

Fernando, Indika; Fei, Jiangang; Stanley, Roger; Enshaei, Hossein; Eyles, Alieta

Article

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Quality deterioration of bananas in the post-harvest supply chain- an empirical study

Quality
deterioration
of bananas

135

Indika Fernando and Jiangang Fei
*Australian Maritime College, University of Tasmania,
Launceston, Australia*
Roger Stanley
*Tasmanian Institute of Agriculture (TIA),
University of Tasmania Tasmanian, Hobart, Australia*
Hossein Enshaei
*Australian Maritime College, University of Tasmania,
Launceston, Australia, and*
Alieta Eyles
*Tasmanian Institute of Agriculture (TIA),
University of Tasmania Tasmanian, Hobart, Australia*

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Abstract

Purpose – Quality deterioration in bananas along the supply chain (SC) due to cosmetic damage has been a persistent challenge in Australia. The purpose of this paper is to investigate the incidence of cosmetic defects in bananas across the post-harvest SC and determining the causes of the diminished fruit quality at the retail stores.

Design/methodology/approach – The study quantified the level of cosmetic damage in 243 cartons of *Cavendish* bananas across three post-harvest SCs in Australia from pack houses to retail stores and identified the risk factors for cosmetic defects.

Findings – The level of cosmetic damage progressively increased from pack house (1.3 per cent) to distribution centre (DC) (9.0 per cent) and retail (13.3 per cent) and was significantly influenced by package height and pallet positioning during transit. Abrasion damage in ripened bananas was influenced by the travel distance between DC and retail store. The study also revealed a range of risk factors contributing to the observed damage including weakened paperboard cartons due to high moisture absorption during the ripening process.

Research limitations/implications – This study only investigated damage incidence in three post-harvest banana SCs in Australia and the damage assessments were confined to packaged bananas.

Originality/value – This study assessed the quality of bananas along the entire post-harvest SC from farm gate to retail store. The study provided knowledge of the extent of the quality defects, when and where the damage occurred and demonstrated the underlying factors for damage along the SC. This will enable the development of practical interventions to improve the quality and minimize wastage of bananas in the retail markets.

Keywords Quality, Supply chain, Banana, Mechanical damage, Post-harvest

Paper type Research paper

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1. Introduction

Fruit quality can be defined as the degree to which a set of inherent characteristics fulfils consumers' expectations (Schröder, 2003). The quality of fresh produce can be related to both intrinsic and extrinsic attributes (Morris and Kamarulzaman, 2014) including sensory properties, nutritive value, chemical constituents, mechanical properties, safety, functional properties and freedom from defects (Abbott, 1999). The visual appearance which is arguably the most important factor in determining fruit quality can be affected by cosmetic defects caused by mechanical damage (Kader, 2002; Opara and Pathare, 2014). Mechanical damage is caused by one or more force loadings acting on produce, resulting in injury to the exocarp of fruit (Li and Thomas, 2014).

The causes for mechanical damage in fruits may present throughout the post-harvest supply chain (SC). Damage in fruits may first occur during the harvesting and packing operations (Mvumi *et al.*, 2016; Manetto *et al.*, 2017; Arazuri *et al.*, 2010). Fruit damage can be also associated with impacts during handling and compression from packaging (Van Zeebroeck *et al.*, 2007), and with compression between fruits or between fruits and the container (Zwiggelaar *et al.*, 1996; Dadzie and Orchard, 1997; Van Zeebroeck *et al.*, 2007). Studies on various fresh fruits have shown that vibration in-transit has been a predominate cause of fruit damage (Barchi *et al.*, 2002; Vursavus and Ozguven, 2004; Fernando *et al.*, 2018). It was further revealed that the extent of fruit damage can be influenced by the stack height of the package and the stacked position of the pallet during transport (Barchi *et al.*, 2002; Berardinelli *et al.*, 2005; Fernando *et al.*, 2018).

Bananas are an example of a major fruit crop where the effects of mechanical damage have a severe impact on the appearance quality of the fruit through causing brown to black discoloration of the skin. However, despite its economic importance as one of the staple fruit crops in the world (FAO, 2019), only few studies have examined the impact of post-harvest mechanical damage on the cosmetic quality of bananas. There are limited studies which investigated the quality deterioration in bananas across the post-harvest SC from the farm to the retail stores. Significant mechanical damage in bananas has been reported during farm and pack house operations (Mvumi *et al.*, 2016), due to improper packing of bananas (Ekanayake and Bandara, 2002; Hailu *et al.*, 2013), rough handling of packages and bunches (Dadzie and Orchard, 1997; Wasala *et al.*, 2014) and during distribution (Da Costa *et al.*, 2010). Studies of vibration-induced mechanical damage on bananas confirmed that vibration during transport may also cause significant cosmetic damage (More *et al.*, 2015; Wasala *et al.*, 2015).

Previous studies have shown that willingness of consumers to purchase bananas is highly driven by the visual appearance with the presence of cosmetic imperfections resulting in reduced consumer acceptance (White *et al.*, 2011; Ekman *et al.*, 2011). Bananas are the most sold supermarket produce in Australia with a farm gate value of AU\$600m in 2016–2017 (ABGC, 2016). Cosmetic damage is a major cause of wastage across the Australian banana SC. It was reported that wastage level in Australia ranges from 5 to 8 per cent of gross volume, valued at AU\$46–73m per annum and that this level was found higher than that of comparative international markets where the average wastage levels were less than 2 per cent of sales volume (Kitchener, 2015). Wastage across the SC and diminished perceived value in retail stores have been an ongoing problem to both banana growers and the retail industry in Australia (White *et al.*, 2011; Kitchener, 2015; Ekman *et al.*, 2011).

Major supermarket chains, which account for more than 74 per cent of the total banana sale in Australia (Day, 2018), have been under constant pressure to deliver “premium” quality bananas to consumers. Propelled by the industry need, a study was initiated by the by the Department of Primary Industries in Queensland to explore the quality deterioration of bananas. The study investigated the occurrence of damage in bananas

during distribution and the consumer perceptions of cosmetic damage (Ekman *et al.*, 2011). It concluded that cosmetic defects in bananas were associated with their perceived value and marketability. The main limitation in the study of Ekman *et al.* (2011) was the restricted sample size during the damage assessments across the SCs. Furthermore, the causes of damage and the risk factors for damage were not thoroughly investigated in the study and therefore a more boarder investigation was proposed.

In Australia, around 95 per cent of the total banana production is concentrated in the tropical region of Northern Queensland (ABGC, 2016), resulting in lengthy interstate SC down the continent to where the major metropolitan markets (i.e. Sydney, Brisbane and Melbourne) are located. The length of road transport could be an important factor leading to higher incidence of damage due to prolonged exposure to vibration. There are, however, only limited contemporary studies have attempted to determine the extent and causes of post-harvest damage that result in quality deterioration of bananas. Over 90 per cent of the commercially grown bananas in Australia are the *Cavendish* (ABGC, 2016). This study therefore examined the occurrence of cosmetic defects in *Cavendish* bananas along post-harvest SCs in Australia aiming to:

- evaluate the progression of mechanical damage in bananas along the post-harvest SC from pack houses to retail stores;
- determine how storage position of a package in a truck may affect the incidence of damage in green bananas during interstate transport and how distribution to retail stores further exacerbates this damage; and
- investigate and identify the major underlying risk factors affecting mechanical damage in bananas within each node of the post-harvest SCs.

2. Material and methods

This study used a combination of quantitative and qualitative approaches to quantify damage and to determine the causes of damage throughout the post-harvest SC from the farm gate to retail store. The selected post-harvest SCs had four key nodes (N1–N4) and three main transit links between the nodes (Figure 1). Quality inspections were made along key inspection points (P1–P3) to quantify damages across the SCs. A field market visit and observation (FMVO) study was performed at each node (N1–N4) to determine potential risk factors for mechanical damage.

2.1 Quantitative evaluation of banana quality across the supply chain

Three SC originating from three farms (A, B and C) located in the Tully region of Northern Queensland in Australia were selected for the study (Figure 1). A total of 81 cartons comprising of “premium grade” (selected and packed as the highest grade) bananas were randomly selected and inspected (P1) at the three pack houses (A, B and C) (27 cartons at each pack house). The same cartons were tracked and re-inspected at the distribution centre (DC) (P2) and retail stores (P3), respectively. The premium bananas only had minor existing damage at the pack houses (P1) which made it possible to clearly detect the damage that occurred in transit and handling during the subsequent inspections along the SC (P2 and P3). For the quality inspection, the farm regions and pack houses were visited in June 2017, while the inspections in the central DC and retail stores were conducted from June to July 2017.

Three truck deliveries transported the inspected cartons (27 per delivery) from the three pack houses (i.e. one truck delivery from each pack house) to the central DC in Melbourne. The DC in Melbourne (which was located approximately 3,400 km by the road route from the growing regions) was specifically selected to assess the occurrence of damages in

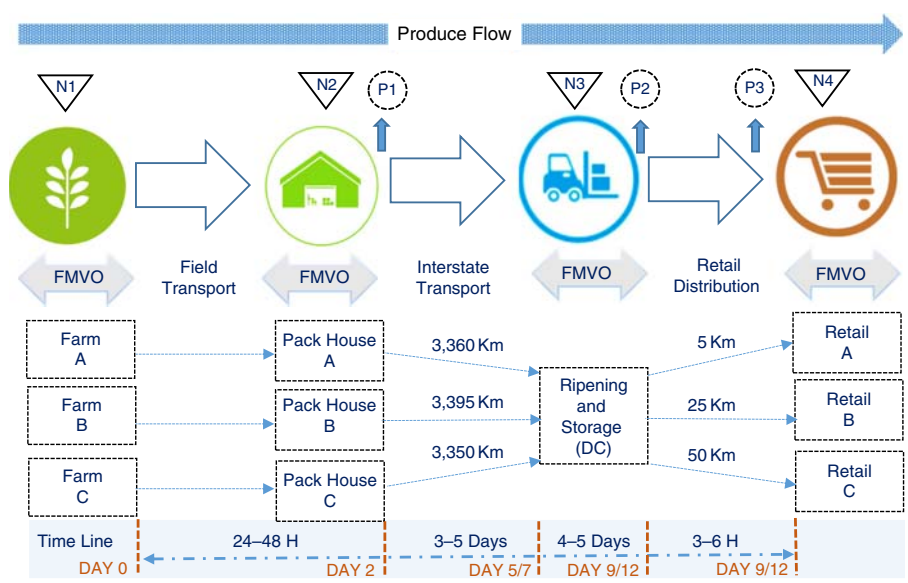
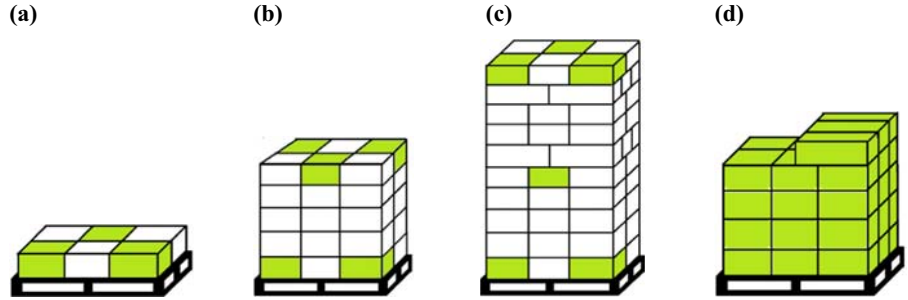


Figure 1. Key nodes (N1–N4) and inspection points (P1–P3) of the three post-harvest banana supply chains

bananas across the long-distance SCs. Each dual trailer truck was fully loaded with 22 pallets of bananas in the rear trailer and 10 pallets of bananas in the front trailer. The inspected packages in each pack house were evenly distributed amongst three pallets and loaded in the front, middle and rear positions of the rear trailer of each truck. On each of the three pallets, inspected packages were stacked in the first (bottom), fifth (middle) and the tenth (top) tier (Figure 2). The aim of this stacking method was to determine how the visual damage of bananas is influenced by the height of the package in a pallet and the position of the pallet on the trailer floor.

Upon arrival of the three consignments at the DC, green bananas were stored in a ripening chamber and gassed with ethylene (C_2H_4) under controlled temperature ($13-18^{\circ}C$) for a period of five days (Figure A1). All the sample packages were re-inspected after ripening (P2). As soon as the re-inspection was completed, the packages were distributed to three supermarket retail stores in Melbourne where the same packages were tracked and re-examined. The distance of the retail stores ranged from 5 to 50 km from the central DC in Melbourne (Figure 1). The packages for all three distribution trips (DC to retail) were stacked as partial stacks (Figure 2) and loaded to the rear position of each

Figure 2. Stacking pattern and position of the inspected packages stacked in Tier 1 (a), Tier 5 (b) and Tier 10 (c) from pack house to the DC and (d) the arrangement of the banana packages during the distribution from DC to retail



temperature-controlled (13–15°C) delivery truck. Each retail store received 27 packages of inspected bananas from the corresponding pack house as illustrated in Figure 1 (i.e. all inspected packages from pack house A to retail A, from pack house B to retail B, etc.). A total of 6,136 individual bananas of 1,424 clusters were inspected in this quality inspection study.

Visual quality assessments were made in accordance with the visual quality assessment chart adapted from Ekman *et al.* (2011). Three main types of cosmetic damages have been frequently identified in bananas (i.e. bruising, abrasion and neck injuries). Damage type and severity were evaluated based on a 0–4-point hedonic scale (0 – no damage; 1 – trace damage; 2 – slight damage; 3 – moderate damage; 4 – severe damage). A visual damage index (VDI) score (Equation (1)) was calculated for each package and the mean VDI was derived to represent the level of cosmetic damage at any given inspection point in the SC. The difference in mean VDI scores (Δ VDI) (Equation (2)) was calculated to determine incremental mechanical damage between any two inspection points. Mean Δ VDI score was used to compare levels of mechanical damage at different package-storage positions in the truck during interstate transport and to calculate the increment in damage levels during retail distribution. One-way analysis of variance and Turkey's Honest Significant Difference) test were performed for the mean VDI scores and Δ VDI score with the use of GraphPad® Prism 7 statistical analysis package (GraphPad Software, La Jolla, CA, USA):

$$\text{VDI}(\%) = (0.1 \times \text{Trace Damages}(\%) + 0.2 \times \text{Slight Damages}(\%) + 0.7 \times \text{Moderate Damages}(\%) + 1.0 \times \text{Severe Damages}(\%)), \quad (1)$$

$$\Delta \text{ VDI } (\%) = \text{VDI}_A(\%) - \text{VDI}_B(\%). \quad (2)$$

2.2 Qualitative assessment: structured observation

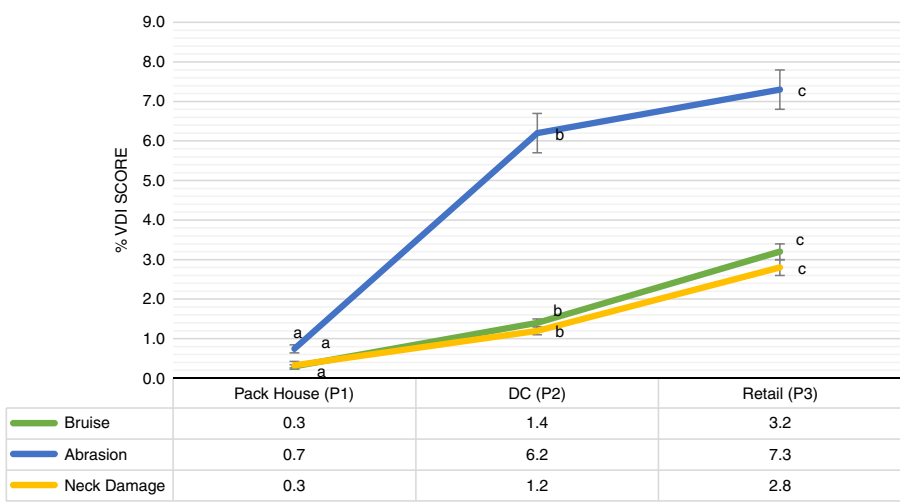
An FMVO (Mvumi *et al.*, 2016) study was performed to identify risk factors for cosmetic damage at each node of the SCs (N1–N4). It included the same three farms and pack houses, as in the quantitative study plus two additional farms and pack houses in far north Queensland; the central DC and the same three retail stores in the quantitative study plus two additional retail stores in Melbourne. The five farms and pack houses were visited separately for the FMVO study in January 2018 while the central DC and the five retail stores were visited from November 2017 to February 2018. The FMVO study was conducted by the structured observation method (Ellram, 1996; Boote and Mathews, 1999) with the use of a checklist (Appendix 2) that was developed based on the preliminary field visits and literature on post-harvest losses in bananas (Ekman *et al.*, 2011; White *et al.*, 2011; Dadzie and Orchard, 1997; Da Costa *et al.*, 2010; Mvumi *et al.*, 2016).

3. Results

3.1 Quantitative assessment of cosmetic damage

3.1.1 Progression of cosmetic damage. The VDI scores for bruising, abrasion and neck injury damage levels were significantly different ($p < 0.01$) at each inspection point, indicating that the cosmetic defects were incremental and progressive from pack house to retail store. At pack house (P1), premium bananas had a very low VDI score (< 1 per cent) for each damage type (Figure 3). At retail (P3), these bananas exhibited 7.3 per cent VDI score for abrasion damage followed by bruising damage (3.2 per cent) and neck damage (2.8 per cent). Most of the reported neck breaks at the retail stores were found to be moderate to severe.

Figure 3.
Progression of
mechanical
damages from pack
house to retail



Notes: a, b and c denote significantly different results ($p < 0.01$) in each damage category

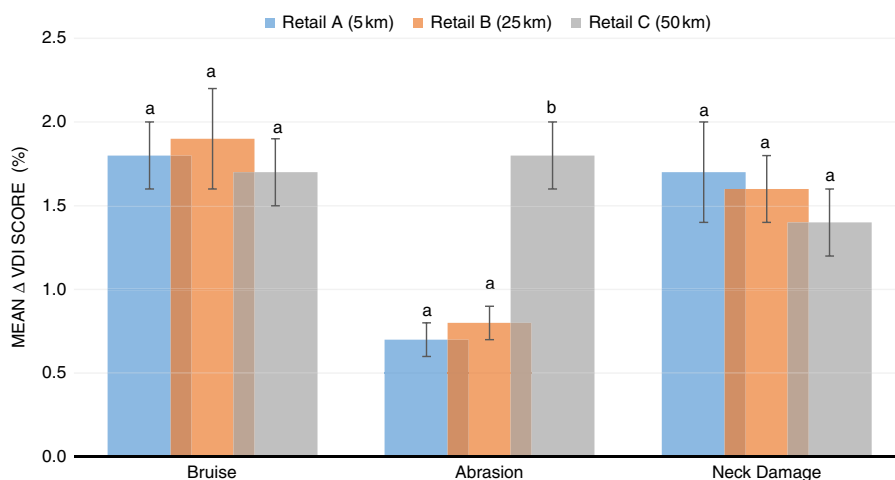
3.1.2 Effect of package position on mechanical damage during long-distance transport. Bruising in the bottom and middle tiers was significantly higher ($p < 0.05$) compared to the top tier (Figure 4) during the interstate transport of packaged bananas from the growing region to the metropolitan DC. Similarly, neck damage was also significantly higher ($p < 0.05$) in the bottom and middle tiers of each pallet compared to the top tiers. A significantly higher ($p < 0.05$) level of abrasion damage was found in the top and bottom tiers compared to the middle tiers. The higher Δ VDI score for abrasion damage in the top and bottom tiers of the pallets was mostly attributed to fruit rub damage.

3.1.3 Effect of transport distance on mechanical damage (DC to retail store). Progression of mechanical damage during the last-leg or the last-mile distribution of ripened bananas from the DC to three different retail stores is given in Figure 5. Abrasion damage of

Figure 4.
 Δ VDI scores in
different package-
storage positions in
the truck during the
interstate transport



Notes: a, b and c denote significantly different results ($p < 0.05$) in each damage category



Notes: a and b denote significantly different results ($p < 0.01$) in each damage category

Figure 5.
Increment of
mechanical damages
(Δ VDI Score) during
the distribution to
three retails from DC

Retail C (50 km) was significantly ($p < 0.05$) higher than Retail A (5 km) and Retail B (25 km). The major contribution for this escalation was the frequent presence of damages caused by rubbing (i.e. blackened rub and scuffing) in ripened bananas. However, there was no significant difference in other damage types (i.e. bruising and neck damage). These damages in the ripened bananas may not necessarily be attributed to the travel distance, but influenced by other causes such as compression during storage and shocks during handling of the packages.

3.2 FMVO study: risk factors affecting mechanical damage







Risk factors affecting mechanical damage, identified during FMVO, were categorized into incidental factors and prevalent factors. Incidental factors are the risks (incidents) that may occur infrequently in the SC, but when they occur, there is a great risk of mechanical damage. For example, accidentally dropping a package while handling can be considered as an incidental (not regular) risk factor. However, the probability of occurrence of such incidental risks is not negligible but minimal compared to other recurrent risks in the SC.

Prevalent factors are the prevailing (regular and recurrent) conditions (or operations) in the SC, which have a degree of risk for mechanical damage. An example would be harvesting or field transport of bunches which are recurrent (regular) operations in the SC. The probability of damage occurrence can be a function of many underlying sub-factors including the skill and the knowledge of the workers, diligence and care at handling, speed and urgency of the operation and the damage preventive mechanisms in place. Prevalent risk factors identified during the FMVO are summarized in Table I. Although rough handling of bunches and packages across the SC can be a significant risk for cosmetic damage in bananas (Dadzie and Orchard, 1997), assessment of human factors relating to mechanical damage was not under the scope of this study.

4. Discussion: risk factors for damage in the post-harvest supply chain

The extent of visual defects arising from mechanical damage along the SC was found to be cumulative, leading to an overall deterioration of banana quality at the retail end. This is consistent with previous studies on bananas which suggested that the cosmetic defects showed an increasing trend along the SC (Maia *et al.*, 2008; Ekman *et al.*, 2011). The most

Table I.
Summary of the prevalent risk factors identified by FMVO as causing mechanical damage in bananas in the post-harvest SC

 <p>Harvesting and Field Transport</p> <ul style="list-style-type: none">• Lack of cushioning during (manual) harvesting• Rough and muddy field tracks• Damaged or misplaced cushioning in field trailers• Unsecured bunches during field transport	 <p>Pack House Operation</p> <ul style="list-style-type: none">• Manual cutting and splitting of clusters• Rough (worn out) conveyer belts• Level drops and obstacles in conveyers• Over-filling/under-filling of cartons• Improper use of liners• Misaligned stacking of packages during palletizing
 <p>Ripening and Storage</p> <ul style="list-style-type: none">• Exposure of packages to high relative humidity (RH)• Weakening and failure of the cartons at high RH• Collapsing of the pallets (due to improper stacking)	 <p>Transport (Interstate and DC to Retail)</p> <ul style="list-style-type: none">• Vibration Transmissibility• Location of the pallet on the trailer of the truck• Height of the package in a stacked pallet• Unsecured pallets
 <p>DC Storage and Dispatch</p> <ul style="list-style-type: none">• Forklift and Layer-Picker handling• Order consolidation• Unstable and unsecured pallets• Misaligned packages in pallets	 <p>Retail</p> <ul style="list-style-type: none">• Improper storage• Unpacking of packages• Lack of cushioning on shelves• Over-stacking the shelves

frequent damage identified during the interstate transport was abrasion, which was significantly ($p < 0.05$) influenced by the package position on a pallet. In addition, the last-mile of the SC had a disproportionate impact on banana quality despite the short distance during distribution from the DC to retail stores. The distance of the retail store exhibited a significant ($p < 0.05$) association with the quality of bananas as the packages received by the store located in the farthest distance from the DC showed increased abrasion damage (rub and scuffing) possibly caused by the exposure to vibration and handling of packages.

As illustrated by Figures 3–5, mainly three types of damages (i.e. bruising, neck injuries and abrasion) occurred in bananas and several types of abrasion damages (i.e. scar, scuffing, fruit rub and blackened rub) were revealed at different stages along the SCs. The results of this research are discussed in Sections 4.1 and 4.2 with regard to the findings of the FMVO study to understand the causes of damage in each stage of the post-harvest SCs. Section 4.1 discusses the risk factors in farms and pack houses, while Section 4.2 further elaborates the potential causes of different types of damage to bananas from the farm gate to the retail store which involved multiple stages of handling and transport.

4.1 Mechanical damage on farm and in pack house

The FMVO revealed that most of the discarded bananas at the pack houses had moderate to severe scar injuries (Plate 2). These scar damages may have occurred during field operations or can be attributed to pre-harvest factors (Dadzie and Orchard, 1997; Mvumi *et al.*, 2016). FMVO further revealed that the most critical causes for fruit damage in the early stages of the SC occurred during the field transport of banana bunches. Severe scar damage in the exocarp of the fruit could occur due to rubbing (friction) of bananas against rigid contacting surfaces. For instance, scars may occur due to friction when bunches rub against the rigid trailer during the field transport from plantation to pack house. The damages can be severe when the cushions on the trailers are contaminated with sand, or when the cushions of the tractor trailers are displaced or damaged (Plate 1). Most of the fruits with these severe damages have been discarded at the pack house. Fruits with trace of slight damages are packed into separate cartons for markets selling second (lower and cheaper) grades of fruit (Plate 2). Both these discard and downgrade operations result in reduced financial returns

for the banana industry and increase on-farm wastage. Pack house rejection was as high as 10–30 per cent of the crop production in banana farms in Australia as highlighted in a previous study by White *et al.* (2011).

Minimizing the incidence of mechanical damage on farm and at the pack house is important for reducing wastage of edible bananas due to cosmetic imperfections. Improving field transport conditions, proper bunch management and careful handling of bunches and clusters have shown to be integral in reducing quality defects in bananas (Dadzie and Orchard, 1997; Mvumi *et al.*, 2016; Macheke *et al.*, 2013). Minor “wet” scars were also detected during the quality inspections at the pack houses (Plate 2). These wet scars can be attributed to the handling of clusters within the pack houses. However, it was found that these minor scar damages were less severe and the incidence highly varied amongst the pack houses.

The optimum and careful packing of bananas into the corrugated cartons (i.e. the packing operation) is critical for ensuring the fruit quality throughout the SC. In addition, proper use of liners and the skill of the fruit packers can be integral in preventing mechanical damage (Ekman *et al.*, 2011; Macheke *et al.*, 2013; Dadzie and Orchard, 1997). Setting appropriate packing rate targets for fruit packers and providing structured training to maintain optimum filling of packages would reduce the risk of cosmetic damage caused by under- or over-filling of packages (Dadzie and Orchard, 1997) during subsequent transport and handling.



Notes: (a) Sand and dirt on the trailer cushion; (b) damaged cushioning on the trailers

Plate 1.
Risk factors affecting
mechanical damage in
bananas in the farm



Notes: (a) Fruit with severe abrasion (scar) injury being removed from the packing line; (b) bananas mostly with scar injuries to be sold for secondary production; (c) a fresh minor scar (wet) injury detected at the pack house

Plate 2.
Bananas with scar
injuries detected
during the
packing process

4.2 Mechanical damage in bananas along the SC

Despite the much shorter distance and transport duration, the overall Δ VDI score from DC to retail (≤ 50 km) was 4.5 per cent, while the same for pack house to DC (approx. 3,400 km) was 7.5 per cent. This signifies that over 30 per cent of the overall damage occurred from DC to retail during the last-mile distribution of ripened bananas. This can be due to the increased susceptibility of ripe bananas to damage than unripe bananas (Yuwana, 1997; Bugaud *et al.*, 2014; Dadzie and Orchard, 1997). Ripening is associated with decreasing peel thickness and reducing fruit firmness (Banks *et al.*, 1991; Banks and Joseph, 1991; Soltani *et al.*, 2010; Fernandes *et al.*, 1979). The rapid increment in damage level in the latter part of the SC may also be due to compression bruising that incurred during the earlier stages becoming more apparent with the ripening of bananas (Chukwu *et al.*, 1998).

4.2.1 *Bruise damage in bananas.* Bruise damage was higher between the DC and retail (1.8 per cent) compared to the pack house and DC (1.1 per cent). It was found that packages stacked in the middle and bottom tiers of the pallet during the interstate transport sustained increased bruise damage (Figure 4). Bruising is caused by impact and compression forces acting on bananas (Dadzie and Orchard, 1997; Del Aguila *et al.*, 2010; Banks and Joseph, 1991; Banks *et al.*, 1991). Compression bruising can be caused by variable pressure on the fruit surface exerted from an adjacent fruit, or from the container holding the fruit (Dadzie and Orchard, 1997). Bruising may also occur when the weight of the load is sustained by the produce in overfilled cartons rather than by the container (Vigneault *et al.*, 2009). Overfilled packages can be associated with mechanical damage in bananas during transport and handling (Dadzie and Orchard, 1997) and increase the risk of bruising caused by top load compression.

The current weight of a standard packaged banana carton in Australia is 15 kg (580 L \times 380 W \times 180 H mm). An additional weight (< 1 kg) is usually packed into the cartons to compensate for possible weight shrinkage during distribution due to factors such as water evaporation and loss of fruit turgidity (Banks and Joseph, 1991). However, overfilled packages with bananas extending out of the top of the package (Plate 3) will support part of the load from the fruit rather than by the corner posts of the corrugated box (as intended). It was evident during the quality inspections that the overfilled packages in the bottom and middle tiers were more susceptible to bruise damage. This can be due to the fruits supporting a significant part of the load in the lower tiers of the pallet.

Bananas are ripened in temperature-controlled (sealed) ripening chambers for several days depending on the desired stage of ripeness. The high relative humidity (RH) of 90–95 per cent (Figure A1) within the ripening environment can weaken the structural integrity of the corrugated paperboard cartons. The strength of a corrugated paperboard



Plate 3.
Over-filled packages
and weakened
banana cartons

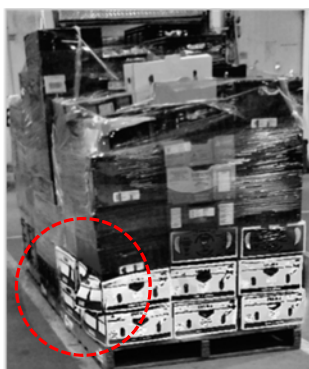
Notes: (a) Over-filled package with bananas in the top layer casting above the corner posts of a package; (b) a carton with weakened structural integrity due to moisture absorption (exposure to high RH)

carton can be reduced by 52 per cent when the moisture content is increased from 7.7 to 16 per cent (Zhang *et al.*, 2011). A corrugated paperboard carton held at 90 per cent RH equilibrium for a short exposure period may lose up to 60 per cent of its original strength (Vigneault *et al.*, 2009). This can lead to packaging failure (Plate 3) exposing the palletized fruit to increased mechanical stresses (Pathare and Opara, 2014). The overall weakening of the corrugated paperboard cartons in the bottom tiers of the pallet may lead to pallet collapse during the distribution (Figure 6). This can escalate the bruise susceptibility of bananas especially in the middle and top tiers of the pallet, where the effect of top load compression can be significant.

At DC, banana cartons are usually stacked in the bottom tier of a consolidated pallet (mix pallet) together with other produce that has been packed in different cartons for distribution to retail stores. Banana packages with higher weight and usually in higher volumes (compared to other produce) are most likely stacked on the bottom tiers (of the consolidated pallet) to stabilize the pallet. It was revealed during the FMVO, that rigid reusable plastic crates (RPC) were often stacked on top of already weakened banana corrugated paperboard packages (Figure 6) during distribution. Stacking rigid RPC on top of a weakened carton may excessively compress packages with ripen bananas on the bottom tiers. This could contribute significantly to the development of bruising and other types of mechanical damage including blackened rub and neck injuries in ripened bananas.

Corrugated paperboard cartons have a critical role in protecting the contents along the SC. The strength of the carton is a major criteria in determining the protective performance of a package (Pålsson and Hellström, 2016). Therefore, further investigation is necessary to determine the failure mechanisms of corrugated paperboard cartons under high RH conditions, subjected to top load compression. Prevention of the carton failure will be important to minimizing bruise damage in packaged bananas caused by package compression, especially in the latter part of the SC.

4.2.2 Neck damage in bananas. It was found that the extent of existing neck injuries detected in the pack house increased significantly at the DC especially in the middle and bottom tiers of the pallet (Figure 4). This could be due to the dynamic compression forces on middle and bottom tier packages caused by transient shocks during transport. The increment in neck injuries during the retail distribution was similar across the three retail stores signifying that the neck damage in ripened bananas can be largely attributed to the storage and handling of the packages rather than the transport distance.



Note: The areas with brand names/trademarks of the cartons have been shaded

Figure 6.
Package failure in a
consolidated pallet

Neck injuries were frequently found in the top layer of bananas inside the package followed by the second layer (Plate 4) and were minimal in the bottom layer. Despite the much shorter transport distance from DC to retail store, neck damage increment was greater (1.6 per cent) in this last-leg compared to the increment between pack house and DC (0.9 per cent). This signifies that the majority (57 per cent) of the neck injuries occurred during the retail distribution. Therefore, to minimize neck injuries in ripened bananas, extra care is needed when handling packages with compromised carton strength (i.e. after the ripening), especially during pallet consolidation and handling at the retail stores.

4.2.3 *Abrasion damage (scars, fruit rub, blackened rub and scuffing) in bananas.* The most frequently observed damage in bananas along the SC was abrasion (Figure 3), primarily caused by friction between fruit and other contacting surfaces. Abrasion damage can occur at any stage of the SC (Maia *et al.*, 2008) and become instantly visible on bananas (Chukwu *et al.*, 1998; Del Aguila *et al.*, 2010). Abrasion can be present in the form of scars, rubbing (fruit rub and blackened rub) and scuffing in bananas.

4.2.3.1 *Fruit (transport) rub.* The increment of abrasion damage in the top and bottom tiers of the pallet in transit from the pack houses to the DC was mostly related to fruit rubs (Plate 4). This can be attributed to the exposure of packages to vibration. As shown in previous studies on various fruits, the intensity and time of exposure to vibration will determine the severity of damage (Vursavus and Ozguven, 2004). Previous research has indicated that road roughness (Soleimani and Ahmadi, 2015), suspension characteristics of trucks (Timm *et al.*, 1996; Ishikawa *et al.*, 2009), vibration frequency and transmissibility (Vursavus and Ozguven, 2004; Fernando *et al.*, 2018) were all critical factors in fruit damage caused by vibration in transit. Other researchers have also shown that the position of the package on the truck floor and the height of the package in a stacked column on a pallet influences the level of damage in variety of fruits during transit (Vursavus and Ozguven, 2004; Barchi *et al.*, 2002; Berardinelli *et al.*, 2005; Slaughter *et al.*, 1998).

Similarly, fruit rub damage in bananas can also be attributed to the vibration transmissibility as well as the freedom of movement of fruits within a package (Slaughter *et al.*, 1998). During interstate transport, the relative movement of bananas may have been

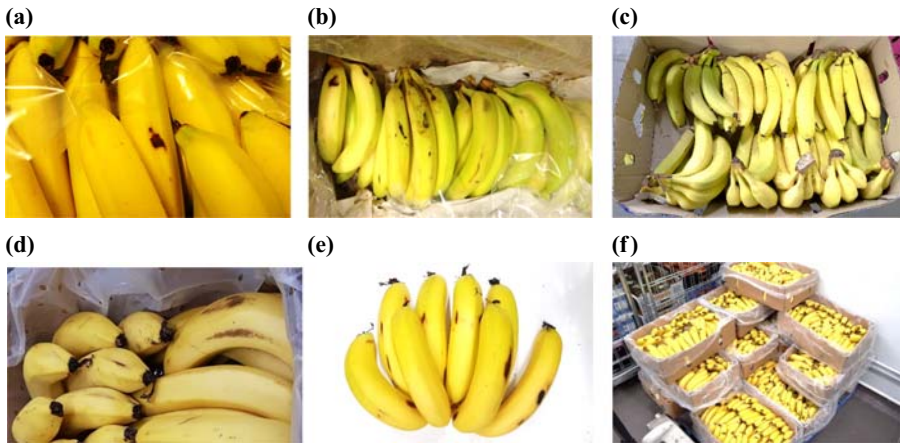


Plate 4.
Different types of
cosmetic defects
in bananas

Notes: (a) Scar damage (tip rub) as the liner is misplaced; (b) scars (crown rub) and bruising in the first layer of bananas inside the package; (c) neck injuries found in the top layer of bananas inside the package; (d) scuffing caused by liner rub; (e) cluster with severe fruit rub; (f) cross-stacked banana packages with lids removed for air-cooling

restricted by the weight of the packages stacked on middle tiers, resulting in reduced rub marks. In contrast, the packages on top tiers had no such constraint for relative movement and exhibited increased rub marks possibly attributed to excessive vibration. However, despite restrictions for relative movement of fruit on the bottom tier packages, increased rub damages were also exhibited. This was possibly due to the higher level of vibration transmissibility to the bottom tiers during transport. More research is needed to examine the vibration transmissibility and resonance characteristics in a stacked column of banana cartons and variations in damage levels up the column to further understand the mechanism of rubbing in bananas caused by vibration excitation.

4.2.3.2 Scuffing and blackened rub. Abrasion damage, particularly blackened rub and scuffing, increased from DC to retail stores (Figure 5). Blackened rub damages can be caused by the contact of bananas with the lid of the carton and rubbing of the lid on the top edges of the fruit, creating damage on the edges of bananas (Plate 4). Corrugated packages can exhibit base sagging (curvature of the bottom panel) (Niskanen, 2012) due to the concentration of weight at the centre of the package (Figure 7). Base sagging can be also aggravated by the moisture absorption in cartons during the ripening that may result in decreasing structural strength. The reverse effect of base sagging may also occur when the packages are over-filled leading to blackened rubs due to the brushing of the lid on bananas. Both these scenarios were found to be associated with blacked rub and scuffing in bananas caused by the rubbing of the corrugated lid against the top layer of fruits.

Blackened rubs and compression bruising were observed in cross-stacked packages with open lids for air-cooling in retail stores. Damages occurred as the packages were resting directly on the fruit instead of the corner posts (Plate 4). Blackened rubs can also develop during shelf replenishment and by repetitive handling of clusters by consumers. As revealed during the FMVO study, shelves with hard surfaces constructed with wood or plastic have an increased risk of rubbing against the edges of the fruit. Retail shelves constructed with hard surfaces need to be covered with adequate protective cushioning to minimize on-shelf damage. To minimize unnecessary rehandling and shuffling of the clusters by consumers (seeking clusters with desired characteristics), the retail shelves could be arranged in a way that clusters with the same number of fingers and ripeness level are placed in different segments on the shelves (with the possible indication on the weight range of the clusters). Alternatively, the clusters could be individually packaged in clear plastic to minimize the occurrence of rub damage on shelves. However, this needs to be considered with respect to the additional cost of cluster packaging.

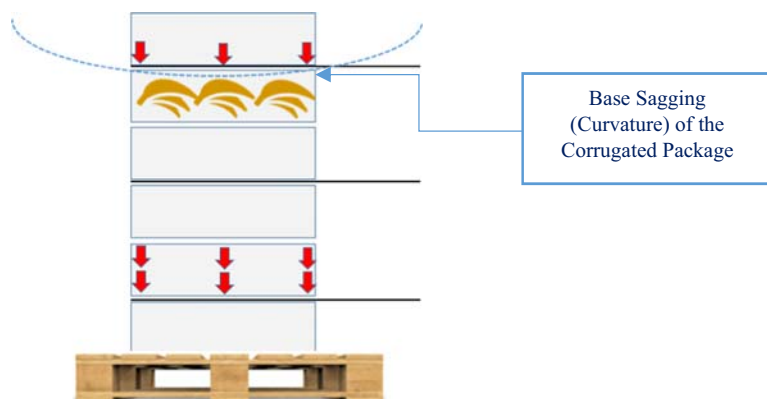


Figure 7.
Base sagging in
banana packages due
to the concentrated
weight at the centre of
the package

4.2.3.3 Scar damage. As discussed in Section 4.1, the most severe scar damages occurred during the field operations on the farm. Since much of the fruit with severe to moderate scar damage was removed during grading and sorting processes at the pack houses, only a marginal level of minor scars was detected on selected premium fruit during the quality inspection at the pack houses. In the subsequent quality inspections, only a minimum level of scar damage was found in packaged bananas throughout the SCs. These were observed to be mostly caused by the rubbing of sharp edges of banana crowns and tips especially when the plastic liners were not correctly placed (Plate 4). Therefore, proper use of liners could be integral for eliminating the occurrence of scar damages in packaged bananas. Minimizing moderate to severe scar injuries in farms and pack houses will essentially require attention to securing bunches during field transport and improving the cushioning of the tractor trailers. This will be integral to minimize the substantial wastage of bananas on farms and pack houses as a result of the disconformity to high cosmetic quality standards (White *et al.*, 2011) imposed by the major retailers including the supermarket chains in Australia.

5. Implications and limitations of the study

This study evaluated the quality deterioration of bananas across the post-harvest SCs in Australia. The main factors affecting cosmetic damage were identified at each stage of the SC. Improving the field transport conditions and optimized packing is essential to reduce wastage levels caused by damage during the post-harvest operations. The importance of careful handling of packages especially in the last-mile distribution of bananas and the need to reducing damage caused by in-transit vibration was emphasized in this study. Evaluation of mechanical damage and knowledge on the risk factors discovered in this study will contribute to the development of remedial actions targeted at improving fruit quality and reducing wastage.

A limitation in this study was the use of a subjective visual damage assessment method, which may result in inconsistencies in damage evaluation. To reduce the inconsistencies, a large number of bananas (i.e. over 6,000 fingers at one location) were inspected and all the assessments across the SC were made by the same assessor. Due to the length of each road-based SC (i.e. over 3,000 km) and the associated costs, this study was limited to three post-harvest SCs in Australia. Quality assessment of bananas in a large number of commercial SCs may further strengthen this study. This study was only focussed on the road-based SCs as it is the only mode of commercial delivery of bananas in Australia. The quality of bananas and the damage susceptibility can also be affected by the seasonality which requires further investigation.

6. Conclusion

Quality deterioration in bananas is progressive across the SC, resulting in reduced fruit quality at the retail stores. Despite the shorter distance and duration in the last-mile distribution from DC to retail, quality deterioration was significant in ripened bananas. During the interstate transport of packaged bananas, upper tier packages in pallets exhibited increased fruit rub damage possibly caused by vibration in transit. Packages in middle and lower tiers showed increased neck injuries and bruising. Transport distance from the DC influenced the abrasion damage level in ripened bananas at the retail stores where the highest damage levels were found in the store located at the farthest distance from the DC.

Minimizing mechanical damage needs to start from farms and pack houses where severe scar damage resulted in significant on-farm wastage. Improving the field transport conditions is important in this regard and will significantly reduce severe damages in

bananas at the early stages of the SC. This study highlighted the importance of optimized packing to minimize damages associated with over-filling and under-filling. Exposure of packages to high RH during ripening weakened the structural integrity of the cartons, increasing the risk of damage during the distribution. Due to the increased susceptibility of damage in ripened fruit and compromised strength of the corrugated carton after the ripening, more emphasis on careful handling of packages is essential in the last-mile of the distribution chain. Further investigations are needed to characterise the abrasion damage in bananas caused by vibration transmissibility up a stacked column and to propose mechanisms to minimize fruit rub damage in the top and bottom tiers of a stacked pallet. More research on package failure mechanisms at elevated RH levels is also required to minimize package collapsing especially in the bottom and middle tiers of the pallets, causing mechanical damage in bananas attributed to top load compression.

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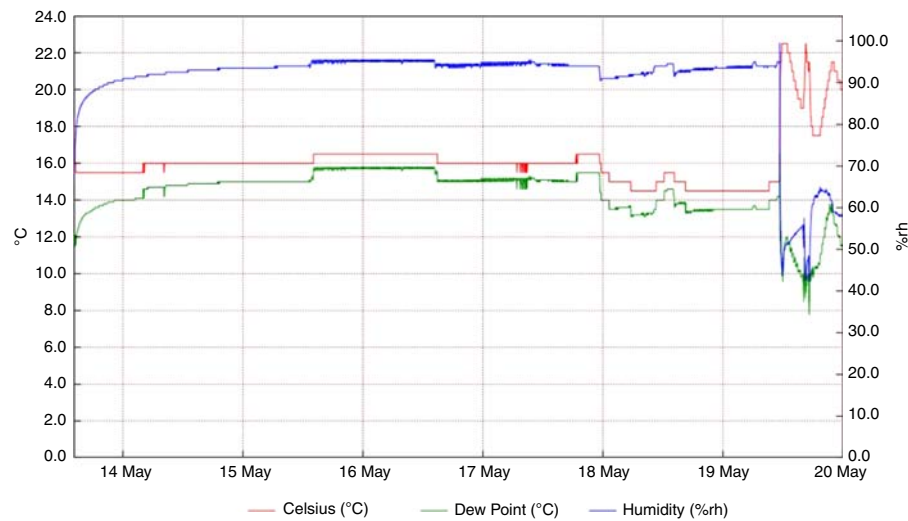
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(The Appendix follows overleaf.)

Figure A1.
Temperature (°C),
relative humidity (RH
per cent) and dew
point (°C) during the
ripening of bananas

Appendix 1. Atmospheric conditions during the ripening of bananas



Appendix 2. The checklist for structured observation study

Quality
deterioration
of bananas

153

Place		Date	
Premises		Time	

Conditions/Risk Factors	Status
Farm and Pack House	
Bunches are well covered protecting the fruit from rodents, insects and bird attacks?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
Notes:	
Cushions and adequate protective material are used when harvesting?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
Notes:	
Field tractors are well cushioned and covered to prevent possible mechanical damages to bunches during transport?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
Notes:	
Bunches are well secured to prevent bouncing and falling during field transport?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
Notes:	
Pack house workers wear protective gloves while handling the banana clusters?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
Notes:	
The conveyer belts have no level drops and rough surfaces that may harm bananas?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
Notes:	
The conveyer belts are free of any obstacles or sharp edges which might directly contact with the moving banana clusters?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
Notes:	
The depth of the water bath is sufficient so that the bananas may float in the water without making a contact with the moving conveyer belt underneath?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
Notes:	
The side walls of the water bath has no rough surfaces and no risk of abrasion injury to bananas?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
Notes:	
There is adequate level of lighting in banana sorting and the grading points?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
Notes:	
The conveyer belts are not moving too fast without giving adequate time for the workers in the grading /sorting points to examine the fruit and remove the defects?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
Notes:	
There are no significant level drops in the package conveyer belts which may result in significant drop impact on the packages?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
Notes:	
The banana pallets are stacked with proper alignment and the pallets are well secured to minimise vibration especially in the upper tiers?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
Notes:	
The pallets are pre-cooled before transport and the temperature is maintained between 13-15 °C?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
Notes:	
Conditions/ Risk Factors	Status
Distribution Centre	
At the arrival in the distribution centre (DC), the integrity of the pallets are maintained without visible deformation of the packages?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
Notes:	
The pallets are stacked straight and without any visible lean or imbalance in the stack which may have caused by compression of the packages in the lower tiers?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
Notes:	

<i>Notes:</i>	
The machinery such as forklifts/ layer pickers have adequate protective mechanisms to avoid compression of the fruit packages during handling operations?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
<i>Notes:</i>	
The pallets which are ready for dispatch to retail stores are stacked straight (corner to corner) without no visible imbalance or deformation\ compression of the banana packages?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
<i>Notes:</i>	
Banana packages are not exposed to harmful low temperatures (below 13 °C) which may result in chilling injury while stacked in the DC?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
<i>Notes:</i>	
Conditions/Risk Factors	Status

Retail Stores

At the arrival in the retail stores, the integrity of the pallets are maintained without visible deformation of the banana packages?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
<i>Notes:</i>	
The pallets are stacked straight and no visible lean or inclination which may cause by compression of the packages in the lower layers?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
<i>Notes:</i>	
Bananas are not exposed to harmful low temperatures (below 13 °C) which may result in chilling injury while stacked in the back of the store?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
<i>Notes:</i>	
Banana crates (packages) are stacked (corner-to- corner) in the back storage area without exposing the fruit to compression or impact damage?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
<i>Notes:</i>	
Retail shelves are not over stacked with banana clusters and the clusters are not stacked on top of each other?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
<i>Notes:</i>	
Retail shelves are adequately covered with cushioning material, free from rough edges and surfaces?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
<i>Notes:</i>	
Retail shelves are arranged in a way that the consumers can chose clusters with the desired number of fingers with minimal handling of fruit?	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
<i>Notes:</i>	

Conditions/Risk Factors	Status
--------------------------------	---------------

General

Are there any other identifiable conditions or factors which may cause mechanical damage (caused by mechanical forces such as compression, impact, abrasion or friction acting on fruits)	<input type="checkbox"/> YES <input type="checkbox"/> NO <input type="checkbox"/> NA.
<i>Notes:</i>	

Corresponding author

Indika Fernando can be contacted at: indika.fernando@utas.edu.au

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