpsl.2019.100387.

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