Quality Deterioration of Packaged Fruits Caused by Mechanical Damage: A Study on 'Cavendish' Banana Supply Chain in Australia

MIGELMANDADIGE INDIKA FERNANDO BSc (Hons), MSCM, MILT (UK)

NATIONAL CENTRE FOR PORTS AND SHIPPING

AUSTRALIAN MARITIME COLLEGE

Submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

UNIVERSITY OF TASMANIA
February 2020

Declarations

Statement of Originality

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.

Statement of Ethical Conduct

The research associated with this thesis abides by the National Statement on Ethical Conduct in Human Research of Australia and is approved by the Social Sciences and Human Research Ethics Committee of the University of Tasmania with Ethics Reference number Ref: H0016997.

Authority of Access

This thesis is not to be made available for loan or copying for two years following the date this statement was signed. Following that time, the thesis may be made available for loan and limited copying and communication in accordance with the Copyright Act 1968.

Statement on Published Work

The publishers of the papers comprising Chapters 4 to Chapter 6 hold the copyright for that content and access to the material should be sought from the respective journals.

(Signed)
M. Indika Fernando.
24.02.2020

Statement of Co-Authorship

The following people contributed to the publication of work undertaken as part of this thesis:

Candidate (Author): Migelmandadige Indika Fernando[1]
Australian Maritime College
University of Tasmania

Co-Author 1: Associate. Professor Jiangang Fei[2]
Australian Maritime College
University of Tasmania

Co-Author 2: Professor Roger Stanley[3]
Tasmanian Institute of Agriculture
University of Tasmania

Co-Author 3: Dr. Hossein Enshaei
Australian Maritime College
University of Tasmania

Co-Author 4: Dr. Alieta Eyles[4]
Tasmanian Institute of Agriculture
University of Tasmania

Co-Author 5: Professor Vincent Rouillard
College of Engineering and Science
Victoria University

[1] Author is also affiliated with the ARC Training Centre for Innovative Horticultural Products (TCIHP)
[2] Co-Author is also affiliated with the ARC Training Centre for Innovative Horticultural Products (TCIHP)
[3] Co-Author is also affiliated with the ARC Training Centre for Innovative Horticultural Products (TCIHP)
[4] Co-Author is also affiliated with the ARC Training Centre for Innovative Horticultural Products (TCIHP)

Peer-reviewed Journal Articles (Published)

Fernando I, Fei J, Stanley R, Enshaei H. (2018) Measurement and evaluation of the effect of vibration on fruits in transit—Review. *Packaging Technology and Science*. 2018; 1–16. 723-738. ISSN 0894-3214 (2018) [Refereed Journal Article] (**PAPER A**) – (Located in Chapter 2)

Fernando, I., Fei, J., Stanley, R., Enshaei, H. and Eyles, A. (2019), Quality deterioration of bananas in the post-harvest supply chain- an empirical study, *Modern Supply Chain Research and Applications*, Vol. 1 No. 2, pp. 135-154. ISSN 2631-3871 (2019) [Refereed Journal Article] (**PAPER B**) – (Located in Chapter 4)

Fernando, I., Fei, J., & Stanley, R. (2019). Measurement and analysis of vibration and mechanical damage to bananas during long-distance interstate transport by multi-trailer road trains. *Postharvest Biology and Tech.*, *158*. Article 110977. ISSN 0925-5214 (2019) [Refereed Journal Article] (**PAPER C**) – (Located in Chapter 5)

Fernando, I., Fei, J., Stanley, R., & Rouillard, V. (2020). Evaluating packaging performance for bananas under simulated vibration. *Food Packaging and Shelf Life*, *23*, Article 100428. ISSN 2214-2894 (2020) [Refereed Journal Article] (**PAPER D**) – (Located in Chapter 6)

Peer-reviewed Conference Articles (Published)

Fernando, I and Fei, J and Stanley, R and Enshaei, H, Assessment and characterizing mechanical damage in packaged bananas in the post-harvest supply chain, MATEC Web of Conferences, 21-23 August 2019, Paris, France, pp. 1-10. ISSN 2261-236X (2019) [Refereed Conference Paper] (**PAPER E**) – (Located in Chapter 4)

Peer-reviewed Journal Articles (Under Review or Revision)

Fernando, I., Fei, J., Stanley, R., & Rouillard, V. (2020) Developing an accelerated vibration simulation test for packaged bananas**,** *Postharvest Biology and Technology*. [Journal Article under Revision] (**PAPER F**) - (Located in Chapter 5)

Fernando, I., Fei, J., Stanley, R., & Hossein E. (2020) Evaluation of packaging for the distribution of ripe bananas in consolidated pallets by temperature-controlled simulated vibration, *Packaging Technology and Science*. [Journal Article under Review] (**PAPER G**) -- (Located in Chapter 6)

Other Research Outputs (Research Project Presentations)

Research project presentation to *the Woolworths Produce Management Team*, Woolworths's Headquarters at *Bella Vista, Sydney* (May 2016).

Research project presentation to *the Senior Management of Costa Banana Exchange* at Woolworths State Distribution Centre, Mulgrave, Victoria (March 2017).

Project methodology demonstration at *AGFEST 2016 exhibition* at *Carrick, Tasmania* (May 2016).

Project methodology demonstration at *Australian Maritime College (AMC) Open day 2016* at Newnham Campus, University of Tasmania (August 2016).

Research project presentation at *ARC Training Centre for Innovative Horticultural Products Conference* at Sandy Bay, Hobart, Tasmania (February 2017).

Research project Presentation at *Orora Research and Development Packaging Laboratory* at Knoxfiled, Victoria (March 2018).

Research project presentation at *ARC Training Centre for Innovative Horticultural Products Conference* at Sandy Bay, Hobart, Tasmania (March 2019).

Other Research Outputs (Poster Presentations)

Research poster presentation at *Graduate Research Conference 2016* at the University of Tasmania, Sandy Bay, Hobart, Tasmania, (September 2016).

Research poster presentation at *Australian Banana Industry Congress (ABIC) 2017* at *Sheraton on the Park, Sydney* (June 2017).

Research poster presentation at *Tasmanian Freight & Logistics Forum 2019*, at the University of Tasmania, Newnham, Tasmania (June 2019).

Other Research Outputs (Electronic and Print Media)

Electronic Article (2016) – *'The bumpy road to perfect fruit',* A demonstration video and an article on the project featured in *the UTAS Research News page* in December 2016.

Newspaper Article (2019) – '*Scientist's Battle against bruised bananas'* in *Sunday Tasmanian Newspaper* on Sunday, the 24th of March 2019.

Magazine Article (2020)- *'Researcher Profile',* A featured article on the project featured in Australian Maritime College (AMC) *Above Board Magazine Summer 2019-20 Ed.* released in February 2020.

Table A: Author (Candidate) and Co-Author Contributions in the Publications

Contribution	Author (Candidate)	Co-Author 1	Co-Author 2	Co-Author 3	Co-Author 4	Co-Author 5
PAPER A*						
Conceptual Design	√	√	√	-	-	-
Methodology Development	√	√	-	-	-	-
Writing the Paper	√	-	-	-	-	-
Critically Reviewing and Proofing	√	√	√	√	-	-
Revising the Paper	√	√	√	-	-	-
PAPER B*						
Conceptual Design	√	√	√	√	-	-
Methodology Development	√	√	√	-	-	-
Experiments and Data Collection (Field\Laboratory)	√	-	-	-	-	-
Data Analysis	√	√	-	√	-	-
Writing the Paper	√	-	-	-	-	-
Critically Reviewing and Proofing	√	√	√	-	√	-
Revising the Paper	√	√	√	-	√	-
PAPER C*						
Conceptual Design	√	√	√	-	-	-
Methodology Development	√	√	√	-	-	-
Experiments and Data Collection (Field\Laboratory)	√	-	-	-	-	√
Data Analysis	√	-	-	-	-	√
Writing the Paper	√	-	-	-	-	-
Critically Reviewing and Proofing	√	√	√	-	-	-
Revising the Paper	√	√	√	-	-	-
PAPER D*						
Conceptual Design	√	√	-	-	-	√
Methodology Development	√	√	√	-	-	√
Experiments and Data Collection (Field\Laboratory)	√	-	-	-	-	-
Data Analysis	√	-	-	-	-	√
Writing the Paper	√	-	-	-	-	-
Critically Reviewing and Proofing	√	√	√	-	-	√
Revising the Paper	√	√	√	-	-	-
PAPER E*						
Conceptual Design	√	√	√	√	-	-
Methodology Development	√	√	√	√	-	√
Experiments and Data Collection (Field\Laboratory)	√	-	-	-	-	-
Data Analysis	√	-	-	√	-	-
Writing the Paper	√	-	-	-	-	-
Critically Reviewing and Proofing	√	√	√	-	-	-
Revising the Paper	√	√	√	-	-	-
PAPER F*						
Conceptual Design	√	√	√	√	-	√
Methodology Development	√	√	√	√	-	√
Experiments and Data Collection (Field\Laboratory)	√	-	-	-	-	-

Data Analysis	√	-	-	-	-	√
Writing the Paper	√	-	-	-	-	-
Critically Reviewing and Proofing	√	√	√	-	-	√
Revising the Paper	√	√	√	-	-	√
PAPER G*						
Conceptual Design	√	√	-	-	-	√
Methodology Development	√	√	√	-	-	-
Experiments and Data Collection (Field\Laboratory)	√	-	-	-	-	√
Data Analysis	√	-	-	-	-	√
Writing the Paper	√	-	-	-	-	-
Critically Reviewing and Proofing	√	√	√	-	-	-
Revising the Paper	√	√	√	-	-	-

**Papers are codified from Paper A to Paper G as indicated in 'Page. iv'. The candidate contributed significantly (i.e. more than 80% of the total workload) in each publication.*

We, the undersigned, endorse the above stated contribution of work undertaken for each of the published (or submitted) peer-reviewed manuscripts contributing to this thesis:

Candidate
M. Indika Fernando　　Date: 24/02/2020
National Centre of Ports and Shipping
Australian Maritime College
University of Tasmania

Signed:　　Date: 24/02/2020
Assoc. Prof. Jiangang Fei
Supervisor
National Centre of Ports and Shipping
Australian Maritime College
University of Tasmania

Signed:　　Date: 12/03/20
Assoc. Prof. Prashant
Head of School
National Centre of Ports and Shipping
Australian Maritime College
University of Tasmania

Dedication

"This work is dedicated to my two beloved Grand-fathers,

Mr. Jayasena Ariyawansa and Late Mr. Norman Fernando

for their loving kindness in molding myself

to be an ambitious human being"

Acknowledgement

It feels overwhelming to have come to this stage of submitting my doctoral thesis, after years of efforts, industry-based work, experiments, writing for journals and, travelling up and down some of the lengthiest produce supply chains in Australia. Doctoral research is inevitably a journey with a series of multifaceted challenges, and an unforgettable chapter in the life of an academic researcher. It is undoubtably true that, the tranquility or the difficulty of each chapter in our life is determined by the environment that we live in, and the people we associate, at least to a great extent. It is these bonding with the people and our surroundings makes this life worth living. The same phenomenon was expectedly true for this chapter in my odyssey. I was fortunate to become a researcher in one of the most quiet, yet enchanted corners of this world, Tasmania and, to be surrounded by many kindhearted people. It is my utmost wish and my obligation to remember the people who helped me throughout this journey and pay my sincere gratitude for their generosity and guidance.

First, I thank my parents Mr. and Mrs. Fernando for their years of dedication for educating me and made it possible for me to pursue a Doctoral degree in the field of my choice. I acknowledge their efforts to make my childhood journey as much fulfilling as possible and setting the stage to face any challenge in life with resilience and perseverance. I believe that their blessings have always been there with me, even though they have been living oceans apart. I must specially thank my beloved wife Mrs. Gayathri Perera who made many sacrifices on my behalf, including the decision to give up her career and relocating with me to Tasmania. She has been an admirer in my victory, and an empathetic friend in my defeat during this roller-coaster journey. I truly appreciate her patience and tolerating my stressful meltdowns which are part and partial of a researcher's life, including the failed experiments and rejected publications, however encouraging me to try even harder and better each time to reach for the success.

I was fortunate to have had a technically well-balanced and a kind supervisory team including my primary supervisor, Associate Professor Jiangang Fei and my co-supervisors Professor Roger Stanley and Dr. Hossein Enshaei. Their guidance and encouragement in my research journey have been enormous. I specially thank them for their flexibility and rapid responses during the tight submission deadlines and their extend support during the period I spent away from the University for my industry-based internship during the research project. I must extend my sincere gratitude to Prof. Vincent Rouillard for his unceasing contribution and guidance to this research. The designing of vibration simulation experiments and analysis of vibration data were made possible by his generosity that permitted me to use his state-of-art packaging technology laboratory in Victoria University in Melbourne. His advice in the designing of the experiments and the feedback on the publications resulted from his research have been invaluable.

I would also like to acknowledge the contribution of the laboratory technician Mr. Luke Simms, who helped me immensely with his knowledge and also with his muscles to stack the heavy banana packages on the simulator during the experiments. In addition, several staff members in the Australian Maritime College (AMC) including Assoc. Professor Peggy Chen, Dr. Hilary Peterman, Dr. Vera Zhang, Ms. Jackie Evans and Ms. Christine Veltman supported my career as a doctoral researcher. I would also like to extend my sincere gratitude towards Assoc. Professor Tom Ross, Dr. Alieta Eyles and Dr. Felicity Denham of the ARC Training Centre for Innovative Horticultural Products (TCIHP) and, to Dr. Ross Corkrey of the Tasmanian Institute of Agriculture (TIA) for their various contributions to this research project.

This project was initiated by the ARC TCIHP in consultation with the industry, where their support in various phases of this work was extraordinary. Firstly, my sincere thanks go to Mr. Mike Cruez and Mr. Bruce Andrews in Definium Technologies, Launceston for their support in the development of the technical infrastructure and several electronic devices for this project. I must specially acknowledge the much productive meetings, conversations, ideas, directions and guidance provided by the industry advisors of this project, Mr. Alex Doyle of Woolworths Pty. Ltd., and Mr. Matthew Oliver of Costa Banana Exchange. I would also like to thank Mr. Brice Lamarque, Mr. Simon Musgrove, and Mr. Eduardo Pena in Woolworths and also, Mr. Duskov Alfirevic and Mr. Richard Marsi in Costa Banana Exchange for their extended support in various stages of this research. I acknowledge the support of Mr. Jim Selway of Orora Packaging and his tremendous support in the latter part of this project that permitted us to use their temperature-controlled packaging research laboratory in Knoxfield, Victoria. The contribution of Mr. Micheal Long and Mr. Micheal Wedding at Orora, made it possible for me to conduct further research on packaging performance in their package testing laboratory.

Last but not least, I thank my friends who made me feel like a part of the closely knitted family in Launceston, far away from my original hometown. I am indebted to Mr. Thusita Fernando and Dr. Ruchira Fernando who always welcomed me and my wife at their home and treated us like family. I also thank Capt. Hirimbure Siriwardena and Dr. Biyanca Perera for their generosity and taking the initiative for the various community events that I had engaged with, as and whenever practicable. I thank Capt. Darrell Silva and Mrs. Alexandria Silva for all the entertaining times filled with moments of laughter, and for not skipping a single sunny day without playing Volleyball with us. It was the friends around who helped me to shift my focus away from research time to time, to ensure the work-life balance. I am fortunate to have had those times with the friends so that we could talk about anything that was happening in and around the world, except 'fruit damage, lengthy supply chains or perfect looking bananas'!

Note

This thesis has been presented as a coherent body of work containing multiple publications as per the guidelines of the University of Tasmania and thus, certain level of repetition among the chapters have been unavoidable.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ABGC	Australian Banana Growers Council
ASTM	American Society of Testing and Materials
ARC	Australian Research Council
BA	Bruise Area
BI	Bruise Index
BS	Bruise Sensitivity
BSR	Bruise Spot Ratio
BR	Bruise Resistance
BRC	Bruise Resistant Coefficient
BV	Bruise Volume
CPSD	Cross Power Spectral Density
DC	Distribution Centre
DPI	Department of Primary Industries
EBI	Equivalent Severe Bruise Index
IE	Impact Energy
FAO	Food and Agriculture Organization
FFT	Fast Fourier Transform
FDI	Fruit Damage Index
FMVO	Field Market Visits and Observation
GBS	General Bruise Susceptibility
GPS	Global Positioning System
GPSD	Global Power Spectral Density
HIA	Horticulture Innovation Australia
IS	Instrumented Sphere
ISTA	International Safe Transit Association
IRD	Impact Recording Devices
MDI	Mechanical Damage Index
MDOF	Multi Degrees of Freedom
PD	Power Density
PDF	Probability Density Function
PDME	Percentage Decay of the Modulus Elasticity
PPO	Polyphenol Oxidase

PSD	**Power Spectral Density**
RGB	**Red-Green-Blue**
RH	**Relative Humidity**
RMS	**Root Mean Square**
RPC	**Reusable Plastic Crate**
SBS	**Specific Bruise Susceptibility**
SC	**Supply Chain**
SDOF	**Single Degree of Freedom**
TA	**Titratable Acidity**
TSS	**Total Soluble Solids**
VDI	**Visual Damage Index**

ABSTRACT

Background: Banana (*Musa spp.*) is the largest horticultural product in Australia with a farm gate value of over AU$ 600 million in 2017. Quality deterioration of bananas in postharvest supply chains (SC) due to mechanical damage results in economic loss to both growers and retailers. However, the mechanism of damage occurrence in packaged bananas, and the underlying causes for deteriorated fruit quality, remains unclear. Over 95% of Australia's banana production is concentrated in the region of far North Queensland and the road supply chains to major markets can extend thousands of kilometres across the continent. This results in prolonged exposure of packaged bananas to transient shocks and vibration in-transit. This research aimed to identify the causes of mechanical damage along the post-harvest SC and to provide recommendations for mitigating the damage and improving the quality of bananas in the retail markets.

Methodology: To achieve the research objectives, mixed research strategies and methods were used. Field research was conducted to investigate the occurrence and extent of damage and identify risk factors along the post-harvest SC. The laboratory experiments were then followed to establish the causes and effects and, develop possible solutions to improve banana quality. Firstly, the mechanical damage levels in packaged bananas were assessed across the SC to understand the frequency and severity of different types of cosmetic defects in bananas. A field observation study along the post-harvest SC was conducted in parallel to damage assessment to identify the risk factors for mechanical damage. Secondly, the mechanisms of damage development in packaged bananas were characterized by using simulated vibration, top-load compression and drop-impact tests. Field vibration data collected during the interstate transport of bananas were used to develop vibration test profiles that were then used in laboratory-based simulation experiments. The performance of a range of packaging alternatives was then tested on the vibration simulator and the results were compared. The compression strength and base-sagging levels in different package types under high relative humidity (RH) ripening conditions were experimentally tested. Finally, the effectiveness of vacuum-tightening banana clusters to minimize mechanical damage caused by simulated vibration was also examined.

Findings: It was revealed that the increase in cosmetic defects caused by mechanical damage was progressive along the SC, resulting in deteriorated appearance quality of bananas in retail stores. Different mechanical stresses on packages such as top-load compression, vibration and drop-impact resulted in markedly different damages in bananas including bruising, abrasion and neck injuries. Both bruising and neck injuries occurred due to top-load compression and were influenced by the package position in a pallet. Neck injuries were also associated with the handling of packages during the last-mile distribution of ripe bananas. Abrasion damage was the most prominent type of damage in packaged bananas across the SC, mainly caused by vibration during transport. Mechanical damage caused by vibration was influenced by the intensity of the input vibration from the truck floor, the vibration transmissibility in a stacked pallet and the freedom of movement of packaged bananas inside the package. Simulated package testing revealed that both vibration transmissibility and the construction material of packaging influenced the mechanical damage levels in bananas. The structural integrity of the corrugated cartons was weakened with exacerbated base-sagging levels due to the moisture absorption in the high RH environment, causing mechanical damage in ripe bananas during the distribution to retail stores. The one-piece corrugated carton showed a better protective performance under simulated vibration, higher compression strength and reduced base-sagging levels compared to the widely used two-piece carton. Improvements in work practices including optimal packing of clusters in pack houses and stacking arrangements of packages in retail stores were highlighted to further minimize mechanical damage to bananas. Finally, column-stacking of packages in the pack houses and careful handling during the pallet consolidation in the distribution centre may further reduce damage to bananas during the 'last-mile' distribution.

Significance: This study made several contributions to the industry practice and field of research. Knowledge of the mechanisms of damage occurrence and the causes of damage along the SC resulted in several practicable interventions for the industry to improve the quality of bananas in the post-harvest SCs. The contributions to the field of research include the introduction of an objective damage estimation method, improved understanding of the vibration characteristics of multi-trailer road trains and the influence of vibration transmissibility in a column of stacked packages, on the development of mechanical damage in packaged fruits. The research developed a method of modelling damage levels in packaged bananas using vibration intensity and exposure duration. This method makes accelerated vibration simulation testing for package fruits realistic and reliable.

Limitations and Future Research: The study showed that the vibration damage can be reduced by vacuum-tightening of bananas. However, additional research is warranted to make it a commercially viable application. Solutions targeted at vibration dampening in pallets can be further researched to reduce the transmission of high-frequency vibration to the lower tiers in the pallet. The protective performance of one-piece carton can be improved through adjusting package height for optimal head-space to allow a quasi-static compression on the fruits while avoiding excessive compression caused by the transfer of weight from the top-tiers of the pallet. The enhancement of moisture-resistant can be considered to further strengthen the carton. RPCs in the current form were not suitable for packing bananas. However, further investigations on improved side-wall cushioning could be considered to

reduce the damage levels. Finally, the proposed advances to the industry practice for improving the quality of bananas require other socio-economic evaluations such as the financial feasibility and the environmental sustainability before the implementation of the proposed recommendations.

1. CHAPTER I

Introduction

This chapter provides the background of the study, the research questions and objectives, and the structure of the thesis followed by the contributions to the focal research fields.

CHAPTER I

Introduction

1.1. Research Background

Quality deterioration and wastage of fresh produce has been an area of interest to both industry and academic researchers for decades. This has been not only due to the costs associated but also because of the increased recent global attention on sustainable food production and distribution systems. The growth of global population and the finite availability of natural resources drive the need for efficient management of food systems. This escalation of population will require the global food production to be nearly doubled within the next 30 years and tripled in the next 50 years (Pillay & Tenkouano 2011). Propelled by the demand and the need for efficiency and improved sustainability, modern food supply chains (SC) require to be extremely quality centric than ever before, to meet the increasing demand for higher quality produce by consumers (Parfitt, Barthel & Macnaughton 2010). This requires the products to be free from defects. However, quality assurance of fresh produce can be challenging due to their very nature of being perishable, contaminable and susceptible to damage within the post-harvest SC.

Fruit quality can be defined as the degree to which a set of inherit characteristics of produce fulfills the requirement of the consumer (Schröder 2003). The 'perceived quality' is determined by the judgement of the consumer based on the excellence or superiority of the product (Zeithaml 1988). Fresh produce quality is a function of the sensory properties, nutritive value, chemical constituents, mechanical, functional properties and freedom from defects (Abbott 1999). Visual appearance is a crucial determinant of fruit quality and can be more important than the retail price (Gamble et al. 2010; Harker 2009) especially for the supermarket and hyper-market consumers. The appearance of fresh produce affects the consumer's choice (Kader 2002). The probability of acceptance or rejection of fruits, also influences potential repeat purchases (Jaeger et al. 2016). Therefore, the cosmetic appearance is a decisive criterion for consumer judgement of fruit quality in the retail markets. However, the quality can be compromised by cosmetic defects in fruits due to their susceptibility to damage.

Mechanical damage is a prominent cause of cosmetic defects in fruits. This can be caused by one or more force loadings acting on produce. It may result in mesocarp bruising or injury to the exocarp of fruits (Mazhar et al. 2015). Fruits are susceptible to mechanical injury during the harvesting and packing operations (Manetto et al. 2017). Fruit damage due to mechanical forces can be attributed to vibration during transport, compression and impact during the storage and handling (Fernando et al. 2018b; Opara & Pathare 2014). The exposure of packaged produce to mechanical hazards can be even more critical, when the supply chains extend to thousands of kilometers in transit and consisting of several SC nodes with multiple handling. Therefore, minimizing the hazards and risk factors for mechanical damage along the post-harvest SC is a critical factor for ensuring the appearance quality of fruits in the retail market.

Banana (Musa spp.) is one of the staple fruit crops in the world with an annual production of over 113 million tons in 2017 (FAO 2019). It is the most sold supermarket produce by volume in Australia and the largest horticultural industry in the State of Queensland with a farm-gate value of AU $ 600 million in 2016/17 (ABGC 2016). An estimated five million bananas are consumed daily in Australia (HIA 2019; Margetts 2014). Cavendish (AAA) is the most common cultivar (95%) of bananas in Australia (ABGC 2016) while the other varieties such as Lady Finger, Gold Finger, Ducasse, Red Dakkas and Plantains account for the rest of the cultivation. Bananas are also the most popular household purchase in Australia with 93% of Australian households purchasing an average of 19 kg of bananas annually (McCabe 2014). Previous studies showed that consumers' willingness to purchase bananas is driven by the visual quality and the presence of cosmetic imperfections, which results in reduced marketability of bananas (Ekman et al. 2011; White, Gallegos & Hundloe 2011). The reduced marketability of bananas and wastage across the SC has been a recurrent problem for both the banana and the retail industries in Australia.

The appearance quality of bananas in retail stores have been continuously challenged by mechanical damages. A previous study reported that nearly 10-30% of total banana production was discarded on the farms (White, Gallegos & Hundloe 2011) . The majority (78%) of the discarded fruit was graded-out of the packing lines due to cosmetic imperfections, resulting in an estimated loss of AU $26.9 million per annum to the growers (White, Gallegos & Hundloe 2011). The wastage of bananas across Australian retailers was estimated around 5-8% of the total volume sold (Kitchener 2015) and costing the industry AU $45.57 million to $ 72.91 million per annum. This percentage is much higher than the comparative international markets, where the average wastage level was reportedly less than 2% (Kitchener 2015). The presence of mechanical damages can affect the perceived value of bananas in retail stores. It was reported that consumer's demand for cosmetically perfect bananas caused nearly 30% of the Australian banana production to be unsold in 2017 (QDAFF 2017). The growing expectations of consumers for fresh produce with increased appearance quality compel the major supermarket chains in Australia to impose stringent quality standards for bananas (White, Gallegos & Hundloe 2011). Therefore, damage to bananas along the post-harvest SCs needs to be minimized to meet the increased quality expected by consumers.

Importing bananas into Australia has been restricted mainly due to quarantine regulations and the focus of the state governments to protect local banana growers (ABGC 2016). Therefore, all the bananas sold and consumed have been produced locally. In Australia, nearly 94% of the total banana production is located in the tropical regions of Northern Queensland due to the favorable climatic conditions (ABGC

2016). The main banana plantations are located in Tully, Johnstone, Babinda, Atherton, Mareeba, Innisfail and Gordonvale to Trinity region (QDAFF 2017). All the other growing regions dispersed around Australia (Fig.1.1) produce less than 6% of the total volume. However, the major markets are located in highly populated metropolitan areas such as Melbourne in Victoria, Sydney in New South Wales, thousands of kilometers away (Fig.1.1) from the main growing region in North Queensland. This results in extremely lengthy SCs down the continent to where the major markets are located. According to the Bureau of Statistics the states of New South Wales and Victoria account for more than 55% of the total population in Australia (ABS 2017) and, they were also reported as two of the three states with the highest population growth rate. The increased growth of these major markets means that the demand characteristics for bananas in these regions will be further intensified, creating more stress on the lengthy interstate SCs.

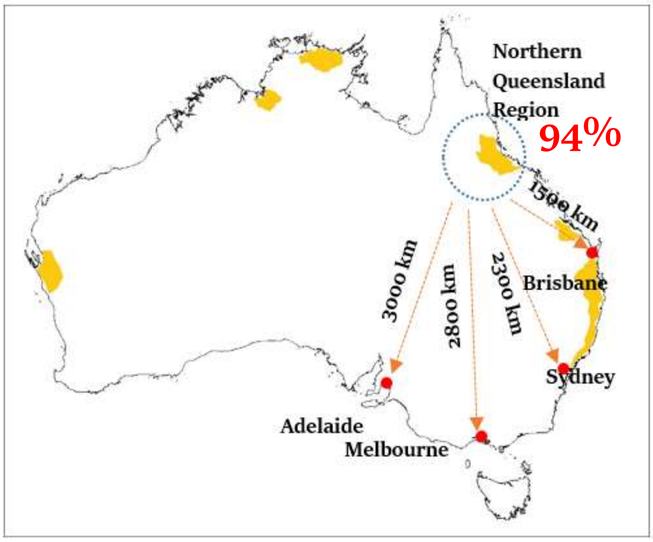


Figure 1.1 -Banana Growing Regions, Major Metropolitan Markets and the Road Transport Distances (Approx.) from the Main Production Region (94%) in Northern Queensland (Source: Author)

Exposure to hazardous vibration and shocks during the lengthy interstate road transport can be an inevitable risk factor for mechanical damage in packaged fruits. Previous studies reported that extended exposure to harmful vibration and shocks may result in mechanical damage in bananas (More et al. 2015; Mvumi, Matsikira & Mutambara 2016). Packaged bananas are ripened and delivered to retail stores from ripening facilities. The ripening facilities are usually located together or at close proximity to the centralized distribution centers (DC). The distribution of ripened bananas to the stores located around the DC can further escalate the existing damages. However, the main problem is that the damage occurred throughout the SC are only visible at the unpacking of the cartons at retail stores. This makes it difficult to determine what caused the damages or where and when they occurred along the SC? Consequently, there has been lack of understanding as to how the mechanical damage to bananas occur along the post-harvest SC. Without an improved understanding of what caused damages, minimizing the same to improving the appearance quality of bananas, had been a constant challenge to the industry.

1.2. Motivation for the Study

Despite its economic importance as one of the staple fruit crops in Australia, only limited studies have examined the impact of mechanical damage on the poor appearance quality of bananas. Previous industry surveys (i.e. BA10016, BA13015 and BA13019) by the Department of Primary Industries (DPI) in Queensland and Horticulture Innovation Australia (HIA) highlighted the need for an extensive study to address the quality deterioration of bananas in the post-harvest SCs in Australia. To address this issue, this research project was initiated in 2016 by the Australian Research Council (ARC) Industrial Transformational Training Centre for Innovative Horticultural Products (IHP) in collaboration with the industry partners, Woolworth Pty Ltd. and Costa Banana Exchange Pty Ltd.

Supermarkets account for 74.4% of total banana sales in Australia (Day 2018), and have been demanding for premium quality bananas with minimal cosmetic damage from the suppliers (White, Gallegos & Hundloe 2011). Woolworths is the largest supermarket chain in Australia in terms of market share with a total share of 32.2% in 2017 (Morgan 2018). Costa Banana Exchange is a major supplier to the three main supermarket chains (i.e. Woolworths, Coles and ALDI) in Australia. This study was conducted in partnership with Woolworths Pty. Ltd. and Costa Bananas Exchange. Initial communication with both industry collaborators revealed that quality deterioration along the SC is a major concern for bananas, however limited knowledge exists, especially with respect to the mechanisms of damage occurrence in packaged bananas. In addition, there is limited research on this domain specifically on how damage occur in packaged fruits along the post-harvest SC. Lack of knowledge on the causes of damage development was a key impediment for improving the fruit quality.

1.3. Post-harvest Banana Supply Chain in Australia

A typical banana SC in Australia consists of three major SC nodes which are, the supplier (i.e. farm and pack-house), distributor (i.e. DC and ripening centre), and the retailer (i.e. supermarket, produce grocers or sellers). Most of the growers own and operate both farms and pack houses while the distributor acts as the contractual agent for the major supermarket chains and coordinates the supply of bananas from different pack houses. Some distributors also operate ripening centers which are co-located with DCs or in close proximity to the DC to minimize logistical complications. Once bananas are ripened, the distributor or the contracted ripening agent transfers the required number of pallets to the centralized DCs. These are mostly owned and operated by the supermarket chains or third-party logistics providers. Figure 1.2 illustrates the key processes in a typical banana SC in Australia.

Bananas are harvested at mature green stage, approximately 13 weeks (in summer) to 20 weeks (winter) after the first appearance of the blossom. When bunches are matured enough, they are harvested and transported to the pack house by field tractors. Once bunches are received into the pack-house they are hydro-cooled and then thoroughly washed to remove dirt from the field. Washed bunches are then moved by a mechanized conveyer chain to a cutting bay where they are cut into large clusters. The clusters are then directly dipped to a water bath for cleaning. The larger clusters are then further separated into smaller clusters of 3-9 fingers. The washed clusters are arranged on the packing lines for grading and sorting. Defective or severely damaged bananas clusters, and fingers, are removed from the packing line. Packers will then pack bananas into the corrugated carton in three layers, up to a gross weight of 15.5-16.5 Kg. Conveyer belts then move the packages into a palletizing bay.

The packages are manually palletized in pack houses and arranged in eight to ten tiers on pallets. The pallets are either stretch taped or wrapped, or machine wrapped with stretch film to improve stabilization. Pallets are transferred into temperature-controlled forced-air cooling rooms where they are stored between 13-14°C until the arrival of a delivery truck. Depending on the order requirements, the pallets are either loaded to a single semi-trailer truck or a dual trailer truck known as a B-double or a Road Train. A single semi-trailer can be loaded with 22-24 pallets and a dual trailer truck (B-double) can be loaded with an additional 10-12 pallets. The trucks are temperature-controlled between 13-15 °C to avoid chilling injury or unexpected induction of ripening during the transit. Currently, road transport is the only mode of interstate transport of packaged bananas in Australia.

Bananas are received at a DC or a ripening facility after the interstate road trip from the growing regions, which can take from a few hours to several days in-transit, depending on the distance. The temperature of the fruit pulp is measured randomly in packages during the receiving operation to confirm that the fruits were transported within the prescribed temperature. Once received, the required number of pallets are queued for ripening. The ripening process takes from four to five days depending on the desired ripeness level. Australian supermarkets sell 'Cavendish' bananas in two ripeness levels (i.e. stage 4.5 and stage 5.5)(Ekman et al. 2011) as different consumers prefer different ripeness levels. After the ripening process the full pallets are transferred to an area where they are broken down to half-pallet loads or six to eight tier pallet loads depending on the demand requirements. The partial pallets are then transferred to a temporary storage area where the packages will be picked as required by 'order pickers'. Banana packages are then consolidated with other fresh produce packages in pallets designated to a given retail store. The consolidated pallets will be then loaded onto the distribution trucks to be delivered to the respective retail stores.

Figure 1.2: Typical Stages of a Post-Harvest Banana Value Chain in Australia

Retail stores receive the consolidated produce pallets from the DC. Unloaded pallets are then de-stacked as required and banana packages are kept with their lids open in the back of the retail storage to facilitate air-cooling. Air-cooling is important to increase the shelf life of bananas as increased temperature inside a closed package may induce ripening. Severely damaged or defective banana fingers and clusters are removed during the shelf replenishment at the retail store. Other banana clusters with minor injuries or no injuries are stacked on shelves for sale. Therefore, the damages that occur along the SC are undisclosed from the point of packing banana clusters into the corrugated cartons until the clusters are taken out form the packages for sale. This results in poor appearance quality of bananas on the shelves for sale and also wastage of damaged bananas at the retail stores.

1.4. Research Question and Objectives

The core research question and the objectives of this study were developed to address the knowledge gap on the damage occurrence in bananas in the post-harvest SC and the development of interventions for improving the fruit quality in the retail markets.

The overarching research question in this study is:

> **"What are the causes of mechanical damage in packaged bananas and what interventions can be recommended to improve the appearance quality within the post-harvest supply chain?"**

The main research question is divided to three derivative research questions as:

- Where and to what extent does the mechanical damage occur in packaged bananas along the SC?
- What factors cause different types of mechanical damage during the transport and handling of packaged bananas?
- How can mechanical damage in bananas be minimized and what interventions can be considered to improve the quality from the farm-gate to the retail store?

Based on the research questions, three research objectives were derived to define the focus and the aims of this study:

- To evaluate mechanical damage in packaged bananas and identify the causes of damage from the farm-gate to retail stores.
- To characterize the relationship between mechanical forces and the consequential mechanical damages in packaged bananas.
- To evaluate the protective performance of packaging for minimizing mechanical damage in bananas and recommend potential interventions for improving banana quality in the SC.

1.5. Thesis Structure

From the review of literature and previous industry survey reports, a problem statement was developed for this study which is 'The presence of different types of mechanical damage in bananas results in poor appearance quality at the retail stores.' Limited industry surveys on the post-harvest banana SCs in Australia (Ekman et al. 2011; Kitchener 2015) provided little understanding of the causes and mechanisms of quality deterioration in packaged bananas. Therefore, the specific causes of damage along the SC were not apparent in the initial stage of the study. Consequently, an empirical industry investigation along the SC was necessary to develop a broader problem definition and to identifying the areas for further research. This empirical study also provided a thorough understanding of the status, extent and the level of severity of the problem. The organization and the inter-connection of the thesis chapters are provided in Fig. 1.3.

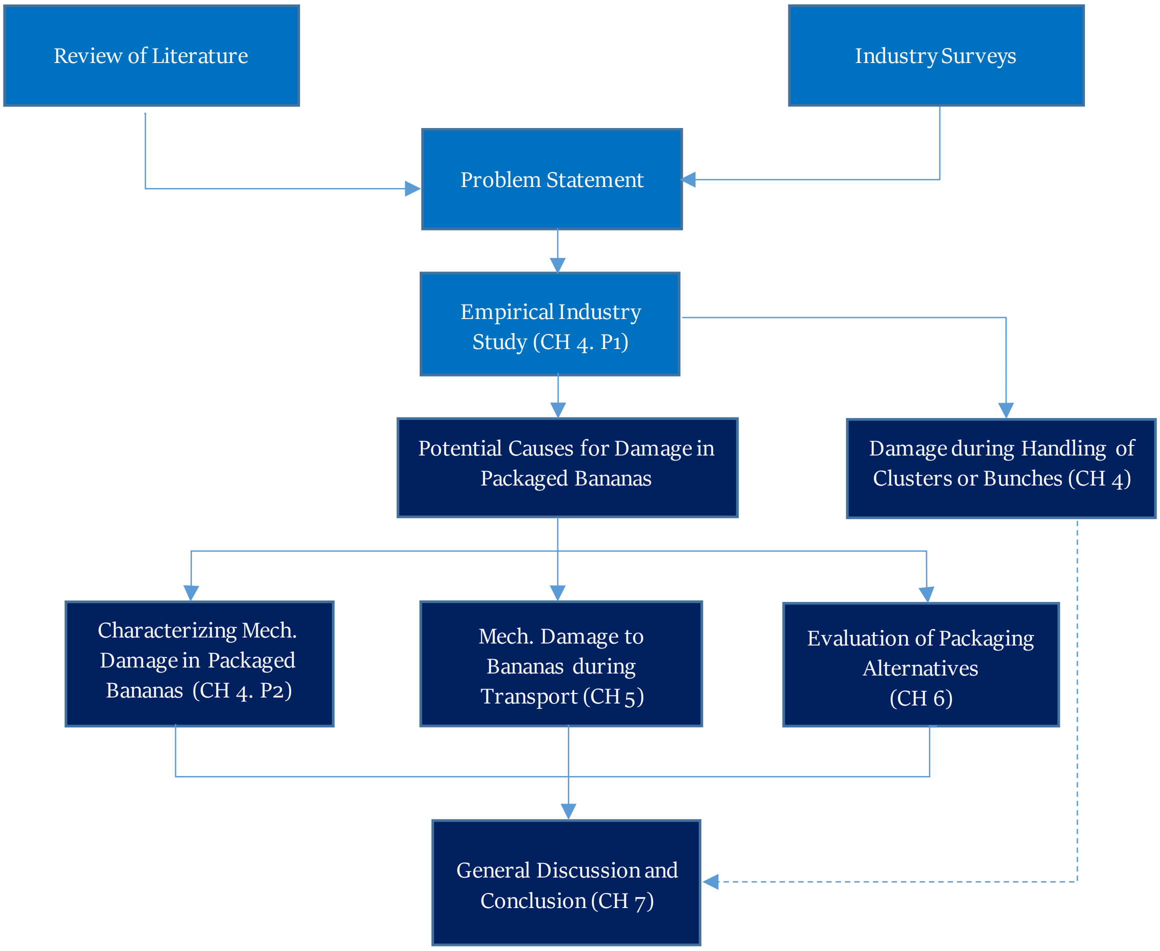


Figure 1.3: Organization of the Key Results Chapters of the Thesis ('CH' - 'Chapter' and 'P'- Part)

The focus of this research was the occurrence of mechanical damage in 'packaged bananas'. However, the empirical study confirmed that damages inevitably occur while bananas are handled as clusters (i.e. out of the package) at either end of the SC (i.e. farm/pack-house and retail stores). Therefore, the causes of damage to bananas when they are not packaged are briefly discussed in Chapter 4 and the potential interventions to minimize such damages, when they are handled as clusters or bunches, are incorporated to the general discussion in Chapter 7. The empirical study further revealed that damage caused during the transport has been one of the major causes that resulted in significant damage to packaged bananas. Based on the early findings of the empirical study the next research directions focused on characterizing different types of mechanical damage in packaged bananas and further investigating the development of damage during long-distance interstate transport.

The alignment of the three main chapters of the thesis with the three research objectives is illustrated in Fig.1.4. This thesis is prepared in accordance with the University of Tasmania guidelines for 'thesis incorporating publications' and therefore the research papers that were resulted from this study have been included as parts in each chapter. The thesis is organized by combining two research papers to constitute each research chapter. The papers are codified from Paper A to Paper G, as indicated in the Publications List ('Pg. iv' of the thesis). The 'Paper A' covers part of the literature review and included in the Chapter 2 of the Thesis.

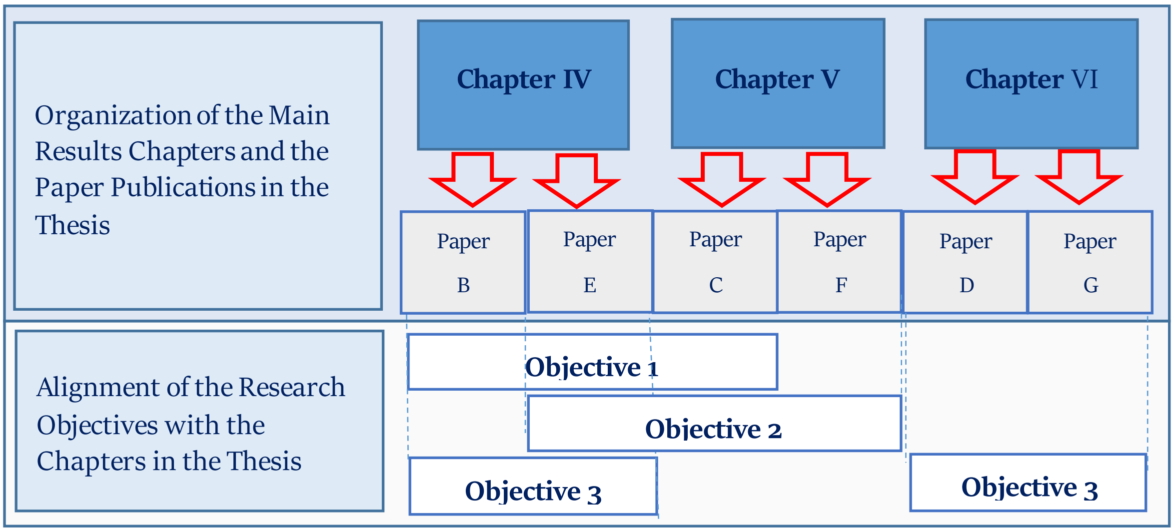


Figure 1.4: Alignment of the Research Objectives with the Results Chapters of the Thesis

The purpose and the focus of each chapter in the thesis is:

Chapter 2- *Literature Review*- This chapter reviews previous research, discusses the findings of the studies related to this research and identifies the research gaps. The chapter also provides knowledge on the mechanisms and causes of fruit mechanical damage with a especial emphasis on packaged fruits during the transport and handling along the SC.

Chapter 3- *General Methodology*- Each of the main research chapters (i.e. Chapter 4-6) in this thesis contain a detailed section of 'Materials and Methods' employed for data collection and analysis. This chapter provides a general outline of the main methods used in this research including the mechanism of damage assessment in bananas, vibration data collection, the development of a model simulation test for packaged bananas and the methods used for package testing and evaluation.

Chapter 4- This chapter is focused on evaluating the damage levels of packaged bananas along the SC and to identifying the potential causes of damage. The first part of this chapter presents the findings of the empirical industry study. The empirical study identified that there were different types of mechanical damage in packaged bananas which occurred in different stages of the SC. The second part of the chapter further evaluates the occurrence of mechanical damage within the key SC nodes and experimentally characterize different types of damage in packaged bananas. The chapter highlighted the need for further investigation on the most frequent abrasion type damages in bananas mostly caused by the exposure to vibration during transport.

Chapter 5- This chapter has two sections. The first section investigated the occurrence of mechanical damage in packaged bananas during the long-distance interstate transport. This research revealed how the damage level in bananas were influenced by the package height and stacked position during the interstate transport. The second section of the chapter further examined the relationship between the mechanical damage levels in packaged bananas in relation to the vibration intensity and exposure duration.

Chapter 6- This chapter evaluates the performance of different packaging alternatives for bananas through simulated transport vibration. The first part of the chapter evaluates packaging for the intestate transport of bananas stacked in ten-tier palletized columns and the second part of the chapter further determines the packaging performance during the retail distribution of ripe bananas in consolidated pallets. This chapter also assesses the effect of highly humid ripening conditions on the structural integrity of different packaging alternatives. Based on the protective performance of packaging, the most suitable packaging type of bananas is recommended to minimize different types of mechanical damages.

Chapter 7- The final chapter of the thesis includes a general discussion of the main research findings and highlights the key conclusions of the study. The interventions and recommendations for improving the quality of bananas in the post-harvest SC are also discussed together with the contributions of this research and industry implications. Finally, the areas for future research are identified and discussed.

1.6. Overview of the Research Methodology

This study used both quantitative and qualitative methods to address the research objectives. Firstly, the empirical study included damage assessment in packaged bananas and a field observation study. This revealed how the mechanical damages in packaged bananas were progressing across the SC from the farm-gate to retail store and, risk factors at various stages of the SC. Next, the damage occurrence in packaged bananas was characterized by applying different mechanical stresses on packages including top-load compression, drop-impact and vibration in laboratory-based experiments. The use of these quantitative and qualitative methods including damage assessment, identification of risk factors by field observation and the experimental validation of the mechanisms for damage development collectively revealed various causes for mechanical damage and the focal areas for further research. Exposure of packages to vibration in-transit and the compromised structural integrity of the cartons in highly humid ripening conditions were found to be the major risk factors causing mechanical damage to packaged bananas in various stages of the SC.

The latter phases of the study were focused on collecting vibration data across the SC to characterize the transport environment and to developing vibration simulation profiles. The simulation profiles based on the field data were used in laboratory simulation experiments to investigate the damage development in packaged bananas. The performance of packaging alternatives was also compared under the simulated vibration and ripening conditions to determine the best packaging type for bananas. In addition, the effectiveness of vacuum-tightening of the banana clusters and alternative pallet-stacking arrangements to minimize vibration damage was also analyzed. Finally, based on the overall knowledge derived in this research recommendations were made to the industry for improving the quality of bananas in the post-harvest SC.

The rationale for the use of different methods in this study are further discussed in Chapter 3 (i.e. General Methodology) and the detailed procedure of executing each method is provided under the Material and Methods sections in each results chapter (i.e. Chapters 4 to 6) of this thesis.

1.7. Novelty and Contribution

This research project made contribution to the industry practice and existing literature in the focal research fields of supply chain management and post-harvest handling of fresh fruits. The research also developed novel methods that can be applied in similar research studies in the future. This study;

- Introduced a novel mechanism to measure and estimate the surface area damages on fruits with the use of a laminated damage area measurement sheet and also developed a scaled mechanical damage index (MDI) for the comparison of damage levels along the SC.
- Revealed when, where and to what extent the mechanical damages occur in packaged bananas from the farm-gate to the retail store and, what type of cosmetic imperfections in bananas are prominent in each stage of the SC.
- Highlighted the risk factors for mechanical damage to bananas and recommended practicable mechanisms to reduce mechanical damage along the SC to further improving the fruit quality, marketability and reducing wastage across the post-harvest SC.

- Characterized different mechanical damage in packaged bananas subjected to compression, impact and vibration forces to confirm the mechanism of how different types of damage occur in bananas.
- Developed a model simulation test for packaged bananas to replicate a comparable field experience during the long-distance interstate transport of bananas, within a time-compressed transport vibration simulation experiment.
- Provided knowledge of the vibration characteristics on the floor of multi-trailer road train trucks that had been only confined to single trailer semi-trucks in the previous literature.
- Improved knowledge of the occurrence of damage in ripe bananas in 'consolidated pallets' with mixed package types.
- Experimentally tested and validated different packing methods and stacking arrangements to minimize damage to both ripe and unripe bananas caused by vibration in-transit.
- Experimentally tested the effect of moisture absorption on the packaging performance (i.e. structural integrity) in high RH ripening conditions of bananas.

These contributions are further discussed in the Chapter 7 of the thesis under Section 7.3.

2. CHAPTER II

Literature Review

This chapter examines the literature and consists of two parts. The first part broadly reviews the literature on fruit mechanical damage and the second part specifically reviews previous research on mechanical damage to bananas. The purpose of this chapter is to identify the research themes, methods employed, and to demonstrate the key findings which are related to the overall design and development of this study. Finally, the research gaps are identified, and the scope of this study has been defined.

Publication included in this Chapter

Section 2.3 of the Thesis was adapted from the Publication – Paper A

PAPER A- *Fernando I, Fei J, Stanley R, Enshaei H. (2018) Measurement and evaluation of the effect of vibration on fruits in transit—Review. Packaging Technology and Science. 2018; 1–16. 723-738. ISSN 0894-3214*

CHAPTER II

Literature Review

PART A – Mechanical Damage in Fruits

2.1. Introduction

Quality deterioration and wastage of fresh produce has been a challenge in post-harvest supply chains. The causes of post-harvest wastage can be broadly classified into mechanical injuries, parasitic diseases and non-parasitic disorders (Harvey 1978). Mechanical damage is one of the fundamental causes of visual quality deterioration in fruits. It can be caused by impact, compression or vibration (Li & Thomas 2014; Opara 2007; Opara & Pathare 2014; Wasala, Dharmasena, Dissanayake & Tilakarathne 2015) resulting in skin bruises, scuffing, scars, abrasion and puncture injuries (Li & Thomas 2014; Mohsenin 1986; Opara & Pathare 2014). There is no universal definition for mechanical damage but researchers have given different contextual definitions to identify a variety of damages in fresh produce (Martinez-Romero et al. 2004). In general, mechanical damage can be broadly described as one or more loadings acting on produce resulting injury to the exocarp (Li & Thomas 2014) or the mesocarp (Labavitch, Greve & Mitcham 1998; Mazhar 2015). In addition, Mohsenin (1986) argued that mechanical damage can also occur due to internal forces such as skin cracks in sweet cherries or in tomatoes. Despite the mechanism of injury, mechanical damage is a leading cause of quality deterioration, especially in delicate produce such as fruits.

Different types of damage can occur in fruits when they are handled, stacked in bulk bins or when packed inside packages such as paperboard cartons. Mechanical damages have been collectively referred as 'bruising' in numerous studies to describe most of the external damages in fruits (Opara 2007; Opara & Pathare 2014; Xing et al. 2005; Xing, Saeys & De Baerdemaeker 2007). Bruising was further categorized into compression bruising, impact bruising and vibration bruising with respect to the mechanism of occurrence and the external force causing the damage (Macleod, Kader & Morris 1976; Vergano, Testin & Newall 1991). 'Bruising' is defined as a damage to plant tissue by external forces causing physical changes (Mohsenin 1986) which may lead to eventual chemical changes in colour, flavour and texture. Bruising may occur due to cell injury as a result of application of force and causes browning of the mesocarp (Mohsenin, Goehlich & Tukey 1962) of fruits without rupturing or breaking the skin (Labavitch, Greve & Mitcham 1998; Mohsenin 1986; Mohsenin 1970). This definition is reasonably applicable to the damage caused by impact and compression forces. However, it is difficult to describe all mechanical damage in fruits as "bruising", as damages caused by friction (abrasion), may break the skin and breach the exocarp of the fruits (Li & Thomas 2014). Therefore, a better damage classification is required to account for various external and internal damages in fruits.

Fruit damage can occur when they are handled individually or as unitized packaged products. In post-harvest SCs, fruits are handled in packages mainly during the transport and distribution. Fruits are handled individually or in bulk usually at the beginning and the end of the SC which are farm/ packing-shed and retail stores. Therefore, during most of the post-harvest journey from the grower to the retailer, fruit remain as packaged products in corrugated cartons or plastic crates that are been used due to the ease of handling, transport and storage of unitized loads.

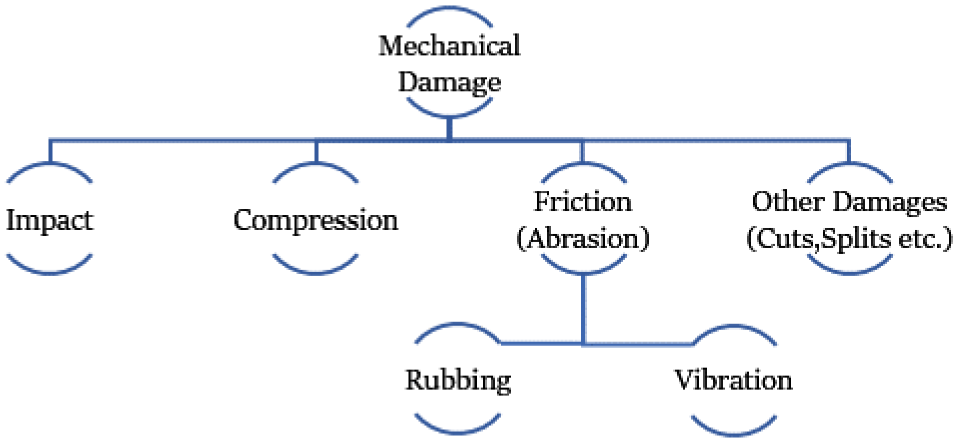


Figure 2.1: Categorization of Mechanical Damage in Fruits

Mechanical damage in fruits can be influenced by the type of packaging and the method of packing. The packaging is subjected to a variety of mechanical forces during the handling and transport in the distribution process. Mechanical damage can occur due to package compression and impact during the handling of packages and also due to the exposure of packaged fruits to vibration (Fadiji et al. 2018). The relative movement of fruit against other contacting surfaces such as rubbing against adjacent fruits or packaging can result in abrasion or friction damage (Fernando et al. 2018b). Damage can also occur during packing operations and handing such as movement along conveyer belts. A classification of various mechanical damages that can occur in fruits is presented in relation to the type of force that causes the damage (Fig.2.1 and described in Table 2.1). In addition to the most common types of mechanical damage caused by impact, compression and friction, other damages such as cuts, puncture and splits can also occur in produce (Opara & Pathare 2014) but the causes and rates of these types of damages in fruits have been rarely reported.

Table 2.1: Description of the of the Main Types of Mechanical Damage in Fruits

Mechanical Damage	Description
Impact Bruising	Impact damage is caused by collision of the fruit against hard surfaces (Del Aguila et al., 2010, Dadzie and Orchard, 1997). It may occur from a sharp blow on the fruit such as an object falling onto the fruit or fruit falling against another fruit or onto a hard surface with sufficient force to damage or even separate the cells.
Compression Bruising	Compression injuries may cause by variable pressure on fruit surface exerted by an adjacent fruit or the container holding the fruit (Dadzie & Orchard 1997).
Abrasion (Friction Damage)	Abrasion is caused by friction between the fruit surface and other contacting surfaces. Injuries can occur by rubbing the fruits against other surfaces or other fruit, creating an instantly visible damage (Chukwu, Ferris & Olorunda 1998) on the fruit skin. A major cause of abrasion is damage in fruits is vibration. Vibration damage is attributed to fatigue due to repeated frictional forces in the fruit resulting in cell rupture beneath the skin (Vursavus & Ozguven 2004) and the intensity and duration of vibration may determine the severity of fruit damage (La Scalia, Aiello, et al. 2015; Vursavus & Ozguven 2004).

2.1.1. Physiology of Mechanical Damage

Fruit damage may induce physio-chemical changes in fresh produce. Mechanical damage can affect both exocarp (abrasion) and mesocarp (bruising) of the fruit and induce physiological and morphological changes (Shewfelt 1987). Skin browning and discoloration is the physical affect to fruits subjected to mechanical damage as a result of oxidation of phenols in the ruptured plant cells (Fischer et al. 1992). Browning can be followed by skin softening (Ahmadi 2012; Baranowski et al. 2012) and distortion (Mohsenin 1986) leading to changes in the shape of the fruit due to damage. Fresh produce is constructed by plant tissue which is a combination of individual plant cells. When the intercellular space in fruit tissue is high, more tissue damage will occur from mechanical damage (Li & Thomas 2014). Surface damages due to external forces may essentially occur in the exocarp of a fruit and subsequent browning in the fruit surface can be explained as a multi-step process including cell damage, enzymatic oxidation and browning of the fruit tissue (Fig.2.2).

Fruit damage often causes the discoloration of the fruit skin (peel) which can affect the consumer perception of the fruit quality and hence, the marketability. Polyphenol oxidase (PPO) is responsible for enzymatic browning in fresh produce, caused by mechanical injury (Luyckx Audrey 2016; Martinez & Whitaker 1995). Compression and impact bruising may result in cell walls and fruit membranes to losing their integrity, resulting in mesocarp browning due to PPO activity (Mazhar 2015). If the phenolic content, PPO and peroxidase activity is higher in the external tissue, as in the case of most fruit, browning occurs externally. However, if the PPO activity is lower in the external tissues of fruits such as pear, tomato and longan, browning can occur internally (Li & Thomas 2014). Factors that affect the rate and intensity of browning include the activity of enzymes, concentration of the specific polyphenols in fruit tissues, availability of oxygen, pH of the substrate and fruit holding temperature (Maia et al. 2011; Martinez & Whitaker 1995; Mazhar 2015).

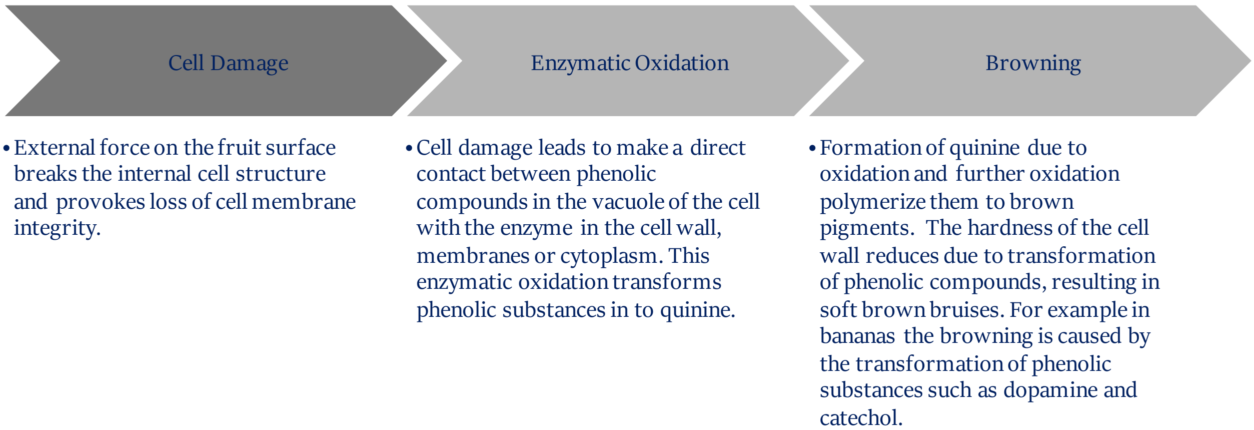


Figure 2.2: Bio-chemical Process of Fruit Browning (Li & Thomas 2014; Luyckx Audrey 2016; Martinez & Whitaker 1995)

2.1.2. **Response of Fruits to Mechanical Damage**

Mechanical damage may cause harmful effects resulting in deterioration of fruit quality due to the adverse physiological changes. Previous studies reported that fruits exhibited loss of firmness, peel discolouration and softening due to the exposure to mechanical vibration (Fischer et al. 1992; La Scalia, Aiello, et al. 2015). Fischer et al. (1992) found that berries can be shattered due to the exposure to vibration and result in discoloration and reduced shelf life. Additionally, strawberries turn dull or watery due to juice oozing from the bruised skin. La Scalia, Aiello, et al. (2015) confirmed that the colour variations of strawberries were affected by transport vibration and fruits lost firmness by up to 26% due to vibration exposure. Prolonged exposure to vibration caused changes in the colour and softening of pears, exhibiting 42.5% firmness loss after 18 days of storage(Zhou et al. 2007). It was also reported that exposure to vibration affected the modulus elasticity in fruits such as grapes (Demir, Kara & Carman 2010) and watermelon (Shahbazi et al. 2010).

In addition, mechanical damage can lead to spoilage and loss of nutritional value in fruits (Pathare & Opara 2014). The fruit decay can be expedited by damage, making it prone to rotting. Quality deterioration can be further exacerbated due to the attacks by microorganisms after the injury (Li & Thomas 2014; Slaughter, Hinsch & Thompson 1993). Damaged fruit may also stimulate undamaged fruit to be infected while in the storage (Lü & Tang 2012; Prusky 2011). Wilson, Boyette and Estes (1995) reported that a single severe bruise in an apple increased the moisture loss up to 400%. It was also found that mechanical injury accelerated weight loss (Çakmak et al. 2010; More et al. 2015) and respiration rate in fruits (Fischer et al. 1992; Wasala, Dharmasena, Dissanayake & Tilakarathne 2015; Yasunaga et al. 2010a). Several studies have reported the effect of mechanical damage as a leading cause for increased microbial and enzyme activity (La Scalia, Aiello, et al. 2015; Zhou et al. 2007), cellular leakage (Mao et al. 1995; Zhou, Su & Li 2008a; Zhou et al. 2007; Zhou, Wang, et al. 2015), changes to titratable acidity and total soluble solids (Chonhenchob, Kamhangwong & Singh 2008b; La Scalia, Aiello, et al. 2015; La Scalia, Enea, et al. 2015b; Yasunaga et al. 2010a), internal fruit temperature increase (Alayunt et al. 1997b; Çakmak et al. 2010), electrical conductivity increase (Zhou et al. 2007; Zhou, Wang, et al. 2015), ethylene production (Mao et al. 1995) and changed sensory properties (Nakamura et al. 2015). These studies emphasize that the responses and changes in fruits due to mechanical injury may accelerate ripening and deteriorate fruit quality, influencing their effective shelf life.

2.2. Bruising in Fruits caused by Impact and Compression

Bruise damage is a frequently reported visual defect in fruits. Bruising may affect both the skin and flesh making the affected parts of the fruit mostly inconsumable. Fruit bruising occurs as a consequence of cell wall ruptures leading to breakage of intercellular bonds or cell deflation as a result of loss of cell fluid (Van Zeebroeck, Van linden, et al. 2007). A common symptom of bruising is water soaked tissues at the point of impact (Quintana & Paull 1993). Mazhar et al. (2015) reported that bruising created a grey colour damage with well-defined margins in avocados. Bruising can be attributed to impact and compression forces causing damage to mesocarp without breaking or rupturing the skin (Labavitch, Greve & Mitcham 1998; Mohsenin 1986; Mohsenin 1970; Studman 1995). Compression bruising may occur due to the variable pressure on fruit surface (Dadzie & Orchard 1997) and impact bruising can be caused by a transient blow/impact on the fruit surface or collision/drop of fruit against hard surfaces (Dadzie & Orchard 1997; Macleod, Kader & Morris 1976; Mohsenin, Jindal & Manor 1978; Opara & Pathare 2014).

2.2.1. Bruise Susceptibility in Fruits

Bruise susceptibility can be explained as the lowest impact energy or the force required to produce or initiate bruising in a given fresh produce. Bruising may occur when the stress or the external force per unit area (pressure) exceeds the resistance which is expressed as the strength of the fruit tissues (Mazhar, 2015, Hyde, 1997). Plant cells are capable of resisting external force (stress) up to a certain extent and the deformation starts to occur in the shape/size/volume of the fruit tissue (strain) once the stress exceed the threshold/ resistance for damage (Mazhar, 2015, Li and Thomas, 2014, Zarifneshat et al., 2010). The resistance for damage is influenced by the bruise susceptibility in fruits. Several researchers studied the behavior of fruits to compression and impact forces with the use of texture analyzers (Guillermin, Camps & Bertrand 2004; Zwiggelaar et al. 1996), pendulum devices (Ahmadi et al. 2010; Bollen, Nguyen & Rue 1999; Kajuna, Bilanski & Mittal 1997; Opara 2007; Zarifneshat et al. 2010), an electronic force gauge (Banks & Joseph 1991), dropping fruit from a height (Jiménez-Jiménez et al. 2012; Jiménez-Jiménez, Castro-García, et al. 2013; Menesatti & Paglia 2001), dropping a guided weight (steel ball/roller) on fruit (Baranowski et al. 2012; Yuwana 1997), and pressure sensors (Herold, Geyer & Studman 2001; Lu et al. 2010b; Stopa, Komarnicki & Młotek 2014).

There can be many factors affecting the bruise susceptibility or resistance to bruising in fruits. The amount of mechanical energy applied and absorbed by produce (Opara & Pathare 2014) will be a critical determinant for the severity of damage. Occurrence of bruise damage has been studied in relation to force (Banks, Borton & Joseph 1991; Brusewitz, McCollum & Zhang 1991), drop height (Vergano, Testin & Newall 1991) and energy absorbed (Ahmadi 2012; Jarimopas et al. 2007; Pang, Studman & Ward 1992). Thomson (1953) revealed that there can be two factors impacting the severity of bruising: the magnitude of the force and the number of repetitions of the force on a given location. Liner correlations were exhibited between the absorbed energy and bruise volume in fruits (Brusewitz & Bartsch 1989; Pang, Studman & Ward 1992). These studies emphasized that energy absorbed by produce during the bruising event is critical to determining the level of resulting damage.

Several researchers developed bruise prediction models using a variety of modeling techniques. These include modeling approaches based on multiple liner regression and nonlinear regression (Abedi & Ahmadi 2014; Ahmadi 2012; Ahmadi et al. 2010), logistic regression (Bollen, Timm & Rue 2001; Van et al. 2006), statistical estimation (Zarifneshat et al. 2010) and artificial neural networks (Zarifneshat et al. 2012). Bruise volume has been positively correlated with the peak contact force (Ahmadi et al. 2010; Van Zeebroeck, Van linden, et al. 2007; Zarifneshat et al. 2010). Peak acceleration and the velocity change (Δv) during the impact have also been correlated with impact bruising (Arazuri, Arana & Jaren 2010; Xu & Li 2015; Yu et al. 2014). Arazuri, Arana and Jaren (2010) showed that lower velocity changes have been associated with greater damage in tomatoes. A rebound velocity closer to the impacting velocity suggests a harder (elastic) surface, resulting in more damage to the fruit (Arazuri, Arana & Jaren 2010; Sober, Zapp & Brown 1990). Models based on finite element (FE) modeling (Lewis et al. 2007) and discrete element modeling (DEM) (Van Zeebroeck, Darius, et al. 2007a; Van Zeebroeck et al. 2006a) were used to develop bruise prediction models in apples. However, the application these methods to other fruits has been limited.

Bruise susceptibility was shown to be further associated with orchard management practices, date and time of harvesting (Banks & Joseph 1991; Opara 2007), and fruit properties such as maturity/degree of ripening (Yuwana 1997), cultivar (Crisosto, Garner, et al. 1993; Pang et al. 1996; Van et al. 2006) and fruit firmness and turgidity (Banks & Joseph 1991; García Fernández, Ruiz-Altisent & Barreiro Elorza 1995). It was further found that the susceptibility was also a function of acoustic stiffness, curvature and the fruit temperature (Ahmadi 2012; Ahmadi et al. 2010; Banks & Joseph 1991; Crisosto, Garner, et al. 1993; Van Zeebroeck et al. 2006a; Van Zeebroeck, Van linden, et al. 2007; Zarifneshat et al. 2010). Yuwana (1997) reported that unripe bananas can be less susceptible to bruising as the energy required for bruising for unripe fruit was greater than for ripe fruits. It was reported that when fruits ripen the cell deformation may occur at a lower force as the fruit tissues soften (Mazhar et al. 2015; Mazhar 2015) leading to increased bruise susceptibility (Ahmadi 2012; Van Zeebroeck, Darius, et al. 2007a; Van Zeebroeck, Darius, et al. 2007b; Yuwana 1997). Mohammad Shafie et al. (2015) showed that higher fruit temperature, firmness and peel thickness reduced bruise damage in pomegranate fruit. The radius of curvature and storage time increased the bruise area and volume respectively. Similarly, Ahmadi et al. (2010) showed that lowering the temperature, increasing the radius of curvature and acoustic stiffness can reduce bruise susceptibility in peaches. Crisosto, Garner, et al. (1993) showed that a higher flesh temperature in cherries resulted in increased impact bruise susceptibility. However, the damage caused by vibration was not influenced by temperature. These studies conclude that a variety of properties related to a given fruit influence the bruise damage susceptibility, in addition to the characteristics of the external force acting on the fruit.

External environmental conditions such as the storage temperature and humidity can influence the bruise susceptibility in fruits, however the studies in this regard have been limited. García Fernández, Ruiz-Altisent and Barreiro Elorza (1995) found that apples and pears stored at high RH had increased susceptibility of bruising. Akkaravessapong, Joyce and Turner (1992) concluded that the storage humidity did not influence the bruise susceptibility in bananas but lower RH caused drying out and rapid darkening of the bruises during the subsequent storage. It is evident that the bruise damage susceptibility is largely subjected to the environmental conditions and properties of the produce. However, the magnitude of the external force and the number of repetitions of the force on a given location of the fruit may still outweigh most other factors associated with fruit bruising.

2.2.2. Fruit Bruising in Post-Harvest Operations

Bruising may unavoidably occur in fruits during early post-harvest operations such as harvesting, packing, transport and handling across the supply chain. Mechanical damage in fruits can occur during picking, filling or transfer of field containers (Crisosto, Mitchell & Johnson 1995). Mechanical harvesting was found to be a major risk factor for fruit damage. Therefore, researchers have examined how to minimize damage to various fruits during harvesting (dos Santos & Ferraz 2007; Gambella, Paschino & Dimauro 2013; Li, Liu & Li 2010; Ma et al. 2017; Peterson & Bennedsen 2005). Previous studies have also evaluated the influence of the packing operations to the development of mechanical damages in fruits such as apples, avocados, cherries, persimmon and papaya (Besada et al. 2009; Grant & Thompson 1997; Guyer et al. 1991; Hofman 2003; Quintana & Paull 1993). Hofman (2003) reported that bruising with light colour discoloration was often associated with hairline cracking of the mesocarp in avocados sampled at the end of the packing line. Cosmetic damages have been the leading cause for the wastage of bananas at the pack house (White, Gallegos & Hundloe 2011). Quintana and Paull (1993) revealed that mechanical injury in papayas were substantially exacerbated from the point of harvest to the end of packing line. These studies emphasize that bruising in fruits has been predominant during the post-harvest handling.

Several studies revealed that produce damage can be associated with impacts during handling, vibration from transport and compression from the packaging (Fadiji, Coetzee, Chen, et al. 2016; Fadiji, Coetzee, Pathare, et al. 2016; Opara & Fadiji 2018; Opara & Pathare 2014). Impact or quasi-static compression during handling and storage is a critical factor causing fresh produce damage (Herold, Geyer & Studman 2001). Compression between fruits or between a fruit and the container during transport and storage has been associated with fruit bruising (Zwiggelaar et al. 1996). Several researchers were interested in measuring the frequency and magnitude of impacts during the post-harvest handling of fresh produce for better and realistic characterization of bruise damage. Data recording devices resembling an actual produce were used for this purpose to quantify the mechanical stresses during harvesting and post-harvest handling of fruits. These devices were mostly identified as instrumented spheres (IS) or rarely as electronic fruit or impact recording devices (IRD) (Opara & Pathare 2014; Van Zeebroeck, Van linden, et al. 2007). Two types of sensors have been used in IS to quantify the mechanical stresses namely, the pressure measuring sensors or load cells to detect compression forces and accelerometer based sensors (Müller et al. 2012; Muller et al. 2009).

IS devices were mostly used to measure dynamic compression forces and impacts on non-packed fruits when they are free to move. It included fruits handled in the field or in packing lines, before being packed into containers. Few studies using IS attempted to identify the critical impact points in packing lines and mechanical stresses on fruits during harvesting (Arazuri, Arana & Jaren 2010; Luo, Lewis, et al. 2012; Xu & Li 2015). IS have been most frequently used to study the development of bruising in apples packing lines (Pang, Studman & Banks 1994; Sober, Zapp & Brown 1990). Several other studies used IS to measure bruising in other fruit packing lines such as tomato (Ferreira, Ferraz & Franco 2004), blueberries (Xu et al. 2015), citrus (Miller & Wagner 1991) and avocado, papaya and pineapple (Timm & Brown 1991). Garcia-Ramos, Ortiz-Canavate and Ruiz-Altisent (2004) researched the development in bruising caused by fruit to fruit impact in apple packing lines and found that most of the impacts in the IS were recorded at the angled transfer points. The same study suggested that the improvement in the transfer points within the apple packing line resulted in minimizing damages to apples during packing. Similarly, Timm and Brown (1991) used an IS to identify the impact points in fruit packing lines and showed that improved cushioning, reducing elevation changes and reducing fruit flow at each transfer point resulted in minimized bruising on avocado, papaya and pineapple. These studies emphasize that fruit mechanical damage during the pack house operations is unavoidable and that modifications to the packing lines can reduce the post-harvest damage to fruits in the early stages of the SC.

2.2.3. **Bruising in Packaged Fruits**

There are only a limited number of studies that have examined the occurrence of bruising caused by impact or compression to fruits when inside their packaging. Ferreira, Ferraz and Franco (2004) quantified the impacts on packaged tomatoes using an IS and found that handling produced highest impact when the operators drop the packages in the packing line. Muller et al. (2009) studied the compression force suffered by packaged apples and oranges using an IS and found that the fruits were often subjected to severe compression forces due to package over-filling. This occurred when an extra layer of fruits was packed into the box to obtain the required box weight. Furthermore, the study suggested that misaligned packages in pallets caused more compression on fruits, and that the peak compression forces greater than 20 kg on fruits have been exhibited during the forklift handling of the pallets. Similarly, Müller et al. (2012) showed that an average compression force of 2.3 kg was recorded by an IS placed inside a package of apples during transport. The compression force rapidly escalated due to the pavement irregularities along the road. Opara and Fadiji (2018) and Fadiji, Coetzee, Pathare, et al. (2016) studied the influence of package design on the compression and impact bruise susceptibility in apples. It was shown that package dimensions and paperboard combination influenced the resistance of packages to compression loading and thus, the resultant bruise damage levels in apples. The latter study also concluded that package design and packaging pattern influenced on the level of bruising in apples subjected to drop impacts. However, bruising caused by impact and compression in packaged fruits has not been widely studied and further research is needed.

2.3. Mechanical Damage to Fruits caused by Vibration

Vibration is the most predominate cause of mechanical damage during transportation of fresh produce. Vibration and shock transmitted from the truck floor causes adverse damage to fruits (Timm, Brown & Armstrong 1996). Prolonged exposure to harmful vibration may also increase the susceptibility of fruit damage (Mvumi, Matsikira & Mutambara 2016; Vursavus & Ozguven 2004). The impact of transit vibration has been evaluated for a range of fruits (Table 2.2). However, many different experimental designs with different variable settings have been used to evaluate the effects of vibration on fruits, making comparison of some of the results challenging.

2.3.1. Experimental Approaches

Vibration studies on fresh produce can be broadly categorised into three experimental approaches for the purposes of comparison. They are *In-Transit* experiments, *Simulation* experiments and a combination of these two approaches that can be termed as *Transit-Simulation (Trans-Sim)* type experiments. Independent variables such as different truck types or suspension systems (Barchi et al. 2002; Berardinelli et al. 2003; Soleimani & Ahmadi 2015), travel speeds (Jarimopas, Singh & Saengnil 2005; Ranathunga et al. 2010) and road conditions (Ranathunga et al. 2010; Soleimani & Ahmadi 2015; Zhou et al. 2007) have been examined in relation to variations in vibration levels. The resultant vibration levels were then correlated with produce damage levels or quality indices to understand the effect on produce. However, some studies measured the dependent variable as peak acceleration (a_{peak}) or root mean square acceleration (G_{rms}) or transmissibility level (T) caused by transit vibration (Soleimani & Ahmadi 2014, 2015). These studies inferred that higher acceleration and transmissibility levels result in more energy transfer to the produce, and hence result in more damage.

In many studies, the measured or the dependent variables were related to the effect on produce such as physiological changes or external damage. Frequently measured physiological changes were the effect on respiration rate, fruit weight, fruit firmness, ethylene production, cell wall permeability, enzyme activity, total soluble solids (TSS) and titratable acidity (TA)(Chonhenchob, Kamhangwong & Singh 2008a; La Scalia, Aiello, et al. 2015; Zhou, Su & Li 2008b; Zhou et al. 2007). Most of these physiological changes in fruits have been primarily caused by mechanical damage due to the imposed vibration. External damage caused by vibration stresses has been assessed visually as a percentage (Berardinelli et al. 2005; Fischer et al. 1992; Jarimopas, Singh & Saengnil 2005; Slaughter, Hinsch & Thompson 1993), length and width of damage (Barchi et al. 2002), bruise diameter and equivalent bruise index (Timm, Brown & Armstrong 1996; Vursavus & Ozguven 2004), bruise depth (Tabatabaekoloor, Hashemi & Taghizade 2013), percentage decay of the modulus elasticity (PDME)(Shahbazi et al. 2010), bruise area, bruise volume and package damage (Fadiji, Coetzee, Chen, et al. 2016), abrasion rating (Timm, Brown & Armstrong 1996) or a bruise score (Çakmak et al. 2010; Slaughter, Hinsch & Thompson 1993) as summarised in Table 2.2. This highlights that most of the studies were focused on the effect of vibration and shocks on the appearance quality of the fruits.

2.3.1.1. In-Transit Experiments

In-Transit experiments were centred on studying the interaction of different variables during transit passage and directly correlating these with the resultant damage or changes in produce quality. Such studies attempted to evaluate the effects of vibration on fresh produce with respect to different parameters under investigation (Jarimopas, Singh & Saengnil 2005; Soleimani & Ahmadi 2014, 2015). Experiments were performed during real transit passage in a live setting while the produce was being transported in a truck or similar other carrier. The effects on the produce were examined before and after transport (Ishikawa, Kitazawa & Shiina 2009; Jarimopas, Singh & Saengnil 2005; Zhou et al. 2007). This approach enabled the vibration parameters to be directly related to changes in produce quality, but the experiments have been mostly restricted to data collected during a single transit trip.

Past studies used piezoelectric accelerometers coupled with charge amplifiers to record the acceleration data in the *in-transit* experiments (Barchi et al. 2002). A contemporary approach has been to use fruit-shaped accelerometer devices to measure the in-transit vibration levels. For instance, Soleimani and Ahmadi (2015) used an electronic sphere resembling the actual fruit shape with an embedded tri-axial accelerometer to assess the impact of vibration on Golden Delicious apples. Past studies recorded either three axis acceleration or were limited to single axis (vertical) vibration, as it has been highlighted that the vertical vibration axis causes most harm to produce (Vursavus & Ozguven 2004).

2.3.1.2. Transit-Simulation (Trans-Sim) Experiments

Trans-Sim type experiments measure the in-transit vibration level along the transport passage and use the derived vibration profiles as the input to drive vibration and shock simulators (Barchi et al. 2002; Berardinelli et al. 2003, 2005; Timm, Brown & Armstrong 1996). *Trans-Sim* experimental designs consist of two distinct experimental stages, namely the data capture stage and the simulation stage. The first in-transit data-capturing stage is performed in the actual transit passage. Accelerometers mounted inside the cargo hold in a truck record the acceleration variations and the data are used to develop the vibration profiles for the truck passage.

Three-axis or single-axis acceleration is recorded in time domain and can then be converted to frequency domain using Fourier transformation. This Fourier analysis of the time-series data can be used to understand the critical frequencies affecting the produce during transit (Smith 2006). Power Spectral Density (PSD) profiles (Barchi et al. 2002; Jarimopas, Singh & Saengnil 2005) developed for the respective routes represent the energy or power of the vibration excitations along that route. PSD can be effectively used to measure the vibration energy in a transit passage, as the bruising injury is a result of the energy absorbed during transportation (Ranathunga et al. 2010). Power Density (PD) of a given vibration signal within a band of frequencies could be derived through Equation (2.1) (Jarimopas, Singh & Saengnil 2005).

$$PD = \frac{1}{BW} \sum \frac{RMS\ gi^2}{N} \qquad \text{Eq. (2.1)}$$

***RMS gi*² is the root mean square acceleration measured in *g* at any instance within a bandwidth (BW) of frequencies; *N* is the number of samples in a given vibration signal)**

In the *Trans-Sim* and *Simulation* type experiments, the variables used during simulation have mainly consisted of frequency, acceleration and duration of vibration (La Scalia, Aiello, et al. 2015; Tabatabaekoloor, Hashemi & Taghizade 2013). The vibration treatment may be either of variable durations (Shahbazi et al. 2010; Vursavus & Ozguven 2004) or of controlled fixed duration (Fadiji, Coetzee, Chen, et al. 2016; Slaughter, Hinsch & Thompson 1993; Tabatabaekoloor, Hashemi & Taghizade 2013). Within a vibration treatment, the frequency may also vary in the range of interest (Fischer et al. 1992; Zhang et al. 2011) or be an identified fixed frequency (Fadiji, Coetzee, Chen, et al. 2016; Ranathunga et al. 2010; Tabatabaekoloor, Hashemi & Taghizade 2013) as determined by the in-transit experiments.

In *Trans-Sim* experiments, the key independent variable for simulation is the vibration treatment consisting of frequency, acceleration and duration values derived from field data. Similarly, to *Simulation* experiments, different vibration treatments have been used as the input variables to determine the effect on produce. Previous studies with different experimental settings have been categorised and summarised in Table 2.2. Studies which had not evaluated the effect on fruits with the parameters of the vibration were excluded from this table.

2.3.1.3. Simulation Experiments

Simulation type experiments are laboratory studies in which a known vibration intensity, based on limited frequencies of interest, or a standard vibration profile has been used to drive a shaker. The vibration frequencies and profiles are often based on set standards such as American Society of Testing and Materials (ASTM)(ASTM 2016a) or International Safe Transit Association (ISTA)(ISTA 2017). For both *Trans-Sim and Simulation* types of experiments a vibration table or a shaker capable of exerting vibration effect in given frequencies needs to be used. The shakers are electro-hydraulic (Fischer et al. 1992; Slaughter, Hinsch & Thompson 1993) or electro-dynamic (Barchi et al. 2002; Berardinelli et al. 2005; Fadiji, Coetzee, Chen, et al. 2016) in the operating mechanism. A schematic diagram of a modern vibration simulator is given in Fig. 2.3. These simulators are usually capable of adjusting the vibration frequency or amplitude or both parameters to exert the decided effect on produce.

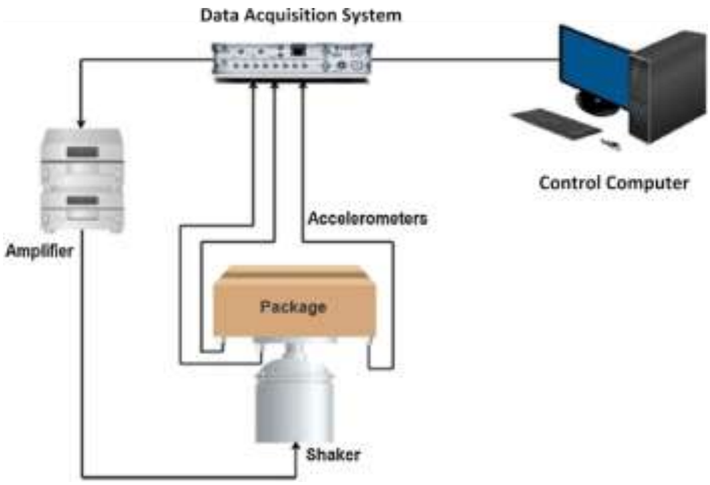


Figure 2.3: A Schematic Diagram of a Modern Vibration Simulator (Fadiji, Coetzee, Chen, et al. 2016)

Most of the studies have used different vibration treatments with varied frequency or acceleration or duration or combination of these parameters as input variables to derive the effects on produce. However there have been some *simulation* type studies which subjected the produce to a constant vibration signal (Chonhenchob & Singh 2005a; Konya et al. 2016; Nakamura et al. 2007). Constant vibration treatment has a fixed frequency, acceleration and duration to drive the simulator. The objective of these type of studies was to determine the effects on produce due to a known vibration signal, but this approach does not analyse how the produce may behave in response to different vibration treatments. However, such studies have been useful for characterising the physiological changes in fruit when subjected to a known vibration. Some studies have chosen the constant vibration approach based on previous research findings on similar produce (Aba et al. 2012; Crisosto, Johnson, et al. 1993; Wasala, Dharmasena, et al. 2015a). Contrastingly, some studies had used arbitrary parameters for the vibration treatment (Konya et al. 2016; Wu & Wang 2014), which makes it difficult to realise why particular parameters were used in a simulation.

Table 2.2: Summary of Studies on the Effect of Vibration Impact to Fruits

Produce	Experiment Type	Conditions \ Variables in Transit	Conditions \ Variables in Simulation	Measured Variable (Y)	Test or Prominent Frequency	Reference
Apple	*Simulation*	*Not Applicable*	Vibration Treatment (ASTM) Vibration Treatment (F) Package Type	Bruise Area Bruise Volume Package Damage	9 Hz ,12 Hz	(Fadiji, Coetzee, Chen, et al. 2016)
	In-Transit	Suspension Type Road Condition Vehicle Speed	*Not Applicable*	Effect on the Artificial Fruit Acceleration Levels Power Density (PD)	0.1–5 Hz	(Soleimani & Ahmadi 2015)
	In-Transit	Suspension Type Package Position* Package Height** Fruit Depth⁺	*Not Applicable*	Effect on the Artificial Fruit Acceleration Levels PD	0.1–5 Hz	(Soleimani & Ahmadi 2014)
	Simulation	*Not Applicable*	Vibration Treatment (F) Cushioning Material	Apple Damage	0-1.6 KHz	(Eissa & Hafiz 2012; Eissa, Albaloushi & Azam 2013)
	Simulation	*Not Applicable*	Vibration Treatment (C) Stack Height	Loading Force on Fruit Damage to Apples	8-9 Hz	(Acican, Alibaş & Özelkök 2007)
	Simulation	*Not Applicable*	Vibration Treatment (FA) Stack Height⁺ Fruit Size	Bruise Diameter Bruise Depth Bruise Volume	4 Hz	(Van Zeebroeck et al. 2006a; Van Zeebroeck et al. 2006b)
	Trans-Sim	Package Position	Vibration Treatment (FAD) Packaging Method	Equivalent Severe Bruise Index (EBI) Bruise Diameter Transmissibility Ratio	5-15 Hz 9 Hz (Peak)	(Vursavus & Ozguven 2004)

	Trans-Sim	Suspension Type Travel Distance Bin Position Fruit Position in the Bin (Middle, Side), Bin Type	Vibration Treatment (ASTM) Vibration Treatment (FA) Bin Type	Bruise and Abrasion Rating Damage Diameter Resonant Frequency	2.5–9 Hz and 20–70 Hz 7–15 Hz (Resonance)	(Timm, Brown & Armstrong 1996)
	Trans-Sim	Suspension Type Road Condition	Vibration Treatment (FA)	Package Type Packing Material	0-10 Hz	(Singh & Xu 1993)
Bananas	*Simulation*	*Not Applicable*	Vibration Treatment (C) Packaging Method	Percentage of Injured Fruit Bruise Area Weight Loss	*Not Given*	(More et al. 2015)
	Simulation	*Not Applicable*	Vibration Treatment (C) Packing Material	Visual Quality Index (VQI) Respiration Rate	3.5 Hz	(Wasala, Dharmasena, et al. 2015a)
Cherries	*In-Transit*	Transport Mode (Air\Road) Suspension Type Transport Route	*Not Applicable*	Damage to Cherries PD	15 Hz (Air Ride) 2–3 Hz (Leaf Spring) 80 Hz (Air Transport)	(Ishikawa, Kitazawa & Shiina 2009)
Cherry Tomato	*Simulation*	*Not Applicable*	Vibration Treatment (F) Package Height	Resonant Frequency Acceleration Levels Transmissibility Ratio	36.61 Hz (Bottom) 10.76 Hz (Middle) 6.44 Hz (Top)	(Zhang et al. 2011)
Fig Fruit	*Trans-Sim*	Road Condition Packing Material Travel Duration	Vibration Treatment (FA) Fruit Cultivar	Visual Quality Weight Loss, Fruit Firmness Internal Temperature	3 Hz and 16 Hz	(Çakmak et al. 2010)
	Simulation	*Not Applicable*	Vibration Treatment (FD) Package Type Orientation of Fruit	Visual Quality Fruit Firmness, Weight Loss Moisture Content Internal Temperature Total Soluble Solids (TSS)	2.5 Hz and 7 Hz	(Alayunt et al. 1997a)

	Simulation	*Not Applicable*	Vibration Treatment (A)	Ethylene Production Respiration Rate Cellular Leakage	Not Given	(Mao et al. 1995)
Grapes	*Simulation*	*Not Applicable*	Vibration Treatment (D) Package Position	Cracking Resistance Separate Resistance Modulus Elasticity	109 Hz (Resonance)	(Demir, Kara & Carman 2010)
	Simulation	*Not Applicable*	Vibration Treatment (F) Package Height	Grape Damage Fruit Firmness Respiration Rate	5-10 Hz	(Fischer et al. 1992)
Mandarin Fruit	*Trans-Sim*	*Fixed Conditions*++	Vibration Treatment (D) Package Type Packing Material	Mandarin Damage	60 Hz	(Raghav & Gupta 2003)
Kiwi Fruit	*Simulation*	*Not Applicable*	Vibration Treatment (FA) Stack Height Fruit Size	Bruise Depth	13 Hz	(Tabatabaekoloor, Hashemi & Taghizade 2013)
	Simulation	*Not Applicable*	Vibration Treatment (ASTM) Vibration Treatment (D) Fill Type (Layer, Bulk) Package Type	Kiwi Damage	Not Given	(Lallu et al. 1999)
Loquats	*In-Transit*	Truck Type Road Condition Package Position Package Height	Vibration Treatment (FAD) Package Height	Loquat Damage	13–25 Hz 9 Hz, 16 Hz (Peak)	(Barchi et al. 2002)
Mango	*In-Transit*	*Fixed Conditions*	*Not Applicable*	Fruit Firmness Respiration Rate TSS	Not Given	(Yasunaga et al. 2010b)

	Tran-Sim	Package Type Packing Material	Vibration Treatment (ASTM) Vibration Treatment (F) Package Type Packing Material	Mango Damage Resonant Frequency	3-17 Hz (Resonance)	(Chonhenchob & Singh 2003b)
Melon	*Trans-Sim*	*Fixed Conditions*	Vibration Treatment (FA)	Fruit Softening Flesh Firmness, Weight Loss Enzyme Activity Cell Wall Constituents Electrical Conductivity	2-10 Hz	(Zhou, Wang, et al. 2015)
Papaya	*Trans-Sim*	Package Type Packing Material	Vibration Treatment (ISTA) Package Type Packing Material	Papaya Damage	4 Hz	(Chonhenchob & Singh 2005a)
Peaches	*Simulation*	*Not Applicable*	Vibration Treatment (D)	Enzyme Activity	5 Hz	(Dantas et al. 2013)
	Trans-Sim	*Fixed Conditions*	Vibration Treatment (F) Packing Method	Skin Discoloration Fruit Firmness	2-25 Hz	(Kitazawa et al. 2008)
Peaches	*Simulation*	*Not Applicable*	Vibration Treatment (C) Fruit Cultivar Fruit Maturity	Bruise Damage	6 Hz	(Vergano, Testin & Newall 1991)
Peaches and Nectarines	*Simulation*	*Not Applicable*	Vibration Treatment (C)	Skin Discoloration	9 Hz	(Crisosto, Johnson, et al. 1993)
Pears	*Simulation*	*Not Applicable*	Vibration Treatment (FAD) Package Height Stack Height	Pear Damage	Not Given	(Li, Cao & You 2011)

Pears	*In-Transit*	Road Condition Packing Material	*Not Applicable*	Pear Damage Fruit Firmness Enzyme Activity Cell Wall Constituents	2-5 Hz 15-20 Hz	(Zhou, Su & Li 2008b)
	In-Transit	Road Condition Package Position	*Not Applicable*	Skin Discolouration Electrical Conductivity Flesh Firmness Enzyme Activity Cell Wall Constituents	2–4.5 Hz 15-40 Hz	(Zhou et al. 2007)
	Trans-Sim	Road Condition Package Position	Vibration Treatment (FA) Package Height	Damage to Pears	10-15 Hz (In-Transit) 8-40 Hz (Simulation)	(Berardinelli et al. 2005)
	Simulation	*Not Applicable*	Vibration Treatment (C) Anti- Browning Solutions (Coatings\ Antioxidants)	Skin Discoloration	3.5-4 Hz	(Feng, Biasi & Mitcham 2004)
	Trans-Sim	Packaging Type Package Position	Vibration Treatment (ASTM) Vibration Treatment (FA) Package Weight\Size Fill Method (Tight, Loose)	Average Injury Score	2–30 Hz	(Slaughter, Thompson & Hinsch 1995, 1998)
	Simulation	*Not Applicable*	Vibration Treatment (ASTM) Vibration Treatment (FA) Fill Method (Tight\Loose) Fill Weight	Mean Bruise Score	3.5 Hz and 18 Hz	(Slaughter, Hinsch & Thompson 1993)
Pears and Plums	*In-Transit*	Transport Route Transport Distance	*Not Applicable*	Damage to Pears\ Plums	1–5 Hz	(Chonhenchob et al. 2009)

Pears and Avocado	*Simulation*	*Not Applicable*	Vibration Treatment (ASTM) Fruit Firmness Packing Material	Bruise Score	Not Given	(Thompson, Slaughter & Arpaia 2008)
Pineapple	*Simulation*	*Not Applicable*	Vibration Treatment (ASTM) Vibration Treatment (F) Package Type Orientation of fruit	Bruise Damage and Decay Skin Discoloration Firmness Titratable Acidity (TA) and TSS Resonant Frequency	6-8 Hz (Resonance)	(Chonhenchob, Kamhangwong & Singh 2008a)
Strawberry	*Simulation*	*Not Applicable*	Vibration Treatment (C) Package Type	Package Performance	2 Hz	(Konya et al. 2016)
	Trans-Sim	Not Given	Vibration Treatment (FAD) Package Height	Skin Discoloration Fruit Firmness Microbial Activity TSS and TA Volatile Organic Compounds	5–20 Hz	(La Scalia, Aiello, et al. 2015; La Scalia, Enea, et al. 2015a)
	Simulation	*Not Applicable*	Vibration Treatment (FD) Package Height	Bruise Percentage\Severity Fruit Firmness Electrical Conductivity TSS and TA	3-5 Hz	(Chaiwong & Bishop 2015)
	Simulation	*Not Applicable*	Vibration Treatment (C) Storage Temperature	Sensory Properties Bacterial Growth	7Hz	(Nakamura et al. 2007)
	Simulation	*Not Applicable*	Vibration Treatment (ASTM) Pre-Cooling Temperature	Shelf Life	Not Given	(Mokkila et al. 1996)
	Simulation	*Not Applicable*	Vibration Treatment (F) Package Height	Strawberry Damage Skin Discoloration Fruit Firmness	5-10 Hz	(Fischer et al. 1992)

Tangerin	*In-Transit*	Truck Type Road Condition Travel Speed Package Height	*Not Applicable*	Tangerine Damage	2–5 Hz	(Jarimopas, Singh & Saengnil 2005)
Tomato	*Simulation*	*Not Applicable*	Vibration Treatment (A)	Tomato Tissue Damage Infrared Spectroscopy of Damaged Tissue	Not Given	(Wu & Wang 2014)
	Simulation	*Not Applicable*	Vibration Treatment (ASTM) Package Type Stack Height	Tomato Damage Transmissibility	Not Given	(Aba et al. 2012)
	Simulation	*Not Applicable*	Vibration Treatment (F) Package Type Ripeness Stage	Modulus Elasticity	3.7 Hz and 6.7 Hz	(Babarinsa & Ige 2012)
Tomato	*Trans-Sim*	Road Condition Vehicle Speed Package Position Fruit Depth	Vibration Treatment (F) Package Height	Tomato Damage	7 Hz	(Ranathunga et al. 2010)
	Simulation	*Not Applicable*	Vibration Treatment (F) Fruit Cultivar Ripeness Stage	Tomato Damage Resonant Frequency	9.1-17.6 Hz	(Idah et al. 2009)
	In-Transit	Road Condition Vehicle Speed Stack Height	*Not Applicable*	Pressure on Fruits Tomato Damage	1.5 Hz and 7 Hz 10-15 Hz	(Geyer et al. 2002)
Watermelon	*Trans-Sim*	Package Position	Vibration Treatment (FAD) Stack height	Percentage Decay of the Modulus Elasticity (PDME)	7.5 Hz (flesh) and 13 Hz (hull)	(Shahbazi et al. 2010)

Vibration Treatment (ASTM)\(ISTA): Standard ASTM\ ISTA profile was used

Vibration Treatment (F): Only Vibration Frequency was considered as a variable ; Vibration Treatment (A) : Only Vibration Acceleration was considered as a variable; Vibration Treatment (D) : Only Vibration Duration was considered as a variable

Vibration Treatment (FA): Vibration Frequency and Acceleration were considered as a variables; Vibration Treatment (AD) : Vibration Acceleration and Duration were considered as variables;

Vibration Treatment (FAD): Vibration Frequency, Acceleration and Duration were considered as a variables

Vibration Treatment (C): Constant Treatment with Fixed Frequency, Acceleration and Duration was used

**Package Position: Refers to the placement of the package along the truck bed; **Package height: Refers to the tier in which the package is stacked along a column of a pallet*

+Stack Height\ Fruit Depth: Refers to the height of the fruit layer inside the package or bin; ++Fixed Conditions: No Variables or Variable Combinations were considered in transit

2.3.2. **Factors affecting the Vibration Damage in Packaged Fruits**

The effects of vibration on fresh produce are related to the energy available for causing mechanical damage (Vursavus & Ozguven 2004) which is dependent on a range of factors. These factors include vibration frequency (Fischer et al. 1992; Hinsch et al. 1993; Slaughter, Hinsch & Thompson 1993), acceleration and transmissibility (Berardinelli et al. 2005; Fadiji, Coetzee, Chen, et al. 2016; Zhang et al. 2011), height and the position of the package (Berardinelli et al. 2003; Hinsch et al. 1993; Jarimopas, Singh & Saengnil 2005; Ranathunga et al. 2010; Soleimani & Ahmadi 2014), vibration duration and travel distance (Shahbazi et al. 2010; Timm, Brown & Armstrong 1996), suspension type or truck type (Ranathunga et al. 2010; Soleimani & Ahmadi 2014), road condition and vehicle speed (Soleimani & Ahmadi 2015; Zhou et al. 2007), fruit depth or stack height (Soleimani & Ahmadi 2014; Tabatabaekoloor, Hashemi & Taghizade 2013) (Table 2.2). The physical properties of the fruits, including properties of the peel and resistance to damage, have been shown to have an influence on the susceptibility to mechanical damage (Opara & Pathare 2014). Additionally, the resonance frequencies of a column of boxes are dependent on the effectiveness of the tight fill packaging, variations in fruit firmness, stacking pattern of the cartons on the pallet and the moisture content of the fibreboard boxes (Hinsch et al. 1993; Slaughter, Hinsch & Thompson 1993). All these factors may influence the extent of the energy exerted on the fruits and thus, the susceptibility to mechanical damage in transit.

2.3.2.1. Critical Frequencies

Previous studies have demonstrated that the critical frequencies that cause significant damage to fresh produce occur in the lower ranges (Lu et al. 2010a; Singh 2006; Vursavus & Ozguven 2004; Zhou, Yan, et al. 2015). The frequency range of 0–10 Hz causes the most damage to the produce (Fischer et al. 1992; La Scalia, Aiello, et al. 2015; Ranathunga et al. 2010). The critical frequency range was further defined by some studies where PSD spectra revealed peaks in the range of 2.5–4 Hz (Hinsch et al. 1993; Slaughter, Hinsch & Thompson 1993; Zhou et al. 2007). Jarimopas, Singh and Saengnil (2005) concluded that the average PSD for all measurements for truck transport was in the range of 0.1–5 Hz and that the PSD decreased beyond this range. Escalated energy levels in the lower frequencies could be attributed to shock suspension responses of the trucks while the frequencies from 5-20 Hz could be attributed to the discontinuity of the road surface (Berardinelli et al. 2003). Fischer et al. (1992) found that the frequency range of 5–10 Hz caused the most damage to grapes and strawberries. More than 55% of the strawberries at the top of the stack suffered severe bruising after the vibration treatment in the 5–10 Hz range. Similarly, Shahbazi et al. (2010) confirmed that the flesh of watermelon was sensitive to frequency of 7.5 Hz and that the hull of the watermelon was sensitive to vibration frequencies around 13 Hz. These findings suggest that lower frequencies, mostly attributed to truck suspension or other similar causes such as package resonance, are a critical factor for damage to the fresh produce being transported. A stack of cartons may resonate at 3–7 Hz with a secondary peak between 10 Hz to 18 Hz (Jones, Holt & Schoorl 1991). This is in concordance with most findings from experiments relating critical frequencies with escalated energy levels.

2.3.2.2. Acceleration and Transmissibility

In the *In-transit* type experiments, the top packages on a pallet have been found to be vibrating at higher acceleration levels than those on the trailer floor as the transmissibility increases in the range of 2–40 Hz (Hinsch et al. 1993; Slaughter, Hinsch & Thompson 1993). For the frequency range of 8–10 Hz the rear top boxes of pears exhibited three times the transmissibility level compared to the bottom box on the floor of the truck (Hinsch et al. 1993). The transmissibility for packing was defined by Vursavus and Ozguven (2004) using Equation (2.2):

$$\textbf{Percentage Transmissibility \% (T)} = \frac{a_b}{a_t} \times 100\% \qquad \text{(Eq 2.2)}$$

a_b –vibration acceleration in the container (g); a_t – vibration acceleration on the table\floor (g)

Higher transmissibility levels can cause fruits in the top layers to move freely inside the package during transit. Fadiji, Coetzee, Chen, et al. (2016) showed that the frequency of 12 Hz exhibited the maximum transmissibility of 243% for packaged apples. Slaughter, Hinsch and Thompson (1993) reported that when the transmissibility level reached 400%, the top boxes became airborne as the vertical acceleration levels exceeded 1 *g*. Vursavus and Ozguven (2004) also found that at 9 Hz the percentage of transmissibility was 160% and when the vertical vibration levels approached 1 g, the top layer of apples moved freely as they received sufficient energy to be weightless against gravity. The study further suggested that the weightlessness caused the apples to rotate and bump against each other, which caused surface discoloration, cell wall fatigue and consequent bruise damage. Similarly, Shahbazi et al. (2010) found that when the acceleration levels in the top layer of fruits approached 1.2 g, the watermelons moved freely resulting in damage and subsequent excessive decay.

2.3.2.3. Position of the Package

The package position on the truck floor has been shown to influence vibration levels experienced by the produce. Hinsch et al. (1993) reported that the highest acceleration level was recorded on the floor at the rear positions, where a vibration peak was exhibited at 3.5 Hz. Berardinelli et al. (2005) found that the global root mean square acceleration values for the entire passage under study were 0.43 ms^{-2} (front), 0.57 ms^{-2} (middle) and 0.92 ms^{-2} (rear) signifying the vibration energy was highest in the rear position of the truck. Many authors were in agreement with this argument that the vibration levels are several times higher in the rear position of the truck than the front (Berardinelli et al. 2003; Hinsch et al. 1993; Soleimani & Ahmadi 2014; Zhou et al. 2007). Ranathunga et al. (2010) found that the rear of the truck produced as high as ten times Root Mean Square (G_{rms}) energy compared to the front of an empty truck bed, which signifies that the produce sitting at the rear of the truck is usually affected more. Barchi et al. (2002) further emphasised this as the acceleration peak in the rear position was about 14 times higher than the peak in the middle position at the peak frequency of 16 Hz and more than 20 times higher than the peak in the front position which occurred at 18 Hz. In summary these findings therefore suggest that the rear of the truck bed exerts the highest vibration, followed by the middle and then the front positions.

2.3.2.4. Height of the Package

Fruit damage levels can correlate with the height of the package in a column. This may be due to the increased peak acceleration from bottom to top. The top box of the stack can show twice the vibration of the middle box and about four times the vibration of the bottom box (Fischer et al. 1992). The highest damage in tangerines occurred in the top crate for every combination of tested variables (Jarimopas, Singh & Saengnil 2005). Barchi et al. (2002) found that the acceleration on the crates increased from bottom to top in the range of 5 Hz to 20 Hz and the resonance peak was identified at 9 Hz. Zhang et al. (2011) used a sinusoidal vibration table with the frequency range of 3–100 Hz with 5 ms^{-2} peak acceleration to measure the vibration impact on cherry tomatoes. The resonance frequencies were found to be 36.61 Hz (bottom), 10.76 Hz (middle) and 6.44 Hz (top) which implied that the resonance frequencies reduced from the bottom to top while the resonance peak acceleration was increasing from the bottom to top.

2.3.2.5. Suspension Type or Truck Type

Truck suspension type has been shown to influence vibration levels. This influence might also be affected by the type of the truck as not only the shock from the road surfaces but part of the truck engine and chassis vibration itself may transfer onto the cargo. The transmissibility of such vibration may be dependent on the damping properties of the chassis structure of the truck and how firmly the pallets and packages are stacked. Timm, Brown and Armstrong (1996) showed that the vibration damage for apples may differ according to the suspension type of the truck. Air ride suspension trucks provided reduced magnitude of vibration and cause less damage to apples compared to leaf spring trucks (Hinsch et al. 1993; Timm, Brown & Armstrong 1996). Usuda et al. (2006) also found that 60% of the vibration peak could be reduced by changing the suspension from leaf spring to air ride. Soleimani and Ahmadi (2015) revealed that the vibration levels for leaf spring suspension trucks are higher than the air ride suspension trucks. For both trucks the PSD peaks occurred at 3 Hz and 1.46 Hz which also signifies that the peaks occur at lower frequencies. Ranathunga et al. (2010) reported that the tyre air pressure of the truck is also related to the resultant vibration. Pierce, Singh and Burgess (1992) concluded that air ride suspension may exhibit lower vibration only when they are maintained properly and a malfunctioning air ride suspension may produce higher vibration levels than that for leaf spring suspension at the lower frequencies.

2.3.2.6.Road Condition and Vehicle Speed

The road condition and the vehicle speed have been shown to be directly related to the resultant vibration and hence the extent of produce damage. Soleimani and Ahmadi (2015) concluded that the vibration levels caused by dirt roads was the highest, followed by asphalt roads and highway roads. Similarly, Jarimopas, Singh and Saengnil (2005) compared the recorded vibration levels with the standard (of ASTM) and concluded that concrete and asphalt roads produce less vibration than the recommended maximum, while unpaved laterite roads result in severe conditions at higher speed levels. Additionally, the greatest damage to tangerines was found on laterite roads followed by concrete roads. The least damage levels were recorded on asphalt roads and also the damage levels increased with speed. Zhou et al. (2007) found that the highest G_{rms} value was recorded for tertiary roads (2.09 ms^{-2}) and the lowest was recorded on the highways (1.78 ms^{-2}). Similarly, Ranathunga et al. (2010) measured the relationship between the International Roughness Index (IRI) of roads and the PSD of the recorded vibration. IRI is defined as the ratio between the accumulated suspension motions to the distance travelled by the vehicle. It was found that poor quality roads with an IRI of between 10–5 produce more vibration than the fair or good quality roads with an IRI in the range of 3.5–0.9. Fei Lu and Satake (2008) analysed the vibration levels in truck transport over seven speed intervals and concluded that higher speeds were positively correlated with G_{rms} vibration in both vertical and lateral directions. This suggests that the condition of roads and vehicle speed are important parameters in transit vibration.

2.3.2.7.Exposure Duration

Vibration duration and the travel distance were correlated with the produce damage, where longer duration and distance result in higher levels of vibration damage (Timm, Brown & Armstrong 1996). La Scalia, Aiello, et al. (2015) found that strawberries showed a reduction in appearance and structural characteristics with the increased duration of vibration. An increment in the vibration duration of 30 minutes in simulation resulted in a 1.52 times higher percentage decay score for watermelon (Shahbazi et al. 2010). Soleimani and Ahmadi (2014) found that, although highways produced smoother road conditions, the vibration impact was more significant than that of the poor roads due to exposure to extended transportation time. Vursavus and Ozguven (2004) calculated the Equivalent Severe Bruise Index (EBI) for apples subsequent to the simulation (8.2 Hz and 12.6 Hz) with the measured acceleration levels (0.33 g and 0.63 g) for the durations of 10, 15 and 20 minutes. The study indicated that the EBI value could reach as high as 40% when the vibration duration increased from 10 minutes to 20 minutes. These studies together conclude that the duration of exposure to vibration is critical to produce damage.

2.3.2.8.Depth of Fruit within a Package (Stack Height)

A few studies have measured the effect of the depth of the fruit inside a container on fruit damage. The depth is calculated from the top of the corrugated box to the position of the produce (Ranathunga et al. 2010; Soleimani & Ahmadi 2014). The same variable has also been defined inversely as the *stack height* in some studies (Shahbazi et al. 2010; Tabatabaekoloor, Hashemi & Taghizade 2013) where the fruit depth is measured from the top of the container and the stack height is measured from the bottom of the container. Soleimani and Ahmadi (2014) confirmed that vibration levels were higher in the top layers in the stack compared to the levels at the bottom of the crate. Shahbazi et al. (2010) showed that the damage to watermelon hull at the three positions inside the bin (top, middle, bottom) had a relationship with the percentage decay of the modulus elasticity of the fruit, confirming the fruit at higher levels exhibit more damage. These studies emphasise that vibration damage increases with the stack height of the fruit inside the package.

2.3.2.9.Other Factors for Vibration Damage to Fruits

Several other variables including fill status, package type, fruit position inside the package and cushioning between the layers of fruit have been considered as influential for the level of vibration damage in fruits, although these parameters have been less frequently examined. Slaughter, Hinsch and Thompson (1993) showed that vibration damage can be reduced by tight-fill packaging where the fruits are immobilised. Timm, Brown and Armstrong (1996) showed that the damage to apples in plastic bins was lower compared to wooden or plywood bins. Differences in apple damage levels were detected for different fruit positions inside the bin such as, if the fruit was placed in the middle of each bin or against a side wall of the bins. Barchi et al. (2002) confirmed that vibration-absorbent sheets reduced the damage to tangerines by 20–40%, as they provided cushioning effect between the layers of fruit and also between the fruit and the bottom of the crate.

2.3.3.**Challenges in Field Vibration Data Collection**

Field and laboratory experiments on the effect of vibration on fresh fruits have been conducted by different researchers for several decades however, there are pragmatic limitations in these experiments even today. These limitations mostly restrict the characterization of the field transport environment and affect the accuracy and reproducibility of field vibration and shocks within simulated laboratory experiments. The limitations in vibration data collection are discussed in this section and the challenges in laboratory vibration simulation are discussed in Section 2.3.4.

2.3.3.1. Limited Time Sampling

A major challenge when collecting vibration data in-transit is the memory capacity and/or power availability of the accelerometer devices which restricted the data recoding time. The early *In-transit* studies used digital audio tape recorders (Berardinelli et al. 2005; Vursavus & Ozguven 2004) while modern vibration measuring devices are equipped with internal memory or data can even be stored on a SD card mounted to the device. However, due to the limitations of memory capacity, peak acceleration override methods were adopted in the past (Garcia-Romeu-Martinez, Singh & Cloquell-Ballester 2008) with potential consequences that useful data along the track may be overridden by a new event. Overriding disables tracking events through the analysis of the timestamp. Therefore, data overriding within the same passage is not advisable. Having GPS tracking capability in the vibration and shock devices also gives an added advantage by providing a spatial meaning to data.

Vibration signals which have been recorded only during a stretch of the journey or during a limited period, such as fixed interval limited sampling, randomised sampling or signal triggered sampling have been frequently reported (Barchi et al. 2002; Berardinelli et al. 2005; Hinsch et al. 1993; Jarimopas, Singh & Saengnil 2005; La Scalia, Aiello, et al. 2015; Timm, Brown & Armstrong 1996). Some researchers used a threshold for acceleration, and below the threshold the logging was not performed (Dunno 2014; Ishikawa, Kitazawa & Shiina 2009). However, having a higher acceleration threshold may only capture the shocks instead of vibration. Continuous data logging without a set threshold is limited by the power or the memory capacity of the device, and the first to run out determines the time of continuous use for a device. Given that, it will be difficult to collect high frequency data throughout transit time for days, especially in interstate supply chains. An alternative proposition is to sample and collect a fraction of the journey to represent the vibration responses in the entire passage.

Several studies have been conducted on the sampling parameters for vibration, with the objective of finding out the minimum duration of sampling required to characterise vibration in a given route. Rouillard and Lamb (2008) suggested that recording data for $1/8^{th}$ of the journey is sufficient for this purpose, while Fei Lu and Satake (2008) found that $1/30^{th}$ for highway travel and $1/15^{th}$ for local roads of the journey is sufficient for the purpose. The differences in sampling parameters given in these studies shows that the minimum duration of sampling is highly dependent on the variables such as the route condition, travel duration and distance. This emphasises that the best sampling interval may be found only after finding out which fractions of sampling time ideally represent the anomalies of vibration within each route segment.

Another approach is to sample vibration responses at different variable settings for a limited period for each road segment and sample shock responses throughout the journey. In this approach, the vibration responses could be sampled for different speed intervals and road segments to develop the respective PSD profiles while the shocks can be recorded as and when they occur throughout the journey by specifying an appropriate shock threshold. Whichever sampling approach is used, the data sampling time can be extended by applying recording thresholds for acceleration to shut down the devices while the truck is not moving or the engine is turned off. Dunno (2014) used this method to capture vibration data while the truck was in motion by depicting a very low (0.1 *g*) signal threshold, potentially capturing all the vibration and shock events pertaining to the journey. This is an effective approach in supply chains extending to several thousands of miles in transit as there are mandatory intermittent rest stops for truck drivers required by regulations in respective countries.

2.3.3.2. Vehicle Speed in Experiments

Most vibration experiments, irrespective of the experimental design, have been conducted to understand the effects of vibration parameters on the internal or external changes in fruits. However, due to constraints such as road conditions or traffic, it is practically impossible to travel constantly at a specified test speed for a long duration. This makes it difficult to reach conclusions on how vehicle speed may affect vibration levels and subsequent produce damage. Therefore, special account is needed when correlating fruit-mechanical damage with vehicular speed levels during In-Transit experiments.

In real In-Transit experiments the speed would be an average rather than a constant. Correlating average speed with the effects on produce is not an ideal method but may work for highway roads where the speed can be kept literally constant for a longer duration. Vursavus and Ozguven (2004) used this method to correlate the effect of transit speed with vibration where the speed was held constant at 50 kmh^{-1} to obtain different acceleration measurements. This controlled experimental method is more suitable for examining the significance of vehicle speed on vibration, rather than averaging the speed for the entire journey to correlate with the vibration intensity. A better method would be to record the vibration levels at each speed interval, derive the PSD profile and replicate the signal in a controlled simulation to ascertain the damage or changes in the produce.

2.3.3.3. Transient Shocks in Vibration Profiles

Some researchers have argued that analysing the shock responses within the vibration profile may affect the quality of data produced in the analysis. This was emphasised in the work by Kipp (2001a) as the probability density function (PDF) resulting from the data mixed with shocks and vibration cannot be considered random and therefore cannot be described accurately with the PSD alone. When the shocks are removed, the PDF can be approximated to a Gaussian distribution. Kipp (2008) further suggested that improvements can be made to the single spectrum PSD approach due to the fact that there is an increased recognition of the non-stationery aspects in-transit as the shock responses cannot be superimposed on vibration.

It is debatable that, if such transient shock responses are not separated from the in-transit vibration responses, the time domain acceleration data may present a misleading picture of the vibration levels of a given route. This may also affect the PSD profile in the frequency domain. Fruits may behave differently to transient shocks compared to vibration and the effect of transient shocks with a significant energy content cannot be neglected (Nei et al. 2008). Shocks also occur within the transit passage, hence they are an integral part of the journey, and therefore shocks should be represented in the overall PSD profile. However, when creating the averaged PSD profiles for simulation purposes, these transient events will also be averaged and will not be significantly represented.

To resolve these issues some researchers have split the spectra into two or three segments of different vibration intensities (Griffiths et al. 2013). For instance in previous research, the spectra was analysed where 30% of the higher acceleration levels were separated from the lower 70% to create two PSD profiles for the same journey (Singh 2006). This method can be identified as split-spectra decomposition. Although it is based on logic, identifying the split is a challenging task. Fei Lu and Satake (2008) conducted an experiment into the effects of sampling parameters on shock and vibration and concluded that a 0.7 g threshold could be used to differentiate vibrations from shocks. Ishikawa, Kitazawa and Shiina (2009) measured vibration and shock during the truck transport passage with a 0.3 g trigger threshold for vibration and 3 g threshold for shock data collection. Nevertheless, determining the threshold would be a challenge without a proper understanding of the magnitude of shocks encountered in the passage, as shocks are essentially characterised by the condition of the road. Frequent bumps and potholes along the road may constitute the force characteristics on the RVL interaction which may ultimately transfer as energy to the produce (Jones, Holt & Schoorl 1991). Determination of the crest factor (defined as the ratio of peak value to RMS value of the waveform) might be useful to detect transient shock events in a composite signal (Lepine, Rouillard & Sek 2015a). However, it is suggested that the threshold to differentiate a shock from the rest of the broadband vibration needs to be defined.

Identifying the number of shock responses separately in each road segment in the distribution chain may also provide an overall understanding of the transport conditions. Once the shock responses in a given distribution environment are identified, a comparative shock simulation may ideally reveal how the cumulative shocks affect the produce and failure mechanisms of the packages that lead to damage to the fruit. An approach to superimpose transit shocks on an accelerated random vibration test profile was suggested in an early study by Kipp (2001a). The author argued that this method is better than increasing the intensity (G_{rms}) of the overall PSD profile with large acceleration levels to account for shocks during product simulation. However, the shocks generated from a drop test on packages may not be equivalent to transit shocks during truck transport, as the force characteristics exerted on the packages will be different. If the shock responses are performed on simulated packages it needs to be a close approximation of the shocks encountered in the field transport.

Another approach to characterising shocks from broadband vibration is to decompose the spectra into segments with different kurtosis levels that vary the sharpness of the peak of a frequency-distribution curve. For this purpose, one of the most widely used methods is wavelet based decomposition which uses the wavelet algorithm to characterise the shocks within vibration profiles. Griffiths et al. (2016) proposed a simulation method based on wavelet analysis to decompose the vibration simulation signal. Comparison of the overall RMS value, the kurtosis of the constructed PSD signal, and the PSD pertaining to field data gave a better correlation of scuffing damages on produce subjected to the simulation, when compared with the field experience. Several authors also reported that the wavelet analysis of the random vehicle vibration produced improved simulation results when compared with the damage produced in field experiments (Griffiths et al. 2016; Lepine, Rouillard & Sek 2015b; Nei et al. 2008). In another recent study (Lepine, Rouillard & Sek 2017), the capability of machine learning to detect shocks in road vibration signals was investigated and reported to also have achieved successful correlation. Further research on these methods to characterise damage on different fruits may develop more accurate test profiles to be used in simulation compared to the conventional averaged PSD spectra-based simulation approach.

2.3.4. **Challenges in Vibration Simulation Experiments**

When there are different PSD profiles generated during the same journey for different variable settings (such as speed, road condition), the PSD profile to be used in the simulation experiment needs to be decided. The conventional approach is to average the PSD profiles or weight and accumulate to derive a global PSD profile for simulation purposes (Berardinelli et al. 2005). In an alternative method, Timm, Brown and Armstrong (1996) used the worst-case PSD input with peak accelerations as the input for simulation representing the worst-case trip scenario. Another approach has been to use fixed time intervals for vibration with the simulator operating at a mean acceleration for a given period. Shahbazi et al. (2010) used this method to simulate the vibration effects on watermelons by using mean values within the highest distribution intervals for frequency and acceleration. However, vibration signals generated with a mean acceleration and a fixed frequency may not ideally represent the real field transport conditions during the simulation.

Some researchers have emphasised the non-stationery and non-Gaussian nature of the road vehicle transport (Charles 1993; Richards 1990; Rouillard, Sek & Perry 1996; Sek 1996). The averaged PSD, which is widely used for simulation, has a constant RMS level and disregards random fluctuations in transport routes (Rouillard & Sek 2013). Consequently, Sek (1996) suggested that the Gaussian nature of the acceleration signal in road vehicle transport has to be determined on a case by case basis. This argument is valid when the route contains frequent road irregularities and an averaged PSD profile would not reasonably replicate the field experience during simulations. Rouillard and Sek (2010) suggested an approach to simulate non-Gaussian transport vibration by synthesising the signal into a series of Gaussian processes of different RMS values and durations. Bins or segments with different RMS values can be created, based on the statistical occurrence of different acceleration intensities within the signal, and then collated to generate a synthesized signal (Rouillard & Sek 2013; Rouillard & Sek 2010; Sek 1996). This method decomposes non-stationery random vibration into a series of independent Gaussian segments with different amplitudes. In a recent study, Hosoyama, Saito and Nakajima (2013) proposed a method based on non-Gaussian simulation which could better characterise the accumulated fatigue on the package contents compared to the conventional simulation approaches. The study concluded that non-Gaussian input acceleration influenced the response acceleration of the package contents and the kurtosis of the vibration table affected the accumulated fatigue of the contents inside the package.

Alternate simulations based on Weighbull distribution (Fei et al. 2014), and a method based on vehicle and road characteristics (Rouillard & Sek 2013) when the PSD profiles of the routes are already known, have also been reported to have achieved similar success. Rouillard (2008) also suggested using pavement profile data available from road maintenance authorities or agencies in the respective countries as an approach for simulating non-stationary vehicle vibration. Increasingly this approach of non-stationery and non-Gaussian phenomena of random vehicle vibration has gained acceptance in many contemporary studies.

More realistic simulation contributes to design optimum packaging for different fruits, which may prevent designing of over-packaging or under-packaging. Both these scenarios lead to increased cost and wastage in fruit supply chains. Therefore, a realistic simulation of the field experience is vital for package design and optimisation research. In the case of ASTM or ISTA certain test standards are specified for repetitive shock, resonance test or random vibration testing. Simulations could be performed as single or multi-axis vibration (Dunno 2014). Kipp (2001a) argued that the use of a standard profile in simulations could be debatable as they might not represent the actual transport conditions. In an earlier study Turczyn et al. (1986) argued that using set standards such as ASTM in simulation may exert intensified effects on produce, and therefore a limited time simulation is more than adequate as a longer duration will result in adverse damage in produce.

The duration of simulation has to be carefully determined considering the objectives of the experiment. The use of shaker simulations can be costly and therefore it might not be viable to simulate journeys which takes many hours or days to replicate. Consequently time compressed simulations should be considered. A simulation could be termed as effective if it produced similar results compared to the field experience. This means that, if the damage in the simulation corresponds to the field, such an experiment would probably be a close approximation for a good simulation (Kipp 2001a). There have been studies based on conventional simulation approaches, which have resulted in outcomes similar to field experience (Timm, Brown & Armstrong 1996).

Jung and Park (2012) simulated a standard ASTM vibration profile for a total journey duration of 331 minutes, replicating the duration of the entire journey in transit to measure the effect on apples. This is not a practical approach in many transport scenarios such as long duration interstate transport. Conversely, Kipp (2001a) implied that time-history reproduction of vibration data in simulation is of less statistical significance and limited to simulation frequencies below 50 Hz (restricted by the simulator capabilities). Furthermore, it can be argued that using a composite PSD in simulation to represent a transit passage may result in 'averages' to be 'averaged'. This is also applicable to the vibration standards such as ASTM and ISTA which are still widely used. A possibility to compress the simulation time is mentioned in the literature and identified as focused simulation(Kipp 2001a) given by the Basquin model(Lepine, Rouillard & Sek 2015a) in Equation (2.3):

$$\frac{t_j}{t_t} = \left(\frac{I_j}{I_t}\right)^k \qquad \text{(Eq. 2.3)}$$

Where t_j is simulation time; t_t is actual transit time; It is intensity (Grms) in the original profile; Ij is intensity in the test profile; k is constant associated with the product for which k=2 is generally used while rarely some studies use k=5. The maximum compression should be 5:1 to preserve the validity (Kipp 2001a).

Dunno (2014) conducted an important study to find out if the time-compressed profile correlates with the actual in-transit vibration outcomes for produce. The results showed that time-compressed (accelerated) simulation did not correlate with the field experience. However, the non-stationary and non-Gaussian simulation method correlated with the field experience and hence could be used to reduce the simulation time. Similarly Griffiths (2011) conducted a study on apples to determine if a Multiple Degrees of Freedom (MDOF) time-compressed simulation would produce similar scuffing damages on apples compared to actual road transport. It was concluded that the modulated RMS simulation and the single spectra PSD approach in a time compressed setting (5:1 where k=2) produced similar levels of damage to time history replication. Furthermore, it revealed that a Single Degree of Freedom (SDOF) Gaussian equivalent simulation gave the best approximation of the scuffing damage on apples. However, a suitable k value needs to be used if a time-compressed simulation is considered in future studies. Shires (2011) concluded that a lower level of time compression was required for the simulation of air-ride suspension trucks to reduce the error sensitivity. This implies that the higher the time compression is, more errors will be encountered in simulation. These studies suggest that more research needs to be conducted on different fruits to find out which simulation approach may best replicate the actual field experience specially for simulation to be used for the purposes of packaging optimisation.

2.4. Mechanical Damage Assessment in Fruits

2.4.1. Damage Measurement

It is a significant challenge to accurately measure damage in fresh fruits caused by external forces. Several researchers used subjective (Jiménez-Jiménez, Castro-Garcia, et al. 2013; Toivonen et al. 2007; Van et al. 2006) and objective (Hadi, Ahmad & Akande 2009; Holt & Schoorl 1977; Vursavus & Ozguven 2004) methods to evaluate various types of fruit-mechanical damage. Cosmetic damages can be identified by visual inspection as the skin discolour due to enzymatic browning of the tissue (Zwiggelaar et al. 1996). Objective damage assessment requires to measurement of each damage on fruits and usually involve cutting open the fruit at the point of impact and measurement (Mazhar 2015), which can be time consuming and restricts application in an industry environment. Therefore, qualitative damage assessment with respect to visual assessment charts have been widely used (Cantwell 2007), due to practicality and time efficiency (Mazhar 2015) in damage measurement.

In the fresh produce industry, it is common to use pre-determined visual charts for quality assessment. The charts are used to categorize visual damage by the severity and the size of the affected area. In visual assessment, a score is given based on the reference scale to indicate the damage severity (Toivonen et al. 2007) and therefore, visual inspections may not have demarcated quantitative boundaries for evaluation.

Hence, visual assessment is limited to a qualitative evaluation which can be subjective and comparatively less precise (Prange & Delong 1998; Toivonen et al. 2007). However, Jiménez-Jiménez, Castro-Garcia, et al. (2013) in their study reported that there was a liner correlation (r^2=0.95) between the bruise area estimation in table olives by visual assessment when compared with objective image analysis. To overcome the limitations in the subjective damage assessment by the visual charts, several objective assessment methods have been developed.

The objective damage assessment methods use a variety of tools and parameters to measure damage on fruits. These include a rating or a score based on the diameter of the damage, depth of the damage tissue or damaged area (Hadi, Ahmad & Akande 2009; Jiménez-Jiménez, Castro-Garcia, et al. 2013). Several researchers used digital calipers to measure the diameter and the depth of the damage tissue (Ahmadi et al. 2010; Timm, Brown & Armstrong 1996) to calculate the damage area and/or bruise volume. When measuring the diameter for bruise quantification, it was presumed that the damage area is circular. Damage area is more suitable to characterize the surface damages than using a single dimensional vector such as the diameter (Li & Thomas 2014). Quantitative measurements were also used to derive a comparable quantitative score for a given fruit sample, such as the equivalent bruise index (EBI) which was used to quantify damage on apples (Vursavus & Ozguven 2004). Development of a damage score or an index permits comparison of damage levels between two or more fruit samples, especially in packaged fruits.

In objective measurements, a formula for bruise volume or bruise area is needed to quantify the damage. Calculating the bruise volume was mostly used to measure the impact bruises and punctures (Chen & Sun 1981; Diener et al. 1979) due to the potential internal damages in fruit in additional to the surface damage. This required measuring the depth of the bruised flesh. Bruise volume can be calculated assuming the fruit is either spherical or ellipsoidal (Bollen, Nguyen & Rue 1999) However, these methods were mostly invasive and performed manually, taking considerable time for quantifying damages in individual fruit. Different quantitative methods were used to derive the bruise volume yet based on similar parameters such as bruise depth and width as summarized in Table 2.3.

For the surface bruises and other mechanical damage such as abrasions and scuffing, damage area is a better measurement parameter than the bruise volume (Li & Thomas 2014). Most surface damage area quantification methods presumed that the area was elliptical or circular. Acican, Alibaş and Özelkök (2007) used a planimeter to increase the accuracy of area measurements. However, this method required tracing each damage onto a trace paper before evaluation, which was time consuming. Bruise width can be measured along its major and minor axis considering the bruise is not circular (Fig.2.4) (Opara &

Pathare 2014).Measurement along the two major axis of a damage is necessary to quantify the area or volume of the bruise considering the affected area or volume of the fruit is either elliptical or ellipsoidal (Holt & Schoorl 1977; Lu et al. 2010b).

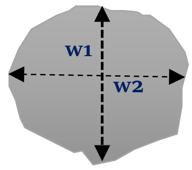


Figure 2.4: Bruise width along the Major and Minor Axis are Denoted by w1 and w2 (Bollen, Nguyen & Rue 1999)

Table 2.3: Different formulas for Bruise Volume or Bruise Area

Formula	Reference
$BV = \frac{\pi}{6} h(0.75D^2 + h^2)$	(Diener et al. 1979)
$BV = \frac{\pi}{6} hD^2$	(Chen & Sun 1981); (Ahmadi et al. 2010)
$BV = \frac{\pi}{8} hw^2$	(Jarimopas et al. 2007; Kitthawee et al. 2011)
$BV = \frac{\pi h}{24}(3w_1 w_2 + 4h^2)$	(Lu et al. 2010b)
$BA = \frac{\pi}{4} w_1 w_2$	(Lu et al. 2010b)

BV- Bruise Volume; BA- Bruise Area; D- Bruise Diameter; h- Bruise Depth, w- Bruise Width; w1 and w2 are bruise widths according to major and minor axis

2.4.2. Damage Indexes

External damage in fruit are collectively termed as *'Bruising'* by many researchers for the convenience of study. However, the indexes referred to as "bruise indexes" or "bruise scores" may also be applicable to other mechanical damages such as scuffing and abrasion damage in fruits. Different damage assessment scales have been used in the literature (Hadi, Ahmad & Akande 2009) to evaluate fruit damage. These scales were mainly based on objective measurements (Blahovec 1999; Pang, Studman & Ward 1992; Vursavus & Ozguven 2004) or visual assessment charts (Cantwell 2007; Ekman et al. 2011; Jiménez-Jiménez, Castro-Garcia, et al. 2013) as described in Section 2.4.1. Objective assessment indexes used in previous studies were based on the bruise diameter (Blahovec, Mareš & Paprštein 2004; Vursavus & Ozguven 2004), bruise area (Hadi, Ahmad & Akande 2009; Jiménez-Jiménez, Castro-Garcia, et al. 2013), or bruise volume (Holt & Schoorl 1977; Opara 2007; Pang, Studman & Ward 1992).

Bruise scores represent relative damage to the whole fruit and are usually expressed as an incremental scale according to the severity of damage. For an example in a study by Prange and Delong (1998), a score of '0' was used to indicate no damage and a score of '3' to indicate severe damage in apples. Similarly, other studies have used damage scores numerically escalating with the severity of damage (Jiménez-Jiménez, Castro-Garcia, et al. 2013; Jiménez et al. 2010; Van et al. 2006). However, Kappel et al. (2009) used a decreasing numerical scale by representing a severe bruise by a score of '1' and absence of bruising by a score of '4' in cherries. Damage indexes based on bruise impact energy and bruise susceptibility have also been used in the literature. This includes general bruise susceptibility (GBS) or specific bruise susceptibility (Opara 2007), bruise sensitivity or bruise Resistance (Pang, Studman & Ward 1992) and bruise resistant coefficient (Holt & Schoorl 1977). Bruise Susceptibility is defined as the ratio of bruise volume to the impact energy absorbed during the impact whereas the bruise resistance is its inverse (Pang et al. 1996). Holt and Schoorl (1977) defined a Bruise Resistant Coefficient (BRC) as the slope of the liner function between the bruise volume and absorbed energy with a zero constant. Frequently reported damage indexes and scores used in literature on a variety of produce are summarized in Table 2.4.

Table 2.4: Indexes for Mechanical Damage Assessment

Produce	**Score/ Index**	**Description/ Equation**	**Reference**
Apple	0-3 Score	0- Absent 1- Slight 2- Moderate 3- Severe	(Prange & Delong 1998)
	1-4 Score	1- No apparent bruising 2- Light brown bruise with no defined edge 3- Moderately dark brown bruise with a well-defined edge 4- Dark brown bruise	(Toivonen et al. 2007)
	Equivalent Severe Bruise Index (EBI)	%EBI = (0.1) x Trace Bruises + (0.2) x Slight Bruises + (0.7) x Medium Bruises + (1.0) x Severe Bruises Equivalent Diameter of aggregate Bruises (mm); None < 12 mm; Trace 12-19 mm; Slight 19-25 mm; Medium 25-32 mm ; Severe > 32 mm	(Vursavus & Ozguven 2004)
	GBS- General Bruise Susceptibility (mm^3J^{-1}) SBS- Specific Bruise Susceptibility ($mm^3J^{-1}g^{-1}$)	$GBS = \frac{BV}{IE}$ $SBS = \frac{GBS}{M_F}$ BV- Bruise Volume; IE- Impact Energy; MF- Mass of fresh Fruit or Vegetable Specimen (g)	(Opara 2007)
	Bruise Sensitivity (BS)	Ratio of Bruise Volume to Loading/Impact Energy	(Blahovec 1999; Pang et al. 1996)

	Bruise Resistance (BR)	Ratio of Bruise Energy to Bruise Volume	(Pang et al. 1996; Pang, Studman & Ward 1992)
	Bruise Resistant Coefficient (BRC)	Slope of the linear function between Bruise Volume and Absorbed Energy (Constant is zero)	(Akkaravessapong, Joyce & Turner 1992; Holt & Schoorl 1977)
	Bruise Threshold	Drop Height at which bruising begins to occur for a given Mass, Shape and Impact Surface	(Bajema & Hyde 1998)
Olive	0-3 Score	0- No Bruising 3- Heavy Bruising	(Jiménez et al. 2010)
	0-4 Score	0- Sound (No Damage) 1- Slight 2- Moderate 3- Severe 4- Cut and Mutilation	(Jiménez-Jiménez, Castro-Garcia, et al. 2013)
	Bruise Index (BI)	$BI = \frac{A_1}{A_2} \times 100$ A1- Total Number of Pixels in the bruised area A2- Total number of Pixels corresponding to the Fruit	(Jiménez-Jiménez, Castro-Garcia, et al. 2013)
	Fruit Damage Index (FDI)	$FDI = \frac{0X_0+1X_1+2X_2+3X_3+4X_4}{X_1+X_2+X_3+X_4}$ X0-4- Number of Sound, Slight, Moderate, Severe Damaged Fruit	(Jiménez-Jiménez, Castro-Garcia, et al. 2013)
Cherry	1-4 Score	1- Severe bruising 2- Moderate Bruising 3- Slight Bruising 4- No Bruising	(Kappel et al. 2009)
Pomegranate	1-9 Hedonic Scale	1- Unusable 3- Poor 5- Good 7- Very Good 9- Excellent	(Defilippi et al. 2006)
Tomato	0-1 Binary Score	0- Absence 1- Presence	(Van et al. 2006)
Pear	Bruise Spot Ratio (BSR)	The ratio of Bruise spot diameter (d) to the Bruise Spot Thickness (t)	(Blahovec, Mareš & Paprštein 2004)
Oil Palm	Bruise Index (BI)	$BI = \frac{1X_1+2.5X_2+5.5X_3+10X_4}{100}$ X1-4- Percentage Weight of fruits with No Bruise, Minor Bruise, Moderate Bruise and Major Bruise as per the Bruise Area	(Hadi, Ahmad & Akande 2009)

It is evident that the damage assessment methods for fruits used in the literature have been different. However, they are based on similar calculation and measurement mechanisms. Even for the same produce the bruise indexes can be defined and applied differently (Table 2.4). Derived damage scores are used for relative comparison between samples subjected to various treatments versus the control or to quantify the decay of a sample of fruits over a given period. Destructive damage assessment methods are not in regular use in an industry setting. They require time and do not easily match the volume of fruits transferred through a given quality inspection or a grading point. Therefore, most industrial applications of damage quantification in fruits have been limited to visual charts (Ekman et al. 2011) for quality assessment.

2.4.3. Non-Destructive Damage Assessment

Non-destructive damage assessment methods have been researched in the recent past with the development of imaging technologies, for the measurement of visible and non-visible fruit damage. They have been used to rapidly identify damage in fruits during the early stage packaging operations, as post-harvest damages in fruits may be not instantly visible (Müller et al. 2012; Sila et al. 2008). Fruit grading and sorting applications have been developed based on machine vision and digital image recognition. For example, Keresztes, Goodarzi and Saeys (2016) concluded that a real time pixel-based bruise detection method could be used to detect fresh bruises in apples with a 98% accuracy within a processing time of 200 milliseconds per apple. Conventional imaging techniques based on red-green-blue (RGB) colour space coupled with image analysis have been used to measure and quantify surface bruises in fruits (Jiménez-Jiménez, Castro-Garcia, et al. 2013). However, the digital imaging may not be an effective option to detect early bruises and underlying flesh damage.

Advanced vision systems were studied in the recent past for damage detection in fresh produce. This included hyper spectral imaging (Huang, Zhang, et al. 2013; Lu 2003; Xing et al. 2005), multi spectral imaging (Huang, Zhao, et al. 2013; Kleynen, Leemans & Destain 2005) and near Infrared (NIR) spectroscopy (Guillermin, Camps & Bertrand 2004; Zhang et al. 2013). These non-destructive damage detection techniques were used to assess damages on a variety of fruits including apples (Baranowski et al. 2012; ElMasry et al. 2008; Lu 2003; Luo, Takahashi, et al. 2012; Xing et al. 2005; Xing, Saeys & De Baerdemaeker 2007); pears (Dang et al. 2012; Zhao et al. 2010); orange (Li, Rao & Ying 2011), strawberry (Nagata, Tallada & Kobayashi 2006), jujube (Zhang et al. 2013), kiwi (Lü et al. 2011), peach (Zwiggelaar et al. 1996), mango (Vélez Rivera et al. 2014) and longan (Pholpho, Pathaveerat & Sirisomboon 2011). However, there are limitations for the widespread commercial use of these artificial vision systems for fruit grading.

Multi spectral or hyper spectral analysis attempt to identify and classify damage areas and find correlations between spectral characteristics and physiochemical properties of damaged areas in fruit (Baranowski et al. 2012). The difference between hyper spectral and multi spectral imaging is that the former generates a hyper cube of the image in continuous spectral bands while the multi spectral images are captured on limited bands of interest. This is generally at the wavelengths with highest discrimination between the sound and bruised tissue (Lorente et al. 2011). Bruise tissue has lower reflectance compared to the normal tissue (Ariana, Lu & Guyer 2006; Baranowski et al. 2012; ElMasry et al. 2008), and the reflectance may increase over time (Lu 2003). The reflectance difference in the bruised tissue occurs as the light scatters more in the bruised area due to the cell wall destruction and chemical changes (Kondo et al. 2005). This reflectance difference has enabled bruise detection in fruits using computer vision systems.

There is a lack of published research on the use of hyper-spectral, multi-spectral imaging for bruise detection and damage assessment in bananas. However, digital image processing and computer vision have been used in bananas for size estimation (Hu, Dong, Malakar, et al. 2015) and, maturity and ripeness estimation (Hu, Dong, Liu, et al. 2015; Ji et al. 2013; Prabha & Kumar 2015; Zhao et al. 2016). Rajkumar et al. (2012) studied maturity stages, internal quality attributes such as the moisture content, soluble solids content in bananas using the NIR spectrum. However, there was no correlation found between the spectral features and the external damage. Hu et al. (2014) investigated the possibility of image processing techniques coupled with double k-means clustering algorithm for banana image segmentation. They reported that the method failed to differentiate mechanical injuries from senescent spots in bananas.

One of the key challenges in implementing non-destructive damage detection and assessment systems in real time fruit inspection lines is still the overall accuracy in damage detection. Even a marginal error in classifying an undamaged fruit may amount to a substantial cost and wastage to the industry. Misclassification of bruised fruit as undamaged may also complicate the fruit grading process. It is challenging for artificial vision systems to detect different defects such as spoilage, microbial contamination, mechanical and freeze damage or fungi in fruit during early stages of fruit grading (Gómez-Sanchis et al. 2013; Vélez Rivera et al. 2014). The detection capability of the non-destructive methods may also depend on the maturity stage of the fruit (Kitthawee et al. 2011; Vélez Rivera et al. 2014). The accuracy can be influenced by the type and cultivar of produce, age of the bruise, bruise type and severity (Lu 2003). Irrespective of the imaging system, the natural surface colour variations in fruit make it difficult to separate bruise areas from the non-bruised surfaces, through image analysis (ElMasry et al. 2008; Zwiggelaar et al. 1996). Lü and Tang (2012) used hyper-spectral imaging to detect hidden bruising in kiwifruit and reported the positive error rate (i.e. normal fruit classified as bruises) was 16.2%

and the false error rate was 12.6%. Xing et al. (2005) also reported that the presence of stalk or calyx complicated the bruise identification in apples and resulted in misclassification. Similarly, Lu (2003) reported a method for apple bruise classification with a 94% accuracy. However, these challenges need to be addressed before artificial vision systems can be reliably used to detect mechanical damage in fruits in industrial packing-lines. In addition to the accuracy, the complexities in setup, and the initial cost of equipment, may also restrict the widespread use of computer vision systems in the industry. Therefore, the practical uses of non-destructive damage assessment systems based on imaging and computer vision technologies have been limited and underdeveloped in the fresh produce industry.

CHAPTER II

Literature Review

PART B – Mechanical Damage in Bananas

2.5. Mechanical Damage in Bananas

In fresh produce supply chains, a certain degree of damage during the post-harvest operations is unavoidable. Mechanical stresses from harvest through to consumers at the retail market are major factors affecting quality deterioration of bananas (Dadzie & Orchard 1997). It leads to increased wastage across the supply chain and diminished appearance quality at retail stores. Post-harvest losses occur in bananas during package handling and distribution (Del Aguila et al. 2010; Wasala, Dharmasena, Dissanayake & Tilakarathne 2015). Bananas may develop different types of cosmetic damages due to various mechanical stresses such as impact, compression and vibration. Cosmetic defects caused by mechanical stresses cause downgrading of bananas and affect the consumer acceptance in retail stores (Ekman et al. 2011). However, there is a lack of research to confirm how different types of damage in bananas are perceived by the consumers. In other words, it is not known whether some types of damages in bananas devalue the product more than the other types of damages. Nonetheless, it is reasonable to presume that the more severe the damage is the more chances for rejection by consumers at the retail stores due to the loss of perceived value of the fruits.

2.5.1. Types of Mechanical Damages in Bananas

Damages caused by various mechanical stresses in bananas are not well defined in the literature. However, a deeper understanding of different types of damage is necessary to determine potential causes. Similar to other fruits, as described in Section 2.1, bananas can also be subjected to compression, impact and friction resulting in various mechanical damages such as bruising, neck injuries and skin blemishes including fruit rub, blackened rub and scuffing (Ekman et al. 2011). Qualitative descriptions for each of these mechanical damages and the symptoms of each damage are given in Table 2.5. The hypothetical relationship with the basic mechanical stresses and their damage to bananas is conceptually presented in Fig.2.5 These conceptual relationships attempt to establish the association between the basic mechanical stresses and the resultant damage in bananas.

Bruising in bananas can occur due to impacts or compression forces (Banks, Borton & Joseph 1991; Banks & Joseph 1991). Bruising, due to impact and compression, can be identified as impact bruising and compression bruising respectively. Bruising may cause flesh damage depending on the severity of the impact/pressure. In addition, cosmetic damages can also occur due to abrasion or friction mostly affecting the external surface (exocarp) of the fruits (Li & Thomas 2014) which is also exhibited in bananas. Damage caused by friction essentially occurs due to the relative movement of the fruit against other contacting surfaces. Therefore, abrasion damages can occur due to the relative movement of packaged bananas when exposed to vibration (Wasala, Dharmasena, et al. 2015b). Exposure to vibration may lead to fruit rub (or transport rub) between the fingers (Table 2.5). Abrasion type damages may also occur due rubbing (of the clusters) which may not be attributed to vibration. For example, when ba nanas are handled in clusters, the clusters can rub against conveyer belts in a packing-line. Unlike most other fruits, bananas may also exhibit stem end tearing known as neck damage or neck injury. This can affect the quality and the consumer acceptance at the retail stores (Ekman et al. 2011). Neck damage is defined as skin break caused by separation of stem from the fruit (Mohsenin 1986). However, the exact mechanism of the occurrence of neck injuries within the post-harvest SC and when bananas are packaged are not well understood and requires further investigation.

Table 2.5: Qualitative Descriptions of Different Types of Damage in Bananas

Damage Cause	Damage Type	Damage Mechanism	Symptom \ Nature of Damage	Visual Appearance
Compression or Impact	Bruising	Sudden impact forces on fruits or compression (pressure) on fruit body	Deformation of the fruit and appears as a grey/ brown area on the peel without clear edges	
Friction (Abrasion)	Scars	Friction between fruit and other contacting hard surfaces	Moderate to severe wet scar marks (sap oozing) with clear edges and appear as dried out black scar marks upon ripening	
	Fruit Rubs	Rubbing against other fruit	Creates a dark brown or black patch mark with clear edges mostly in the top or the basal end on the fruit body	
	Scuffing	Superficial (light) widespread rubbing of the fruit against contact surfaces such as other fruit and carton box	Light brown skin marks in the body of the fruit without clear edges	
	Blacked Rubs	Rubbing of the edges of the fruit from top to bottom against hard surfaces such as corrugated box	Thin black or grey line along the edges (mostly back) of the fruit	

Stem end tearing	Neck Damages	Movement of individual fruits in a cluster with respect to the stem	Neck breaks lead to detachment of the fruit from its cluster	

It is apparent that mechanical stresses are present in the SCs. However, it is not clear how these mechanical stresses may influence the development of different damages within different segments of the SC. In the context of Australia damages that occur to bananas remain latent until they are detected at unpacking of cartons in the retail stores. Therefore, the occurrence of these damages in bananas along the SC, and understanding the underlying risk factors affecting mechanical damage, need further investigation.

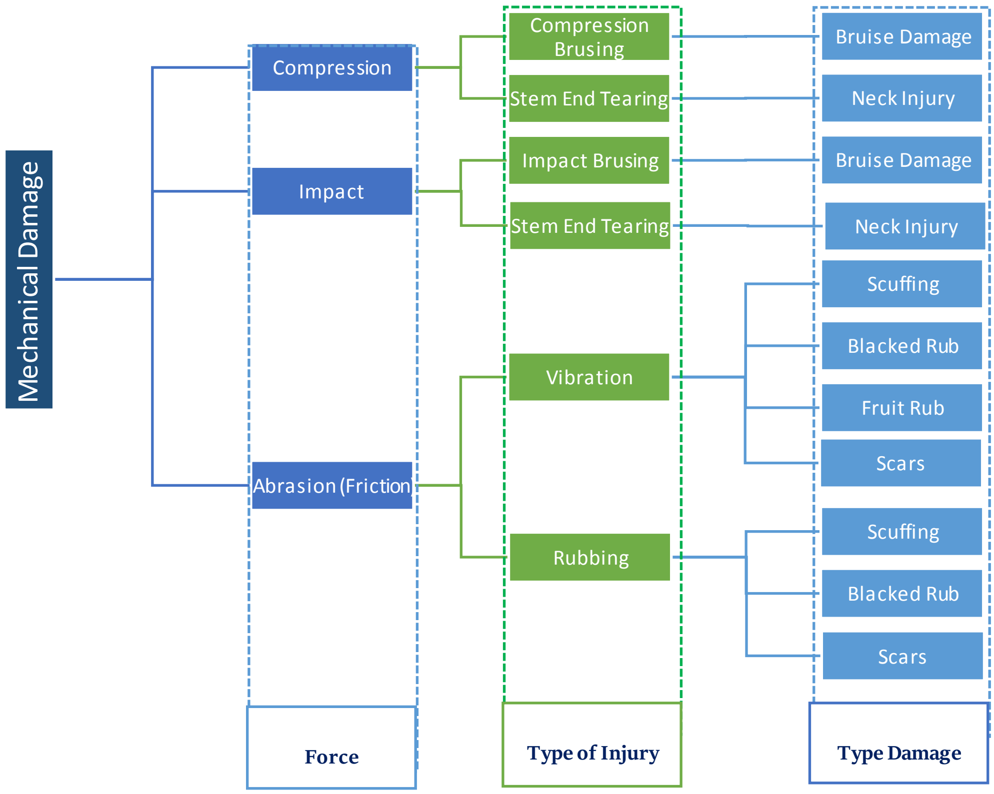


Figure 2.5: Conceptual Illustration of the Relationship between Mechanical Forces and Types of Damages in Banana

2.5.2. Response of Bananas to Mechanical Damage

Similar to other fresh produce bananas may also exhibit different degrees of physio-chemical change due to mechanical injury. Ferris et al. (1993) showed that abrasion may instantly create a visible damage in bananas but bruise damage may not be immediately visible. One of the most significant and an immediate response of mechanical damage is the attack of microorganisms, which may cause further decay in bananas (Maia et al. 2015). Similar to any other fruit, mechanical damages cause browning in bananas due to the oxidation of polyphenols (Maia et al. 2011). Maia et al. (2015) also found that mechanical damage caused higher enzyme activity in the affected area followed by alternations in colour, flavour, rapid tissue softening and induced ripening. Maia et al. (2011) reported an increase in enzyme activity in bananas when subjected to mechanical damage such as cutting, abrasion and impacts. They also found that the browning, due to enzyme activity, resulted in an unpleasant taste in bananas in addition to the alterations in colour and texture.

Mechanical damage induced higher respiration in bananas (Del Aguila et al. 2010; Maia et al. 2011). This may be caused by the injuries leading to loss of moisture due to surface evaporation (Mvumi, Matsikira & Mutambara 2016). Increased respiration rates were reported in bananas subjected to impact and compression bruising (Chukwu, Ferris & Olorunda 1998; Da Costa et al. 2010) and abrasion damage (Chukwu, Ferris & Olorunda 1998). Chukwu, Ferris and Olorunda (1998) further reported that abrasion damage caused rapid moisture loss and weight loss compared to impact bruising in bananas. Similarly, Maia et al. (2011) reported that abrasion and cuts resulted in the highest fresh weight loss in bananas compared to the other injuries. Loss of fruit weight can occur due to the breakdown of cell walls and increase in permeability of the outer cell layers to water vapor (Dadzie & Orchard 1997). Therefore, abrasion damage in bananas can have the most influence on reducing shelf of the fruit compared to bruise damage. It was reported that the TSS content escalated rapidly in the mechanically injured fruit when compared with the control, yet final levels of sucrose, glucose and fructose levels were similar once the fruits were fully ripened (Dadzie & Orchard 1997). A similar finding was reported by Maia et al. (2011) where mechanical damage precipitated ripening and increased the rate of conversation of starch into TSS in the pulp tissues. These findings conclude that mechanical injury induces ripening, hence reducing the effective shelf life of bananas.

Bananas subjected to mechanical damage exhibit other physiological and biological changes such as elevated ethylene production, electrolyte leakage and chlorophyll degradation. Mechanical damages in fruit may induce ethylene biosynthesis (Del Aguila et al. 2010; Luyckx Audrey 2016; Maia et al. 2015), which can lead to premature ripening. Ethylene production increased in mechanically injured bananas with accelerated tissue softening after the damage (Maia et al. 2011; Santana Llado & Marrero Dominguez 1997). Maia et al. (2015) and Maia et al. (2011) revealed that cutting, abrasion and impact damages in bananas had elevated levels of the electrolyte leakage and chlorophyll degradation subsequent to impact damage. These studies suggest that physio-chemical effects in bananas occur due to various mechanical damages with implications for fruit quality and consumer acceptance.

2.5.3. Mechanical Damage Susceptibility

The susceptibility of mechanical damage in bananas is associated with fruit properties and atmospheric conditions. Impact bruise susceptibility was defined as the lowest impact energy that is capable of creating a visible bruise in bananas (Bugaud et al. 2014). This definition can be extended to other mechanical damages in bananas caused by compression and abrasion. Bruise susceptibility essentially depends on the condition of the bruising event and the internal fruit properties (Guillermin, Camps & Bertrand 2004). Kajuna, Bilanski and Mittal (1997) found that the bruise volume in bananas was proportional to the impact energy and to the energy absorbed by fruits. The bruise impact threshold for bananas can be very different to that of any fruit due to the fact that damages are occurring to latex vessels which run longitudinally in banana skin (Banks, Borton & Joseph 1991). However, most of the factors, which affect the damage susceptibility of other fresh produce, as discussed in Section 2.2.1, can be also applicable for bananas.

Bruise sensitivity in bananas can be a function several factors including the fruit properties such as the peel characteristics, ripeness stage, maturity stage at harvest and flesh firmness at the time of injury (Banks, Borton & Joseph 1991; Banks & Joseph 1991). It was reported that fruit firmness decreased with maturity (Soltani, Alimardani & Omid 2010) and the less firmer fruit could be more susceptible to damage. Banks, Borton and Joseph (1991) found that a 3-5 N force is required to create a visible bruise in bananas, whereas a lesser force was required in later stages of ripening. This could be due to the osmotic uptake of water by the pulp leading to decreased peel thickness in bananas as the fruit ripens (Banks, Borton & Joseph 1991). Increased peel thickness in bananas could therefore be an advantage against mechanical damage (Al-Hosni et al. 2008) but the peel thickness reduces with fruit ripening (Banks, Borton & Joseph 1991; Simmonds 1966). Maia et al. (2011) showed that compression didn't cause any harmful effect to bananas in the early stages of ripening and the green fruit subjected to a compression was resistant to deformation. However, the fruit beyond ripening stage four was permanently deformed. Yuwana (1997) showed that the bruise volume per unit of energy of unripe banana was lower than that of ripe bananas, suggesting that for the same amount of energy, ripe bananas were more bruised than unripe bananas. Further it was found that the minimum impact energies to initiate bruising for ripe and unripe bananas were 0.09 J and 0.36 J showing that the bruise susceptibility of bananas increases with the ripening.

Peel characteristics of bananas can be influenced by the fruit turgidity. Maximizing the turgidity could elevate the threshold of which bananas begin to resist compression bruising (Banks & Joseph 1991). Further study suggested that the fruit harvested in early morning had 18% greater threshold for bruising and the damage threshold declined from morning to mid-day harvested bananas due to the decline in turgidity. Da Costa et al. (2010) reported that the level of skin damage in bananas showed a seasonality as the damage levels were escalated by 1.5 to 2.4-fold in spring season compared to the winter. This could be due to the peel characteristics influenced by the temperature and humidity. Bugaud, Daribo and Dubois (2007) found that the peel of green bananas harvested during hot-humid season was softer compared to that of bananas harvested in the dry-cool season. The study further found a positive correlation between the level of rain fall and peel hardness, suggesting more rainfall can lead to harder peel characteristics and firmer bananas that could be less susceptible to damage.

Like any other fresh produce, the damage susceptibility of bananas can be influenced by atmospheric conditions and other environmental factors. Temperature can be one of the most influential factors in maintaining the post-harvest quality of fresh produce (Prusky 2011). Temperature and humidity were shown to have an influence on the mechanical damage susceptibility and subsequent worsening of the sustained damages in bananas (Akkaravessapong, Joyce & Turner 1992; Da Costa et al. 2010; Del Aguila et al. 2010). Banks and Joseph (1991) showed that the compression bruising threshold for bananas were lower in higher temperatures, but the impact bruising threshold was markedly higher at 30 °C than in 19 °C. This suggests that higher temperatures lead to more bruise susceptibility in bananas due to compression and lesser susceptibility to impact bruising. However the exact reason is not known. Akkaravessapong, Joyce and Turner (1992) revealed that the RH at which the bananas were stored or ripened did not affect the susceptibility of mechanical injury. The bruises on bananas at low RH environments quickly dried out to a black colour while the bananas kept in humid environment only exhibited light brown colour bruising. Higher temperatures in the spring season elevate the activity of polyphenol oxidase on the banana skin (Da Costa et al. 2010) and the increased enzyme activity can be associated with darkening of the skin bruises. The skin blemishes may also worsen or be dried out due to the osmotic uptake of water by the pulp of bananas during the ripening (Banks, Borton & Joseph 1991; Simmonds 1966). These studies concluded that temperature is associated with the bruise susceptibility in bananas and that relative humidity has less significance on the susceptibility. However, reduced RH can be associated with the worsening of the existing mechanical damages.

Ethylene in fruit SCs could present due to combustion engines in the vicinity of produce such as from fuel-powered forklifts, trucks and cooling units (Blanke 2014). Presence of ethylene by itself may not affect the susceptibility of mechanical damage in bananas however, bananas may ripen faster due to the exposure to ethylene and, ripe bananas are more susceptible to mechanical damage. Therefore, presence of ethylene may accelerate the fruit ripening and indirectly induce the damage susceptibility of bananas. These studies suggest that controlling the storage temperature, humidity and ethylene concentration may contribute to control the worsening of already existing damage in bananas. As discussed in Section 2.2.1

several other factors such as curvature of the fruit surface, acoustic stiffness and fruit cultivar were found to be influential factors in mechanical damage susceptibility in fresh fruits.

2.5.4. **Mechanical Damage to Bananas in Post-harvest Supply Chains**

Most of the previous studies on the factors affecting mechanical damage and quality of bananas in SCs were limited to a few qualitative studies. The factors highlighted in these studies can be categorized into pre-harvest and post-harvest factors. Literature on pre-harvest factors affecting mechanical damage in bananas is limited. Dadzie and Orchard (1997) revealed that pre-harvest factors such as weather, wind, spraying fertilizer, insect pests, birds, rodents may cause mechanical injury to bananas. The influence of hail and wind may result in quality issues in fruits including cosmetic damage (Kays 1999). However, in the absence of studies, the interaction of pre-harvest factors such as soil condition, irrigation and climatic conditions on mechanical damage susceptibility in bananas remains unclear. Banks and Joseph (1991) found that the threshold compression force to create a visible bruise on bananas was negatively correlated with the farm altitude but the exact reason for this relationship could not be determined.

Similar to other fresh produce, mechanical stresses caused by impact, compression and vibration were identified as the three major sources of damage in bananas (Dadzie & Orchard 1997; Del Aguila et al. 2010). Some authors argued that the factors at the farm level were more critical for damage (Mvumi, Matsikira & Mutambara 2016) while some studies reported the damages were higher during the post-harvest transport and handling (Ekanayake & Bandara 2002; Vidanagama & Piyathilaka 2011; Wasala et al. 2014). The instances of damage may persist throughout the post-harvest SC including the impact on bananas during the harvesting of bunches. At harvesting, poor handling techniques, such as forced falling of bunches to the ground, may result in scarring of the fruit (Mvumi, Matsikira & Mutambara 2016). Scott (1971) also reported that much of the damage in bananas may occur due to inappropriate methods used in harvesting. Harvested over-matured produce may not survive the handling stresses during marketing of the product and therefore it is important to harvest bananas at the correct maturity (Harvey 1978).

Post-harvest damages to bananas occur during farm and pack house operations (Mvumi, Matsikira & Mutambara 2016), handling of banana bunches, clusters and packages (Dadzie & Orchard 1997; Ekman et al. 2011) and during transport (Da Costa et al. 2010; Wasala et al. 2014; Wasala, Dharmasena, Dissanayake & Tilakarathne 2015; Wasala, Dharmasena, et al. 2015b). Mechanical damages occurring in the SC could be higher at the handling nodes more than during the transport of bananas (Ekman et al. 2011). Maia et al. (2008) investigated mechanical damage at four distinct locations in the banana supply chain (pre-selection, after packing, after transport and retail market) and concluded that the damaged level was increasing along the chain. Da Costa et al. (2010) showed that at harvest a total area of 6.9 cm^2 per banana fruit was already injured in the field which corresponded to a 3.2% of the total area of a bunch. The damage level increased to 4.4% after transporting to the packing-shed through an aerial cable and further escalated to 5.9% after the operations at the pack house. Ultimately, the cumulative damage area escalated to 12% after shipping, emphasizing that nearly 9% increment of damage in bananas occurred during the post-harvest operations, out of which 6% was attributed to shipping.

The quality of the produce can be substantially reduced in the absence of care at handling (Li & Thomas 2014). Some of the damages in bananas can be also attributed to the rough or improper handling (Ekman et al. 2011). It was reported that reckless handling of the fruit and poor sanitation conditions in the pack houses caused much of the physical damage to bananas in Zimbabwe (Mvumi, Matsikira & Mutambara 2016). Absence of information coordination and unexpected demand fluctuations have been major causes for intensified pressure on pack house operation (Mvumi, Matsikira & Mutambara 2016; Vidanagama & Piyathilaka 2011). Mvumi, Matsikira and Mutambara (2016) reported that abrupt demand changes and lack of information passing up the chain to the growers would periodically stress the pack houses with excessive workload resulting in unrealistic targets and careless or rapid handling across the SC.

In addition, over packing and under packing of cartons, bulk transport in over filled trucks and careless handling during the loading and unloading operations were reported as significant risk factors for banana damage (Dadzie & Orchard 1997; Wasala et al. 2014). Ekman et al. (2011) reported the packing method and packer's skill, carton type and strength, type of pallet used, pallet stabilization and number of pallet movements between the farm and retail can affect the cosmetic appearance of packaged bananas. Previous studies showed that vibration during transport has been a critical factor for the development of mechanical damage in packaged bananas (Wasala, Dharmasena, Dissanayake & Tilakarathne 2015; Wasala, Dharmasena, et al. 2015b). Repeated and prolonged vibration can damage bananas during transport (Dadzie & Orchard 1997) and the damage can be severe in loosely packed fruits compared to the tightly packed fruits, as evidenced in other soft fruits such as pears (Slaughter, Hinsch & Thompson 1993; Slaughter, Thompson & Hinsch 1998; Sommer et al. 1957). However, it is apparent that the causes and levels of damage to bananas in each SC can be unique and influenced by a variety of factors. Therefore, the findings of one study may not be directly extendable to another context where the fruit handling, packing, packaging and transport practices are different.

2.6. Recent Industry Surveys on Banana Damage

Mechanical damage in bananas has been a major concern for both the banana and the fruit retail industries in Australia. The causes of damage to bananas have been unclear but the damages were reported in retail stores. This is of significant concern for major supermarket retailers that claim a 'premium' price for high quality produce. Visual defects along the supply chain exert pressures on the suppliers to these major supermarket chains who account for nearly three quarters of the total banana sale in Australia (Day 2018). Considering that bananas are the most sold supermarket produce in Australia (Margetts 2014), the importance of the marketability of bananas at the retail store is of a great interest to the retailers. Therefore, several previous studies were initiated by the industry to improve the quality of bananas in Australia. A major study in this regard was a project by the Department of Primary Industries (DPI) in Queensland (Ekman et al. 2011) which primarily focused on the consumer perception of cosmetic damage in bananas and the damage occurrence in limited (i.e. Two) post-harvest SCs. In addition, another study was undertaken by Kitchener (2015) on the carton management practices in the banana industry due to the increased concern on the failure of packages along the SC.

The preliminary findings and conclusions reached through these studies have been highly applicable and relevant in this research because these surveys were exclusively focused on the context of Australian SCs. However, several limitations existed in the previous industry studies which prompted the need for further research on the quality deterioration of bananas during the distribution. Several knowledge gaps and opportunities for further investigation were highlighted in Ekman et al. (2011) and Kitchener (2015) in their respective industry reports. The main limitation in the study by Ekman et al. (2011) was the restricted sample size assessed and evaluated across the supply chain, which limited the generalization of findings and reaching boarder conclusions on the damage occurrence. Their major supply chain study assessed three cartons in the pack house, 30 cartons in the distribution center and 18 cartons at the retail stores. Therefore, a greater sample size and an experimental design is necessary to evaluate the progression of damage across the banana SC. Even though the study identified different damage types in bananas (e.g. neck injuries, bruising, rubbing) the cause of these damages were not substantiated in their study (Ekman et al. 2011). Instead, the study highlighted probable causes for the reduced quality of bananas along the SC by collecting data from focused panels and industry experts. Therefore, more investigations on the evaluation of mechanical damages, and the identification of risk factors for quality deterioration is necessary to recommend potential remedial measures to improve the banana quality at the retail stores.

The findings and recommendations made by Kitchener (2015) need to be further testified experimentally as no experimental validations have been made within their study as to what extent the fruit damage can be minimized by the proposed recommendations, especially by switching to the single piece carton as suggested. However, in the absence of proper package evaluation, and factual evidence on the single piece cartons for their ability to minimize damages, the industry is still skeptical to move towards single piece cartons or re-usable plastic crates for bananas. In their industry report, Ekman et al. (2011) suggested that the damage incidence in bananas varied between the type of package. Further investigations were endorsed in this regard to reach conclusions. Therefore, the suitability and the protective performance of packaging can only be confirmed through a proper package testing experiment to determine if a new packaging design may minimize such damage in the post-harvest SC. Ekman et al. (2011) further advocated increasing the carton strength and height, packing fruit into bag liners instead of standard liners and improved stabilization of the pallets can be potential solutions to reduce damages in packaged bananas. However, the study lacked experimental validation of the proposed interventions that had marginal influence on the industry practice.

2.7. Scope of the Current Study

Sources of mechanical damage to fruits persist throughout the supply chain and the factors affecting the damages must be understood for minimizing cosmetic defects (Ahmadi et al. 2010; Sila et al. 2008). Bananas are a delicate produce and being exposed to mechanical stresses within lengthy road-based supply chains in Australia from the farm gate to retail stores. Identifying causes of mechanical damage in bananas is critical for loss prevention and reducing wastage (Mvumi, Matsikira & Mutambara 2016). From the previous industry studies (Ekman et al. 2011; Kitchener 2015) it is evident that cosmetic damages and quality inconsistencies have been an ongoing concern to both the banana and retail industries. What is known from the previous studies conducted in Australia is that majority of bananas (approximately 50%) on retail shelves had noticeable cosmetic damages out of which 20% sustained moderate to severe injuries (Ekman et al. 2011). The perceived value of bananas at the retail stores have been affected by damages along the SC. Furthermore, the quality of bananas is associated with the retail price (Ekman et al. 2011) which also affects their marketability.

There is a lack of studies that analyzed the development of mechanical damage in bananas within the post-harvest SCs in Australia and therefore, the exact level of damage, the progression of damage and the causes affecting the damage remains unclear. In order to understand the causes of cosmetic defects, knowledge of the post-harvest handling systems and the sources of kinetic energy inputs to bananas along the SCs (Akkaravessapong, Joyce & Turner 1992) need to be further investigated. Studies in this regard need to measure the extent, place and kind of losses in the SC to understand the contributing factors to prioritize implementation of preventive mechanisms (Harvey 1978). In this regard, there is a scope for research in the banana SC in Australia, to reduce wastage and increase the perceived quality.

Bananas remain packaged within most part of the post-harvest supply chain. However, studies targeted at damage occurrence in packaged bananas has been limited. In addition, the causes of different types of damages in packaged bananas are not well understood. Therefore, a need exists to characterize damage in bananas at the exposure of packages to impact, compression and vibration forces. Kitchener (2015) highlighted that all major Australian retailers were discontented on the quality inconsistencies in bananas largely attributed to carton failures within the post-harvest supply chain. In the absence of knowledge on how or where the damages may have occurred, the debate is between the growers and the retailers, regarding the responsibility for the lowered quality of bananas at the retail store. Therefore, this study aims to quantify the mechanical damage in bananas along the post-harvest SC with a special focus on damages occurring in packaged bananas. Damage assessments along the SCs, experimental characterization of the damage mechanisms and testing of improved packaging through simulation based on field conditions, will be performed through this study to develop factual recommendations to the industry to proposing solutions for the improvement of the quality of bananas in the post-harvest SCs Australia.

3. CHAPTER III

General Methodology

This chapter provides a general overview of the main methods used in this research and the justification for the use of these methods. The methods discussed in this chapter include the mechanisms of damage assessment in bananas, vibration data collection, the development of a model simulation test for packaged bananas and the methods used for package performance testing and evaluation.

Chapter III

General Methodology

This chapter is to provide an overall understanding of the research framework and the key methods and principles used in this research. Each result chapter in this thesis contains a standalone section of Materials and Methods specifically used in that chapter to explain the procedure of data collection and analysis in detail.

3.1. Research Framework

The key focus of this research was to determine the factors affecting mechanical damage in packaged bananas and recommend interventions to preserve the fruit quality along the supply chain (SC). Mechanical damage development in packaged fruits is a function of a series of factors such as the exposure to damage-causing external mechanical forces such as vibration, impact and compression (Fig. 3.1). In addition, the damage susceptibility can be influenced by the fruit properties such as fruit ripeness level, turgidity, firmness, size and curvature (Banks & Joseph 1991; Yuwana 1997). The incidence and severity of damage in packaged fruits can also be affected by the atmospheric conditions such as temperature and humidity (Banks, Borton & Joseph 1991; Banks & Joseph 1991; Bugaud, Daribo & Dubois 2007; Bugaud et al. 2014; Da Costa et al. 2010; Del Aguila et al. 2010). The atmospheric conditions can be also interrelated with the fruit properties and influence their damage susceptibility. For example increased temperature can induce the ripening of tropical fruits while decreased humidity can increase the respiration level (Akkaravessapong, Joyce & Turner 1992; Da Costa et al. 2010). The research was divided into three study phases (i.e. Evaluate, Characterize and Minimize). The Research Framework (Fig.3.1) illustrates these three phases and the related components of this study.

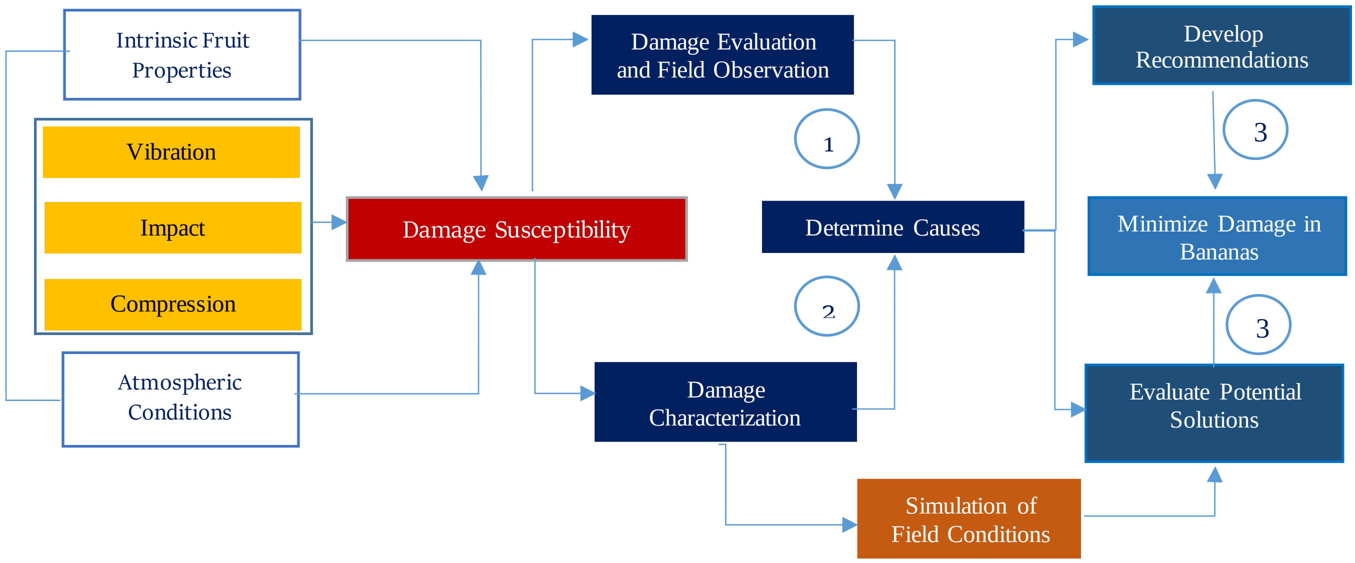


Figure 3.1: Research Framework (Research Phases are circled as 1, 2 and 3)

Phase 1 (Evaluate): Evaluate mechanical damage levels in packaged bananas and identify the potential causes along the post-harvest SC.

The first objective of the study was to evaluate the damage along the SC and determine the potential causes of damage in packaged bananas. To achieve this objective, the damage levels in packaged bananas were assessed and quantified in three distinct locations across the SC (i.e. pack-house, DC and retail stores). Two package sampling methods (i.e. random package inspection and follow-up package inspection) were used to understand how the damage levels progress along the SC, which is further elaborated in Sections 4.1.2 and 4.2.2. Parallel to the damage assessment, a field market observation study was conducted to identify the potential risk factors for mechanical damage along the SC. The first phase of the study focuses on the first research objective which is expanded in Chapter 4 of the thesis.

Phase 2 (Characterize): Characterize the relationship between the mechanical stresses and the occurrence of mechanical damages in packaged bananas.

At the completion of the first research phase, markedly different types of cosmetic defects were identified in bananas. However, their mechanisms of occurrence remained unclear and required further investigation. Therefore, different types of damages caused by vibration, impact and compression in packaged bananas were characterized by laboratory experiments. The findings of Phase 1 of this research also indicated that rubbing damage caused by vibration in-transit has been one of the most significant causes of appearance quality deterioration in packaged bananas throughout the SC. Therefore, in Phase 2 of this study, the damage development in packaged bananas during the interstate transport was further explored. Transport conditions from the farm-gate to the retail store were characterized by recording vibration, temperature and humidity data in-transit. The parameters recorded during the field transport were then used to simulate the field conditions in laboratory settings in order to evaluate potential solutions for minimizing damage.

Phase 3 (Minimize): Evaluation of packaging alternatives and recommending interventions to minimize mechanical damage in bananas.

The findings and results from the first two phrases were used as input for the evaluation of potential solutions to minimizing damage and providing recommendations to the industry. Packaging is an integral component during fruit distribution which provides the protection against various environmental hazards along the post-harvest SC. The failure of this primary protection during the post-harvest transport, handling and storage can critically affect the occurrence of damages in fruits. Therefore, the evaluation of the protective performance of packaging was a prominent focus in previous research studies on a variety of fruits (Chonhenchob, Kamhangwong & Singh 2008b; Chonhenchob & Singh 2003a, 2005b; Fadiji, Coetzee, Chen, et al. 2016; Fadiji, Coetzee, Pathare, et al. 2016; Opara & Fadiji 2018). Consequently, the final objective of this study focused on evaluating the performance of different packaging methods for minimizing damage to bananas. In addition, different pallet stacking arrangements and inner packing methods were also tested for their effectiveness in minimizing mechanical damage. Existence of many different types of mechanical damages in bananas such as bruising, abrasion and neck injuries and the distinctly different mechanisms of damage occurrence means that multiple interventions are needed to minimize such damage at each stage of the SC. Therefore, other interventions for minimizing fruit mechanical damage are examined and discussed in the final phase of the study and recommendations are made in Chapter 7.

3.2. Overview of the Main Methods by Chapter

This section provides an overview of the main methods used in this study. Qualitative and quantitative data collection methods were employed to generate a broad understanding of when, where and how bananas are damaged along the SC. Two damage quantification methods, i.e. Visual Damage Index (VDI) and Mechanical Damage Index (MDI) were used in this study and the field observation method was used to identify the risk factors for mechanical damage at the key nodes in the SC. The empirical study (Chapter 4) revealed that vibration in-transit is a major cause for the mechanical damage in bananas throughout the SC. Therefore, several methods were used to characterize damage in bananas through simulated vibration. Finally, the methods used to test improved packaging methods to minimize damage to bananas are summarized. A summary of the methods and their association with the research phases and chapters in this thesis is provided in Table 3.1.

Table 3.1: Summary of the Research Methods used in this Thesis

Research Phase	Chapter(s) in the Thesis	Main Methods Used
Damage Evaluation	Chapter 4	▪ VDI, MDI ▪ Damage assessments – Random damage inspection – Follow-up damage inspection ▪ Qualitative study – Field observation (Non-participatory) – Damage risk assessment ▪ Temperature/ Humidity data collection
Damage Characterization	Chapter 4 and Chapter 5	▪ Vibration data collection ▪ Vibration data analysis ▪ Temperature/ Humidity/ GPS data collection ▪ VDI, MDI ▪ Damage characterization by:

		– Drop-impact testing – Simulated vibration testing – Package compression testing

Damage Minimization	Chapter 6 and Chapter 7	▪ MDI
		▪ Vibration data collection
		▪ Vibration data analysis
		▪ Simulated vibration testing
		  – Unripe bananas- Full pallets
		  – Ripe bananas- Consolidated pallets
		▪ Carton testing under simulated ripening conditions
		  – Base-sagging testing
		  – Compression strength testing
		▪ Development of recommendations- Based on qualitative data analysis

3.2.1. **Plant Material**

All packaged bananas used in different experiments in this study were 'Cavendish' cultivar and sourced from a single farm in Tully, Queensland. For each controlled experiment, 'premium' grade bananas as per the supermarket specifications for bananas (Appendix B2) from the same harvesting batch were used. The summary of specifications of 'premium-grade' bananas are given in Table 3.2.

A total of 240 cartons (3600 kg) of ripe and unripe bananas were used in the laboratory-experiments in this study and a total of 300 cartons were inspected for damages at each node of the SC from the pack-house to the retail stores. Another 81 cartons of bananas were followed-up and assessed three times across the SC, for quality deterioration from pack-house to retail stores.

Table 3.2: Properties of the 'Cavendish' Bananas used in this Research

Finger Length	Finger Girth	Fingers per Hand/Cluster	Average Clusters-per-layer	Layers/ Carton	Package (net.) Weight	Package (gross) Weight
200-260 mm	30-40 mm	4-9	6	3	15.0-15.5 kg	15.5-16.0 kg

3.2.2. **Environmental Conditioning and Storage of Sample Packages**

Packaged bananas used for experiments in this study were stored in 13-14 °C, and 50-60% RH for a minimum of 48 hours before testing. For package testing under the simulated ripening conditions, bananas were stored in 15-18 °C and 90-100% RH to replicate the atmospheric conditions during the ripening process. Once the testing was completed, the damages were assessed within 12-24 hours after each experiment. A reasonable time was allowed after each test treatment before the damage assessment to ensure that the latent damage, that may have occurred in bananas became visible before the assessments. Until the damage was assessed, all packages were stored in 13-14 °C and 50-60% RH storage environment after the experiments.

3.2.3. **Damage Evaluation – Mechanical Damage Index (MDI) and Visual Damage Index (VDI)**

The first objective of this research was to quantify the mechanical damage levels along the SC to determine how the damages were progressing in packaged bananas from the pack houses to the retail stores. This required a damage estimation method which is practical, rapid and reasonably accurate. Different damage estimation methods in various fruits have been reviewed in Section 2.4, which included qualitative (subjective) and quantitative (objective) damage assessment. Most objective fruit damage estimation methods, based on damage volume, were destructive and required cutting through the damage area of the fruit to calculate the volume of the affected area. Since this study is focused on the visual damages on bananas affecting the perceived value of the product, external damage area has been used as an indicator of the severity and frequency of mechanical damage. Furthermore, objective damage area quantification requires the measurement of either the radius or the diameter of damage by the methods discussed in Section 2.4.1. Measuring the radius or diameter of each damage on bananas can be challenging in an industrial SC due to the time-constraints and the rapid pace of operations. Therefore, a practicable and rapid damage estimation method, with reasonable accuracy had to be developed. A method which permitted estimating the damage area on bananas without manually measuring the radius of individual damage spots was considered necessary for this purpose.

A novel objective assessment method based on the transparent area measurement sheet (Appendix C1) was introduced to estimate the surface damage area on bananas. This method was used to calculate the damage area and estimate a damage score for packaged bananas based on the frequency and severity of damages. An objective damage index score based on the damage area was introduced as the Mechanical Damage Index (MDI). MDI, based on the damage area on bananas, were effective in quantifying the surface damages such as bruising and abrasion. However, neck injuries which usually appear as a thin line around the stem (neck) of bananas, could not be measured by the damage area. Therefore, MDI was not effective to measure all types of damages on bananas but was used in the latter stages of this study to quantify the surface abrasion damages (i.e. fruit-rub and scuffing) caused by vibration. The MDI was calculated by the Equation 3.1.

$$\textbf{MDI (\%)} = 0.1 \times \textbf{Trace Damages (\%)} + 0.2 \times \textbf{Slight Damages (\%)} + 0.7 \times \textbf{Moderate Damages (\%)} + 1.0 \times \textbf{Severe Damages (\%)} \qquad \text{(Eq.3.1)}$$

(Damage Area (A) ≥3 cm^2 – Severe; 2 cm^2≤A<3 cm^2 – Moderate; 1 cm^2≤A<2 cm^2 – Slight; 0.5 cm^2≤A<1 cm^2 – Trace)

For the initial stages of the study including the damage assessment along the SC (Chapter 4), a broad and rapid damage assessment method was required. This was due to the need of quantifying neck injuries which could not be measured by MDI based on the damage area. Therefore, the current damage evaluation methods used in the banana industry, based on the visual damage assessment charts (Ekman et al. 2011) (Appendix B1) were used to develop a visual damage index (VDI). VDI was calculated by Equation 3.2. VDI was used in this research which generated an overall understanding of the types of damages occurring in bananas along the SC. The subjectivity of damage assessment has been minimized through the inspection of visual damages in bananas by a single assessor (i.e. the researcher) across different stages in the SC and inspecting a relatively large number of bananas (i.e. More than 30,000 fingers) across the SC.

$$\text{VDI (\%)} = 0.1 \times \text{Trace Damages (\%)} + 0.2 \times \text{Slight Damages (\%)} + 0.7 \times \text{Moderate Damages (\%)} + 1.0 \times \text{Severe Damages (\%)} \quad \text{(Eq.3.2)}$$

(Damage Categories- Trace, Slight, Moderate, Severe are defined in the Damage Assessment Chart - Appendix B1)

3.2.4. Field Observation Study (Non-participatory Observation)

Most of the methods used in this study were quantitative however, a qualitative research method was incorporated to thoroughly investigate the risk factors for mechanical damage to bananas. The key focus of this research was to investigate the causes of damage in packaged bananas. However, for the completeness of the study, potential risk factors have been also identified in either ends of the post-harvest SC (i.e. pack-house and the retail stores) where bananas are handled in clusters and bunches. To understand the risk factors along the SC, an appropriate method had to be identified based on the type of data and the type of analysis. Ellram (1996) highlighted that in logistics research, case-study and field observation methods have been widely used to collect empirical data. Observation method was previously used to identify the factors affecting the quality of bananas in post-harvest SCs (Dadzie & Orchard 1997; Mvumi, Matsikira & Mutambara 2016).

As per the classification by Ellram (1996), the next best method to understand the risk factors for mechanical damage along the SC was to conduct a questionnaire survey. This only captures the opinions of the participants rather than the risk factors for damage directly. The focused group questionnaire method was used previously by Ekman et al. (2011) to understand the potential causes for banana quality deterioration along the SCs, however the extent to which these risk factors were applicable or the prevalence of these risks in the industrial SCs was unknown. Therefore, the observation method was used in this study, where the researcher observed the risk factors for mechanical damage along SCs and recorded first-hand data to determine the causes of damage.

Boote and Mathews (1999) outlined the criteria for using observation as a market research technique. A key criterion was that the 'phenomenon' under investigation has to be easily observable and occurs at a subconscious level (unintentional). In this study, banana growing conditions, harvesting, packing and retailing are observable activities. 'The phenomenon' in this study is the mechanisms of fruit damage during the post-harvest handling. The damage during handling may occur due to various 'unintended' causes such as rapid handling or worn-out conveyer belts in packing lines.

Observation studies are exploratory in nature. Observation studies can be conducted as structured-observation or un-structured observation. The degree to which an observation is structured is dependent on the stage of the research project (Boote & Mathews 1999). The observation tends to be unstructured when it is conducted to identify variables which require further investigation. For unstructured observation, field notes are usually used to record as much data as possible to identify the themes and areas for a more detailed investigation. In this study, the initial field visits were conducted in the form of unstructured observation to capture as much qualitative data as possible on the potential risk factors for mechanical damage along the post-harvest SC. This was important to obtain 'site-specific knowledge' (Wilson & Streatfield 1981) to design a more focused observation study. The field data collected during the initial visits were used to develop a checklist (Appendix B3) which was then used for a structured observation study.

Observation as a research method can be conducted in the form of participatory or non-participatory observation. The participant observation method requires the researcher to integrate with the process and collect field data while being actively involved in operations. This was not a feasible method given the time and cost constraints of this research project. Therefore, non-participatory observation method was used in this study with a structured observation checklist for the collection of qualitative data. There are several advantages and disadvantages in non-participatory observation as highlighted by Boote and Mathews (1999). The main advantage is that the observer does not have to internalize the values of the group and is less risky than the participatory observation. However, there can be several disadvantages including the bias of the observer to capture or record the events that are chosen and therefore, result in skewed or erroneous results due to subjectivity. In this research subjectivity was minimized with the use of a structured checklist during the qualitative data collection across the SC.

3.2.5. Mechanical Damage Characterization

Packaged fruits are subjected to different mechanical stresses along the SC and the simulation of such stresses in a laboratory environment is useful to understand the reasons for the consequential damages in fruits. Literature on fruit mechanical damage is abundant as discussed in Chapter 2. However, there is limited research on the development damage to fruits due to compression, vibration and impact when they are packaged inside corrugated paperboard cartons (Opara & Fadiji 2018). There are several different types of damages in bananas including bruising, abrasion and neck injuries (Ekman et al. 2011) as discussed in Section 2.5.1 which may occur throughout the SC. The occurrence of different types of damages in packaged bananas due to these various mechanical stresses has not been well understood.

Damage to fruits caused by drop impacts of packages during the post-harvest handling has been experimentally assessed by vertical drop testers. In drop impact testing the packages are dropped from a pre-determined height for simulating the shipping environment, during which the package contents are subjected to transient shock impacts that may result in fruit damage (Zhang et al. 2011). Accelerometers can be placed inside the packages to quantify the magnitude of the shock during the drop impact (Fadiji, Coetzee, Pathare, et al. 2016) and to compare the shock absorbent properties of different package designs. In this study, the drop testing was used to characterize the damages that can be potentially caused by rough handling of the packages along the SC. Packages are subjected to impacts during manual stacking of pallets and also during the pallet consolidation.

During transport and storage, packages are often stacked on top of each other. This can cause the packages at the bottom to experience excessive load in the form of compression (Fadiji et al. 2018; Opara & Fadiji 2018). Package failure occurs when the load causes the collapse of the packaging exposing its contents to damage. Package compression tests are widely used to measure the strength of packaging and to determine the maximum amount of compression the package can withstand (Fadiji et al. 2017; Fadiji et al. 2018; Opara & Fadiji 2018). The great significance of the compression strength of packaging is due to its association to the stacking performance. The compression strength also demonstrates the quality of the paperboard materials used for its construction (Fadiji et al. 2018). Therefore, this study aimed to identify the damage that may occur in bananas due to the top-load compression.

Ripe bananas are more susceptible to damage (Yuwana 1997) and thus, used in the compression and drop testing experiments. Trace or slight bruise damages were more distinguishable and easily detected in ripe bananas compared to unripe bananas. Both ripe and unripe bananas were subjected to simulated vibration to understand the influence of ripeness level on the occurrence of abrasion damage. Further information on the simulated vibration test settings is provided in Section 3.2.7. The test parameters used in drop-impact and top-load compression experiments are summarized in Table 3.3 and further elaborated in Chapter 4.

Table 3.3- Test Parameters used for the Damage Characterization Tests in Packaged Bananas

Test	Treatment	Ripeness Level (Bananas)	Assessment Method
Vibration Simulation	0.36 g acceleration for 3 hours	Ripe and Unripe	MDI
Drop Testing	0.3 m and 0.5 m vertical drop	Ripe	VDI
Top-load Compression	16 mm and 25 mm crush test	Ripe	MDI

The mechanical damage level in bananas after each test was evaluated by MDI/VDI damage indexing methods as described in Section 3.2.3. Damage caused by vibration and compression often resulted in darkened surface damage on bananas and thus, the damage levels were quantified based on the damage area (MDI). However, drop testing of packages often created neck injuries which were not able to be quantified based on the damage area. Therefore, a VDI damage score has been used for the evaluation and comparison of damage between the treatments.

3.2.6. Vibration Data Collection and Analysis

Collecting vibration data during transport is often complicated and can be considerably costly. As discussed in Section 2.3.1, previous researchers used three experimental designs (i.e. In-transit, Simulation and Trans-sim experiments) to study the effect of vibration on fruits. For this study the best method to collect vibration data was determined, considering the challenges in data collection during the interstate transport of bananas, which extends to thousands of kilometers and several days in-transit. Several previous experiments only measured the vibration levels along transit routes without evaluating the effect on produce damage (Chonhenchob et al. 2009; Rissi et al. 2008; Singh & Marcondes 1992; Zhou, Yan, et al. 2015). An underlying assumption of such studies was that higher acceleration levels may cause more damage to the produce. However, the level of produce damage may not be quantified accurately unless the fruits are examined before and after the in-transit experiments.

It is important to examine the relationship between different vibration levels and their effects on fruits to enable understanding of the response of produce. This allows better characterisation of the produce damage at different vibration intensities. In this study, vibration data during the actual road truck transport were collected by pre-calibrated piezo-electric accelerometers (Slam Stick - MIDE Technology Inc., Massachusetts, USA). However, the on-device battery restricted the operating life of the device to 12 hours of operation (at 400 Hz). This was insufficient to collect data from end-to-end of the journey during the interstate transport of bananas. Therefore, to support the continuous operation of the device, an external battery pack (Voltaic Inc., USA) was plugged to the devices. Data collection during the other shorter duration trips (i.e. distribution of bananas to the retail stores) and to capture data during the simulated vibration experiments didn't require the use of an external battery pack due to the short durations of data capturing.

Vibration data were analyzed in the time- and frequency domains. First the non-useful data, such as the segments during truck stoppages, were removed. Time synchronized GPS coordinates were used to identify the truck stoppages during field transport. Fast Fourier analysis of the time-series data were used to identify the critical frequencies (Smith 1997) and the power-spectral density (PSD) profiles were developed to represent the energy of the vibration signals (Randall & Tech 1987). Matlab (ver. 2014b, Mathworks, Natick, MA, USA signal) processing toolbox was used for the estimation of Fast-Fourier Transform (FFT) and to develop PSD profiles for time-series acceleration signals. Calculating the PSD of a vibration signal is a widely used method to determine the effect on fresh produce due to transport vibration (Fernando et al. 2018a). As discussed in Section 2.3.1, the PSD of a signal can be calculated by the acceleration data to derive the energy (g^2/Hz) content across different frequency ranges. The ratio between the output (excitation) and the input acceleration was used to calculate the vibration transmissibility (T). The detailed procedure of vibration data collection and analysis is further described in Chapter 5 and Chapter 6 of this thesis.

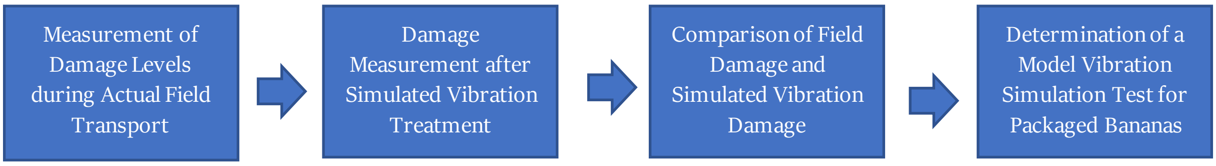
3.2.7. **Simulated Vibration Testing**

A computer controlled electro-hydraulic vibration simulation table (Lansmont Model 1800, Frequency Range 1-300 Hz, Max Acceleration- 10g) was used for all simulation experiments in this study. Vibration simulation was used to characterize the damage in packaged bananas and to evaluate the protective performance of different packaging alternatives. This study developed a model-simulation test which can reasonably replicate the field experience for packaged bananas during the long-distance interstate transport. The process of developing the model simulation test is explained briefly below and the detailed experiments of the test development is elaborated in Chapter 5.

The development of the model vibration simulation test included four steps as illustrated in Fig. 3.2. First, the vibration level and the damage levels in packaged bananas during the intestate transport from Tully region in Queensland to one of the major banana markets in Australia (i.e. Melbourne) was measured. Tully region in far north Queensland has the largest concentration of large-scale banana growers (ABGC 2016) and Melbourne is one of the most populated cities in Australia (ABS 2017) with a high demand for bananas. Therefore, amongst different road routes of banana distribution, the route from Tully to Melbourne has been one of the most significant routes with high volume transport of packaged bananas by road trains. The measurement of damage in packaged bananas was performed by the MDI method described in the Section 3.2.3.

A series of vibration simulation tests were conducted in the laboratory by exposing packaged bananas to different vibration doses (based on the PSD spectra derived from the field vibration data) to determine ‘the right dose’ that produces similar mechanical damage levels compared to the field damage. The derived vibration dose was used for further package testing experiments, as it closely and realistically replicated the field damage levels during the long-distance interstate transport of bananas. Further information on this experiment is detailed in Chapter 5.

Figure 3.2: Steps in the Development of a Model Vibration Simulation Test for Packaged Bananas



Retail distribution of packaged bananas from the DC often uses ‘consolidated pallets’ or mixed-stacked pallets with a variety of packaged produce. Therefore, the type of packaging that is best suited for the retail distribution of bananas requires the capability to withstand different dynamic forces within a ‘consolidated pallet’. There can be many stacking arrangements and packaging combinations in a consolidated pallet. However, the empirical study (Chapter 4) revealed that stacking rigid reusable-plastic-crates (RPC) can be a risk factor for the collapsing of corrugated cartons packed with bananas. Therefore, a ‘model consolidated pallet’, stacked with a mix of corrugated cartons and RPC packed with bananas, was subjected to simulated vibration to examine the occurrence of mechanical damage during the distribution of ripe bananas. Further details of this experimental study are included in Chapter 6.

3.2.8. **Package Testing under Simulated Ripening Conditions**

The empirical study revealed that corrugated cartons used in the distribution process were sporadically collapsing after the exposure to increased RH conditions (> 90% RH) for several days of ripening. Properties of corrugated paperboard can be adversely affected by moisture, weakening the highly porous fibers resulting in reduced paperboard strength (Fadiji et al. 2017; Fadiji et al. 2018; Twede et al. 2014). Therefore, the effect of the moisture absorption of the corrugated cartons which were exposed to high RH- simulated ripening conditions was examined in this study. Top-load compression on packages and base-sagging was associated with different types of mechanical damage in ripe bananas, especially in the latter part of the SC. Comparison of different types of packaging under the simulated ripening conditions therefore, revealed the best packaging alternative which could minimize damage to bananas, during the distribution to the retail stores. The detailed procedure of these experiments is included in Chapter 6 of this thesis.

4. CHAPTER IV

Mechanical Damage in Bananas along the Post-harvest Supply Chain

PREFACE

This chapter is focused on assessing banana damage along the supply chain (SC) and identifying the potential causes of damage. There is a dearth of literature examining the post-harvest banana supply chains in Australia. The limited industry surveys provided little understanding of the causes and mechanisms of quality deterioration in bananas. Therefore, it is necessary to investigate the entire SC to develop a good understanding of the problems and the areas requiring further research. The first part of this chapter presents the results of the empirical study. This study also provided a thorough understanding of the present state of the problems in Australia. The empirical study identified different types of mechanical damage in packaged bananas occurring in different stages of the supply chain. The second part of the chapter experimentally characterized different types of damage in packaged bananas exposed to simulated field conditions such as package handling, transport and storage. This chapter therefore evaluates the levels of mechanical damage in bananas across the supply chain, identifies the causes for damage and characterizes the damage in packaged bananas caused by different mechanical stresses.

Publications included in this Chapter

- ***Section 4. PART A-*** Fernando, I., Fei, J., Stanley, R., Enshaei, H. and Eyles, A. (2019), Quality deterioration of bananas in the post-harvest supply chain- an empirical study, *Modern Supply Chain Research and Applications*, Vol. 1 No. 2, pp. 135-154. ISSN 2631-3871

- ***Section 4. PART B-*** Fernando, I and Fei, J and Stanley, R and Enshaei, H, Assessment and characterizing mechanical damage in packaged bananas in the post-harvest supply chain, *MATEC Web of Conferences*, 21-23 August 2019, Paris, France, pp. 1-10. ISSN 2261-236X

PART A

Quality Deterioration of Bananas in the Post-Harvest Supply Chain- An Empirical Study

ABSTRACT

Quality deterioration in bananas along the supply chain (SC) due to cosmetic damage has been a persistent challenge in Australia. This study focused on investigating the incidence of cosmetic defects in bananas across the post-harvest SC and determining the causes of diminished fruit quality at retail stores. 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. The level of cosmetic damage progressively increased from pack house (1.3%) to distribution centre (DC) (9.0%) and retail (13.3%) 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. This study only investigated damage incidence in three post-harvest banana SCs in Australia and the damage assessments were confined to packaged bananas. 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.

Key Words: Post-Harvest, Supply Chain, Banana, Quality, Mechanical Damage

4.1. Quality Deterioration of Bananas in the Post-Harvest Supply Chain- An Empirical Study

4.1.1. 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 & 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 & Pathare 2014). Mechanical damage is caused by one or more force loadings acting on produce, resulting in injury to the exocarp of fruit (Li & Thomas 2014).

The causes for mechanical damage in fruits may present throughout the post-harvest supply chain (SC). Damage to fruits may first occur during the harvesting and packing operations (Arazuri, Arana & Jaren 2010; Manetto et al. 2017; Mvumi, Matsikira & Mutambara 2016). Fruit damage can be also associated with impacts during handling and compression from packaging (Van Zeebroeck, Van linden, et al. 2007), and with compression among fruits or between fruits and the container (Dadzie & Orchard 1997; Van Zeebroeck, Van linden, et al. 2007; Zwiggelaar et al. 1996). Studies on various fresh fruits have shown that vibration in-transit has been a predominate cause of fruit damage (Barchi et al. 2002; Fernando et al. 2018b; Vursavus & Ozguven 2004). 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. 2018b).

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 that have investigated the quality deterioration in bananas across the post-harvest SC from the farm to the retail stores. Mechanical damage in bananas has been reported during farm and pack house operations (Mvumi, Matsikira & Mutambara 2016), due to improper packing of bananas (Ekanayake & Bandara 2002; Hailu, Workneh & Belew 2013), rough handling of packages and bunches (Dadzie & 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, Dharmasena, et al. 2015a).

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 (Ekman et al. 2011; White, Gallegos & Hundloe 2011). Bananas are the most sold supermarket produce in Australia with a farm gate value of AU$ 600 million in 2016/17 (ABGC 2016). Cosmetic damage is a major cause of wastage across the banana SC. It was reported that wastage level in Australia ranges from 5% to 8% of gross volume, valued at AU$ 46 million to 73 million per annum and that this level was found higher than that of comparative international markets where the average wastage levels were less than 2% of sales volume (Kitchener 2015). Wastage across the SC and diminished perceived value in retail stores has been an ongoing problem to both banana growers and the retail industry in Australia (Ekman et al. 2011; Kitchener 2015; White, Gallegos & Hundloe 2011).

Major supermarket chains, which account for more than 74% of the total banana sales 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 Department of Primary Industries (DPI) 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% of the total banana production is concentrated in the tropical region of Northern Queensland (ABGC 2016), resulting in lengthy interstate supply chains down the continent to where the major metropolitan markets (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% 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.

- Investigate and identify the major underlying risk factors affecting mechanical damage in bananas within each node of the post-harvest SCs.

4.1.2. **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 to N4*) and three main transit links between the nodes (Fig. 4.1). Quality inspections were made along key inspection points (*P1 to P3*) to quantify damages across the SCs. A field market visit and observation (FMVO) study was performed at each node (*N1 to N4*) to determine potential risk factors for mechanical damage.

4.1.2.1. Quantitative Evaluation of Banana Quality across the Supply Chain

Three supply chains originating from three farms (A, B and C) located in the Tully region of Northern Queensland in Australia were selected for the study (Fig. 4.1). 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, 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 2017 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 (located approximately 3400 km by the road route from the growing regions) was specifically selected to assess the occurrence of damages in 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 (Fig. 4.2). 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.

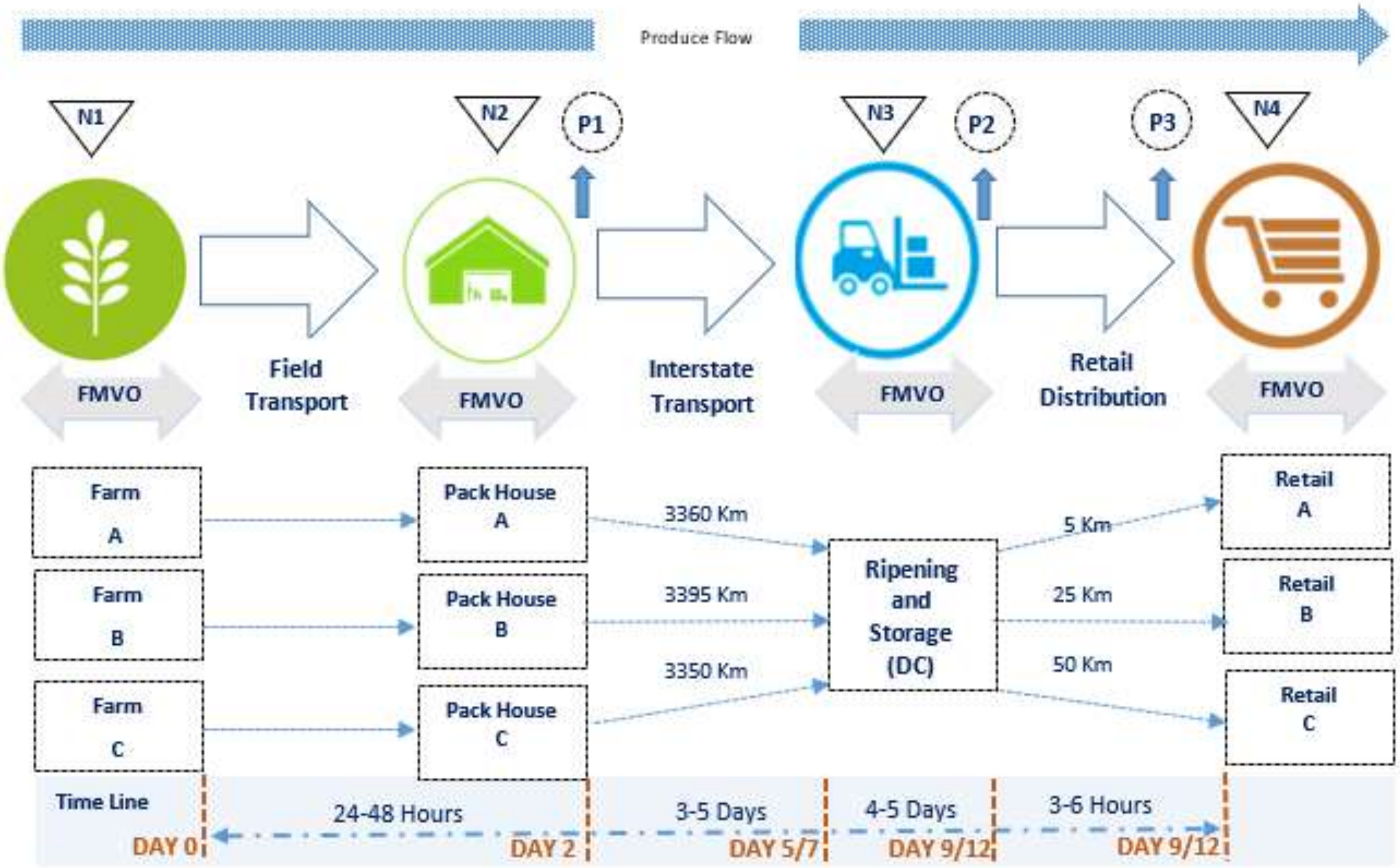


Figure. 4.1: Key Nodes (N1-N4) and Inspection Points (P1-P3) of the three Post-harvest Banana Supply Chains

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 °C) for a period of five days (Appendix C3). 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 (Fig. 4.1). The packages for all three distribution trips (DC to retail) were stacked as partial stacks (Fig. 4.2) and loaded to the rear position of each temperature-controlled (13-15 °C) delivery truck. Each retail store received 27 packages of inspected bananas from the corresponding pack house as illustrated in Fig. 4.1 (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.

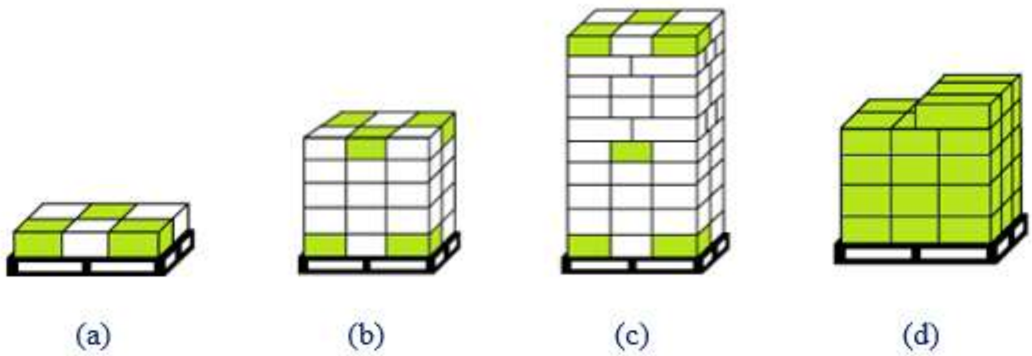


Figure 4.2: Stacking Pattern and Position of the Inspected Packages Stacked in Tier 1 (a), Tier 5 (b) and Tier 10 (c) from Pack-house to the DC and (d) The Arrangement of the Banana Packages during the Distribution from DC to Retail

Visual quality assessments were made in accordance with the visual quality assessment chart adapted from Ekman et al. (2011) (Appendix B1). Three main types of cosmetic damages have been frequently identified in bananas (i.e. bruising, abrasion and neck injuries; Appendix B1). 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; refer Appendix B1). A visual damage index (VDI) score (Eq.4.1) 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 (ΔVDI) (Eq. 4.2) was calculated to determine incremental mechanical damage between any two inspection points. Mean ΔVDI 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 (ANOVA) and Turkey's Honest Significant Difference (HSD) test were performed for the mean VDI scores and ΔVDI score with the use of GraphPad® Prism 7 statistical analysis package (GraphPad Software, La Jolla, CA, USA).

$$\text{VDI (\%)} = (0.1 \times \text{Trace Damages (\%)} + 0.2 \times \text{Slight Damages (\%)} + 0.7 \times \text{Moderate Damages (\%)} + 1.0 \times \text{Severe Damages (\%)} \quad \text{(Eq.4.1)}$$

$$\Delta\text{VDI (\%)} = \text{VDI A (\%)} - \text{VDI B (\%)} \quad \text{(Eq.4.2)}$$

4.1.2.2. Qualitative Assessment: Structured Observation

A FMVO (Mvumi, Matsikira & Mutambara 2016) study was performed to identify risk factors for cosmetic damage at each node of the SCs (*N1 to 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 (Boote & Mathews 1999; Ellram 1996) with the use of a checklist (Appendix B3) that was developed based on the preliminary field visits and literature on post-harvest losses in bananas (Da Costa et al. 2010; Dadzie & Orchard 1997; Ekman et al. 2011; Mvumi, Matsikira & Mutambara 2016; White, Gallegos & Hundloe 2011).

4.1.3. **Results**

4.1.3.1. Quantitative Assessment 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%) for each damage type (Fig. 4.3). At retail (P3), these bananas exhibited 7.3 % VDI score for abrasion damage followed by bruising damage (*3.2%*) and neck damage (2.8%). Most of the reported neck breaks at the retail stores were found to be moderate to severe.

Bruising in the bottom and middle tiers was significantly higher ($P<0.05$) compared to the top tier (Fig. 4.4) 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 ΔVDI score for abrasion damage in the top tiers and bottom tiers of the pallets was mostly attributed to fruit rub damage.

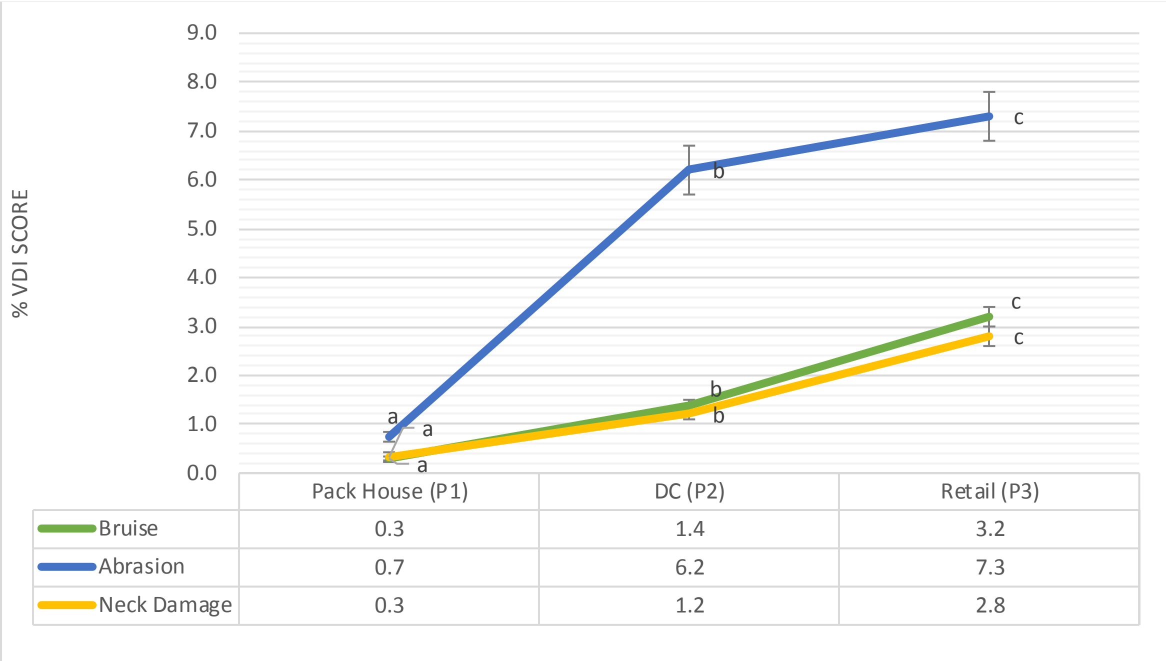


Figure 4.3: Progression of Mechanical Damages from Pack House to Retail [a, b and c denote significantly different results (P<0.01) in each damage category]

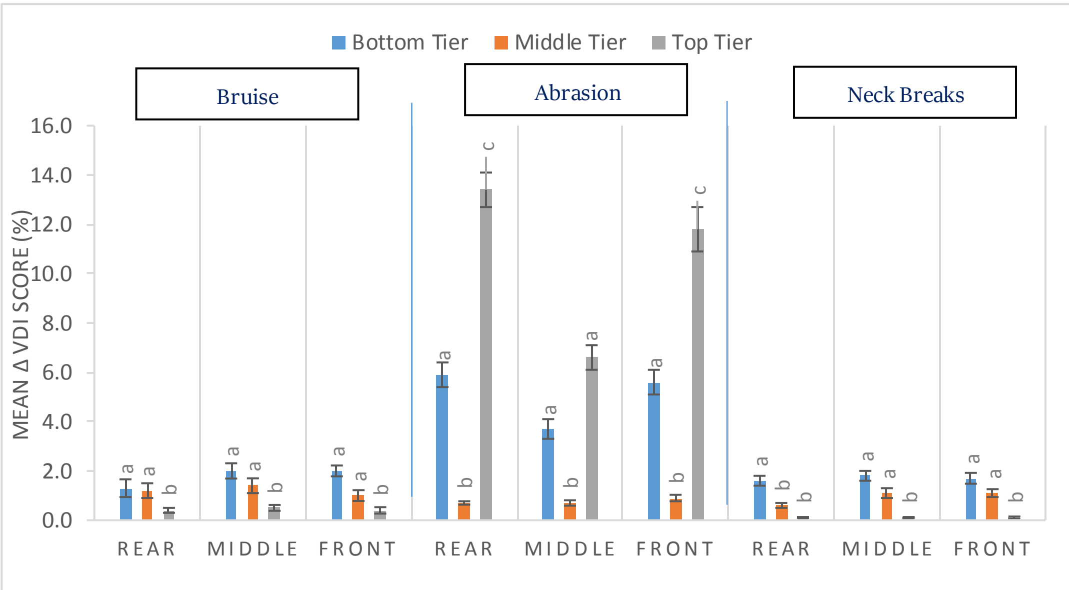


Figure 4.4: Δ VDI Scores in Different Package Storage Positions in the Truck during the Interstate Transport [a, b and c denote significantly different results (P<0.05) in each damage category]

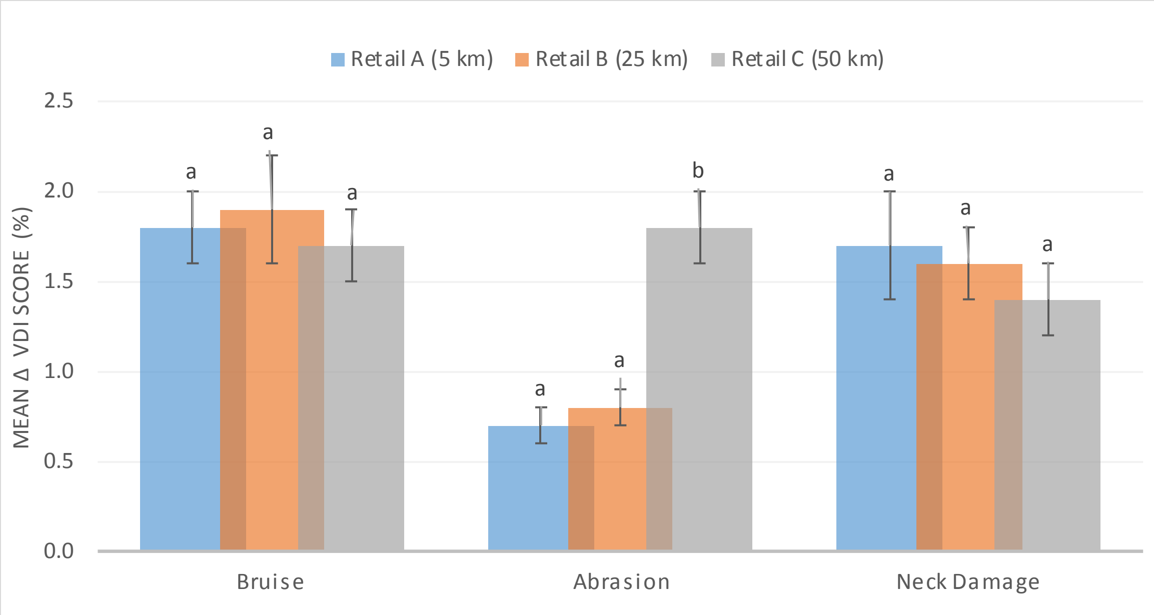


Figure 4.5: Increment of Mechanical Damages (Δ VDI Score) during the Distribution to Three Retails from DC [*a* and *b* denote significantly different results ($P<0.01$) in each damage category]

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 4.5. Abrasion damage of 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.

4.1.3.2. FMVO Study: Risk Factors Affecting Mechanical Damage

Risk factors affecting mechanical damage, identified during FMVO were categorised 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.

Table 4.1: Summary of the Prevalent Risk Factors identified by FMVO as Causing Mechanical Damage in Bananas in the Post-Harvest SC

Harvesting and Field Transport

- Lack of cushioning during (manual) harvesting
- Rough and muddy field tracks
- Damaged or misplaced cushioning in field trailers
- Unsecured bunches during field transport

Pack House Operation

- 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

Ripening and Storage

- 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 - Fig.4.9)

Transport (Interstate and DC to Retail)

- Vibration Transmissibility
- Location of the pallet on the trailer of the truck
- Height of the package in a stacked pallet
- Unsecured pallets

DC Storage and Dispatch

- Forklift and Layer-Picker handling
- Order consolidation
- Unstable and unsecured pallets (Fig. 4.9)
- Misaligned packages in pallets

Retail

- Improper storage
- Unpacking of packages
- Lack of cushioning on shelves
- Over-stacking the shelves

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 summarised in Table 4.1. Although rough handling of bunches and packages across the SC can be a significant risk for cosmetic damage in bananas (Dadzie & Orchard 1997), assessment of human factors relating to mechanical damage was not under the scope of this study.

4.1.4. 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 (Ekman et al. 2011; Maia et al. 2008). The most 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 Fig. 4.3-4.5, 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) (Appendix B1) were revealed at different stages along the SCs. The results of this research are discussed in Sections 4.1.4.1 and 4.1.4.2 with regard to the findings of the FMVO study to understand the causes of damage in each stage of the post-harvest SCs. Section 4.1.4.1 discusses the risk factors in farms and pack houses while Section 4.1.4.2 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.

4.1.4.1. 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 (Fig. 4.7). These scar damages may have occurred during field operations or can be attributed to pre-harvest factors (Dadzie & Orchard 1997; Mvumi, Matsikira & Mutambara 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 (Fig. 4.6). Most of the fruits with these severe damages have been discarded at the pack house. Fruit with trace to slight damages are packed into separate cartons for markets selling second (lower and cheaper) grades of fruit (Fig.4.7). 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% of the crop production in banana farms in Australia as highlighted in a previous study by White, Gallegos and Hundloe (2011).

Figure 4.6: Risk Factors affecting Mechanical Damage in Bananas in the Farm (a) Sand and dirt on the trailer cushion; (b) Damaged cushioning on the trailers

Figure 4.7: (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

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 & Orchard 1997; Macheka et al. 2013; Mvumi, Matsikira & Mutambara 2016). Minor 'wet' scars were also detected during the quality inspections at the pack houses (Fig. 4.7). 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 among 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 (Dadzie & Orchard 1997; Ekman et al. 2011; Macheka et al. 2013). 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 & Orchard 1997) during subsequent transport and handling.

4.1.4.2. Mechanical Damage in Bananas along the SC

Despite the much shorter distance and transport duration, the overall ΔVDI score from DC to retail (≤ 50 Km) was 4.3% while the same for pack house to DC (approx. 3400 km) was 7.7%. This signifies that nearly 30% 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

(Bugaud et al. 2014; Dadzie & Orchard 1997; Yuwana 1997). Ripening is associated with decreasing peel thickness and reducing fruit firmness (Banks, Borton & Joseph 1991; Banks & Joseph 1991; Fernandes ; Soltani, Alimardani & Omid 2010). 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, Ferris & Olorunda 1998).

- *Bruise Damage in Bananas*

Bruise damage was higher between the DC and retail (1.8%) compared to the pack house and DC (1.1%). It was found that packages stacked in the middle and bottom tiers of the pallet during the interstate transport sustained increased bruise damage (Fig. 4.4). Bruising is caused by impact and compression forces acting on bananas (Banks, Borton & Joseph 1991; Banks & Joseph 1991; Dadzie & Orchard 1997; Del Aguila et al. 2010). 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 & 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). Over-filled packages can be associated with mechanical damage in bananas during transport and handling (Dadzie & 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 (547L x 360W x 175H 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 & Joseph 1991). However, over-filled packages with bananas extending out of the top of the package (Fig. 4.8) 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 over-filled 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.

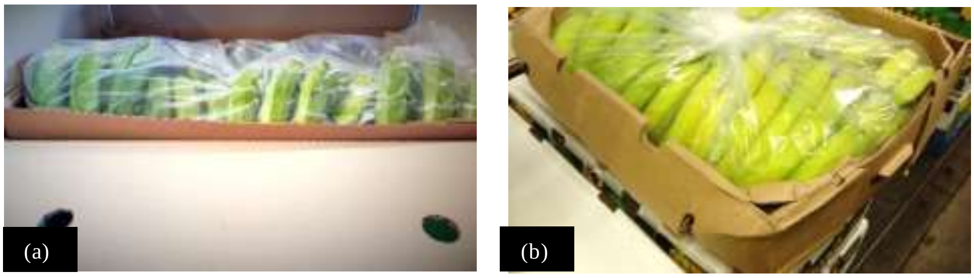


Figure 4.8: (a) Over-filled Package with Bananas in the Top Layer casting above the corner posts of a package (b) A carton with weakened structural integrity due to moisture absorption (exposure to high RH)

Figure 4.9: Package Failure in a Consolidated Pallet (Please note that the areas with brand names\ trademarks of the cratons have been shaded)

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% (Appendix C3) within the ripening environment can weaken the structural integrity of the corrugated paperboard cartons. The strength of a corrugated paperboard carton can be reduced by 52% when the moisture content is increased from 7.7% to 16% (Zhang, Chen & Wu 2011). A corrugated paperboard carton held at 90% RH equilibrium for a short exposure period may lose up to 60% of its original strength (Vigneault et al. 2009). This can lead to packaging failure (Fig. 4.8) exposing the palletised fruit to increased mechanical stresses (Pathare & 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 (Fig.4.9). 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 (Fig. 4.9) 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.

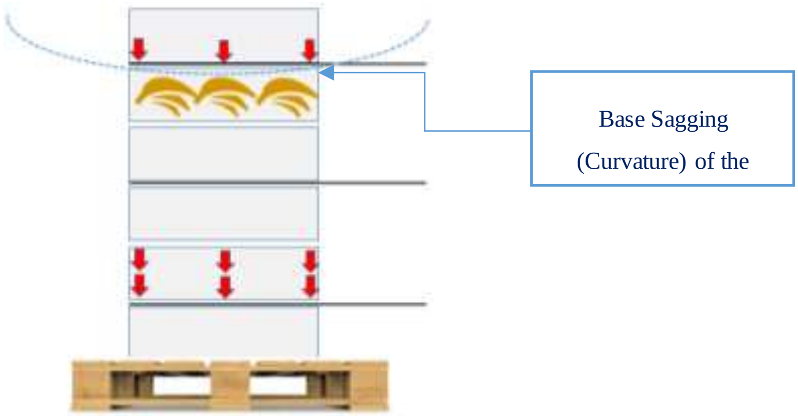


Figure 4.10: Base-sagging in Banana Packages due to the Concentrated Weight at the Centre of the Package

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 & 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.

- *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 (Fig. 4.4). 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 were 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.

Neck injuries were frequently found in the top layer of bananas inside the package followed by the second layer (Fig. 4.11) 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%) in this last-leg compared to the increment between pack house to DC (0.9%). This signifies that the majority (57%) of the neck injuries occurred during the retail distribution. Therefore, to minimise 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.

- *Abrasion Damage (Scars, Fruit Rub, Blackened Rub and Scuffing) in Bananas*

The most frequently observed damage in bananas along the SC was abrasion (Fig. 4.3), 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 becomes instantly visible on bananas (Chukwu, Ferris & Olorunda 1998; Del Aguila et al. 2010). Abrasion can present in the form of scars, rubbing (fruit rub and blacked rub) and scuffing in bananas.

- *Fruit (Transport) Rub*

The increment of cosmetic 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 (Fig. 4.11). 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 & Ozguven 2004). Previous research has indicated that vibration frequency and transmissibility (Fernando et al. 2018b; Vursavus & Ozguven 2004) were 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 (Barchi et al. 2002; Berardinelli et al. 2005; Slaughter, Thompson & Hinsch 1998; Vursavus & Ozguven 2004).

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, Thompson & Hinsch 1998). During interstate transport, the relative movement of bananas may have been 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.

- *Scuffing and Blackened Rub*

Abrasion damage, particularly blackened rub and scuffing increased from DC to retail stores (Fig. 4.5). 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 (Fig. 4.11). 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 (Fig. 4.10). 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 (Fig. 4.11). 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 minimise 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 minimise the occurrence of rub damage on shelves. However, this needs to be considered with respect to the additional cost of cluster packaging.

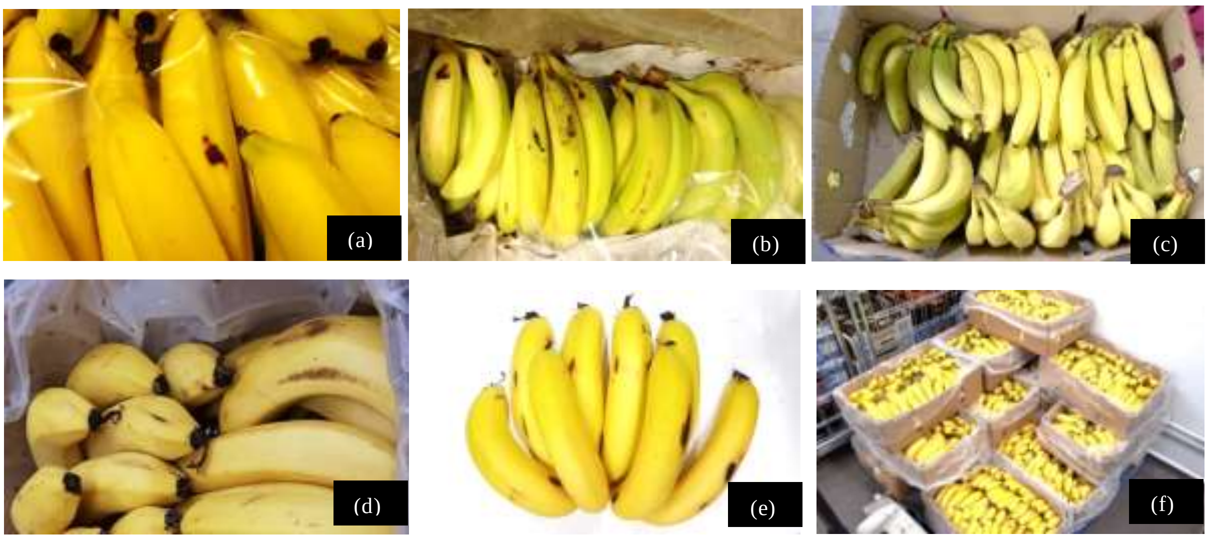


Figure 4.11: (a) Scar damage (tip rub) as the liner is misplaced; (b) Scars (crown rub) and bruising in the first layer of bananas inside the package; (c) Neck injuries found in the top layer of bananas inside the package; (d) Scuffing caused by liner rub; (e) Cluster with severe fruit rub; (f) Cross-stacked banana packages with lids removed for air-cooling

- *Scar Damage*

As discussed in Section 4.1.4.1, 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 (Fig. 4.11). 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, Gallegos & Hundloe 2011) imposed by the major retailers including the supermarket chains in Australia.

4.1.5. **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 are essential to reduce wastage levels caused by damage during the post-harvest operations. The importance of careful handling of packages specially in the last-mile distribution of bananas and the need to reducing damage caused by in-transit vibration were 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 3000 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 focused 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.

4.1.6. 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 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 optimised packing to minimise 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 minimise package collapsing especially in the bottom and middle tiers of the pallets, causing mechanical damage in bananas attributed to top load compression.

CHAPTER IV

PART B

Assessment and Characterizing Mechanical Damage in Packaged Bananas in the Post-harvest Supply Chain

Abstract

Quality deterioration in packaged bananas caused by mechanical damage along the post-harvest supply chains (SC) remains obscure until the packages are unpacked for sale at the retail stores and therefore, the mechanism of damage occurrence remains unclear. This study assessed the mechanical damage levels of bananas in 300 cartons from pack houses to retail stores in Australia. The damage across the SC were shown to be progressive across the SC. Bruising and neck damage levels in bananas increased from the distribution centre (DC) to the retail stores. Mechanical damage in unripe bananas was influenced by the package location in the stacked-pallet, and the transport and handling of packages within the last-mile of the SC (DC to retail) further exacerbated the damage. This study further characterized the damage development by subjecting packaged bananas to simulated vibration, top-load compression and drop impact. It was revealed that the exposure to vibration resulted in rubbing; top-load package compression contributed to bruising and, the drop impact caused severe neck injuries in bananas. The knowledge of the damage incidences across the SC and causes of damage may contribute to the development of interventions targeted at improving the quality of bananas in the post-harvest SC in Australia.

Key Words: Supply Chain, Banana, Quality, Mechanical Damage, Vibration, Compression, Impact

4.2. Assessment and Characterizing Mechanical Damage in Packaged Bananas in the Post-harvest Supply Chain

4.2.1. Introduction

In most post-harvest supply chains (SC), a certain degree of mechanical damage to fresh produce during the distribution is unavoidable. Appearance quality of fruits is a major determinant for the consumer's willingness to purchase (Jaeger et al. 2016). Previous studies have shown that cosmetic damages in bananas resulted in poor consumer acceptance and marketability (Ekman et al. 2011). Bananas have been the most sold supermarket produce in Australia (Margetts 2014) and their quality is of a great interest not only to the banana industry but also to the major supermarket chains which account for over 74% of the total banana sales (Day 2018) in Australia. Bananas, like any other fruit are subjected to mechanical stresses from harvest through to consumers which is one of the major factors for the post-harvest quality deterioration (Dadzie & Orchard 1997; Del Aguila et al. 2010). It was estimated that 5-8% of the gross volume of bananas has been accounted as wastage in the post-harvest SC in Australia which amounts to AU$ 46-73 million per annum (Kitchener 2015). Therefore, mechanical damages in bananas have been a significant concern for both the banana and retail industries in Australia, requiring a systematic investigation.

Like other fresh produce, bananas also exhibit a degree of physio-chemical changes due to mechanical injury. One of the most significant and immediate consequence of mechanical damage is the attack of microorganisms, which may cause further decay in fruits (Maia et al. 2015). Mechanical damages cause browning in bananas due to the oxidation of poly phenols (Maia et al. 2011). Maia et al. (2015) found that mechanical damage caused higher enzyme activity in the affected area followed by alternations in colour, flavour, rapid tissue softening and induced ripening. It was also showed that mechanical damage induced respiration levels in bananas (Del Aguila et al. 2010; Maia et al. 2011). Chukwu, Ferris and Olorunda (1998) further reported that abrasion damage caused rapid moisture and weight loss compared to impact bruising in bananas. Similarly Maia et al. (2011) reported that abrasion and cut damages resulted in the highest fresh weight loss in bananas compared to the other treatments. Furthermore, Maia et al. (2011) showed that mechanical damage expedited ripening and influenced the rate of conversion of starch into total soluble sugars (TSS) in the pulp. These findings conclude that mechanical injury induce ripening, hence reduce the effective shelf-life of the fruit. The most significant consequence of these alterations would be the implications on fruit quality and the perceived value of bananas, which can directly affect the marketability.

Mechanical damage in fruits can occur due to compression, impact and vibration when fruits are transported in packages or in bulk bins. Bruising can occur due to impacts or compression forces (Banks, Borton & Joseph 1991; Banks & Joseph 1991) resulting in peel and/or flesh damage in bananas depending on the severity of the impact/pressure. Damage caused by friction occurs due to the relative movement of the fruit against other contacting surfaces. Abrasion damages such as rubbing in bananas can occur due to vibration or when bananas are handled in clusters (e.g. when clusters are rubbing against conveyer belts in a packing line). Several studies showed that vibration during transport was a critical factor for the development of mechanical damage in bananas (More et al. 2015; Wasala, Dharmasena, Dissanayake & Tilakarathne 2015) and prolonged exposure to vibration could escalate the incidence of damage (Dadzie & Orchard 1997). Studies on other packaged fruits revealed that the vibration damage can be severe in loosely packed fruits compared to the tightly packed fruits (Slaughter, Hinsch & Thompson 1993; Sommer et al. 1957). Unlike most other fruits, bananas may also exhibit stem end tearing or neck damage. Neck injuries are caused by separation of stem from the fruit (Mohsenin 1986) which can affect the quality and the consumer acceptance at the retail stores (Ekman et al. 2011). However, limited knowledge exists on the exact mechanism of the occurrence of neck injuries especially when banana clusters are packed inside corrugated paperboard cartons during distribution.

Studies assessing the occurrence of mechanical damage in bananas across the SC, from the farm gate to the retail-shelf are limited. Maia et al. (2008) investigated mechanical damage at four distinct locations in the banana SC (pre-selection, after packing, after transport and retail market) and concluded that the damaged levels increased and accumulated along the chain. A similar study revealed that the damage to bananas was progressive along the SC and the highest damage occurred during the post-harvest distribution (Da Costa et al. 2010). However, damages caused by different mechanical stresses in bananas are not well defined in literature and a deep understanding of different types of damages is necessary to determine the causes of such damage. Previous studies revealed several types of cosmetic damages in bananas (Fig.4.12) (Ekman et al. 2011) however their mechanism of occurrence, especially within a package and during the handling across SC has not been well understood. Therefore, this study aims to (1) assess and quantify the mechanical damages in bananas across the post-harvest SC in Australia and (2) characterize different types of damages in packaged bananas caused by induced mechanical stresses including vibration, compression and transient impacts.

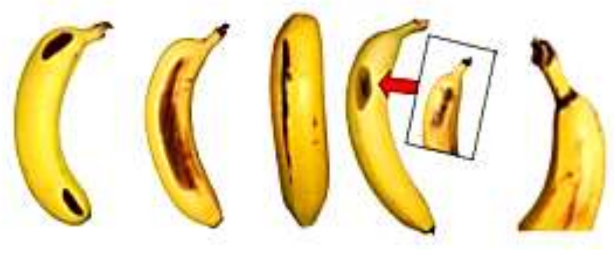


Figure 4.12- Types of Cosmetic Damages in Bananas (Refer Appendix B1 for details)

4.2.2. **Materials and Methods**

4.2.2.1. Damage Assessment in Packaged Bananas

To understand the occurrence of cosmetic damages in bananas, the damage levels were assessed in three locations across the chain, from the pack-houses through the distribution centre (DC) to the retail stores (Fig.4.13). Bananas are commonly packed in three grades (i.e. premium, extra-large and large) for different markets and the 'premium' grade (selected and packed as the highest grade) is intended for the major supermarket chains in Australia. Cartons packed with 'premium' grade bananas were selected for this study because they are generally graded before the packing process with minimal pre-existing damage. Having a minimal (or none) existing damage in bananas at the initial stage of the SC (i.e. pack-house) is essential for the damage comparison to distinguish the damage development at the later stages of the SC (i.e. DC and retail stores).

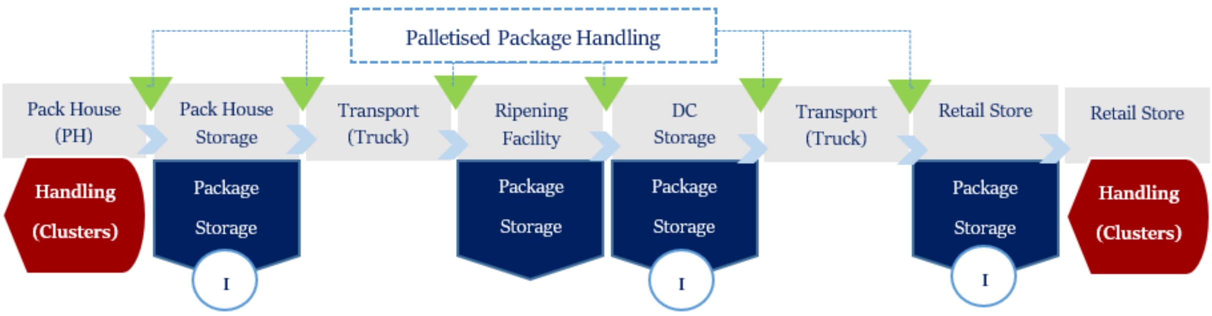


Figure. 4.13- Simplified Post-harvest Banana SC ('I' Indicates the Inspection Points)

Five SCs were selected for the study, originating from five pack houses in Northern Queensland to the retail stores in Melbourne (over 3000 km via the road route) through a regional DC in Melbourne. A sample of 100 packages were selected randomly in each location (i.e. pack-house, DC, retail store) for damage assessment. Twenty packages were assessed in each pack house and retail store. The stacked-tier of the selected packages in the pallets in each location is given in Table 4.2. Banana packages were stacked in 10 tiers on wooden pallets during the distribution from the pack-houses to DC and stacked only up to five tiers (mostly consolidated with other produce packages) from the DC to retail stores. Therefore, number of cartons inspected in each tier was 10 and 20 in the DC and retail stores respectively. A total of 300 cartons packed with 3,240 clusters of bananas (15,261 individual fingers) were assessed for mechanical damage and quality defects across the SC.

Table 4.2: Number of packages inspected in each Tier of the Pallet at the DC and Retail during the Random Inspection

Location	**No. of Packages Inspected in Each Tier of the Pallet**										**Total**
Tier Number	1	2	3	4	5	6	7	8	9	10	
Pack-house	10	10	10	10	10	10	10	10	10	10	100
DC	10	10	10	10	10	10	10	10	10	10	100
Retail	20	20	20	20	20	-	-	-	-	-	100

4.2.2.2. Characterizing Mechanical Damage in Packaged Bananas

Packaged bananas were subjected to simulated vibration, top-load compression and simulated handling (drop impact) to determine the causes of different types of mechanical damage in bananas. Forty (40) sample banana cartons were arranged for the experiments. All sample cartons were sourced from the same batch of fruits, harvested/packed from the same farm/pack-house in Tully, Queensland. Fifteen (15) cartons were packed with unripe bananas (stage two) and the rest were packed with ripe bananas (stage six) as per the ripeness chart in Ekman et al. (2011). The cartons were packed in three-layers (5-7 clusters per layer arrangement) inside each package. All sample cartons were pre-inspected for existing damage and the clusters with pre-existing damages were replaced with non-damaged clusters prior to each experiment. All cartons with unripe bananas were conditioned for 48 hours at 13.5 °C and 50-60% relative humidity (RH) and the ripe bananas were stored in 15-18 °C at 90-100% RH (inside the ripening chamber) for 48 hours before the experiments.

- Simulation of Package Handling and Top-load Compression

A drop-testing machine (Lansmont PDT 80, CA, USA) was used to drop packaged bananas (ripe) from heights of 0.3 m and 0.5 m (Fig. 4.14). Each carton was dropped from these specified heights three times during each test and the experiment was conducted in a randomized block design in pentaplicates (5 x 2). For the package compression experiment, ten cartons of ripe bananas were subjected to top-load compression by a compression testing machine (Instron 1185, MA, USA). Five sample cartons with ripe bananas were crushed to 16 mm and the other five cartons were crushed to 25 mm vertical displacement levels. Each package compression experiment was conducted in randomized block design in pentaplicates. All the sample packages were stored in 13.5 °C and 50-60% RH and the damage levels in packaged bananas were assessed 12 hours after each experiment by the procedure described in Section 4.2.2.3 to derive a damage score for each package.

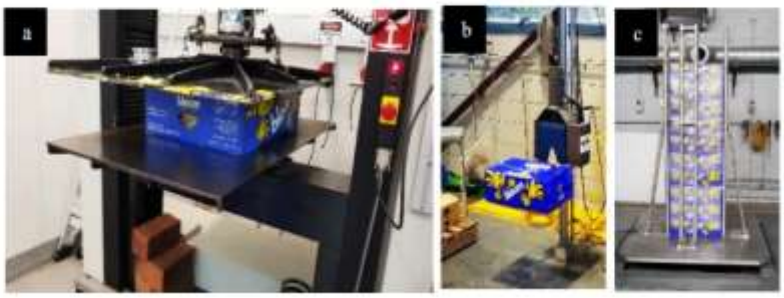


Figure 4.14- Characterizing Mechanical Damage by (a) Top-load compression (b) Drop impact and (c) Simulated Vibration

- Simulated Vibration Testing

A single vertical column of ten banana cartons (unripe) was subjected to simulated vibration intensity of 0.36 g for a duration of 3 hours by an electro-hydraulic vibration simulation table. The vibration profile of ASTM-D4169 was used (ASTM 2016a). The column was triple-stretch-wrapped with transparent stretch film and supported by vertical steel columns fixtures, attached to the table from either side to avoid the collapsing of the packages during the test (Fig. 4.14). After each experiment the cartons in the bottom (1^{st} tier), middle (5^{th} tier) and top (10^{th} tier) were removed from the column for damage assessment and the three sample positions were stacked with fresh (non-vibrated) cartons. The packages in the rest of the positions of the column were reused as dummy packages in each repeat experiment. The damage level in bananas stacked in the three sample positions of the column were evaluated 12 hours after each experiment by the procedure described in Section 4.2.2.3. This experimental procedure was repeated for ripe bananas. All vibration simulation experiments were conducted in pentaplicates in a randomized block design (3 x 5).

4.2.2.3. Damage Assessment and Analysis

The damage in packaged bananas was assessed by a 0-4 point hedonic scale (0- No damage; 1- Trace damage; 2- Slight Damage; 3- Moderate Damage; 4- Severe Damage) in accordance with the visual quality assessment chart (Ekman et al. 2011). A visual damage index (VDI) score was calculated by the Eq. 4.3 for each package similar to the equivalent bruise index for apples (Vursavus & Ozguven 2004). The mean VDI score was used for the comparison of damage levels in bananas occurred after each treatment.

VDI (%) = (0.1 x Trace Damages (%) + 0.2 x Slight Damages (%) + 0.7 x Moderate Damages (%) + 1.0 x Severe Damages (%) (Eq.4.3)

One-way analysis of variance (ANOVA) and Turkey's Honest Significant Difference (HSD) test were performed to test for significant differences within the means by GraphPad® Prism 7 statistical analysis package (GraphPad Software, La Jolla, CA, USA).

4.2.3. Results

4.2.3.1. Mechanical Damage along the Supply Chain

Different types of mechanical damages exhibited in different stages of the SC during the damage inspection is given in Fig. 4.15. The levels of neck damage, bruising and various abrasion damages (i.e. scuffing, fruit rub, and blackened rub) by the stacked-tier in the pallet as revealed in the DC and retail stores are given in Figure 4.16 and Figure 4.17 respectively. Damage assessment in packaged bananas revealed that the accumulated damage level was escalated by 1.8% to 8.9% from the pack houses to the retail stores (Fig. 4.15). The highest increment in damage (5.1%) was revealed in abrasion type damage while bruising and neck damage exhibited a relatively less increment (<2%) from the pack houses to the retail stores. The highest increment of damage between two SC nodes was revealed in abrasion damage between the pack houses and DC (2.6%) and the abrasion damage level has further worsened between the DC and retail stores (2.5%). The level of bruise and neck damage at the pack houses marginally increased at the DC however neck damage levels had nearly doubled between the DC and retail stores.

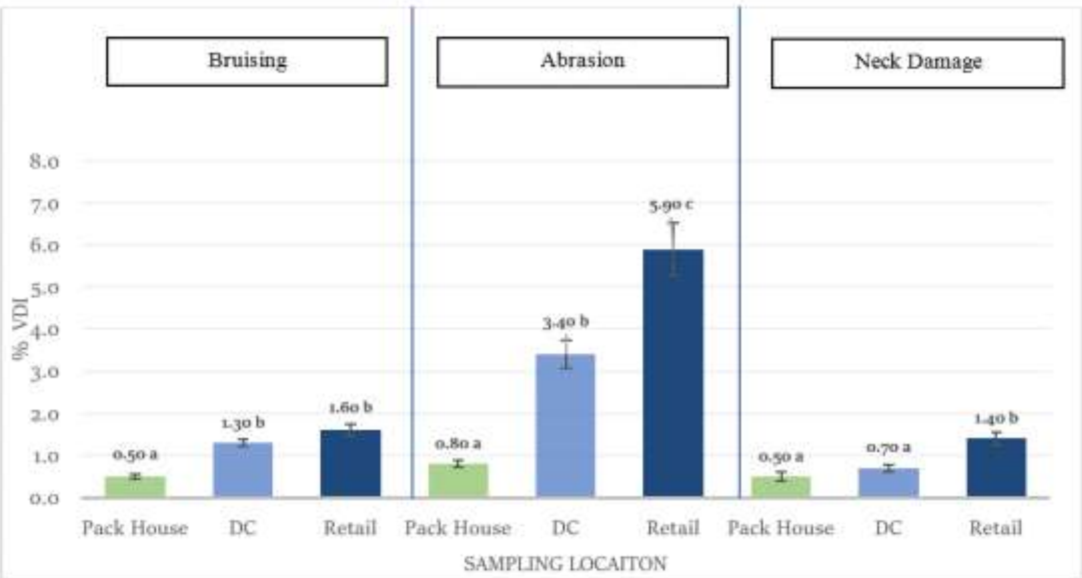


Figure 4.15 – Mechanical Damage in Bananas by the Sampling Location in the SC [Different characters indicate significantly different (P<0.01) results in each damage category]

Figure 4.16 illustrates the different types of damage in bananas by the stacked tier which were revealed during the damage assessment at the DC. The best-fitted line (3rd order polynomial) for the overall damage level from tier one to ten elaborates that the highest damage level in a stacked pallet was found in the most top and the bottom packages. The accumulated damage level is minimal in the mid-tier packages of the pallet. Abrasion damage largely contributed to the escalation of the overall damage level in the two bottom tiers and the three top tiers. It is also revealed that the bruise damage and neck injury levels decreased from the bottom to top of the pallet. Statistical analysis revealed that the bruise damage levels in the first six tiers are significantly different ($P<0.01$) to that of the top four tiers. Similarly, the neck damage levels of the top four tiers are significantly different ($P<0.01$) to that of the rest of the lower tiers in the pallet. The abrasion damage level in the most bottom tier is significantly different ($P<0.01$) to the rest of the tiers except for the damage level in the ninth tier. There was no statistical difference in abrasion damage levels from the third tier to the seventh tier however, the highest abrasion damage level was revealed in the top tier packages which was statistically different ($P<0.01$) to the rest of the tiers. Most of the abrasion damage levels were influenced by the frequent occurrence of fruit rubbing and scuffing especially in the most bottom and top tiers of the pallet.

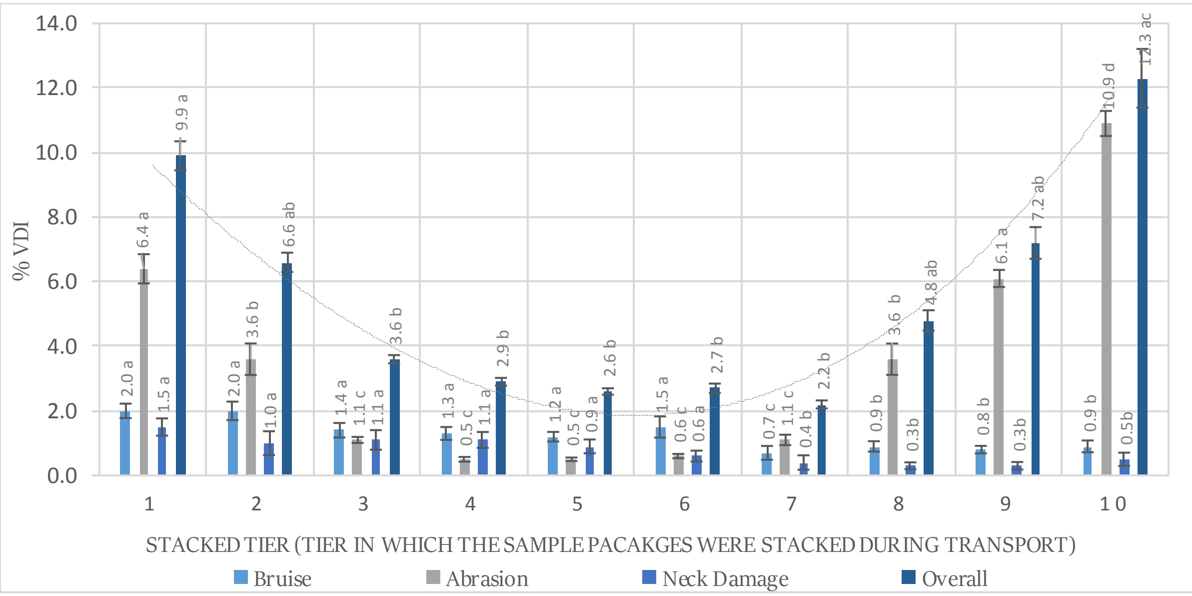


Figure. 4.16 – Mechanical Damage in Bananas by the Stacked Tier at the DC [Different characters indicate significantly different ($P<0.01$) results in each damage category]

As exhibited in Fig. 4.17 there are no statistically significant differences found for any damage type or for the overall damage level based on the stacked tier of the packages at the retail stores. It was also revealed that, at the retail stores the most critical damage was abrasion. As illustrated in Fig. 4.18, the most frequent abrasion damage at the retail stores was rubbing damage (70%) including the fruit rub and blacked rub however, the other abrasion damages such as scuffing (17%) and scars (13%) were marginally exhibited.

Inside each package, bananas are packed in three layers (Fig. 4.19) and the damage level by the layer of fruit inside the carton is given in Fig. 4.20. It was revealed that a higher incidence of bruising (1.2%) existed in the first layer of fruits inside the carton and the frequency of abrasion type damages such as fruit rub and scuffing was higher in the second and third layer inside the carton. Neck injuries were also escalated in the third layer and the second layer (1.3%) than the first layer (0.1%).

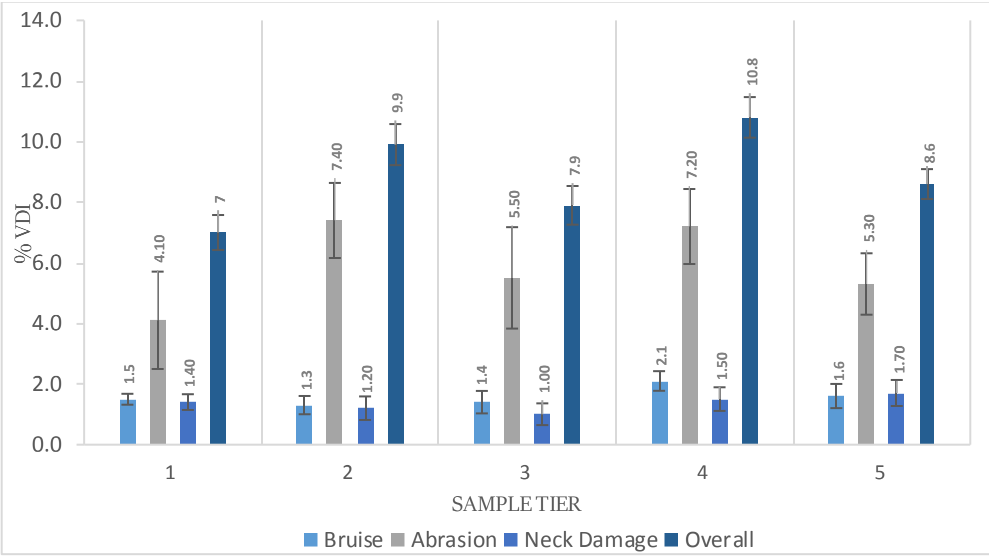


Figure 4.17 – Overall Mechanical Damage Levels in Bananas Recorded during the Random Inspection at each stage of the SC [No statistically different results (P<0.01) for each damage category have been exhibited]

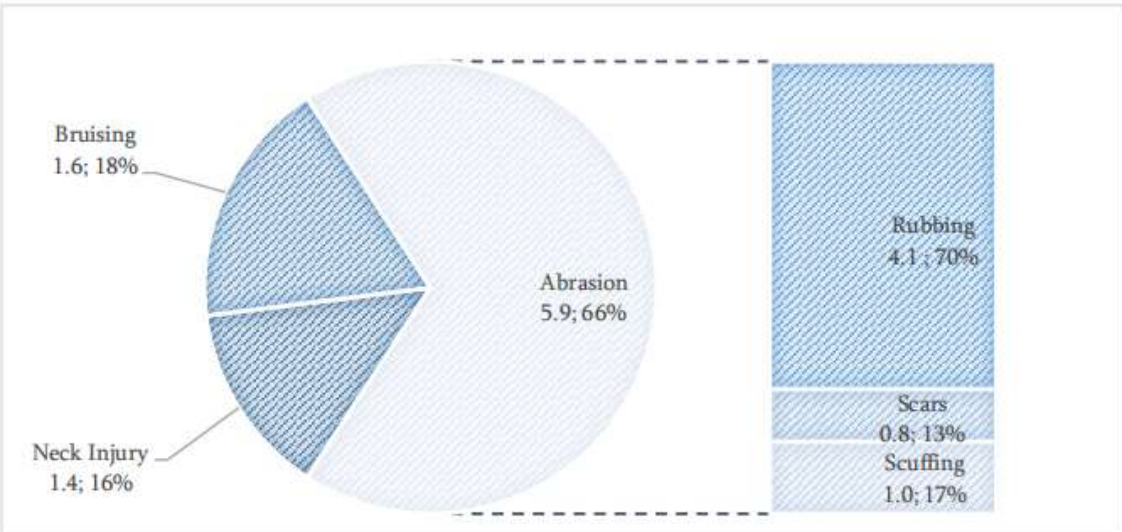


Figure 4.18 – Breakdown of VDI Score and the Percentage (%) by each Damage Type for the Retail Stores

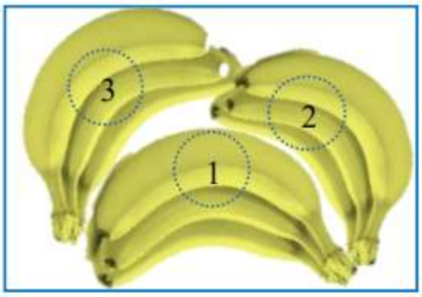


Figure 4.19 – Spatial Arrangement of Bananas inside the Carton Packed in Three Layers (Layer 1,2 and 3)

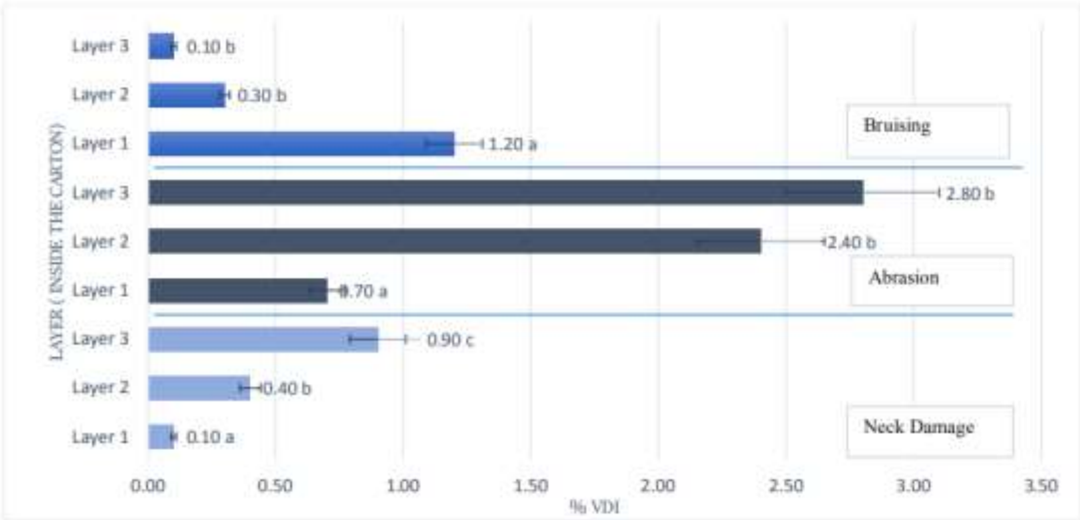


Figure 4.20 – VDI for the Layer of Bananas inside the Carton (Retail) [Different characters indicate significantly different ($P<0.01$) results in each damage category]

4.2.3.2. Characterizing Mechanical Damage in Packaged Bananas

Different types of mechanical damages occurred in packaged bananas due to package drop, top-load compression and vibration (Fig. 4.21). Package drop mainly resulted in neck injuries and package compression resulted in bruise damage (Fig. 4.21). In addition to neck injuries, package drop occasionally resulted in minor levels of bruising in ripe bananas. Exposure of packages to simulated vibration mainly resulted in abrasion damage in bananas (Fig. 4.22). For the same vibration treatment, the damage levels were significantly higher ($P<0.05$) in ripe bananas compared to the unripe (green) bananas (Fig. 4.22) and majority of the vibration damage occurred in the top two layers of bananas inside the package.

As illustrated in Fig. 4.23, the neck damage level (VDI %) worsened ($P=0.076$) with the increasing drop height of the packages. Nearly 94% and 91% of the neck injuries (attributed to 0.3m and 0.5m drop heights respectively) were concentrated in the top two layers of bananas inside the package (Fig. 4.23). Bruise damage level (VDI %) in bananas significantly ($P<0.05$) proliferated due to the increased top-load compression of the packages from 16 mm 25 mm (Fig. 4.23). Nearly 72% of bruising damage occurred under the 16 mm compression and 84% under the 25 mm compression was localized in the first layer inside the package.

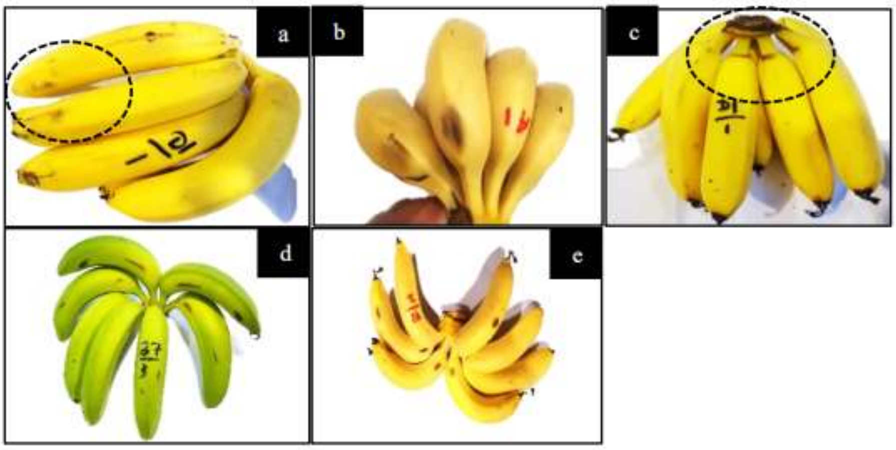


Figure 4.21 – Different types of Mechanical Damages Occurred in Bananas (a) Minor (trace) levels of bruising (b) Shoulder bruising occurred by top-load compression (25mm) (c) Severe neck damage due to drop-impact (d) Fruit-rub in unripe bananas and (e) Fruit- rub ripe bananas caused by simulated vibration

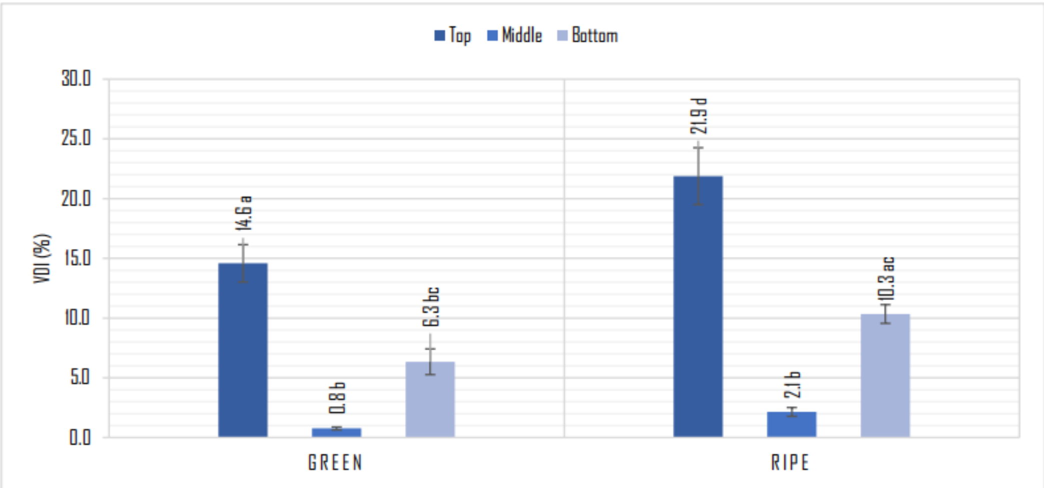


Figure 4.22 – Mechanical Damage Levels (i.e. abrasion) in Green and Ripe Bananas caused by Simulated Vibration [Different letters indicate significantly different results (P<0.05)]

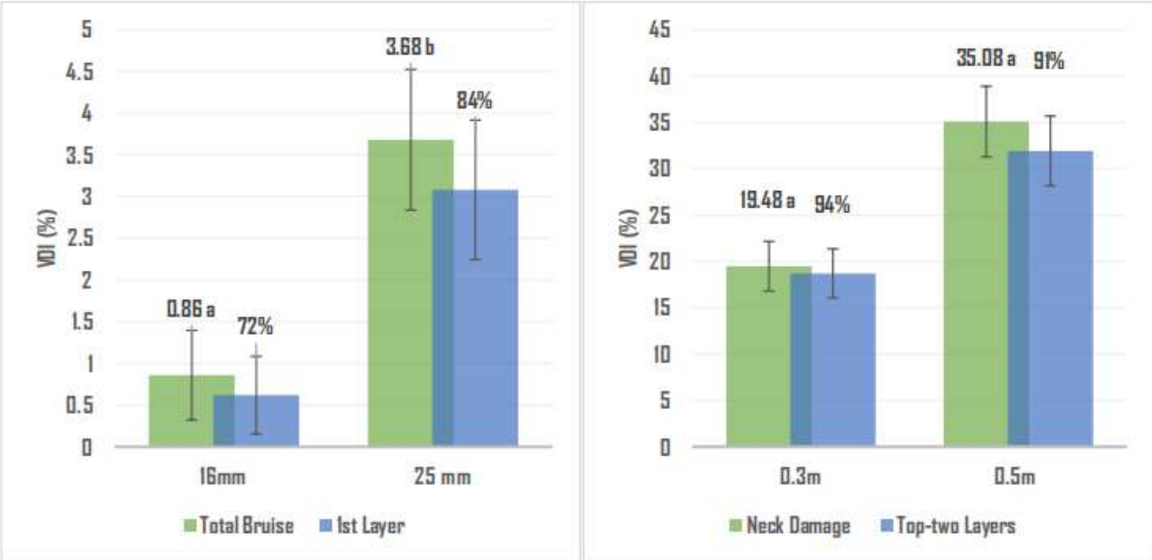


Figure 4.23 – Mechanical Damage Levels Occurred during the Top-load compression (left) and Drop Impact Testing (right) [Different letters indicate significantly different results ($P<0.05$) in each test]

4.2.4. **Discussion**

The results from the damage assessment indicates that all types of damages in bananas (i.e. bruising, neck injuries, abrasion) exacerbated along the SC, resulting in poor visual quality at the retail stores. At all three stages of the SC, abrasion damages were the most frequently reported. It was also revealed that most fruit rub damages occurred between pack houses and DC while blackened rub and scuffing damages were mostly caused during the DC to retail stores. These results indicate that damages in bananas are accumulating along the SC, leading to an overall quality deterioration at the retail end. In addition, abrasion damage is the predominant type of damage in the bananas. Similar results were reported in previous studies which reported that mechanical damages in bananas were progressive along the SC (Da Costa et al. 2010; Maia et al. 2015; Maia et al. 2011; Maia et al. 2008) and the abrasion type damages were predominant in packaged bananas (Ekman et al. 2011).

The simulation tests revealed that ripe bananas were more susceptible to vibration damage compared to the unripe (green) bananas (Fig. 4.22). This could be the reason for the disproportionate increment of damage during the last-mile distribution of ripe bananas (from DC to retail). The results show that the interstate transport and handling of bananas (over several thousand kilometers) resulted in 2.6% damage increment in unripe (green) bananas while the distribution of ripe bananas to retail stores located less than 100 km from the DC caused 2.5% increment in abrasion damage. Similarly neck injuries in bananas nearly doubled between the DC to retail stores.

The drop tests confirmed that one of the major reasons for neck injuries in bananas is the manual handling of packages. The significant increase in neck injuries in the latter part of the SC (from DC to retail) indicates that softer ripe bananas become more susceptible to neck damage than the harder unripe (green) bananas during handling. Therefore, it is essential that packages with ripe bananas are handled cautiously, especially during the palletizing and package consolidation i.e. staking different produce packages together in mix-pallets at the DC to be dispatched to different retail stores to minimize neck injuries. Similar results were reported in the previous studies inciting that the susceptibility of bruising in bananas escalated with ripening (Maia et al. 2011; Yuwana 1997) and thus, carefully handling and storage packages will be integral to improving the quality.

Most of the abrasion damage recorded at the DC was concentrated in the top and bottom tiers of the pallet (Fig.4.16), while the middle tier packages (tier 4 to tier 7) exhibited a minimal level of abrasion (i.e. fruit rub). Most of the fruit rub damage in the bottom and top tiers of the pallet were caused by relative motion of fruits in the package, which was associated with the transmissibility of vibration in a pallet. The simulated vibration tests revealed similar results, confirming that more vibration damage occurred in the bottom and top tier packages with minimal damage occurring in the middle tiers (Fig. 4.22). This result coincides with the previous studies which have shown that the highest vibration damage in fruits were often revealed in the most top tier packages of a pallet \column (Fischer et al. 1992; Jarimopas, Singh & Saengnil 2005). However, the reason for reduced damage in the middle tiers of the pallet requires further investigation, including examining the vibration dampening properties of corrugated packaging.

Bruising and neck damage levels escalated in the bottom tiers of the pallet, revealing the highest levels of damage in the most bottom tier packages (Fig. 4.16). Top-load compression tests confirmed that bruising in bananas occurred mostly due to the compression of the packages from the upper tiers. The weight from the upper tiers act on bananas as quasi-static compression during storage, handling and transport. Dynamic compression forces on packages during transport may also occur due to shocks encountered by palletized packages. However, more research is necessary to determine the influence of transient shocks during transport on the occurrence of damage in packaged bananas. Despite the relatively lower bruise and neck damage levels in the upper tiers of the pallet, the overall accumulated damage levels still increased in the top tiers, due to the high levels of abrasion damage (Fig. 4.16).

The presence of increased neck injuries in the bottom tier packages at the DC indicates that neck injuries are not only caused by package handling but also associated with the weight of the fruits stacked on-top of a given package. It was revealed during the damage assessment that occasional package failure in the bottom tiers was closely associated with a higher incidence of neck injuries in bananas. However, the reasons for such sporadic package failure was not always straightforward but observed to be associated with misaligned stacking of packages on pallets and moisture absorption by paperboard cartons during the ripening process.

Most abrasion damage was concentrated in the top two layers inside the package (Fig. 4.20). This can be due to the increased freedom of movement of fruits when exposed to vibration and the movement or bouncing of clusters inside the package due to the shock impacts (e.g. package dropping). When individual fingers are free to move inside the package, it results in rubbing between the fingers and clusters. The weight of the two upper layers and the inter-locking mechanism of clusters inside the package (Fig. 4.19) restricted the freedom of movement for clusters in the first layer of the carton resulting in reduced abrasion damage in the first layer. During the package drop tests, the energy of the transient shock events (e.g. by hitting the floor/ ground) was partially transmitted to banana clusters packed inside. The top two layers of fruit (especially the most top layer) had more freedom to bounce resulting high incidence of neck injuries in the top two layers inside the package. Similar results were reported by Ekman et al. (2011).

4.2.5. **Conclusion**

Minimizing quality deterioration in bananas requires knowledge on the incidence of mechanical damage along the SC and the mechanism of damage occurrence in packaged bananas. This study evaluated the cosmetic damage levels in bananas along the post-harvest SC and experimentally tested and confirmed the causes for damage occurrences. The knowledge gained by these experiments reveal what type of damages occur along the post-harvest SC and why such damages occur in each stage of the SC.

The damage levels were found progressive along the SC from the pack houses to the retail stores. The damage levels in green bananas were significantly influenced by the package position in the stacked-pallet. The abrasion damage was mostly concentrated in the top and bottom tier packages while both neck injuries and bruise damage were frequently found in the middle and lower tier packages of the pallet. All types of damages further proliferated during the distribution of ripe bananas to the retail stores and bruising and neck injury levels nearly doubled from DC to retail stores. The laboratory simulation experiments confirmed the observed field damages and revealed that top-load compression on the packages resulted in bruise damage in bananas while the simulated package drop resulted in severe neck injuries. Exposure to simulated vibration contributed to the development of fruit rub damage in the most top and bottom tier packages of the stacked column however, the middle tiers exhibited minor level of rubbing damage. Minimizing bruising and neck injuries in bananas requires careful storage and handling of packages especially during the distribution from the DC to retail stores. Further research is warranted to examine the failure mechanisms of paperboard packaging caused by moisture absorption during the ripening process as partial package failure was associated with increased neck injuries in bananas. Minimizing mechanical damage caused by vibration also requires further investigation on the vibration transmissibility and dampening properties of pallets and packaging.

5. CHAPTER V

Mechanical Damage to Packaged Bananas caused by Vibration during Long-distance Transport

PREFACE

The empirical study revealed that damage caused during transport has been one of the major causes that resulted in significant damage to packaged bananas. Therefore, this chapter further characterized the damage in packaged bananas caused by in-transit vibration during the long-distance interstate transport. This chapter consists of two sections. The first section investigates the occurrence of mechanical damage in packaged bananas and demonstrates how the damage levels are influenced by the package height and stacked position in the road trucks. In the second part of this chapter, the mechanical damage levels were modelled in relation to the vibration dose as a function of vibration intensity and exposure duration. Modelling the damage levels in packaged bananas revealed a 'vibration dose', comparable to the field experience during long-distance transport of packaged bananas which was used for further package testing purposes.

Publications included in this Chapter

- ***Section 5. PART A*** - Fernando, I., Fei, J., & Stanley, R. (2019). Measurement and analysis of vibration and mechanical damage to bananas during long-distance interstate transport by multi-trailer road trains. *Postharvest Biology and Tech.*, *158*. Article 110977. ISSN 0925-5214 [Refereed Journal Article]
- ***Section 5. PART B-*** Fernando, I., Fei, J., Stanley, R., & Rouillard, V. (2020) Developing an accelerated vibration simulation test for packaged bananas, *Postharvest Biology and Technology*. [Journal Article]

PART A

Measurement and Analysis of Vibration and Mechanical Damage to Bananas during Long-Distance Interstate Transport by Multi-Trailer Road Trains

Abstract

Mechanical damage induced by vibration is a known cause of quality deterioration and wastage of fresh produce in post-harvest supply chains. The need to minimise visual defects in fruits, such as bananas, is being driven by the growing consumer preference for high quality produce. Transport of produce interstate and internationally from the growing regions to major retail markets, however, increases the risk of exposure of fruits to injurious vibration excitation. This study measured the vibration, and consequential mechanical damage, to bananas stacked at different stack heights and positions in a multi-trailer road train during an interstate road transport of over 3000 km in distance. Significantly different damage levels in bananas were observed in different pallet positions of the road train with the highest damage propensity revealed at the most rear pallet position. The damage levels in each pallet position were found to closely correspond with the Root-Mean-Square (RMS) acceleration of the vibration excitation on the trailer floor. The highest energy Power-Spectral Density (PSD) peaks were revealed to be concentrated in the lower frequency range (0.1-5 Hz). The cartons stacked in the top tiers of each pallet showed significantly increased mechanical damage followed by the bottom tiers with the middle-tiers exhibiting minimal damage. Palletized banana cartons subjected to simulated vibration, on a laboratory vibration simulator, demonstrated that vibration in the high frequency range (>30 Hz) was attenuated with the height of the carton in the pallet. However, the transmissibility of vibration energy in the range of 3-20 Hz was the greatest in the top-tier cartons, resulting in excessive mechanical damage to the bananas. The characterization of damage to bananas at different stack positions\heights of multi-trailer road trains is an integral step for the development of damage reduction mechanisms. These would require the design, optimization, and simulation testing of better packaging alternatives targeted at minimizing the occurrence of mechanical injury in-transit.

Key Words: Fruit, Bananas, Transport, Road Train, Vibration, Mechanical Damage

5.1. Measurement and Analysis of Vibration and Mechanical Damage to Bananas during Long-Distance Interstate Transport by Multi-Trailer Road Trains

5.1.1. Introduction

Visual defects to fresh produce, caused by mechanical damage, during transit from the farm-gate to the retail stores can critically reduce their perceived quality and the marketability costing both growers and retailers (Chonhenchob et al. 2009; Li & Thomas 2014; Opara & Pathare 2014). Mechanical vibration is a crucial factor affecting both the visual quality and causing physiological changes in fruits (Fernando et al. 2018a). The vibration and shock transmitted from the truck floor may not only cause damage to produce (Timm, Brown & Armstrong 1996), but also lead to physiological alterations such as fruit softening (La Scalia, Aiello, et al. 2015; Zhou, Wang, et al. 2015). Mechanical damage due to transport vibration affected the peel color, peel softening, integrity of the plasma membrane of the skin cells and the cell wall constituents in pears (Zhou et al. 2007) and caused shattering, discoloration and reduced shelf life in berries (Fischer et al. 1992). The extent of fruit damage can be influenced by the characteristics of the produce (Vursavus & Ozguven 2004) and the energy exerted during transit. The energy transmitted to produce is a function of the properties of packaging, suspension characteristics of the vehicle, energy input to the system through the interaction of road roughness and the vehicle speed (Fernando et al. 2018a; Jones, Holt & Schoorl 1991; Singh 2006).

Expansion of fresh produce supply chains to interstate and international routes escalates the risk of prolonged exposure of produce to vibration and shocks. Interstate supply chains in Australia can extend over thousands of kilometres. They utilise road trains or trucks with multiple trailers due to their enhanced capacity and economies of scale (Young & Williams 1990). Road trains are articulated vehicles hauling one or two trailers or rigid trucks hauling two or three trailers (Widdup & Pedersen 1981). These have been introduced for transporting high volume fresh produce, such as bananas, from the tropical growing regions in the state of Queensland and Northern Territory to the other States in Australia.

Mechanical damage occurs due to the energy transferred to and absorbed by fresh produce. The energy is exerted by the input vibration excitation of the truck floor as a result of the Road-Vehicle- Load (RVL) interaction during the road transport (Jones, Holt & Schoorl 1991). Several previous studies have analysed truck vibration levels during transit passage with respect to variables such as truck suspension type, truck speed, road condition and payload (Garcia-Romeu-Martinez et al., 2008, Zhou et al., 2015, Singh and Marcondes, 1992, Singh, 2006, Lu et al., 2008, Chonhenchob et al., 2010, Rissi et al., 2008). The effects of vibration frequency (Hinsch et al., 1993, Slaughter et al., 1993, Fischer et al., 1992), acceleration and transmissibility (Berardinelli et al., 2005, Fadiji et al., 2016, Zhang et al., 2011), height and the position of the package (Berardinelli et al., 2003, Hinsch et al., 1993, Soleimani and Ahmadi, 2014, Ranathunga et al., 2010, Jarimopas et al., 2005), vibration duration and travel distance (Timm et al., 1996, Shahbazi et al., 2010) as a function of vibration excitation in the truck floor, have also been evaluated in the literature. It was also shown that the vertical acceleration was the highest compared to the lateral and longitudinal accelerations during road truck transport (Chonhenchob et al. 2009; Vursavus & Ozguven 2004). The vibration excitation of the trailer floor in road trains may be different to that of single-trailer semi-trucks due to the interactive motions of multiple trailers coupled together with the prime mover and different placement of trailer-axles. However, there is a lack knowledge on how vibration levels in long-haul multi-trailer road train trucks affect the produce being transported.

Vibration must be measured and analyzed to understand the energy input from the truck floor and the energy transmitted to the palletized fresh produce stacked directly on top of the floor. Several studies have shown that the level of damage to fresh produce, caused by vibration, was influenced by the stacked position of the package on the truck, the stack height of the package and the level of vibration transmissibility in a stacked column of fruit packages (Barchi et al. 2002; Berardinelli et al. 2003, 2005; Soleimani & Ahmadi 2014). The affect of the stack position and\or height of the fruit packages in a semi-trailer truck, with respect to the vibration excitation, has been studied for a range of produce including apples (Soleimani & Ahmadi 2014), pears (Berardinelli et al. 2005; Slaughter, Thompson & Hinsch 1995, 1998; Zhou et al. 2007), loquats (Barchi et al. 2002), tangerines (Jarimopas, Singh & Saengnil 2005), tomatoes (Ranathunga et al. 2010) and watermelons (Shahbazi et al. 2010). Bananas, however, are the fruit with the highest volumes traded and exported internationally with an annual global production of 113 million MT in 2017(FAO 2019). They are also highly susceptible to the manifestation of damage from mechanical shock and vibration (Da Costa et al. 2010; More et al. 2015; Wasala, Dharmasena, et al. 2015b).

Modern retail markets need to address the large increase in the expectations of consumers for high visual standards in fruits (Parfitt, Barthel & Macnaughton 2010; White, Gallegos & Hundloe 2011). Mechanical damage in bananas can significantly reduce the produce quality, marketability and increase wastage along the supply chains in Australia (Ekman et al. 2011; White, Gallegos & Hundloe 2011). Therefore, understanding the occurrence and causes of mechanical damage to bananas during long distance road train transport is necessary develop appropriate preventive mechanisms for improving the fruit quality.

Measurement and analysis of vibration levels during transport is also essential to develop test parameters that can be used for laboratory vibration simulation studies. Such simulation studies have been conducted to determine the effect of vibration on produce (Godshall 1971; Lallu et al. 1999; Shahbazi et al. 2010; Tabatabaekoloor, Hashemi & Taghizade 2013) and also for package testing and optimization (Fadiji, Coetzee, Chen, et al. 2016; Konya et al. 2016; Singh & Xu 1993; Slaughter, Hinsch & Thompson 1993).

The development of test profiles for vibration simulation of packaged produce transported in road trains requires measurement and analysis of vibration in actual field transport. Therefore, this study was to: (1) measure and quantify the vibration levels in multi-trailer road trains in Australia, (2) determine the vibration characteristics, and any subsequent mechanical damage levels in packaged bananas, as a function of the stacked position and stack height during long distance transit and (3) validate the transmissibility of vibration in a stacked pallet of banana cartons as a function of the carton height using a laboratory vibration simulator.

5.1.2. **Material and Methods**

5.1.2.1. Vehicle and Route

A road train truck (Nine-Axle B-Double) with dual trailers (i.e. "A" trailer in the front and "B" in the Rear) pulled by a prime mover (Model: Kenworth K200) was used to collect vibration data from Tully in north Queensland to Melbourne in South Victoria, Australia. The distance of the journey was approximately 3300 km and travelled along the eastern coastal route from Queensland via the Bruce Highway, Pacific Highway and Western Freeway to Melbourne, Victoria (Fig. 5.1). The roads were bitumen sealed highways predominately being single lane carriageways with overtaking lanes. The truck and the trailers contained air-ride suspension and the two trailers were fully loaded with packaged and palletised bananas with 10 pallets in the A trailer and 22 pallets in the B trailer. The fully-loaded road train had a payload of 32 metric tonnes with approximately 22 tonnes in the B trailer and 10 tonnes in the A trailer. The road train left the depot in Tully at 10 am on the 18th of January and arrived in the central distribution centre (DC) in Melbourne at 12 am on the 22nd of January 2018.

5.1.2.2. Measurement of Vibration

Five piezoelectric accelerometer data logger devices (Slam Stick Logger- MIDE Technology Inc., Massachusetts, USA) were installed to measure the vibration on the truck floor. The devices were attached to the base of each wooden pallet by means of silicon glue as shown in Fig. 5.1. The patterned-steel plate on the trailer floor (Fig. 5.1) was not an appropriate surface to attach the devices, considering the greater risk of detachment and the potential disconnection of the device from the power source during the long transit. Therefore, the rigid wooden pallets stacked firmly on the trailer floor were considered a more suitable position for the mounting of the devices. The devices were securely attached to the bottom of each wooden pallet to minimize the risk of detachment. The accelerometers were set-up to continuously sample at 400 Hz and were coupled with an external battery pack (10,000 mAH, Voltaic Inc., USA) to enable continuous sampling during the 86-hour journey (i.e. three days and fourteen hours for transit including the mandatory truck stoppages).

Figure 5.1: (a) Road Train with two trailers (A and B) attached to the prime mover head (b) Air-ride suspension system in the A trailer (c) Accelerometer Logger (MIDE Slam Stick, USA) attached to the base of the pallet and couple with the external battery pack; (d) Transit route of the road train from Tully, Queensland to Melbourne, Victoria (approx. 3300 km) (Source: Google Maps, Google Inc. CA, USA.)

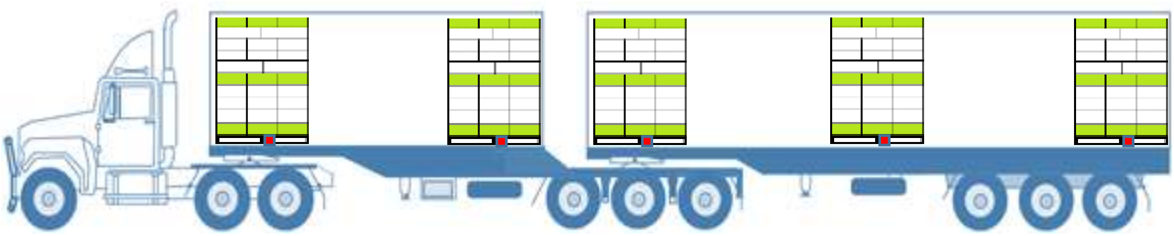


Figure 5.2: Placement of the Inspected Pallets, Cartons (shaded in green) and the Accelerometer Devices in the Road Train [Position of the accelerometers ("■") attached to the Pallets in Front and Rear of the A-Trailer and Front, Rear, Middle of B-Trailer]

Most previous studies have overcome limitations in the memory capacities and utilizable battery power availability in the vibration measurement loggers by using randomised sampling methods, signal triggered sampling or fixed interval limited-time sampling to collect vibration data along a given route (Barchi et al. 2002; Jarimopas, Singh & Saengnil 2005; La Scalia, Aiello, et al. 2015; Soleimani & Ahmadi 2014; Zhou et al. 2007). However, partial vibration data collection along a given route may not represent the anomalies of the entire transit route and may affect the accuracy of the global Root-Mean-Square (RMS) acceleration level (Fernando et al. 2018a). Therefore, end-to-end vibration data from the point of the start of the journey to the finish have been measured and recorded to calculate the global RMS levels in this study. A GPS data recorder (LAS Inc., Illinois, USA) was placed in the cabin of the road train and was also powered by an external battery pack. The timestamp of all the data logger devices and GPS device was synchronized before transport. Time synchronization was important to specify and identify the vibration\shocks encountered in different segments of the journey, and to also remove non-useful data (idling time and stoppages) during the analysis. The temperature and humidity data were collected at a frequency of 1 Hz by a logger (EasyLog USB, Lascar Electronics, Essex, UK) attached to the top-tier of the middle pallet stacked in the rear trailer of the road train truck.

5.1.2.3. Fruit Samples and Damage Evaluation

The extent of mechanical damage in packaged bananas caused during transit was quantified in this study to understand the possible relationship between the vibration encountered and the visual damage that has occurred in bananas. Ninety banana (cv. Cavendish) cartons were randomly selected and inspected in a commercial banana pack house in Tully, Queensland. Extra-large grade bananas (i.e. finger length 200-260 mm, finger girth 30-40 mm) were firmly packed in three layers inside the carton with a liner-bag inside each carton and a plastic liner between the layers.

Every banana cluster in each carton was examined for existing mechanical damages to ensure that the fruit in sample cartons were initially free from damage. All inspected clusters were photographed and a sticker was attached (Fig.5.3) for tracing and damage evaluation purposes at a later stage. The inspected cartons were evenly distributed into five pallets with six packages on the top, middle and bottom tiers of the pallet (i.e. First Tier, Fifth Tier and the Tenth Tier) (Fig.5.2). The five pallets with sample banana cartons were stored at 13-15 °C temperature for 12 hours in a temperature-controlled chamber before being loaded into the road train. The five pallets were then placed in the rear, front and middle position of the B trailer of the road train and front and rear positions of the A trailer (Fig. 5.2). Once the load arrived at the destination (DC), the clusters with sample cartons were re-examined and assessed for damage caused by vibration in-transit.

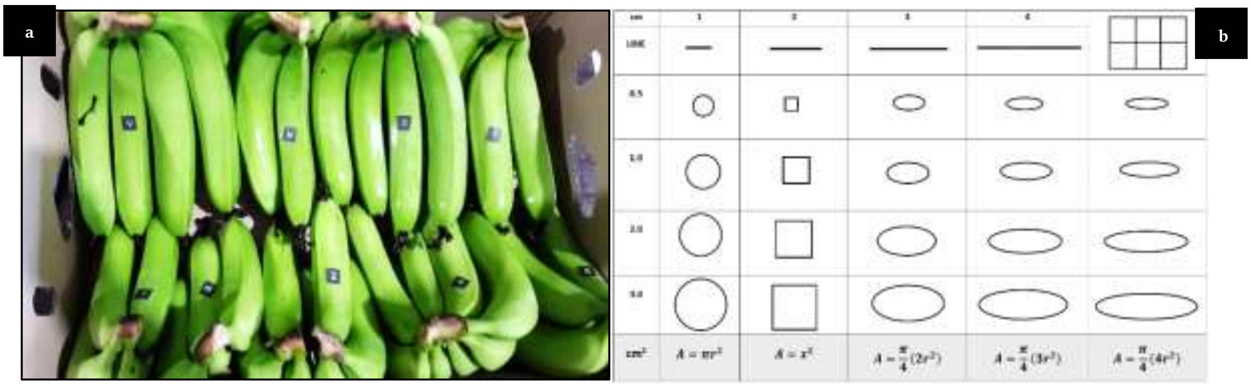


Figure 5.3: (a) A package with pre-inspected clusters demarcated with uniquely identifiable stickers (b) Transparent damage measurement sheet (Appendix C1) for quantifying mechanical damage in bananas

Mechanical damages caused by vibration often appear as blackened surface abrasion on bananas and mostly resemble an elliptical shape. Therefore, the usual damage estimation methods based on damage diameter (assuming that the damage is round) was not appropriate to estimate damage to bananas. In this study, mechanical damage was therefore quantitatively estimated using a laminated (transparent) damage area measurement sheet (Fig.5.3) which was developed for measuring external abrasion damages. A Mechanical Damage Index (MDI) was calculated (Eq.5.1) based on the estimated damage area to derive an index score for each fruit carton, by adapting a similar method to derive the Equivalent Bruise Index (EBI) for apples from the damage diameter (Vursavus & Ozguven 2004).

MDI (%) = 0.1 x Trace Damages (%) + 0.2 x Slight Damages (%) + 0.7 x Moderate Damages (%) + 1.0 x Severe Damages (%) (Eq.5.1)

(Damage Area (A) ≥3 cm2 – Severe; 2 cm2≤A<3 cm2 – Moderate; 1 cm2≤A<2 cm2 – Slight; 0.5 cm2≤A<1 cm2 - Trace)

5.1.2.4. Data Analysis

Data from all the accelerometer devices were processed through Slam Stick Lab (ver.1.6) software to convert the recorded data files to comma-separated-value (CSV) format for the analysis. Acceleration data in the five devices were synchronized using the timestamp and compared against the coordinates recorded by the GPS device to remove all the intermittent stoppages of the road train during the 86-hour inter-state trip. Vertical acceleration has been found to be the highest and most critical for inducing produce damage (Vursavus & Ozguven 2004). Therefore, only vertical acceleration (Z-axis) data were further analysed in the frequency domain in this study. After the non-useful data were removed, the vertical vibration data from each device were clustered to 42-minute segments (one million data points sampled at 400 Hz) for convenience of analysis.

Fourier analysis of the time-series data can be used to understand the critical frequencies affecting the produce during transit (Smith 2006). Development of power spectral density (PSD) profiles based on the vibration levels is essential to understanding the exposure of produce to vibration energy in a given transit route (Singh 2006). Power Density (PD) of a given vibration signal within a band of frequencies can be derived through the Eq. 5.2 (Jarimopas, Singh & Saengnil 2005). Data were analyzed in the frequency range of 0.1-200 Hz as 200 Hz was the Nyquist frequency (Piersol & Harris 2017) corresponding to half the sampling rate of the accelerometers. Time series vibration data were converted to the frequency domain by Fast-Fourier Transform (FFT) with the use of the signal processing toolbox in Matlab ver. 2014b (Mathworks, Natick, MA, USA).

$$PD = \frac{1}{BW} \sum \frac{RMS\ G^2}{N} \qquad \text{(Eq. 5.2)}$$

($RMS\ G$ is the root mean square acceleration measured in g at any instance within a given bandwidth (BW) of frequencies and N is the number of samples in a given vibration signal).

MDI data for each sample banana carton stacked in different positions in the pallets were analyzed for statistical significance by the Analysis of Variance (ANOVA) and Turkey's HSD Test method with the use of GraphPad Prism 7 statistical analysis package (GraphPad® Software, San Diego, CA, USA).

5.1.2.5. Transmissibility Testing in a Stacked Pallet

An electro-hydraulic vibration simulator table was used to examine the transmissibility of vibration in a stacked pallet of banana cartons. A full pallet with sixty (60) cartons of bananas was subjected to simulated vibration based on a PSD profile developed from the field data at an overall Root-Mean-Square (RMS) acceleration of 0.36g (Fig.5.4). The sixth and the top tiers were cross-stacked and the pallet was fully (triple) stretch wrapped similarly to the stacking and wrapping arrangements during the field transport. Four piezoelectric accelerometer data loggers (Slam Stick Logger- MIDE Technology Inc., Massachusetts, USA) were placed on the simulator table and inside the cartons in the first, fifth and tenth (top) tier and configured for sampling at 400 Hz. Data were analysed in the frequency domain to derive the PSD curves for each position of the trailer floor by the same analysis method described in Section 5.1.2.4.

Figure 5.4: A Full Pallet of Banana Cartons Subjected to Simulated Vibration by an Electro-hydraulic Simulation Table

5.1.3. **Results**

It was revealed that the vertical acceleration of all positions on the floor of the road train was mostly confined in the range of ± 1 g. The temperature during the transport of bananas was held at 14 °C ± 1 °C and the relative humidity (RH) level oscillated between 80% RH to 90% RH (Appendix C2). The root-mean-square (RMS) acceleration was calculated by Eq.5.3. for the vertical acceleration data to derive the RMS value for each position of the truck floor. The RMS acceleration recorded for each position on the truck floor is given in Table 5.1. The averaged RMS acceleration level for the rear position of the truck was calculated for each of the 42-minute segments of one million acceleration data points for the entire interstate journey. The probability distribution of the RMS acceleration for each position of the truck is given in Fig.5.5. Averaged PSD profiles for the front (A(F)) and rear (A(R)) positions of the A trailer, and those for the front (B(F)), middle (B(M)) and rear (B(R)) positions of the B trailer are given in Fig.5.7(a) and Fig.5.7(b) respectively. The comparison of the averaged PSD curves of different positions in the trailer floor to the PSD curves as defined by the ASTM D 4169-16 D3(ASTM 2016b) is illustrated in Fig.5.7(c). The PSD curves for the bottom, middle and the top cartons stacked on the pallet during the simulated vibration test are given in Fig.5.7 (d).

$$RMS\{x|n|\} = \left(\frac{1}{\mathrm{N}}\sum_{n} x^2|n|\right)^{1/2} \quad \text{(Eq.5.3)}$$

(N- Number of Samples; n- nth element of the vibration signal; RMS- Root Mean Square Acceleration)

The PSD peaks were exhibited in the lower frequency range (0-10 Hz) for all positions on the floor of both trailers (Table 1). All the PSD peaks found in this study for the multi-trailer road train truck were in the 0.1-5 Hz range. The secondary and tertiary PSD peaks were within the frequency ranges of 15-20 Hz and 45-90 Hz respectively as given in Table 5.1. It was found that the PSD peak in the rear position of the B trailer (B(R)) was over two times higher than the middle position (B (M)) and nearly two times of the front position (B (F)). It was also revealed that the PSD peak in the front of the A trailer (A (F)) was more than two times the peak in the rear position (A(R)). This was also signified by the elevated RMS acceleration in these positions (Table 5.1) mostly attributed to the energy in the lower frequency range (<10 Hz) of the spectrum.

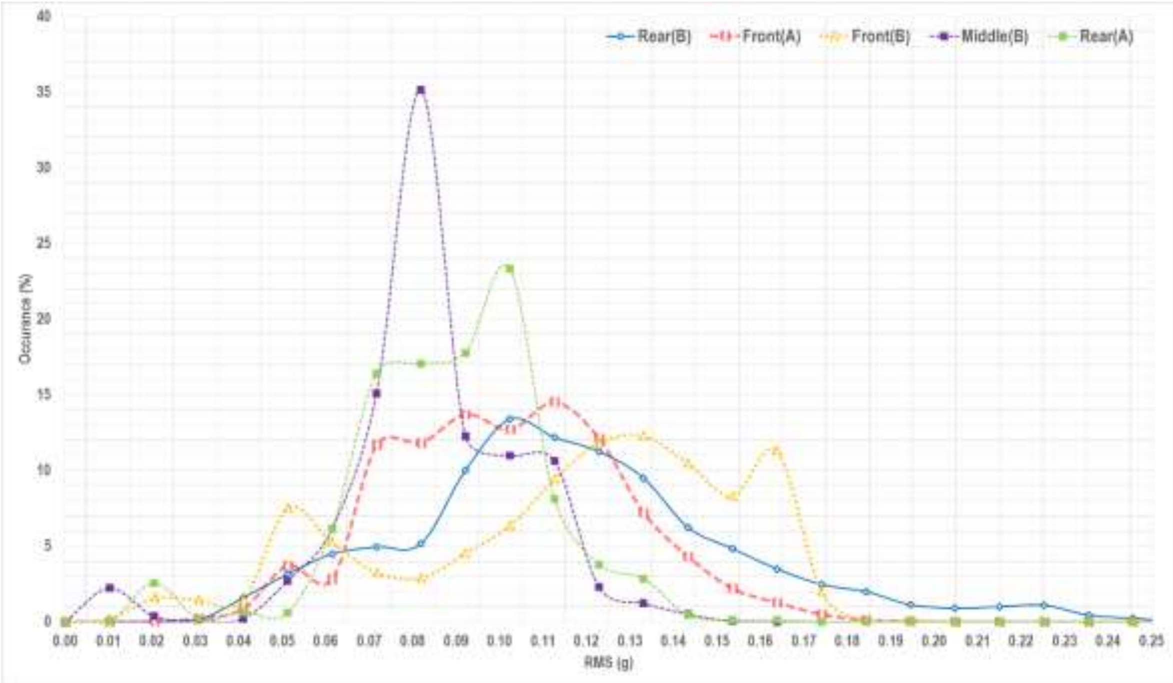


Figure 5.5: RMS Distributions for the Different Positions of the Truck

Table 5.1: RMS and the PSD Peaks within the Frequency Ranges for the Floor Positions in the Road Train

PSD Profile	RMS acceleration (g)	Peak frequency (Hz) [PSD Peak (g^2/Hz)]		
		0-10 Hz	10-30 Hz	30-100 Hz
A (F)	0.1056	1.8 [0.007]	17.8 [0.0004]	86 Hz [0.0007]
A (R)	0.0840	1.8 [0.003]	17.4 [0.0004]	69 Hz [0.0001]
B (F)	0.1146	1.4 [0.005]	17.2 [0.0005]	66 Hz [0.0005]
B (M)	0.0789	1.6 [0.004]	17.5 [0.0003]	61 Hz [0.0001]
B (R)	0.1244	1.6 [0.01]	17.4 [0.0006]	48 Hz [0.0003]

The majority of the mechanical damages in bananas, consequentially resulting in the brown-black discoloration of the banana skin, was caused by vibration rubbing as a result of abrasion (friction) of the fruit against each other or the corrugated carton walls (Fig. 5.6). The rubbing damage caused by abrasion between bananas was mostly confined to the sides of the banana fingers and revealed as a dark brown-black damage area. The abrasion damages observed in bananas did not cause flesh damage.

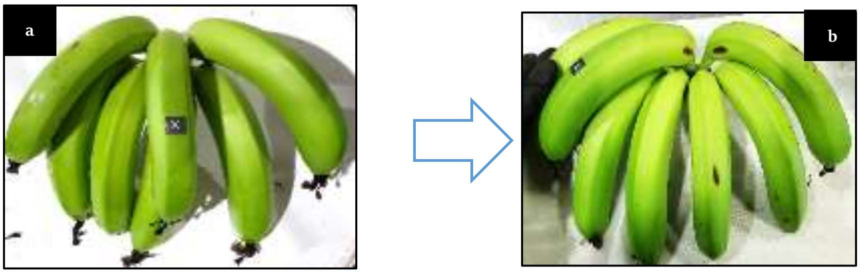


Figure 5.6: Development of Mechanical Damage (Fruit Rub) caused by Vibration Before (a) and After (b) Transport

The damage levels were significantly (P<0.01) influenced by the position of the package within the stacked pallet and the position of the pallet on the truck floor (Table 5.2). The cartons in pallets stacked in the rear and the front ends of the B trailer were affected more than the pallet stacked in the middle position. Relatively higher levels of damage were observed in the cartons stacked in the front position of the A trailer compared to the rear position. The overall average damage level in bananas (MDI %) corresponded with the level of input vibration (RMS vibration) received by the pallets stacked in different positions of the truck (Fig.5.2) as summarized in Table 5.2.

Table 5.2: Mean MDI Levels in Packaged Bananas Stacked in Different Pallet Positions\ Heights during Transit

Position of the Pallet (Trailer)	**RMS Vibration (Pallet Base)**	**Height of the Package**	**Mean MDI* (%) for Package ± (SD)†**
Front (A Trailer) – [A(F)]	0.11g	Top	13.6 ± (1.5)^{a}
		Middle	0.2 ± (0.2)^{b}
		Bottom	7.3 ± (0.6)^{c}
Rear (A Trailer) – [A(R)]	0.08g	Top	4.4± (0.8)^{cd}
		Middle	0.1 ± (0.1)^{b}
		Bottom	2.1 ± (0.4)^{e}
Front (B Trailer) – [B(F)]	0.11g	Top	12.6 ± (1.2)^{a}
		Middle	0.1 ± (0.1)^{b}
		Bottom	7.1 ± (0.6)^{cdf}
Middle (B Trailer) –[B(M)]	0.08g	Top	4.1 ± (0.8)^{d}
		Middle	0.1 ± (0.1)^{b}
		Bottom	2.4 ± (0.4)^{e}
Rear (B Trailer) – [B(R)]	0.12g	Top	15.1 ± (1.6)^{a}
		Middle	0.2 ± (0.1)^{b}
		Bottom	7.9 ± (1.7)^{cdf}

***MDI- Mechanical Damage Index; †SD- Standard Deviation; a-f Different Letters Indicate Statistically Different Results (P<0.01)**

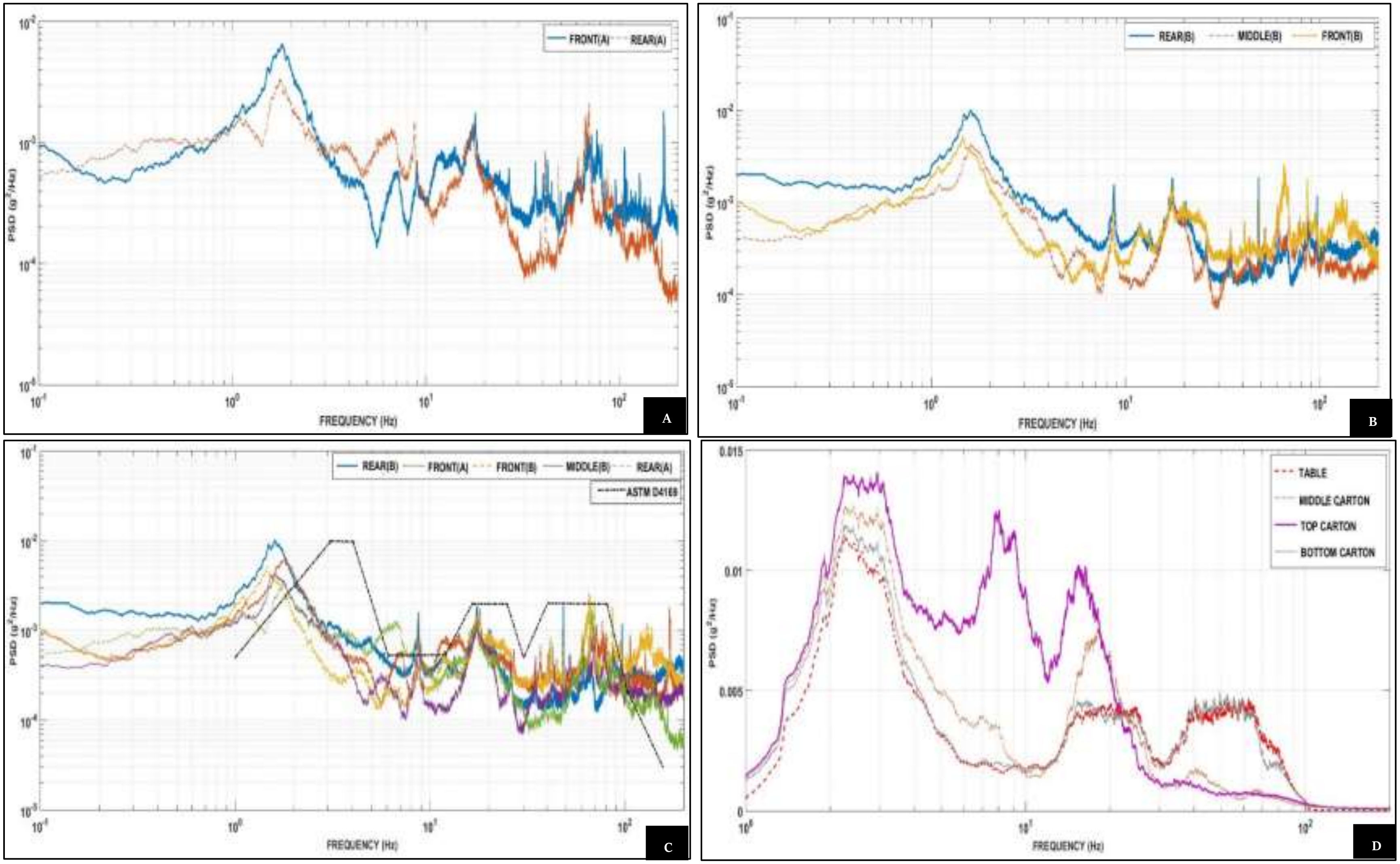


Figure 5.7: (A) Averaged PSD curves for the front and rear positions of the A trailer (B) Averaged PSD curves for the front, middle and rear positions of the B trailer (C) Average PSD curves for all trailer positions compared with the ASTM D4169 (2016)-Level 3 (D) PSD curves for the simulator table, first (bottom), fifth (middle) and tenth (top) cartons

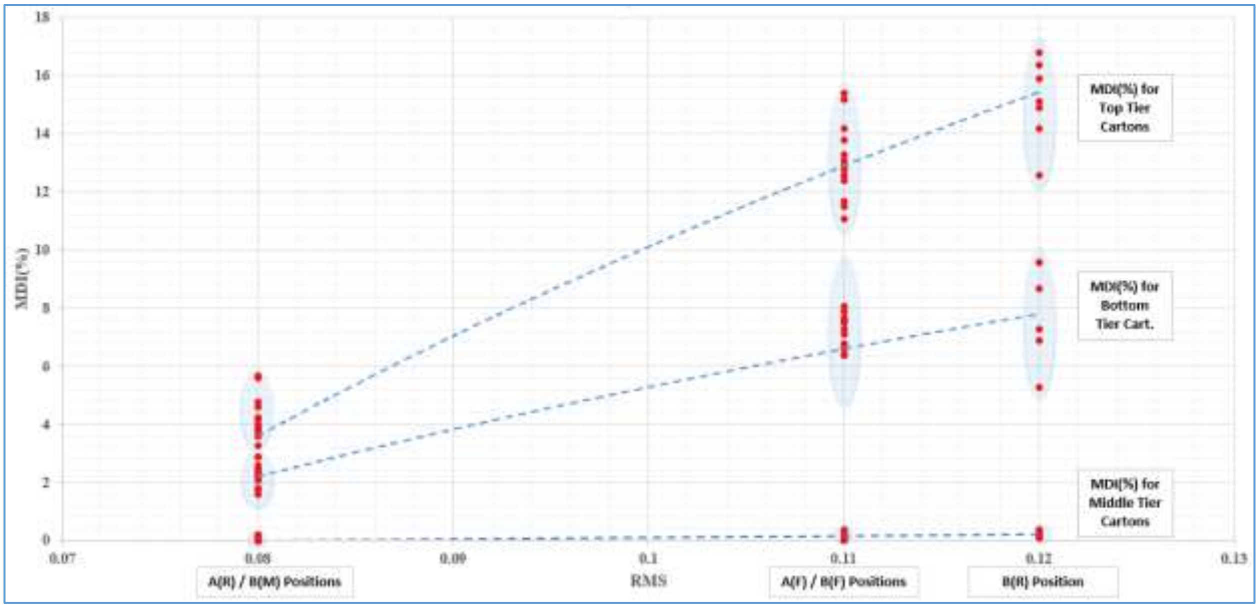


Figure 5.8: MDI (%) for the Top, Middle and Bottom Tier Cartons in the Trailer Positions with Different RMS Vibration

As illustrated in Fig.5.8, the least levels of vibration intensities (RMS) were exhibited in the middle position of the B trailer(B(M)) and the rear position of the A trailer (A(R)) (RMS<0.1g), compared to the rest of the pallet positions. Consequently, the pallets stacked in these positions showed the least overall damage levels (Fig.5.8 and Fig.5.9) compared to those of the rest of the pallet positions. Contrastingly, higher levels of overall mechanical damage (MDI %) were found in the rear position of the B trailer, followed by the front position of the A trailer and the front position of the B trailer and, corresponded with the elevated vibration excitation (RMS>0.1g) of these trailer positions (Fig.5.9).

The highest averaged damage level (MDI=15.1) was exhibited in the top tier packages of the pallet stacked in the rear of the B-trailer (Table 5.2). This corresponded with the increased energy and input vibration levels in the rear position of the B- trailer as illustrated by the PSD curve in Fig.5.7. Similarly, the second and the third highest damage levels were revealed in the top tiers of the front position of the A trailer and the front position of the B trailer respectively (Fig.5.8). Statistically different (P<0.01) damage levels have been found in the top, middle and bottom cartons in each pallet position. In all pallet positions, the MDI (%) level in the top tier cartons was significantly higher (P<0.01) than the bottom tier cartons. However, the middle tier cartons showed a very minor level of mechanical damage (MDI<= 0.6) irrespective of the position of the pallet on the floor (Fig.5.9).

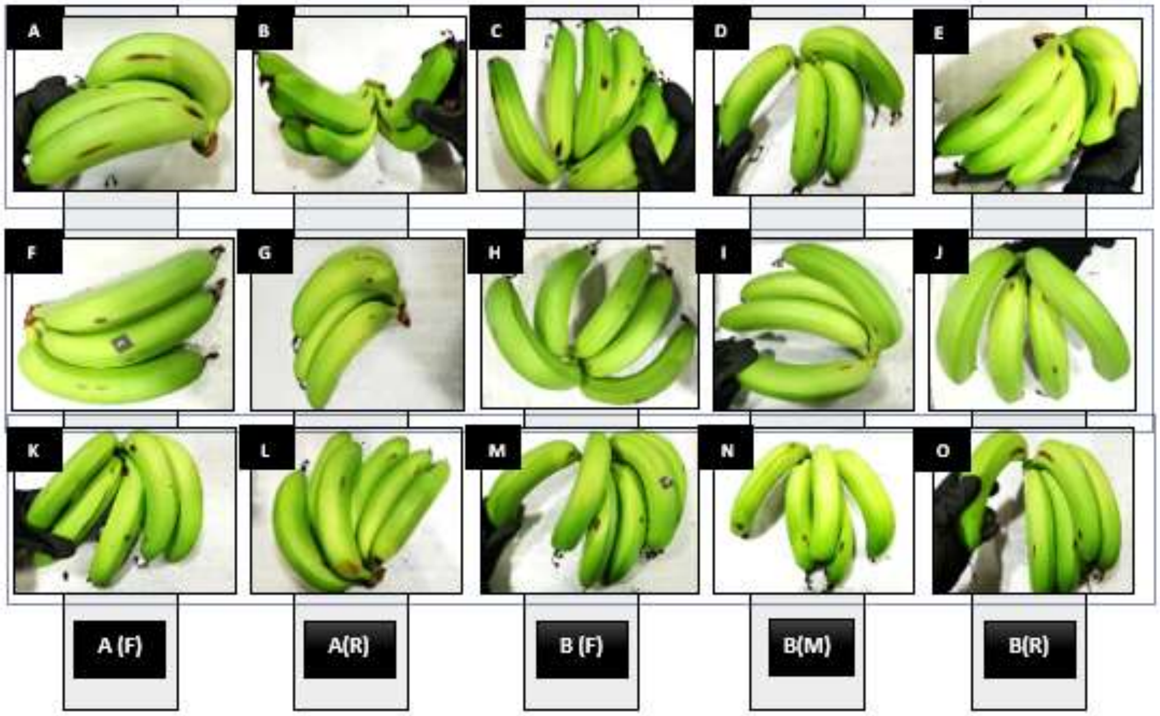


Figure 5.9: Clusters with Increased Mechanical Damage in Top-Tier Cartons [A-E]; Clusters with Minimal Mechanical Damage in Middle-Tier Cartons [F-J] and Clusters with Moderate Mechanical Damage in Bottom-Tier Cartons [K-O] Staked in Different Pallet Positions in the Road Train [A(F): A Trailer-Front; A(R): A-Trailer Rear; B(F): B-Trailer Front; B(M): B-Trailer Middle and B(R): B-Trailer Rear]

5.1.4. Discussion

In this study, abrasion damages observed in packaged bananas caused by rubbing (friction) were the most prominent cause of mechanical damage. Surface abrasion, as a result of vibration, is a major cause of visual quality deterioration for bananas as well as in most other soft fruits (Li & Thomas 2014). Similar findings were revealed by Berardinelli et al. (2005) suggesting that pears subjected to vibration showed darkened streaks on the skin with majority of the pears exhibiting no bruise or flesh damage. Zhou et al. (2007) reported that for pears, darkened burnings of the skin and bruises with little or no penetration into the flesh, are the main injuries caused by vibration. Analogous findings have also been reported for fruits such as loquats, strawberries and apples suggesting that skin discoloration, scuffing and rubbing occurred due to exposure to transit vibration (Barchi et al. 2002; Berardinelli et al. 2005; La Scalia, Aiello, et al. 2015; Vursavus & Ozguven 2004).

This study revealed significant differences ($P<0.01$) for mechanical damage levels in bananas stacked on pallets at different positions of the road train (Table 5.2). Similar results were reported by Zhou et al. (2007), finding that the damage levels of pears loaded on different positions in the semi-truck were significantly different. The differences in damage levels in packaged bananas stacked in different pallet positions, found in this study, can be related to the varying energy levels (RMS) exerted by the trailer floor in each pallet position (Fig. 5.8). The PSD peaks revealed in this study (Fig.5.7), and the corresponding mechanical damage levels, were significantly higher (Fig.5.8) for each pallet position with increased vibration intensity (RMS) (i.e. A(F),B(F) and B(R)), than the damage levels revealed for the pallet positions with weaker RMS vibration intensity (i.e. A(R) and B(M)). Therefore, the fruits (bananas) stacked in pallets in the positions with intensified vibration levels certainly exhibited a relatively escalated mechanical (rubbing) damage (Fig. 5.9). Previous studies confirmed that vibration in lower frequencies caused the most damage to produce (Fischer et al. 1992; La Scalia, Aiello, et al. 2015) and that having PSD peaks in the lower range of the spectrum is critical for fruit-mechanical damage (Fernando et al. 2018a).

The highest RMS acceleration was found in the rear position of the B trailer. Similar findings were reported in previous studies that revealed the highest RMS levels were found in the rear positions of the semi-trailer trucks (Barchi et al. 2002; Berardinelli et al. 2005; Soleimani & Ahmadi 2014; Zhou et al. 2007). Soleimani and Ahmadi (2014) showed that the global RMS acceleration for the rear position of the semi-truck (leaf-spring) ranged from 0.95 ms^{-2} to 1.48 ms^{-2}. Similarly, in this study the global RMS level for the rear position of the B trailer was 1.2 ms^{-2} (0.12 g). However, the global RMS acceleration level for the front position of the semi- truck reported by Soleimani and Ahmadi (2014) was ranged from 0.65 to 0.96 ms^{-2} whereas, this study found a slightly elevated RMS level (1.1 ms^{-2}) in the front positions of the A and B trailers of the road train. Several other studies have revealed reduced vibration levels in the front positions of semi-trailer trucks compared to the rear and middle positions (Berardinelli et al. 2005; Ranathunga et al. 2010; Soleimani & Ahmadi 2014).

An escalated RMS vibration in the front position, compared to the middle position, in this study can be attributed to the different force and vibration dynamics in dual trailer road trains having multiple adjoining trailers coupled together in contrast to a truck with a single semi-trailer. An increased RMS acceleration and the low frequency PSD peaks (Table 5.1) in this study was associated with the placement of the suspension\axels of the dual trailers of the road train. The truck type and the road terrain characteristics can be influential factors for the differences in averaged RMS vibration levels during road truck transport

(Fernando et al., 2018). As illustrated in Fig.5.1 the accelerometers that were placed vertically above the wheels\suspension of the trailers (attached to the pallet bases) exhibited higher RMS acceleration and an increased power (g^2/Hz) in the PSD peaks in the lower frequency range of 0.1-5 Hz. This signifies that the produce pallet stacked in these positions of the trailer floor can be highly exposed to escalated vibration excitation and input energy levels from the trailer floor.

All the PSD peaks found in this study for the multi-trailer road train trucks were in the 0.1-5 Hz range and are similar to the results of previous studies on semi-trailer trucks with air-ride suspensions (Paternoster, Vanlanduit, et al. 2017; Soleimani & Ahmadi 2014). The lower frequency peaks were found to be attributed to the suspension response of the truck (Singh 2006). Several studies have shown similar findings confirming that the PSD peaks were revealed in the lower frequency range below 10 Hz for semi-trucks resulting critical injury to produce (Hinsch et al. 1993; Lu et al. 2010a; Vursavus & Ozguven 2004; Zhou, Yan, et al. 2015). Jarimopas, Singh and Saengnil (2005) further narrowed down the critical frequency range to be between 0.1-5 Hz and concluded that the PSD decreased beyond this range, which is in concurrence with the PSD peaks found in this study. The peak in the lower frequency range of the front (0.007 g^2/Hz) of the A trailer was more than two times higher than that of the rear position (0.003 g^2/Hz), while less than the magnitude of the peak that occurred in the rear of the B trailer (0.01 g^2/Hz). Similarly, elevated RMS acceleration and a higher PSD peak in the front (0.005 g^2/Hz) of the B trailer (B (F)) may also result in an elevated risk for produce damage. The lower RMS levels and attenuated PSD peaks (0.004 g^2/Hz) in the middle position of the B trailer (B (M)) and the rear position of the A trailer (A(R)) suggest that the vibration excitations have been weakened in these floor positions with decreased PSD peaks in the lower frequency range and reduced overall RMS level(<0.1g).

The secondary and tertiary PSD peaks in this study occurred within the frequency ranges of 15-20 Hz and 48-86 Hz respectively. Comparable findings in previous studies confirmed that a lower intense secondary peak occurred in the range of 12-28 Hz (Soleimani & Ahmadi 2014) and another similar study revealed a secondary PSD peak between 15-40 Hz in (Zhou et al. 2007) for semi-trailer trucks. Previous studies also showed that the spectral peak occurred in the range of 10-20 Hz which was attributed to the road unevenness (Barchi et al. 2002; Berardinelli et al. 2005). The secondary peak in the 15-20 Hz range in this study can be attributed to the vibration response from the interaction between the tires and the road terrain. The tertiary peaks in the range of 48-86 Hz is generated by the structural vibration of the truck-trailer (Paternoster, Vanlanduit, et al. 2017; Singh 2006) which can be caused by a combination of vibrating components of the truck such as truck chassis, engine and refrigeration unit.

The peaks in the PSD curves in this study have been compared with the standard ASTM standard for semi-trucks (ASTM 2016b). A discrepancy exists in the PSD peak in the ASTM curve (3-4 Hz) compared to the PSD peaks centred around 1.5-2 Hz in this study. The PSD peak can be influenced by the suspension characteristics and the stiffness of the suspension in each vehicle (Fernando et al. 2018a). A similar finding with a lower PSD peak compared to the same ASTM standard was also revealed in a recent study by Paternoster, Vanlanduit, et al. (2017) for air-ride suspension trucks. The secondary and the tertiary PSD peaks in this study correspond with the ASTM standard PSD curve.

For every position in the trailer floor, the top tier cartons exhibited the highest mechanical damage (MDI%). Similar results were reported by several researchers, showing that the vibration level, and the damage levels in fruits have been highest in the top tier containers\packages (Slaughter, Hinsch & Thompson 1993; Zhou et al. 2007). The mechanical damage levels from the bottom, middle and the top tier of the pallet were shown to be associated with the transmission of vibration up the pallet from the bottom to top as well as the freedom of movement of individual banana fingers in the clusters. This vibration resulted in relative movement and rubbing between the fingers.

The PSD curve for the bottom carton mostly resembled the input vibration from the simulator table (illustrated in Fig.5.7). However, as the height of the pallet increased the high frequency vibration (> 20 Hz) was significantly attenuated in the middle and top tier cartons. The top tier cartons exhibited an increased vibration transmissibility in the lower frequency range of 3-20 Hz, creating a large envelope between the input (simulator table) vibration and the vibration excitation in the top-tier cartons. However, the middle tier cartons revealed an attenuated vibration excitation in the high frequency range (>20 Hz) and a much lower vibration energy transmissibility compared to the top tier. This was possibly due to the energy absorbing\ dampening properties of banana clusters stacked inside the cartons. The higher transmissibility of vibration to the top tier cartons at the resonance frequencies caused an increase in mechanical damage in the top cartons. However, the attenuation of high frequency (>20Hz) vibration up a stacked pallet resulted in reduced damage to the bananas in the middle tiers. Direct transmission of vibration in the entire frequency range (0-100 Hz) from the truck floor (with lower energy compared to the top tiers as illustrated in Fig.5.7) has caused bananas in the bottom tiers to exhibit moderate levels of mechanical damage.

The damage caused by vibration can also be influenced by the freedom of movement of the fruits within the carton. In this study, the freedom of movement for individual banana fingers and the vibration characteristics of the fruit was restricted by the top-load compression due to the weight of the cartons stacked on top of the bottom and middle tier cartons. Slaughter, Hinsch and Thompson (1993) showed that the fill-status (freedom of movement) of the fruits inside the cartons had influenced the level of vibration damage in pears. For bananas, the effect of the top-load compression is lesser from the bottom to the top of the pallet and the bananas in the top tier packages have no such constraint or top-load, restricting their relative movement. This can also influence the incidence of rub marks in the top tier as the damages can be exacerbated by the unconstrained rubbing of individual banana fingers. Despite the restriction of movement for bananas in the most bottom tier cartons, the damage levels have been significantly higher ($P<0.01$), possibly due to the direct transmission of the vibration from the trailer floor in the high frequency range (>30) which has been reduced in the middle tiers (Fig.5.7). The fractional vibration transmissibility in the high frequency range (>20Hz), and the top-load (weight) may have restricted the relative moment of the banana fingers in the middle tier cartons, resulting in the least mechanical damage.

Characterization of mechanical damage in bananas during the transport in multi-trailer road trains and the investigation of damage levels with respect to the stack height\position of the cartons is an essential step towards minimizing the fruit quality deterioration in-transit. In the absence of other studies on the measurement of vibration levels in multi-trailer road trains, this study is important for vibration simulation studies for produce transported in road trains. Knowledge on the damage that occurs during transport and understanding the mechanism causing damage in packaged fruits is integral for the development of solutions for amelioration. These could include packing and package optimization, not only for bananas but also for a variety of fresh produce that are susceptible to vibration damage. Minimized fruit damage, especially in long-distance interstate supply chains, can significantly contribute to reduced wastage, increased consumer acceptance and marketability of fresh produce in retail stores across Australia.

5.1.5. **Conclusion**

This study measured the vertical vibration levels along the trailer of a dual-trailer road train truck stacked with palletised banana packages during long-distance interstate transport. The mechanical damage levels in bananas were influenced by the package height and the stacked position of the pallet. The damage levels in bananas were particularly higher in the pallet positions with increased root-mean-square (RMS) acceleration, exhibiting the worst damage in the most-rear pallet position of the rear trailer of the road train. The highest damage levels were also revealed in the top-tier banana packages in each pallet position followed by moderate damage levels in the bottom-tier packages and least damage levels in the middle-tier packages. Investigation of vibration transmission in a stacked pallet of banana packages further revealed that the vibration in the high frequency range (>30 Hz) attenuated from the bottom-tiers to top-tiers of the pallet. However, the top-tiers exhibited critically amplified vibration energy around the resonance frequencies, resulting in excessive damage to bananas. The damage levels that were exacerbated by the increased freedom-of movement of bananas in the top-tiers have been shown to be reduced in the middle and bottom-tier packages. Future research on the effectiveness of vibration isolation mechanisms, such as polymer-based vibration dampening pads, can be examined for minimizing the transmission of vibration energy from the truck floor to the stacked-pallets. Improved packaging and decreasing freedom of movement of bananas by increasing fill-tightness of clusters are essential to minimize damage in the bottom and top-tiers where damage levels have been critically elevated. An extension of this study needs to be focused on the evaluation of improved packaging alternatives and packing methods for the interstate transport of bananas for minimizing mechanical injuries and improving the fruit quality in the post-harvest supply chain.

PART B

Developing an Accelerated Vibration Simulation Test for Packaged Bananas

ABSTRACT

Mechanical damage in packaged fruits is known to be exacerbated by the intensity and exposure duration of vibration excitation during road transport. However, the current single degree of freedom (SDOF) vibration simulation test standards for road vehicle transport have limitations for simulating long distance road trips. The accelerated vibration simulation testing based on the Basquin model of cyclic fatigue has been used for reducing the simulation test time. However, the time-compression factor used in this model can result in significant errors in simulation outcome as the power constant is usually assumed (i.e. k=2 or 5). In this study the power constant was validated by comparing the simulation-induced mechanical damage levels in packaged bananas, with those occurred during the field transport. A SDOF averaged power-spectra derived from the measurement of vertical acceleration levels during the field transport, with a vibration intensity of 0.36 g for a test duration of 3 hours, was found to be the most suitable test protocol that closely replicated the field damage levels during long distance transport of bananas. The value of k in this experiment was 2.3 for the accelerated simulation experiment. This study therefore provides a realistic simulation test for packaged bananas and other similar fruits that require long distance transport. The comparison of vibration levels in column-stacked and cross-stacked pallets revealed that cross-stacking resulted in higher vibration levels in the top-tiers due to the increased vibration excitation in the mid-frequency range around the resonance frequencies. Therefore, column stacking of packages may reduce damage caused by unrestricted vibration of fruits in the top-tiers. Improved package testing will contribute to developing solutions to minimize damage to delicate fruits in-transit.

Key Words: Mechanical Damage, Vibration, Transport, Simulation, Bananas, Package Testing, Supply Chain

5.2. Developing an Accelerated Vibration Simulation Test for Packaged Bananas

5.2.1. Introduction

Modern fruit supply chains extend to intestate and internationally across continents, exposing the palletized produce packages to substantial vibration and shocks in-transit. The continuous interactions of road-vehicle-load during road transport cause excitation of truck floor thereby exposing the packaged produce to broadband random vibration (Jones, Holt & Schoorl 1991; Shires 2011). The energy absorbed by the produce may result in, not only to physical damage, but also exacerbation of the produce quality due to the physio-chemical and physiological changes (Li & Thomas 2014; Opara & Pathare 2014; Zhou et al. 2007). The occurrence of vibration during transport is difficult to avoid, and is a major hazard to maintaining fruit quality during distribution in the supply chain.

In Australia, the region of northern Queensland accounts for over 90% of the total banana production (ABGC 2016). However, major markets including Melbourne (Victoria), Sydney (New South Wales), and other populated cities, are located thousands of kilometres away from the growing regions. This results in lengthy road-based interstate transport across the continent, exposing the fruits to prolonged vibration and shocks in-transit. For example, a journey from Tully, which is one of the main growing regions in Queensland (ABGC 2016), to Melbourne takes 35-40 hours of transport time, excluding the mandatory stops for the truck drivers (NHVR 2019). Therefore, the extreme length of the road-based supply chains and the continuous exposure to harmful vibration increases the level of mechanical damage to packaged bananas in Australia.

Fruit damage caused by vibration is influenced by several factors including the condition of the road surface and the type of transport vehicle. Previous studies reported that the level of vibration excitation of the truck floor during transit is affected by the type of the truck suspension (i.e. air-ride or leaf-spring), travel speed, road condition and the payload (Garcia-Romeu-Martinez, Singh & Cloquell-Ballester 2008; Singh & Marcondes 1992; Soleimani & Ahmadi 2015; Zhou, Yan, et al. 2015). The effect of vibration on fruit mechanical damage is associated with the transmissibility of vibration, height and the position of the package, the position of the fruit inside the package, fill-tightness and the type of fruit packaging (Berardinelli et al. 2005; Chonhenchob & Singh 2005b; Slaughter, Hinsch & Thompson 1993; Slaughter, Thompson & Hinsch 1998; Soleimani & Ahmadi 2014; Vursavus & Ozguven 2004). Several studies have also confirmed the influence of transport or exposure duration on the exacerbation of mechanical damage to fruits (Çakmak et al. 2010; La Scalia, Aiello, et al. 2015; Shahbazi et al. 2010).

Characterizing fruit mechanical damage caused by in-transit vibration, and the evaluation of optimized packaging solutions for minimizing such damage, requires laboratory-based vibration simulation testing. Programmable vibration simulators (shakers) have been extensively used in packaging research. Vibration simulation testing of packaging can be performed as repetitive shock tests, random vibration tests and multi-axis vibration tests (Dunno 2014). The repetitive shock test is not generally regarded as an equivalent simulation of actual transport conditions due to the non-Gaussian and non-stationary characteristics of random vibration that occurs during road transport (Fernando et al. 2018a; Kipp 2001b). Multi-axis vibration simulation requires a multiple degrees of freedom (MDOF) simulation table which is expensive and not widely accessible. Research shows that vertical vibration is the most critical factor in road transport compared to lateral or longitudinal vibration (Shires 2011; Vursavus & Ozguven 2004). Previous research also revealed that the simpler Single degree of freedom (SDOF) vibration simulation along the vertical axis produced effects comparable to that of actual field conditions (Griffiths 2011; Griffiths et al. 2013). Consequently, the simulation of SDOF (vertical) broadband random vibration has been the most widely used method for package testing (Dunno 2014; Shires 2011). The SDOF simulation testing method has been also prescribed in most package simulation standards such as ISTA and ASTM (ASTM 2016b; ISTA 2017b).

There are two key challenges in the simulation of broadband transport vibration. Firstly, the accuracy of which the vibration that occurred in-transit can be reproduced on a laboratory vibration simulator. Secondly, how the duration of vibration of a simulation test time can be minimized in each laboratory test to allow practical, realistic and cost-effective simulation testing. The goal of a laboratory vibration test is to closely replicate the actual vibration experienced by the produce in-transit (Dunno 2014). In addition, a laboratory test needs to be economical and repeatable and thus, deriving the shortest possible equivalent test time is necessary.

Conventional vibration simulation test methods, including the standards such as ISTA and ASTM, are based on averaged intensity (single-level) simplified Power-Spectral-Density (PSD) profiles with highly generalized characteristics (Griffiths 2012; Griffiths et al. 2013). The testing is simplified to the Root-Mean Square (RMS) acceleration which corresponds to the square root of the area under the PSD curve (Lepine, Rouillard & Sek 2015a; Shires 2011). Stationary random vibration is characterized by statistical parameters that remain reasonably constant with time (Dunno 2014). However, the non-stationary aspects of road vibration, due to the occurrence of high energy transient-shocks in-transit (Shires 2011), have been emphasized in numerous studies (Lepine, Rouillard & Sek 2015a; Rouillard & Lamb 2008; Rouillard & Sek 2013; Rouillard & Sek 2010;

Zhou & Wang 2018). Consequently, the conventional simulation methods based on a single vibration intensity have been challenged (Fernando et al. 2018a). Several studies have argued that the single-level PSD simulation can be improved by enhanced simulation methods such as split spectra decomposition (Shires 2011; Singh 2006), wavelet decomposition (Griffiths et al. 2016; Lepine, Rouillard & Sek 2015b), shock on random (Kipp 2001b), shock extraction (Zhou & Wang 2018), RMS modulation (Rouillard 2007) and kurtosis control (Griffiths et al. 2013; Van Baren 2005). Random Gaussian sequence decomposition (Rouillard 2009) has been a frontier study in this regard, which decomposed a non-stationary vibration signals into a collection of short vibration periods with Gaussian and stationary characteristics. A recent study based on weighted Gaussian decomposition showed that the probability density function (PDF) of vibration during the actual road transport can be reconstructed by three to four weighted Gaussian PDFs which can be used for more accurate transport simulation (Bonnin et al. 2018).

The effectiveness of most of these test methods, with respect to the actual product damage during the field transport compared with the outcomes of the laboratory simulation, has rarely been investigated. Most test regimes require an equivalent duration to that of the actual field transport to yield the expected results. For lengthy interstate supply chain, which usually take several days of road transport, conducting package simulation tests based on equivalent or actual transport duration is impractical and unrealistic. To set this into perspective, for example, to replicate an interstate road trip transporting packaged bananas from Tully in North Queensland to Melbourne in Victoria which takes more than 35 hours to transit, will require 35 hours for each test. Therefore, vibration simulation tests with equivalent simulation test time to that of actual long-distance road transport is impracticable.

Many products including fresh produce can spend long-hours on the roads which may not be practical to simulate in a laboratory test setting with an equivalent test duration. Due to the complexities in simulating long-distance (duration) road trips, accelerated simulation testing has been introduced. Time-compressed or accelerated simulation has been an attractive option to reduce the simulation time. However, this method requires the products to be exposed to an intensified vibration stress to compensate for the compressed simulation time (Dunno 2014; Fernando et al. 2018a; Griffiths et al. 2013). This is derived from the Basquin model of cyclic fatigue (Eq.5.4) (Fernando et al. 2018a; Lepine, Rouillard & Sek 2015a; Shires 2011). Despite the widespread use of time-compressed simulation (Shires 2011), limited research has been conducted to verify whether such time-compression or test-acceleration may reasonably replicate the field experience for the products under investigation. A study of electronic appliances subjected to time-compressed simulation showed that the results from the accelerated simulation did not correlate with the field experience (i.e. damage levels occurred in the field). However, the non-stationary/non-Gaussian simulation method produced results similar to the field experience, and could be effective in reducing the simulation time (Dunno 2014). In contrast, a study on packaged apples found that accelerated simulation testing (5:1 time-compression where k=2) produced similar scuffing damage levels on apples compared to the field damage. Conversely, it has been argued that higher time compression can lead to more errors in transport simulation tests (Shires 2011).

$$\frac{t_j}{t_t} = \left(\frac{I_j}{I_t}\right)^k$$

[Where t_j is simulation time; t_t is actual transit time; I_t is intensity (G_{rms}) in the original profile; I_j is intensity in the test profile; k is a constant associated with the product and k=2 is generally used while rarely some studies use k=5 (Fernando et al. 2018b)]. (Eq. 5.4)

During the time compression tests the *k* value is assumed (usually to be 2 or 5), but not experimentally derived. The value for *k* is assumed because the applicability of fatigue models in package testing has not been experimentally proven (Griffiths et al. 2016; Griffiths et al. 2013; Shires 2011). This value can be influenced by the properties of the product, packaging and the test setting. If the appropriate value has not been used, it may result in very large errors in simulation compared to the actual field transport (Shires 2011). This is because '*k*' in Eq.5.4 is a power factor which affects the level of time compression. However, due to the resource and time limitations this value is still assumed in vibration simulation testing for most products and experiments. Therefore, developing a reasonable transport vibration simulation test which replicates the field experience for long-distance road transport can still be challenging.

A solution for simulating long distance transport is to focus on the basic goal for road vibration simulation, that is, an effective simulation must produce similar results to that of the field experience. Regardless of the method used, the best demonstration of a laboratory simulation test is the closest correlation of damage or performance against the field damage during the actual transport (Kipp 2001b). For fresh produce, this means that if the damage levels in produce after the simulation, closely correspond with the damage occurred during the actual road transport, such a simulation test can be regarded as an approximation for a good laboratory-simulation (Dunno 2014; Fernando et al. 2018a; Griffiths et al. 2013). To determine the appropriateness of the simulation, the actual damage levels in the field must be known for a given product.

Recent studies attempted to model and characterize the vibration behaviour of different products based on damage-rate-curves or scuffing-life curves (Ge & Pan 2018; Wang, Wang & Rouillard 2018). Some damage induced by vibration, especially surface abrasion and bruising of fruits may not be caused by the stresses at the resonance frequencies but are often resulted from the accumulation of low stress vibration (Ge & Pan 2018). A damage-rate curve is a plot exhibiting the relationship between a given 'vibration dose' with the resultant damage level in a product. 'Vibration dose is a cumulative measure of vibration expressed in relation to the acceleration intensity and the number of vibration cycles or the exposure duration (Gebresenbet et al. 2011). Ge and Pan (2018) demonstrated that vibration damage-rate curves based on the standard ASTM vibration profile (single-level SDOF simulation) can be used for accelerated random vibration testing since they effectively reproduce an equivalent field damage for printed package products during the laboratory simulation. However, damage-rate curves are specific to each product and influenced by a series of variables during the field simulation experiment. Therefore, damage-rate curves of a given product can provide guidance for further simulation testing on similar products but cannot be readily or universally applied to all products. Therefore, it is essential to establish the relationship between the vibration intensity RMS, exposure duration (or the number of cycles) and the damage level for a given product to determine a reasonable simulation test that, can replicate a similar field experience or damage level during long-distance transport.

Modern fruit supply chains use pallets for storage, transport and handling of packaged produce due to the convenience of handling large fruit volumes in unitized loads. Vertical vibration excitations from the vehicle floor can cause great acceleration amplification in one or more units in the stack resulting in intermittent loss of contact between units (Rouillard, Sek & Crawford 2004). Dynamics in a stack of ten-tier packages on a pallet can be modelled as a ten-degree-of-freedom system with ten critical frequencies, each being potentially a damaging resonant to the products (Urbanik 1978). Although the behaviour of single-unit packaging systems have been thoroughly studied, the vibrational behaviour of a stacked column of individual packaging units can be much more complex (Rouillard, Sek & Crawford 2004; Wang & Fang 2016). Packaged bananas are usually transported on wooden or plastic pallets with the 6th and 10th tier being cross-stacked (Fig. 5.10). The vibration dynamics of the cross-stacked pallet can be different to that in a column-stacked pallet. The vibration characteristics of packages in cross-stacked and column-stacked pallets have not been adequately explored, although it has been an ongoing industry practice to cross-stack to stabilise the pallet. A comparison of the vibration responses in these two pallet arrangements may reveal which stacking method is more effective to reduce vibration damage. Additionally, the experimental validation of the transmissibility characteristics in these two pallet arrangements is essential to identify the discrepancies between the vibration damage that may occur in bananas during the actual field transport and the laboratory simulation testing.

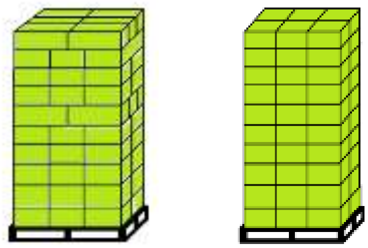


Figure 5.10: (Left) Cross-Stacked Pallet of Banana Cartons (Right) Column-Stacked Pallet of Cartons

The development of a model simulation test capable of replicating field damage level will be important to realistically reproduce the damages that may occur during the actual long-distance interstate transport and to compare the protective performance of packaging used in lengthy supply chains. Therefore, this study aimed to (1) develop a laboratory vibration simulation test to replicate the field damage levels in bananas during the long-distance road transport and (2) to examine and compare the vibration characteristics of cross- and column-stacked pallets subjected to simulated random vibration.

5.2.2. **Material and Methods**

5.2.2.1. Measurement of mechanical damage in column-stacked banana packages

Sixty (60) cartons of bananas were inspected for existing mechanical damage in a commercial packing facility in Tully, Queensland to ensure that bananas were free from pre-existing vibration damage. The inspected clusters were photographed and a numbered sticker was attached to each cluster for damage evaluation after the transport. All inspected sample cartons were stacked in three columns on one side of a wooden pallet (Fig.5.11) and the rest were stacked with another 30 cartons to make a full column-stacked pallet for transport. Two-pallets with 30 sample cartons in each were stacked in column-stack arrangement and were loaded onto the rear most position in the B-trailer of a dual trailer road train-truck (Fig.5.11). The pallets were loaded to this position, as it was revealed that the rear position of the B-trailer had the highest vibration excitation from the trailer floor, resulting in the worst damage in bananas compared to the rest of the pallet positions(Fernando, Fei & Stanley 2019). Both pallets were loaded to the curb (left) side of the trailer as it was revealed that the curb-side of the vehicle is usually exposed to the worst vibration and shock excitations (Griffiths 2012). The road train was fully-loaded with 10 pallets of bananas in the A-trailer and 22 pallets of bananas in the B-trailer (including the sample pallets).

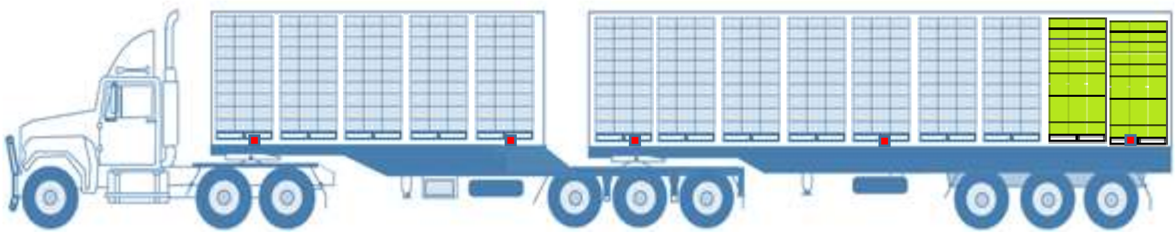


Figure 5.11: Position of the Column-stacked Pallets (Green) and the Accelerometer Devices on the Five Positions (■) inside the Truck

The B-double truck left the depot in Tully, Queensland and reached the Distribution Centre (DC) in Melbourne, Victoria after traveling nearly 3,400 km in 3 days and 14 hours to transit (inclusive of the mandatory driver-rest stoppages). Once the road train arrived at the DC, the two pallets with the column-stacked cartons were unloaded and the mechanical damage level in each carton was measured. A transparent damage area measurement sheet (Appendix C1) was used for this purpose and MDI score (Mechanical Damage Index) based on the damage area on bananas was calculated by Eq. 5.5.

MDI (%) = 0.1 x Trace Damages (%) + 0.2 x Slight Damages (%) + 0.7 x Moderate Damages (%) + 1.0 x Severe Damages (%) (Eq.5.5)

(Damage Area (A) ≥3 cm² – Severe; 2 cm²≤A<3 cm² – Moderate; 1 cm²≤A<2 cm² – Slight; 0.5 cm²≤A<1 cm² - Trace)

Figure 5.12: (a) Inspected clusters attached with an identifiable sticker, (b) Accelerometer data logger attached to the base of the pallet (c) Packages stacked in column-stack arrangement on a pallet up to ten-tiers

5.2.2.2. Measurement of Vibration and Analysis

Five piezo-electric accelerometer data loggers (Slam Stick - MIDE Technology Inc., Massachusetts, USA) were attached to the base of wooden pallets stacked in five pallet positions in the dual trailer truck (Fig. 5.11) to record the in-transit vibration during the journey. Each device was configured for sampling at a rate of 400 Hz. The accelerometer loggers were connected to an external battery pack to increase the operating time of the device, enabling the continuous capturing of data for several days in-transit (Fig.5.12). Once the dual-trailer truck reached the DC in Melbourne, the accelerometers were removed from the pallet bases and the data in the devices were downloaded and then converted to Comma-separated (CSV) file format using Slam Stick Labs (ver.1.6, MIDE Technology Inc., Massachusetts, USA) software. Only the vertical acceleration data were analyzed as it has been reported that the vertical acceleration was predominant over comparatively insignificant longitudinal\lateral vibration during the road truck transport (Shires 2011; Singh 2006; Vursavus & Ozguven 2004). The dataset was sliced to one million data points (42-minute segments at 400 Hz) after removing all the truck stoppages for the analysis. The time-domain data were converted to frequency domain using Fast Fourier Transformation (FFT) (Randall & Tech 1987; Smith 1997) using Matlab (ver. 2014b, Mathworks, Natick, MA, USA) signal processing toolbox. Cross power spectral density (Lalanne 2002; Smith 1997) was calculated for the time-series dataset (windowing with 50% overlap) to generate averaged PSD profiles, also known as Global Power Spectral Density (GPSD) for each position of the truck.

5.2.2.3. Development of an Accelerated Simulation Test for Packaged Bananas

Ninety (90) banana cartons were inspected for existing mechanical damage and the clusters with damaged banana fingers were replaced with undamaged clusters. Each carton had a gross weight of 15.5-16.5 kg with bananas (extra-large grade, 200-220 mm in length, 30-40 mm girth) packed in three layers with 5-7 clusters in each layer. A single column of cartons was stacked on a vibration simulation table for the experiment (Fig.5.13). The column was triple stretch-wrapped and was guided by four removable steel columns. An averaged PSD profile developed from the field data was used as the input vibration spectrum to drive the simulator (Fig.5.14).

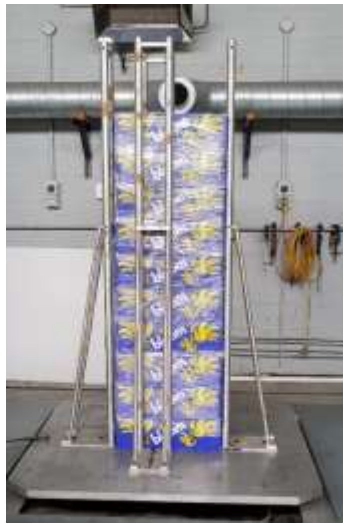


Figure 5.13: A Column of Ten Banana Packages Stacked Vertically on the Vibration Simulator

A series of tests with different vibration doses consisting of different RMS intensities and durations were performed as per the test sequence given in Table 5.3. At the end of each simulation test, the bottom (1st), middle (5th) and the top (10th) banana cartons of the column were removed for damage assessment. The test sequence was determined in concurrence with the assessment of damage levels in bananas after each treatment. This means that after each simulation test, the damages were assessed (using the transparent damage area measurement sheet- Appendix C1) and the RMS level or the test duration were changed until a comparable damage level to that of the actual field transport was found. Each simulation test was performed in triplicates. Mechanical damage in each carton was evaluated by the same method described in Section 5.1.2.3. A MDI score was calculated for each sample carton (Eq. 5.5) and compared against the average damage levels occurred in the field transport.

Table 5.3: Test Sequence for Packaged Bananas

Test Sequence	RMS%	Intensity (RMS)	Duration (Hours)
1	100%	0.12	3
2	400%	0.48	2
3	400%	0.48	1
4	350%	0.42	2
5	350%	0.42	1
6	300%	0.36	3
7	300%	0.36	2
8	300%	0.36	1
9	200%	0.24	3
10	200%	0.24	2

5.2.2.4. Comparison of the vibration transmission characteristics in a Cross-stacked versus a Column-stacked pallet

A laboratory simulation test was performed to analyze the vibration transmissibility characteristics in a cross-stacked pallet and a column-stacked pallet. The vibration simulation table was configured at an overall RMS level of 0.36g in each simulation test using the same custom-made PSD profile (Fig.5.14). Firstly, the cross-stacked pallet was placed on the vibration simulator with an accelerometer attached firmly to the base of a carton of bananas. This carton was then placed in the bottom tier of the pallet and the rest of the cartons in the pallet were stacked to make a full cross-stacked pallet. The pallet was triple-wrapped using a transparent stretch film and subjected to simulated vibration for each three minute-triplicates. After each test, the carton with the accelerometer device was moved to the second tier and the entire pallet was re-stacked in the same cross-stack arrangement. In the same manner, the carton with the accelerometer was moved from the bottom tier to top tier and exposed the cross-stack pallet for three-minute triplicates of simulated vibration. Secondly, the vibration measurements were taken from the column-stacked pallet by first placing the carton with the accelerometer in the bottom tier. Similar to the cross-stacked pallet, the column-pallet was triple stretch-wrapped and subjected to simulated vibration for three-minute period triplicates. The carton with the accelerometer was moved from the bottom tier to top tier after each test triplicate in each tier.

During all tests an accelerometer device (Slam Stick, MIDE Technology) was placed on the simulator table to record the input vibration excitation of the table. After all simulation tests, the accelerometer data was acquired via the Slam Stick Labs software and analyzed by the signal processing toolbox in Matlab 2014b software. Averaged PSD curves for each position in the carton during each test performed have been developed. The transmissibility of vibration has been calculated by Eq. 5.6 as the ratio between the input acceleration of the vibration table and the output acceleration (excitation).

$$\text{Transmissibility (T)} = \frac{A_{output}}{A_{input}} \qquad \text{(Eq.5.6)}$$

(Where 'T' is the transmissibility ratio; A_{output} is the vibration excitation of the carton within a given bandwidth of frequencies; A_{input} is the vibration input from the simulator table)

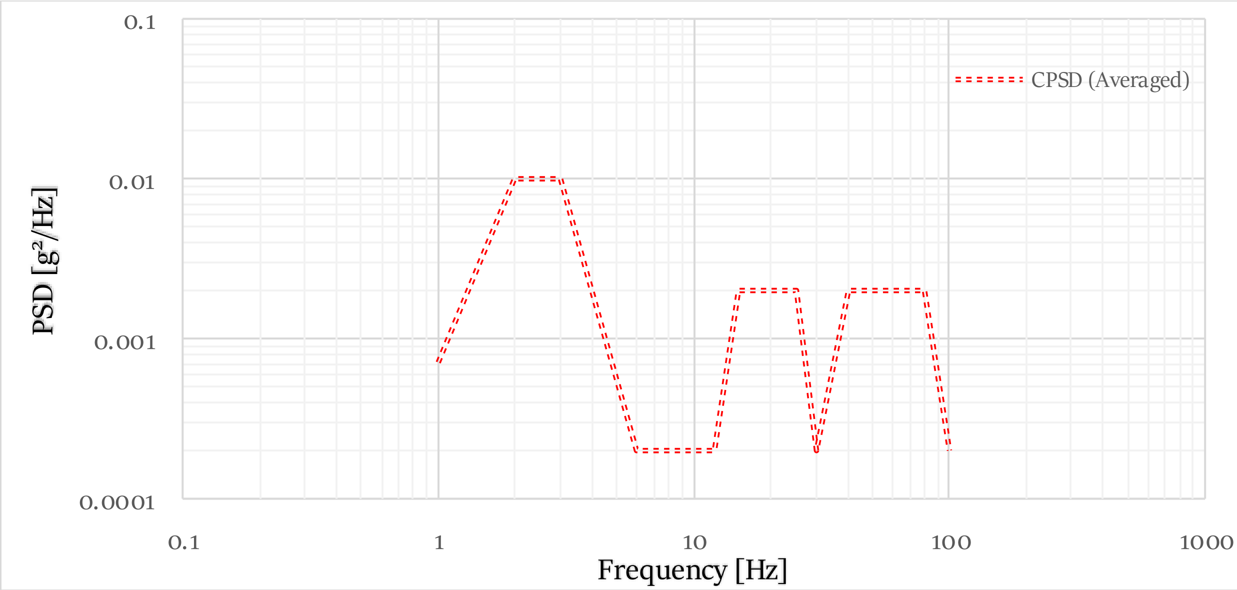


Fig.5.14: Break-points of the Simulated PSD Spectra (Adjusted) with the PSD-shape correspond to the Averaged GPSD of the truck

5.2.3. **Results and Discussion**

5.2.3.1. Constructing the GPSD from the Field Data

Field data collected during the actual road transport was used to derive the GPSD profile for the most rear position of the dual-trailer truck (Fig.5.15). An averaged GPSD profile for the truck was developed by averaging the individual GPSD profiles attributed to each of the five floor positions in the truck (Fig.5.11). The difference between the GPSD of the rear position and the averaged GPSD is that the rear position exhibited a higher energy peak in the lower-frequency range (<5Hz) attributed to the suspension response of the truck. The vibration energy in the high frequency range (>30 Hz) was significantly attenuated in the most-rear position. The averaged GPSD exhibited three spectral peaks across the spectrum (0.1-100 Hz), with an escalated energy in the high-frequency range (>30 Hz), which was attributed to the vibration of the vehicle structure (Singh 2006).

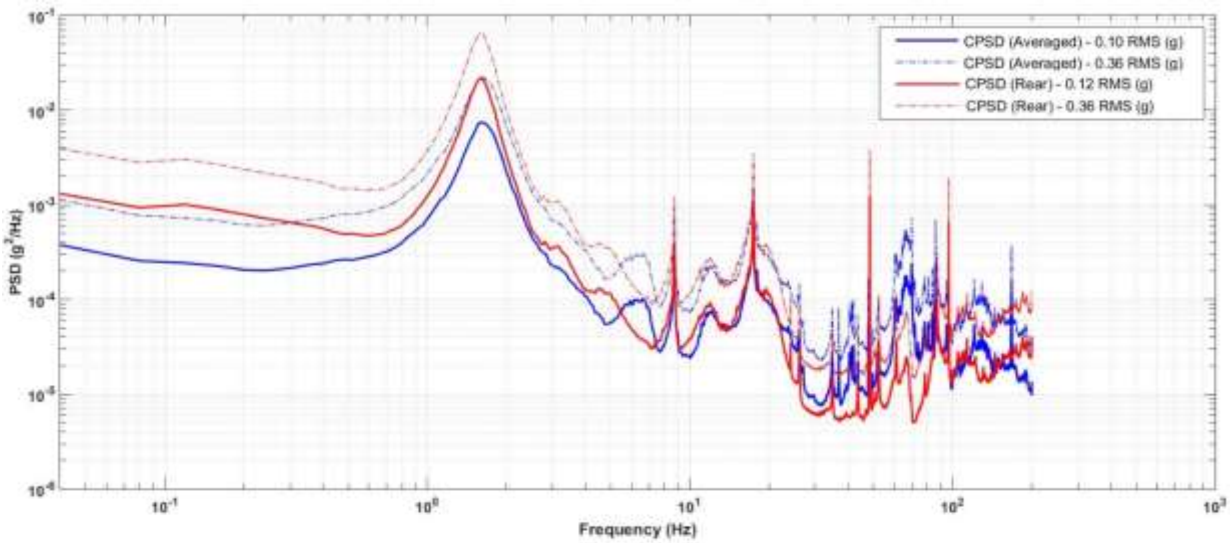


Figure 5.15: GPSD profiles for the Rear Position and the Averaged GPSD for the Truck Represented at Different RMS Acceleration Levels

Based on these GPSD profiles, as given in Fig.5.15, an averaged spectrum for the vibration simulation was developed (Fig.5.14) and was then used for laboratory vibration simulation. Simulation of transport vibration has several limitations which were mostly due to the technical incapability of the vibration simulator. The spectral peak between 1.5-2 Hz in the GPSD profiles could not be reproduced during the simulation due to the technical limitations of the simulator table. Even the most modern vibration simulators are only capable of simulating vibration in the range of 2-50 or 2-100 Hz with restrictions for maximum displacement and payload. When the high energy peak in the low frequency range was attempted, the maximum displacement of the simulator table was exceeded. Therefore, the peak that occurred at 1.5-2 Hz during the actual road transport was replicated in the frequency range of 2-3 Hz in order to operate the simulator within the safe technical working limits (Fig.5.14). The occurrence of the low-frequency peak in a PSD profile is attributed to the suspension characteristics in each truck. An abundance of studies have reported that this low frequency peak falls within in the range of 1.5-4 Hz as does the widely used ASTM simulation standard (peak in the range of 3-4 Hz)(ASTM 2016b). Therefore, this slight adjustment in the lower frequency PSD peak during the simulation was assumed to have marginal effect on the results (damage levels).

One of the most important factors in single-level road vibration simulation is the determination of the RMS acceleration level. This has to be carefully selected in relation to the field transport conditions (Fernando et al. 2018a). The average RMS acceleration of the rear position of the truck during the entire long-distance road transport is given in Fig.5.16. The averaged RMS distribution of the journey is given in Fig.5.17 and accordingly, the (global) average RMS for the rear position of the truck was found to be 0.12 g. However, using this RMS may require a laboratory test duration equivalent to that of actual road transport (in this case 38+ hours at minimum) or for nearly eight hours duration in a time-compressed setting (with a time compression of 5:1) as per the Basquin model (Eq.5.4). Both these test durations are highly impractical and uneconomical for simulation testing.

Additionally, there is still a challenge to determine a suitable RMS acceleration value for a comparable simulation due to the unknown *k* value. If the *k* value is assumed to be 2, then according to Eq.5.4 the RMS acceleration for the test needs to be increased to 0.27 g. However, the value of *k* is dependent on the properties of the product and the stiffness and dampening of the entire system. Therefore, the best proposition is to experimentally determine the damage levels in a laboratory setting and compare these against the field damage levels. This will not only help to derive a reasonable test setting for packaged bananas but also to experimentally obtain the *k* value which otherwise needs to be arbitrarily assumed. This experimental validation is further explained in the Section 5.2.3.2.

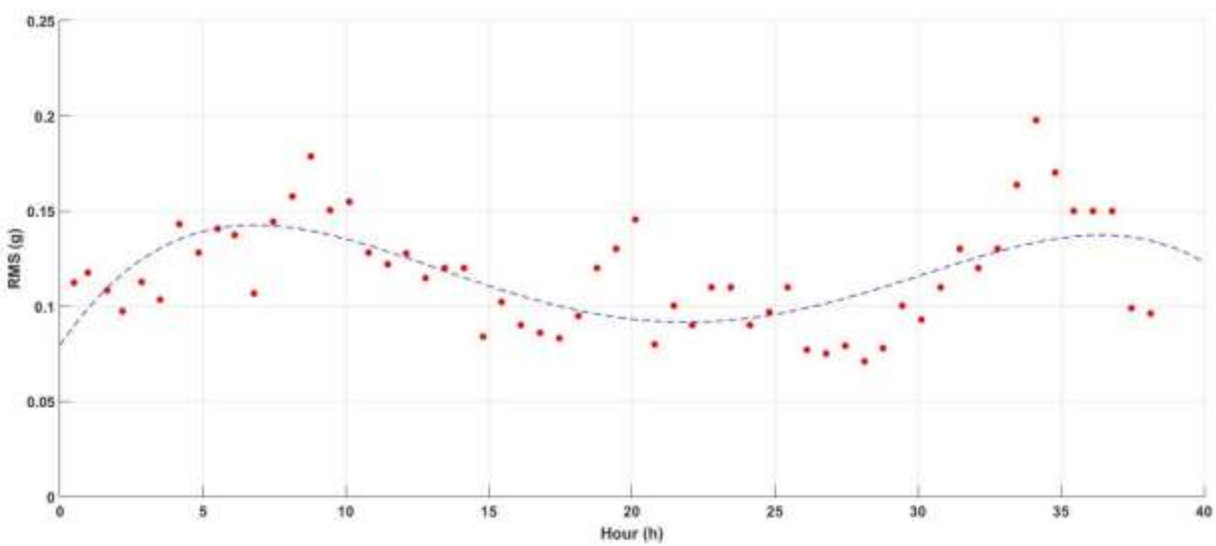


Figure 5.16: RMS of the Journey by the Hour (Time) for the Rear Position (Calculated for each 42-minute Segments)

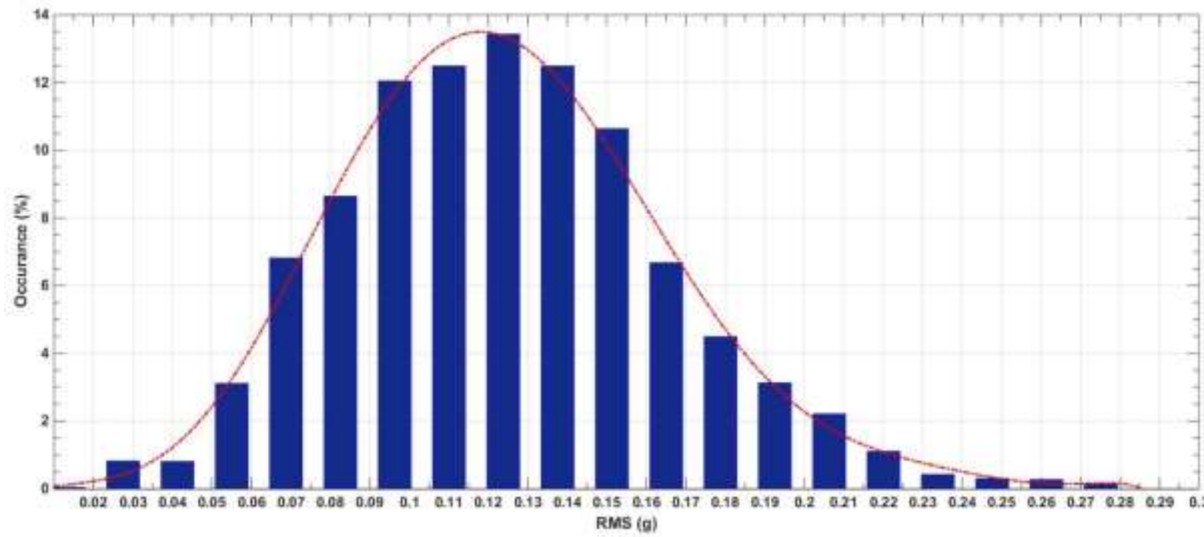


Figure 5.17: RMS Distribution for the Rear Position of the Truck

5.2.3.2. Development of an Accelerated Simulation by Damage Level Correlation

The damage levels in the top, middle and bottom positions of the column-stacked banana packages were compared against the actual field damage levels for the same positions after each vibration treatment. The MDI score calculated for each simulated vibration treatment and the MDI calculated during the field transport (i.e. 13.9, 0.9 and 7.4 for the top, middle and bottom respectively) are given in Table 5.4. The damage curves for packaged bananas stacked in the top-position of the column corresponding to different vibration doses are illustrated in Fig. 5.18.

Table 5.4: MDI% Values for each Vibration Treatment during the Simulation and the Difference of MDI against the Field Damage Levels

				MDI(%) (Sim)			**Difference in MDI (%) MDI (Field) - MDI (Sim.)**		
Test Sequence	**RMS%**	**Intensity (g)**	**Duration (H)**	**Top**	**Middle**	**Bottom**	**Top**	**Middle**	**Bottom**
							13.9	**0.9**	**7.4**
1 a	100%	0.12	1	0.5 a	0.0 a	0.0 a	- 13.5	-0.9	-7.4
10 b	200%	0.24	2	1.8 ac	0.00 a	0.6 a	-12.2	-0.9	-6.9
9 c	200%	0.24	3	2.8 ac	0.4 a	1.3 a	-11.1	-0.5	-6.2
8 d	300%	0.36	1	5.8 acd	0.4 a	2.6 a	-8.1	-0.6	-4.8
7 e	300%	0.36	2	7.5 ace	0.5 a	3.7 a	-6.5	-0.4	-3.8
6 f	**300%**	**0.36**	**3**	**14.1 e**	**0.9 a**	**6.8 ac**	**0.2**	**0.0**	**-0.6**
5 g	350%	0.42	1	12.3 de	1.0 a	5.5 a	-1.6	0.1	-1.9
4 h	350%	0.42	2	27.8 b	3.4 b	13.3 bc	13.8	2.5	5.9
2 i	400%	0.48	1	34.0 b	4.3 b	15.8 b	19.9	3.4	8.4
3 j	400%	0.48	2	54.2 f	8.5 c	31.0 c	40.2	7.6	23.5

This comparison shows that the vibration treatment with 0.36 g RMS for three hours (test sequence 6) closely correlated with the average damage levels in packaged bananas stacked in the top, middle and bottom positions. Furthermore, damage levels escalated exponentially with the increase in RMS (Fig. 5.19) and worsened with exposure duration as illustrated. It was also revealed that a single level SDOF simulation test at the averaged vibration intensity of 0.12 g (corresponding to the actual field transport) produced far less damage in bananas and therefore can be regarded as an under-test. Similar results have been reported in previous studies, confirming that even a non-time compressed single level simulations based on the averaged PSD would generally represent an under-test for most products (Griffiths 2011; Griffiths 2012; Griffiths et al. 2013; Shires 2011) . Griffiths et al. (2013) also found that an accelerated vibration test at an assumed *k* value of 2 produced similar results (scuffing damage) in apples, comparable to that of field experience.

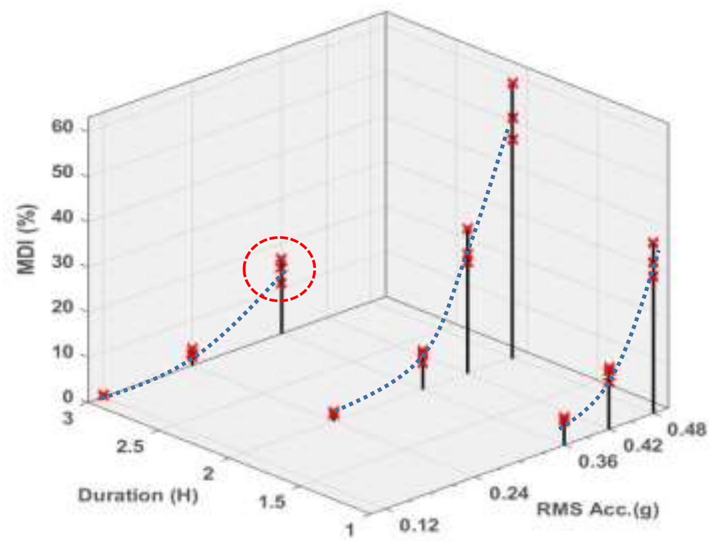
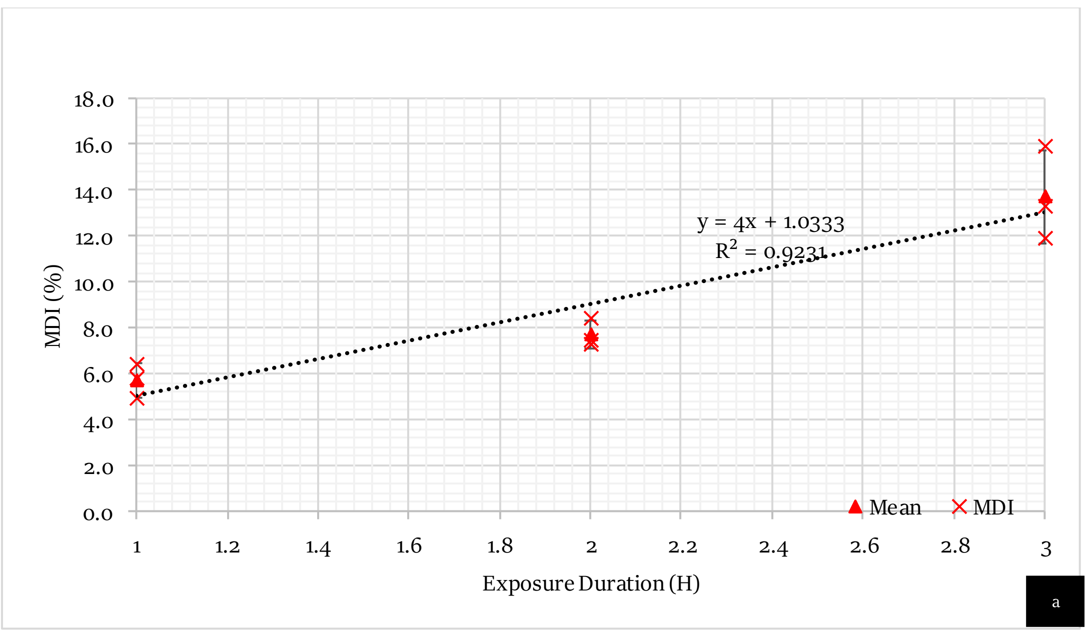


Figure .5.18: Damage Levels (MDI %) in the Top-position of the Package for Different Vibration Treatments (The treatment with the least deviation from the field MDI value is circled)

The ASTM standard for package testing (ASTM 2016b) specifies a RMS acceleration value of 0.37 g for the assurance level 3 for packaged products (irrespective of the product type). This is in close agreement with the vibration intensity of 0.36 g derived in this study. From the experimental data, the value of *k* can be calculated by equating the field damage levels and those of the simulation by re-arranging the Eq.5.4. Given that the RMS value of 0.36 g and a 3-hour simulation corresponded with the damage levels during the 38-hour field transport, the *k* value can be determined as 2.3 as per the Eq.5.4. It can be inferred that, for packaged bananas, a better representation of damage compared to the field occurs at a higher *k* value (2.3). In previous studies Griffith showed that a '*k*' value of 2 produced a similar field experience for apples in a time-compressed vibration simulation test while Ge and Pan (2018) revealed that a better correlation for the damage levels for printed packaging products were found at k =1.1. These studies concluded that the k value is highly dependent on the product characteristics, and other factors such as the combination of packaging used for each product. Therefore, time compression or test acceleration has to be carefully performed in simulated package testing and, ideally performed in comparison with the field damage levels (if known). However, when the field damage levels are unknown, a moderate time compression level of 5:1 with an assumed k value of ‘2’ can still be considered (Griffiths 2011; Griffiths et al. 2016; Griffiths et al. 2013; Shires 2011). However, the accuracy of the simulation may not be as good as when the field or actual damage levels for a given product are reasonably known.

$$\frac{T_j}{T_t} = \left(\frac{A_j}{A_t}\right)^k = \frac{38}{3} = \left(\frac{0.36}{0.12}\right)^k \qquad \text{(Eq.5.4)}$$



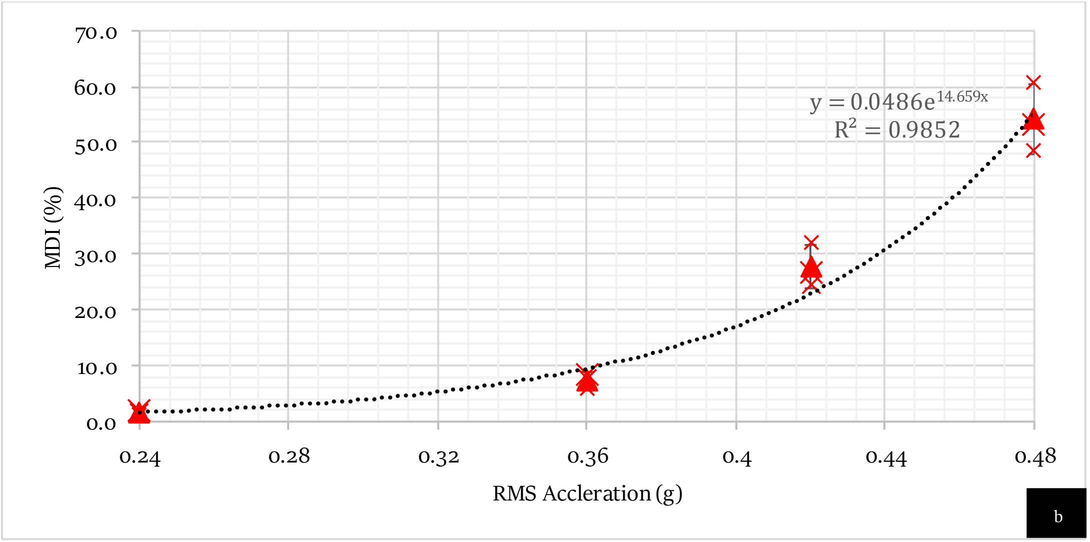


Figure 5.19: Damage Levels (MDI %) in the Top-position of the Package (a) for Different Durations at 0.36 g and (b) for Different RMS (g) Levels after two Hours of Vibration Exposure

5.2.3.3. Comparing the Vibration Characteristics and Transmissibility in a Cross-Stacked and a Column- Stacked Pallet

The PSD curves for each position of the column-stacked pallet and the cross-stacked pallet are given in Fig.5.20. In both pallet arrangements, the vibration spectra of the bottom package was similar across the entire frequency range and closely corresponded with the input vibration of the table. From the second tier onwards the input vibration from the simulator table was dampened after 27.4 Hz in the cross-stacked pallet and after 27.6 Hz in the column-stacked pallet. The transmissibility of vibration up the column-stacked and cross-stacked pallets were similar (Fig.5.21), signifying that in both pallet stacking arrangements, the high frequency vibration (>30 Hz) was attenuated up the column. This result coincides with that of Paternoster et al, (2018) where the high-frequency vibration was dampened by corrugated paperboard cartons. In a column of corrugated cartons, each carton acts as an integrated component in a spring-mass system (Rouillard, Sek & Crawford 2004). This can result in amplification or attenuation of the input vibration up the column. The compressive stiffness of packages interact with the content masses to amplify or attenuate motions created by input vibration through the height of the column (Urbanik 1978). It is evident in this study, that the high frequency vibration was absorbed by the fruit (bananas), and the cartons stacked in the lower tiers, resulting in attenuation of the high frequency vibration energy up the stack.

It is suggested from the curves given in Fig.5.20 that the two systems behaved similarly at the excitation of the simulated vibration. However, there were several exceptions between the vibration characteristics of the two stacking arrangements. Firstly, the top package (Tier-10) in the cross-stacked pallet exhibited significant vibration amplification between 10-15 Hz range which did not occur in the column-stacked pallet. Secondly, the first resonance occurred for both pallets in the range of 7-9 Hz. However, the amplification of energy in the packages (Tier-6 onwards) was higher in the cross-stacked pallet than the column-stacked pallet (Fig.5.20). This is also signified by the escalated PSD peaks which occurred in this frequency range (7-9 Hz) as summarised in Table 5.5. Godshall (1971) reported that a column of stacked corrugated cartons resonated between 8.4-18.2 Hz which is in concurrence with this study. Furthermore, the findings of this study agree with the study of Wang and Fang (2016) which revealed that the PSD of the top container exhibited more vibration energy than the middle and the bottom containers around the first resonance mode.

Table 5.5: PSD Peaks in the First (Principle) Resonance Mode

Package Position (Tier)	PSD Peak at the First Resonance (g^2 /Hz)	
	Cross-stacked	Column-stacked
Tier-1	7 Hz (0.002)	8 Hz (0.001)
Tier-2	7Hz (0.002)	8 Hz (0.001)
Tier-3	7 Hz (0.002)	8 Hz (0.002)
Tier-4	7 Hz (0.003)	8 HZ (0.003)
Tier-5	7 Hz (0.004)	8 Hz (0.003)
Tier-6	7.8 Hz (0.006)	7.8 Hz (0.004)
Tier-7	7.7 Hz (0.006)	8 Hz (0.006)
Tier-8	7 Hz (0.009)	8 Hz (0.006)
Tier-9	8 Hz (0.01)	8 Hz (0.007)
Tier-10	7.8 Hz (0.012)	8.6 Hz (0.01)

The transmissibility of vibration in column-stacked and cross-stacked pallets are illustrated in Fig.5.21. In the bottom tier, the transmissibility level was similar (~1) and the vibration energy closely corresponded with the input vibration from the table. The transmissibility of vibration was also similar in the middle tiers (Fig.5.21). However, the middle tiers in the cross-stacked pallet revealed a slightly higher transmissibility (T ~ 1.3) in the mid-frequency range (10-20 Hz) compared to the column-stacked pallet (T~1.1). The attenuation of vibration in the top position occurred at 15.8 Hz in the column-stacked pallet and 21.7 Hz in the column-stacked pallet. This was due to the occurrence of a third spectral peak in the spectrum of the top package in the cross-stacked pallet (Fig.5.20). Consequently, the vibration energy in the top-tier cartons in the cross-stacked pallet was higher than the energy of the same position in the column-stacked pallet. This would create a higher risk of damage to bananas, especially around the resonance frequencies. Therefore, by cross-stacking the sixth tier of the pallet, the natural dampening characteristics of the packages up the column of banana cartons were disturbed specially in the mid-frequency range (10-25 Hz). Additionally, cross-stacking of the tenth tier resulted in unrestricted excitation of the top-tier packages with increased vibration energy. This may cause bananas in the top tiers to exhibit more damage compared to that of the column-stacked pallets due to the higher vibration transmissibility (Fig. 5.21) specially in the mid-frequency range. Consequently, more damage to bananas stacked in the top-tier cartons can be expected in cross-stacked pallets compared to the column-stacked pallets during the actual road transport.

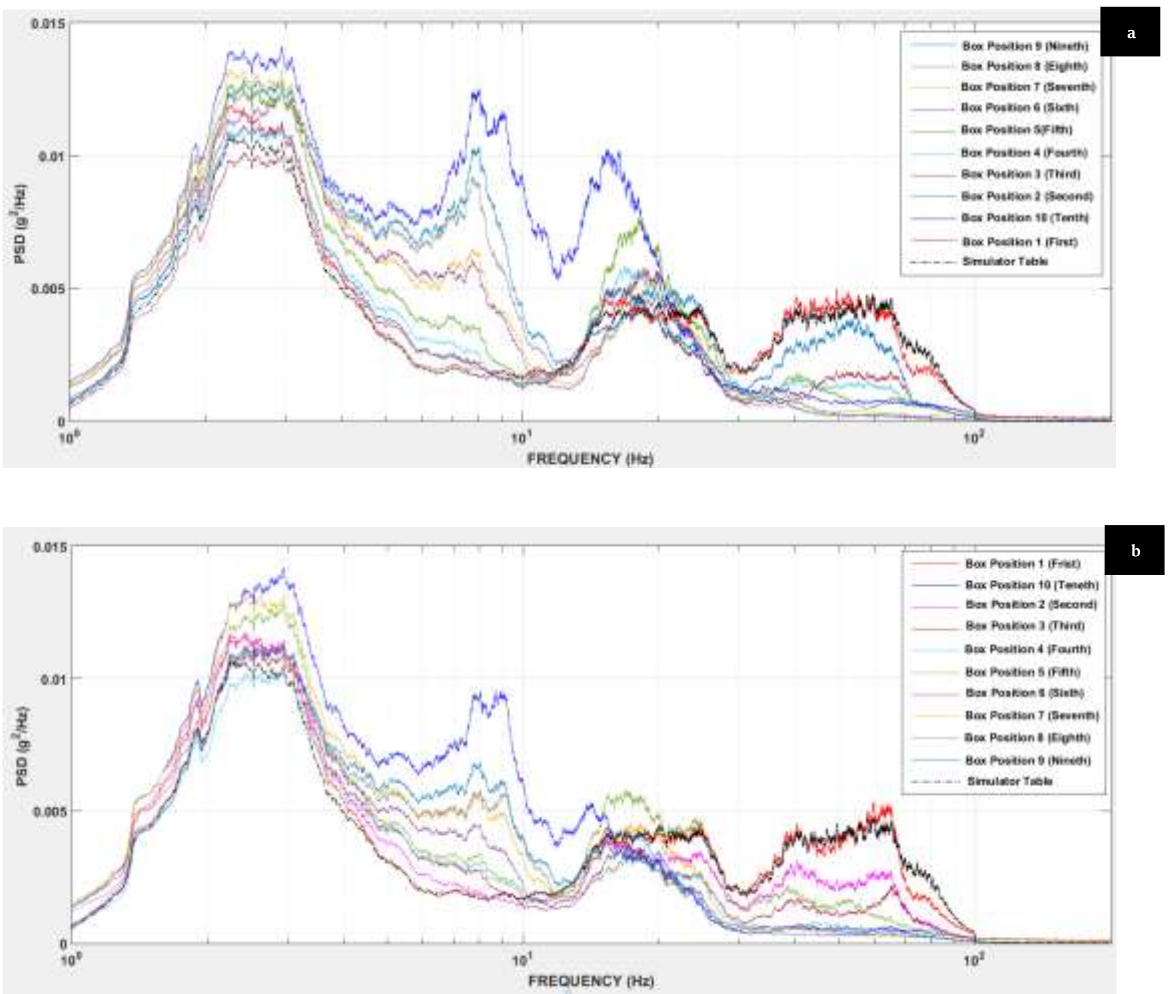


Figure 5.20: PSD for Different Package Positions of the (a) Cross-stacked and (b) Column-stacked Pallet

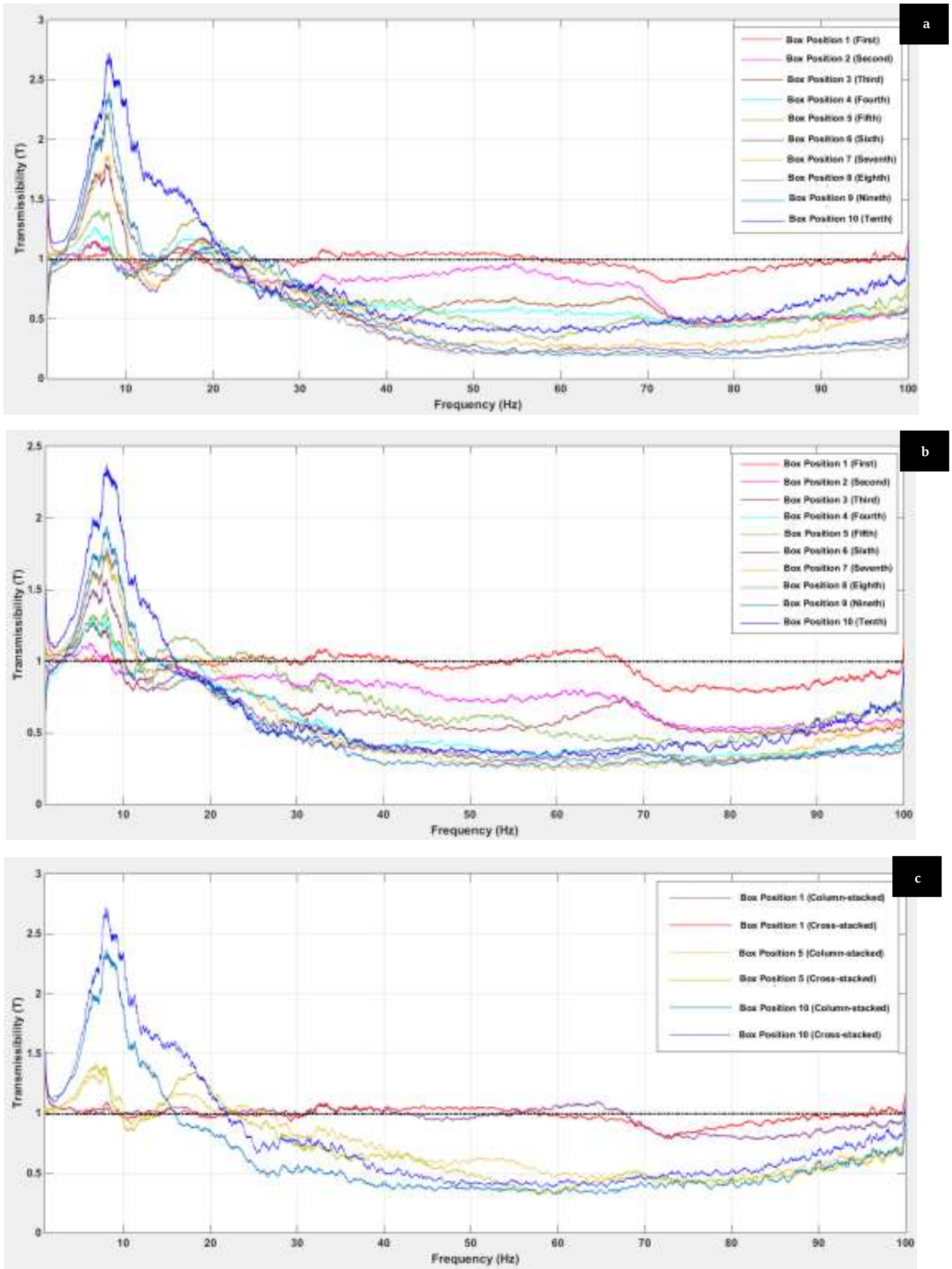


Figure 5.21: Vibration Transmissibility Curves for the (a) Cross-stacked (b) Column-stacked Pallets and (c) the Comparison of Transmissibility in the Bottom, Middle and Top Positions of the Pallet

5.2.4. Conclusion

This study developed an improved vibration test protocol for packaged bananas by replicating the field damage levels in a laboratory-based accelerated vibration simulation. The single degree of freedom (SDOF) simulation at the averaged RMS acceleration intensity of 0.12 g produced less damage in packaged bananas compared to the field damage and consequently results in an under-test. Mechanical damage levels exponentially increased with the escalation of the averaged RMS acceleration and also showed a linear increment with the exposure duration. This suggests that packaged bananas are more sensitive to vibration intensity (G_{rms}) than the exposure duration. The vibration treatment of 0.36 g for three hours based on the SDOF power spectra reproduced equivalent damage levels in packaged bananas during the laboratory vibration simulation at a time compressed setting with a power factor of k=2.3. This implies that the value of k in accelerated vibration simulation is highly dependent on the properties of the products and the vibration characteristics of packaging. This also indicates that an assumed value of k may lead to larger errors in laboratory-based vibration simulation. Therefore, it is best to determine the 'k' value experimentally in comparison with the field damage levels. However, when the field damage levels are not known the value of k may be at least determined in comparison to similar products and/or packaging arrangements. The effect of lateral and longitudinal motion during the vertical vibration simulation was minimized in this study with the use of triple stretch-wrapping and vertical steel fixtures. Therefore, the effect on damage levels due to the sway motions during the simulation of a single column was considered negligible.

This study will further contribute to vibration simulation experiments on bananas or similar delicate fruits, where mechanical damage is significant during transport. The transmissibility of vibration up a pallet of cross-stacked and column-stacked packages is similar where high frequency vibration is dampened up the column by the packaged fruit. However, the cross-stacking of pallets can result in escalated vibration levels in the mid frequency range where unrestricted vibration excitation occurs in the top-tiers around the resonance frequencies. Therefore, column-stacking of packages can be recommended to reduce the level of vibration and consequential fruit damage in the top tiers but a securing mechanism, such as the use of corner-posts, may need to be considered to ensure the stability.

6. CHAPTER VI

Evaluating the Packaging Alternatives for Bananas

PREFACE

Bananas remain packed for most duration of the post-harvest supply chain until they are delivered to retail stores and unpacked for sale. The previous chapters showed that vibration and top-load compression on packaged bananas specially in the latter part of the supply chain (SC), largely contributes to the development of abrasion, bruising and neck damages. Packaging is the primary protection for most delicate produce preventing the fruit from mechanical damages. This chapter evaluates the performance of different packaging alternatives for bananas by simulated transport vibration. The first part of the chapter evaluates packaging alternatives for the intestate transport of bananas stacked in ten-tier palletized columns and the second part of the chapter further assesses the packaging performance for the retail distribution of ripe bananas in consolidated pallets. The vibration transmissibility in column-stacked and cross-stacked pallet arrangements was analyzed and the effectiveness of vacuum-tightening banana clusters for minimizing abrasion damage levels was evaluated. Finally, the chapter assesses the effect of highly humid (RH) ripening conditions on the structural integrity of different packaging alternatives. Based on the protective performance of packaging, the most suitable packaging type of bananas is recommended to minimize mechanical damage in bananas in the post-harvest SC.

Publications included in this Chapter

- ***Section 6. PART A -*** Fernando, I., Fei, J., Stanley, R., & Rouillard, V. (2020). Evaluating packaging performance for bananas under simulated vibration. *Food Packaging and Shelf Life*, *23*, Article 100428. ISSN 2214-2894 (2020) [Refereed Journal Article]
- ***Section 6. PART B -*** Fernando, I., Fei, J., Stanley, R., & Hossein E. (2020) Evaluation of packaging for the distribution of ripe bananas in consolidated pallets by temperature-controlled simulated vibration, *Packaging Technology and Science*. [Journal Article]

PART A

Evaluating Packaging Performance for Unripe Bananas under Simulated Vibration

ABSTRACT

Packaging is the primary protection of fresh produce against the environmental hazards such as vibration in the distribution process. This study evaluated the effectiveness of two types of corrugated paperboard packaging, reusable plastic creates (RPC) and vacuum tightening for their protective performance in reducing damage of bananas under simulated transport vibration. Both vibration transmissibility and the construction material of packaging influenced the mechanical damage levels in bananas with the RPCs showing the highest damage levels. The best protective performance for bananas was exhibited by one-piece corrugated paperboard cartons with additional benefits of reduced vibration transmissibility at the top-tiers. Vacuum tightening effectively reduced the vibration damage, especially in the most bottom and top tier packages, by over 70% and thus, can be considered for further reducing mechanical damage to bananas. One-piece cartons, with the possible addition of vacuum tightening or tensioned plastic wrapping, could therefore substitute the widely used two-piece carton in Australia in order to minimize mechanical damage to bananas in-transit.

Key Words: **Mechanical Damage, Vibration, Simulation, Packaging, Transmissibility, RPC, Banana**

6.1. Evaluating Packaging Performance for Unripe Bananas under Simulated Vibration

6.1.1. Introduction

Food packaging is needed to prevent contamination, damage and to extend the shelf life of fresh produce in the environment of the distribution chain. Packaging with improved protection, ventilation and temperature control can have a significant impact on ensuring the produce quality and reducing food waste (Verghese et al. 2015). Corrugated paperboard cartons are frequently used in food packaging due to the ease of transport and handling of produce from growers to the consumers. Fruits can be damaged due to the occurrence of mechanical stresses such as compression and impact forces during the storage and handling of packages (Fadiji, Coetzee, Pathare, et al. 2016; Opara & Fadiji 2018; Van Zeebroeck, Darius, et al. 2007b; Van Zeebroeck, Van linden, et al. 2007). Vibration is a prominent cause of mechanical damage to fruits during transit (Fernando et al. 2018a). As vibration during transport cannot be completely eliminated it is therefore important that both the package and products are able to endure the vibration hazards in transit (Dunno 2014).

Simulation studies on packaged fruits contribute to understanding the behavior of fruits inside the package when exposed to mechanical vibration, potentially resulting in damage due to static and dynamic loads. The effectiveness, and the protective performance of packaging, have been previously studied for various fresh fruits (Chonhenchob & Singh 2003a, 2005b; Fadiji, Coetzee, Chen, et al. 2016; Slaughter, Thompson & Hinsch 1998). Stacking of multiple packaging units together as a column, stacking of multiple layers of products inside the package and the stacking arrangement of the packages can all influence the vibrational characteristics of packaged products (Paternoster, Van Camp, et al. 2017). Resonance of a stack of paperboard cartons was shown to have been exhibited in the frequency range of 8-18 Hz (Godshall 1971). This frequency range was shown to also be occurring in the transport environment (Vursavus & Ozguven 2004), resulting in critical dynamic stresses and eventual damage to packaged produce (Rouillard, Sek & Crawford 2004). Therefore, the vibration transmissibility up a column of packaged produce can be complicated.

The effect of packaging and the vibration transmissibility on the occurrence of damage to apples showed that the damage levels were significantly affected by the vibration frequency, intensity, exposure duration and the packaging method (Vursavus & Ozguven 2004). In a similar study, Fadiji, Coetzee, Chen, et al. (2016) evaluated the effectiveness of two package designs by simulated vibration and revealed that the design of the package, length-height ratio, vibration characteristics and transmissibility affected the protective performance for apples in each package. Damage levels in other produce have similarly been shown to be influenced by the stack-height of the package, where most of the damage generally occurred in the top-most containers (Barchi et al. 2002; Soleimani & Ahmadi 2014). The stiffness components and the dampening parameters of different packaging and the structure can contribute to the attenuation or the amplification of vibration up a stacked column (Paternoster, Van Camp, et al. 2017; Paternoster et al. 2018). Therefore, studies on package characteristics and vibration transmissibility are needed to understand how these factors influence fruit damage when packages are exposed to mechanical vibration.

Bananas are the highest volume fruit traded globally (FAO 2019) and are the most sold produce in Australian supermarkets (ABGC 2016). The most widely used packaging in the banana industry in Australia is the two-piece corrugated paperboard carton (Fig. 6.1) carrying six-clusters per layer with a net weight of 15 kg. However, previous studies have highlighted that the deterioration of quality of bananas in Australia, due to post-harvest damages during the distribution, amounts to millions of dollars per annum (Ekman et al. 2011; White, Gallegos & Hundloe 2011). There is a lack of research for minimizing mechanical damage in bananas caused by vibration although mechanical damage caused by vibration to other fruits has been extensively studied in literature (Barchi et al. 2002; Fernando et al. 2018a; Shahbazi et al. 2010). Nonetheless, field trials on the effectiveness of different packaging designs can be costly and complicated. Experimental validation of the protective performance of packaging on various fruits has therefore been assessed by simulated vibration.

Different novel packaging methods have been developed which claim to have better performance than the conventional two-piece corrugated package which is currently used in Australia (Ekman et al. 2011; Kitchener 2015). Re-usable plastic crates (RPC) have been increasingly considered in the recent years for the distribution of fresh produce (Accorsi et al. 2014) due to the potential cost-advantages gained by the reusability and the environmental friendliness compared to single use paperboard cartons. However, the use of RPC's has been restricted with industry concerns on how the rigid surfaces of the plastic crates might affect produce. The protective performance of RPC's during fruit distribution needs to be evaluated before they are considered as a feasible alternative for substituting single use corrugated cartons for a given fresh produce. Several previous studies using simulated vibration evaluated the protective performance of RPC's for different fruits such as mangoes and pineapples (Chonhenchob, Kamhangwong & Singh 2008b; Chonhenchob & Singh 2003a). However, there are lack of studies which evaluated the suitability of RPC's for the protective performance of bananas. Given that bananas are packed in clusters, unlike most other fruits, and are highly susceptible to mechanical damage, the behavior of bananas inside the RPC requires evaluation to determine their protective performance against vibration stresses.

Mechanical damage to fruits can be minimized with the use of improved inner packing and cushioning materials. Chonhenchob and Singh (2005) compared the effectiveness of two cushioning (inner packing) materials (i.e. foam nets and paper-based wrap) for the distribution of papaya fruit and concluded that both packing methods provided similar protection to the fruit. Bruising in apples, caused by impact during transport and handling, was shown to be reduced by plastic and paper-based protective wraps (Jarimopas et al. 2007). A similar study found that the foam-net and paper-wraps effectively reduced the vibration damage in apples (Eissa & Hafiz 2012). In another study, More et al. (2015) found that the use of foam sheets inside the corrugated package reduced mechanical damage to bananas. These studies reveal that the use of cushioning and inner packing material inside corrugated cartons were considered as an effective solution to minimize fruit damage caused by vibration in-transit. Therefore, the objectives of this study were to (1) compare the protective performance of different packaging alternatives for bananas and (2) to evaluate the effectiveness of vacuum tightening of banana clusters to reduce damage by simulated transport vibration.

6.1.2. **Materials and Methods**

6.1.2.1. Evaluation of Package Performance under Simulated Vibration

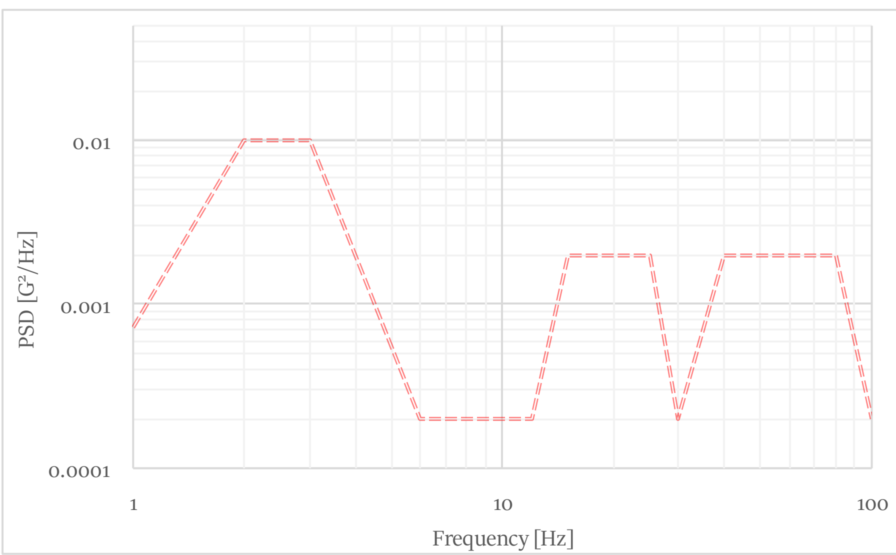
Different package types (Fig. 6.1) were subjected to simulated vibration generated by an electro-hydraulic simulation table and evaluated for the protective performance of bananas. A forty-eight (48) cartons of packaged bananas was pre-inspected for existing mechanical damage and damaged clusters were replaced with non-damaged clusters. All clusters were repacked into the three different package types (Table 6.1). Each corrugated carton was packed in three layers of banana clusters (Fig. 6.2), with a gross weight of 15.5-16.5 kg per package. For the RPCs the gross weight was 17-18 kg due to the higher tare weight of the crates compared to the corrugated cartons. As illustrated in Fig. 6.5, four columns with ten packages in each column (from each package type) were stacked on top of the vibration simulator table for the package testing experiments. The simulated vibration excitations were generated by a computer controlled electro-hydraulic vibration simulation table.

Figure 6.1: Different Packaging Types for Bananas (One-Piece Corrugated Carton\ Two-Piece Corrugated Carton\ RPC)

Table 6.1: Details of the Package Types

Package Type	Package Material	Package Design	Tare Weight	Inner Dimensions of the Tray (L x W x D) (mm)
Two-Piece	Corrugated	Telescope	1.0 kg	547 x 360 x 175
One-Piece	Corrugated	HSC*	0.9 kg	542 x 365 x 175
RPC†	Plastic	Tray	1.8 kg	553 x 357 x 203
*HSC – Half Slotted Container †RPC- Reusable Plastic Crate				

Figure 6.2: (Left) Spatial Arrangement of the Clusters in Three Layers (i.e. Layer 1,2,3) inside the Package (Right) Top-view of a One-piece Carton Packed with Three-layers of Bananas inside the Plastic Liner



Frequency (Hz)	Power (g²/Hz)
1	0.00072
2	0.01
3	0.01
6	0.0002
12	0.0002
15	0.002
25	0.002
30	0.0002
40	0.002
80	0.002
100	0.0002

Figure 6.3: Break-points of the PSD Profile used in the Simulation Tests

A power-spectral-density (PSD) profile (Fig.6.3) was developed based on the prior field data collected during the interstate transport of bananas from Tully in Queensland to Mulgrave in Victoria by road trucks with air-ride suspension. The PSD was used as an input spectrum to the simulator for the package simulation testing at an averaged acceleration intensity of 0.36g for three hours. The averaged vibration intensity of 0.36 g and three hours duration for the vibration treatment was derived experimentally by modelling the mechanical damage level in packaged bananas with respect to different vibration doses (Refer Section 5.2.3.2). Each experiment was repeated four times by replacing the packages in the bottom (1^{st} tier), middle (5^{th} tier) and top (10^{th} tier) positions in each column. After each experiment, the packages in the three replacing positions in each column were inspected for mechanical damage. The damage level in each sample package was quantified and converted to an index score for damage comparison as described in Section 6.1.2.3.

6.1.2.2. Evaluating the Effectiveness of Vacuum Tightening Banana Clusters

Fifteen sample banana packages were packed into two-piece cartons, each with a gross weight of 15.5-16.5 kg, and were pre-inspected for existing damage. Clusters with existing damage were replaced with non-damaged ones. Each two-piece corrugated carton was packed with 5-7 clusters per layer and each cluster was vacuum- tightened in a plastic bag (low-density polyethylene), using an industrial vacuuming machine (Make-Dewalt, Model- DXV53P). The vacuum-tightened clusters were twist-wrapped at the top, tightened with a sealing-adhesive-tape, and then packed into the corrugated carton in three-layers (Fig.6.4). The effectiveness of vacuum tightening was examined using a vibration simulator table where the sample packages were stacked in a single column. The sample cartons with vacuum-tightened clusters were stacked in a ten-tier column at the bottom (1^{st}), middle (5^{th}) and top (10^{th}) positions on the simulator table with others being standard two-piece cartons to fill the column (Fig.6.5). Each column of ten banana cartons was triple-stretch wrapped and was guided by fixed vertical steel columns to avoid collapsing and movements during the test. The cartons were subjected to simulated vibration with an overall RMS acceleration of 0.36 g for three hours using the PSD spectra given in Fig.6.3. Each test of vacuum-tightened banana clusters was repeated for four times. After each test run, the sample cartons were re-inspected for mechanical damage.

Figure 6.4: Individually Vacuum-tightened Clusters Packed in Three-layers inside the Corrugated Carton

Figure 6.5: (Left) Four-columns Stacked Vertically on the Simulator for Package Testing (Right) Single-column Stacked Vertically on the Simulator for Testing Cartons with Vacuum-tightened Clusters

In total these experiments in this study used over 900 kg of packaged bananas (60 cartons) inclusive of the additional bananas required for the replacement of damaged clusters prior to each experiment. However, due to resource restrictions, only the most bottom, middle and top-tier packages were evaluated for damages during the experiments.

6.1.2.3. Measurement of Damage

After each experiment, the damage level in each package stacked at the bottom (1^{st} tier), middle (5^{th} tier) and top (10^{th} tier) of the column were examined and the damage areas were estimated by a transparent damage area measurement sheet (Fig.6.6). The damage level was quantified using Eq. 6.1 to calculate the Mechanical Damage Index (MDI %) score for each sample package subjected to simulated vibration.

$$\text{MDI (\%)} = 0.1 \times \text{Trace Damages (\%)} + 0.2 \times \text{Slight Damages (\%)} + 0.7 \times \text{Moderate Damages (\%)} + 1.0 \times \text{Severe Damages (\%)} \quad \text{(Eq.6.1)}$$

(Damage Area (A) $\geq 3\ cm^2$ – Severe; $2\ cm^2 \leq A < 3\ cm^2$ – Moderate; $1\ cm^2 \leq A < 2\ cm^2$ – Slight; $0.5\ cm^2 \leq A < 1\ cm^2$ - Trace)

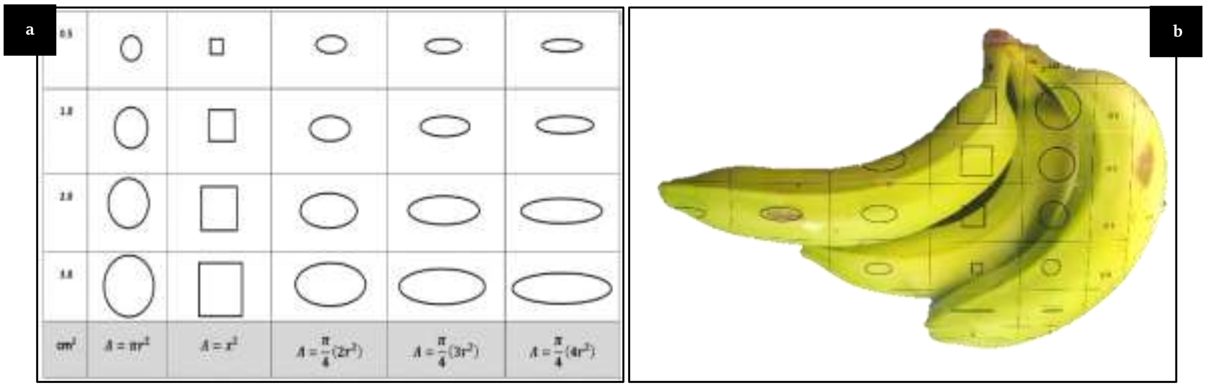


Figure 6.6: (a) Transparent Damage Measurement Sheet (b) Estimation of damage area by the Transparent Measurement Sheet

6.1.2.4. Vibration Transmissibility and Data Analysis

To understand the vibration characteristics and transmissibility in each package, accelerometer data loggers were placed in the top (10st tier), middle (5th tier) and bottom (1st tier) position packages. Four piezo-electric Slam Stick accelerometers (MIDE Technology Inc., Massachusetts, USA) were used with three of the accelerometer devices inside the three sample packages and one device attached to the simulator table. The accelerometer data were acquired by Slam Stick Labs software (ver. 1.6) and analyzed by the signal processing toolbox in Matlab 2015a software (Mathworks, Natick, MA, USA). Time-series data were converted to the frequency domain by Fast-Fourier-Transform (FFT) (Smith 1997) and the PSD profiles were generated for each of the sample packages/positions of the stacked column. The transmissibility was defined by the ratio of the response amplitude to the excitation between two measured vibration signals (Kim et al. 2013). The transmissibility of vibration was calculated using Eq. 6.2 as the ratio between the input (Table- A_o) and the output (Package- A_i) acceleration (Fadiji, Coetzee, Chen, et al. 2016; Vursavus & Ozguven 2004).

$$\text{Transmissibility (T)} = A_o / A_i \qquad \text{(Eq.6.2)}$$

6.1.3. **Results and Discussion**

6.1.3.1. Comparison of the Protective Performance of Packaging

The cosmetic damage levels that occurred in packaged bananas in different types of packaging under simulated vibration treatments are summarized in Fig. 6.8. For all stacked positions (i.e. bottom, middle and top tiers), the highest level of damage occurred in RPCs, followed by the two-piece cartons and the least damage occurred in the one-piece cartons. The damage level in the top-position was significantly higher ($P<0.05$) in RPCs and moderately higher ($P>0.05$) in the one-piece cartons compared to the two-piece cartons. In the bottom-position, the damage level was significantly higher ($P<0.05$) in RPCs compared to both types of corrugated cartons. A similar damage level was observed in both corrugated cartons in the middle position. However, the RPCs showed a significantly higher damage ($P<0.05$) similar to thos e observed in the top and bottom positions.

The damage to bananas in each type of packaging was influenced by the energy of the vibration transmitted through the stacked column. For all package types, the top tier packages resulted in the greatest vibration damage and exhibited increased vibration energy around the resonance frequency. The first resonance peak with the highest transmissiblity occurred between 8-13 Hz in all package types (Fig.6.9 and Fig.6.10). When the magnitude of the transmissibilty (T) curve was above one ($T>1$), it indicated an amplification of the input vibration levels and a magnitude between zero to one ($0<T<1$) showed an attenuation of the vibration from the simulator table. In the latter case, when the meassured transmissibility of a package was less than one, within a specific frequency range the package tended to behave as a vibration damper (Paternoster, Van Camp, et al. 2017). Several previous studies confirmed that the vibration damage in fruits was greatest in the topmost package of a stack and that the higher transmissibility of vibration was associated with incr eased fruit damage (Fadiji, Coetzee, Chen, et al. 2016; Fischer et al. 1992; Jarimopas, Singh & Saengnil 2005). Fischer et al. (1992) found that the greatest damage in apples occurred in the topmost container in the frequency range of 5-10 Hz and Jarimopas, Singh and Saengnil (2005) concluded in their study that the damage to tangerines was largest in the topmost container for every combination of road, truck type and travelling speed. Similarly, Barchi et al. (2002) showed that the highest acceleration occurred in the top crate packed with loquats which exhibited a resonance peak at 9 Hz. Vursavus and Ozguven (2004) also reported that the most critical frequencies for packaged apples occurred in the frequency range of 3 to 15 Hz with the highest transmissibility revealed in the frequency range of 8-9 Hz. These studies correspond with the findings of this study where the highest damage occurred in the top most package for all package types.

During the simulation test, relatively greater ($P>0.05$) damage levels occurred in the two-piece carton in the top-tier packages compared to the one-piece carton. The two-piece carton exhibited the highest vibration transmissibility ($T\sim3.5$) at the principle resonance frequency and had a relatively ($P>0.05$) higher damage level than the one-piece carton. In both types of corrugated packages, maximum transmissibility (in the top-tiers) occurred around 7-10 Hz. When the resonance of a stacked column of packages corresponds with the excitation frequency, the fruits can vibrate with an amplified energy resulting in severe fruit damage (Fadiji, Coetzee, Chen, et al. 2016). In this study, an increased transmissibility of vibration in the top-tiers around the resonance frequencies was also associated with escalated damage levels in packaged bananas. The design of paperboard cartons should therefore also consider vibration transmissibility as a factor, and in this study one-piece corrugated paperboard cartons showed less vibration transmission and better performance than two-piece cartons around the resonance frequencies. However, the greatest damaged occurred in the top-tiers of RPC's despite the relatively lower transmissibility (T~2.5) of vibration at the principle resonance peak (12-13 Hz) compared to the two-piece carton. Compared to the corrugated cartons, RPC exhibited six times more damage in the top-tiers and nearly four times more in the bottom tiers and therefore, showed the worst protective performance for bananas. This can be attributed to the construction properties of RPCs and the vibration transmissibility characteristics in the mid-frequency range (15-30 Hz) compared to the corrugated paperboard cartons. In RPCs, the attenuation of vibration (T<1) in the middle and top packages occurred around 25 Hz, and the dampening of vibration in the mid frequency range (15-30 Hz) was not as effective as the corrugated cartons (Fig.6.10). The most critical reason for the escalated damage level in RPCs was severe abrasion injuries of the clusters in the top two layers inside each package by rubbing against the side walls of the rigid crates (Fig. 6.7). This emphasizes that, not only vibration transmissibility characteristics, but also the construction of the package critically influences the level of mechanical damage to bananas.

For all package types, the greater susceptibility of damage to bananas in the top two layers of fruit inside the packages indicated that the freedom of movement of fruits further affected the damage levels. Inter-locking of banana clusters in the bottom tiers, by the weight of the clusters on the top two layers, restricts their relative movement. A previously study on packaged bananas also reported that a reduced level of vibration damage occurred in the most-bottom layers of fruit inside the package (Ekman et al. 2011). Other studies on a variety of fruits have also reported that the greatest damage in fruits was frequently localized in the top layer of fruits inside the package (Fadiji, Coetzee, Chen, et al. 2016; Shahbazi et al. 2010; Soleimani & Ahmadi 2014). Restricting the movement of fruit in the topmost layers of a package should therefore be addressed to minimize damage due to vibration transmission during transport.

In one-piece cartons, the bottom tier vibration closely corresponded with the input vibration spectrum of the simulator table, although the vibration was dampened after 13 Hz in both middle and top tier packages (Fig.6.9). The two-piece cartons exhibited similar vibration transmissibility at the bottom tier across the frequency spectrum but vibration was attenuated in the middle and top tier after 15Hz. Soft bananas inside the packages may absorb the vibration energy from the bottom to top of the stack. High frequency vibration absorbed by fruits (i.e. bananas) from the bottom to top of the stacked column resulted in the diminishing damage levels up the column with the least damage revealed in the middle tiers. However, due to the occurrence of resonance, the vibration level and the corresponding damage caused by the unrestricted movement of bananas was increased in the most top-tiers. Despite the restriction of movement, the bottom tiers exhibited a moderate level of damage. This can be attributed to the transmission of high-frequency vibration (>30Hz) as shown in Fig.6.9 in all types of packaging. Therefore, it can be established that the occurrence of damage in the bottom tiers of bananas was attributable to the transmission of high frequency vibration and the excessive damage in the top-tiers was caused by the unrestricted vibration of bananas around the resonance frequencies (8-13 Hz) of the stack.

Figure 6.7: (a) Severe damage caused by rubbing of the clusters in the top layer against the rigid side-walls inside the top-tier RPC (b) Fruit-rub/ scuffing damages occurred in the top-tier one-piece and (c) two-piece cartons

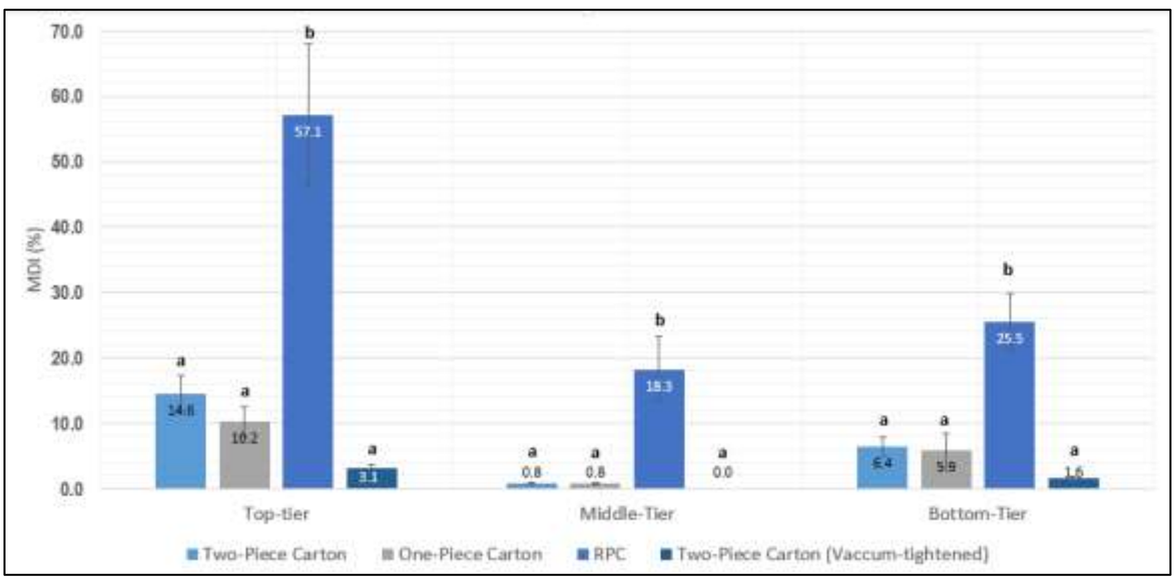
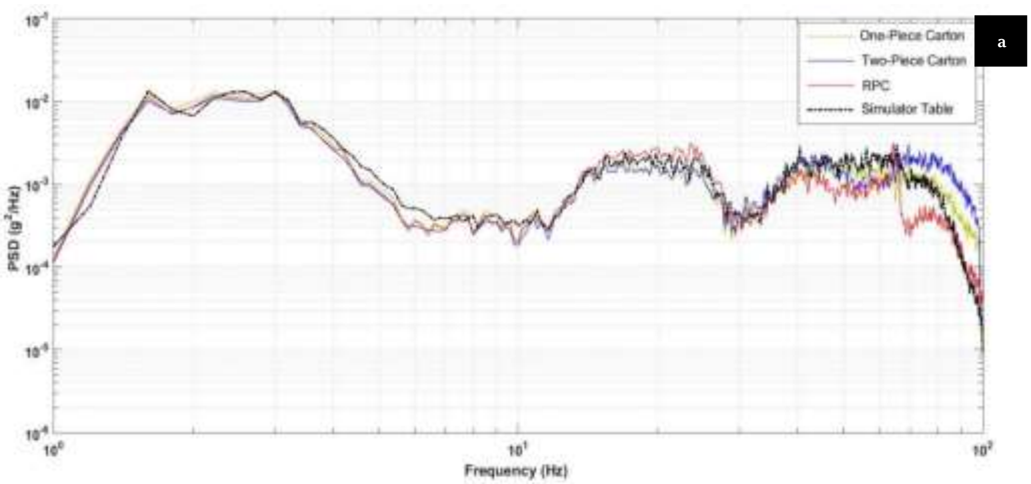


Figure 6.8: MDI (%) in each Package Subjected to Simulated Vibration Treatment [Different characters indicate significantly different results ($P<0.05$) in each package tier]

6.1.3.2. Effect of vacuum tightening of clusters inside the carton

Restricting the movement of fruit inside the packages effectively reduced the level of damage in bananas. It was found that vacuum tightening of clusters reduced the fruit rub and scuffing in bananas compared to the control in the two-piece cartons. The abrasion damages caused by vibration were reduced by 79 % in the top-tier packages and by 75 % for the bottom tier packages (Fig.6.8). This can be attributed to the increased fill-tightness between the banana fingers, which effectively reduced the relative motions causing frictional damage between the fingers (fruit-rub). A previous study found that fill-tightness inside the containers significantly influenced the mechanical damage level in pears caused by vibration (Slaughter, Hinsch & Thompson 1993). Vacuum tightening of individual clusters therefore increased the fill-tightness of bananas inside the package and reduced abrasion damage. The plastic bag used for the vacuum tightening of individual clusters may also act as a protective wrap around the clusters to reduce the rubbing between the clusters caused by relative movement. This also is in agreement with the studies of Jarimopas et al. (2007) and Eissa and Hafiz (2012) in which both plastic and paper-based protective wraps were found to be effective in providing protection against bruising in apples packed in corrugated cartons.

In this study, a vacuuming machine was used to manually tighten the individual banana clusters inside the plastic bags. However, the vacuum-tightened clusters were tied-off to retain the tension but not sealed. Therefore, air-leaking inside the plastic bags can cause the clusters to eventually lose the tightening over a period. Vacuum-packing banana clusters inside air-sealed plastic bags can also cause the fruits to experience anaerobic respiration. For industrial applications the tensioned plastic bags or wraps restraining cluster movement could be perforated to prevent anaerobic respiration. However, further research is needed on different mechanism of tightening the fruits inside plastic bags to make it a viable industrial application.



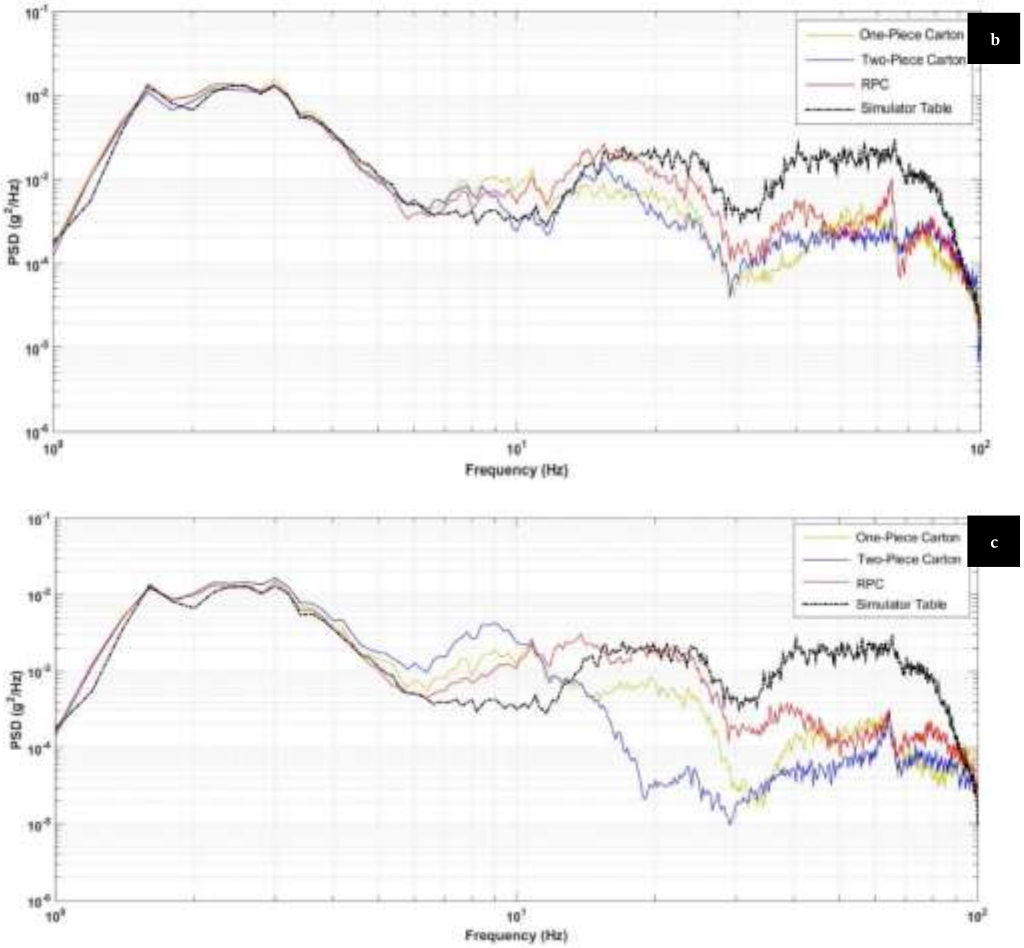
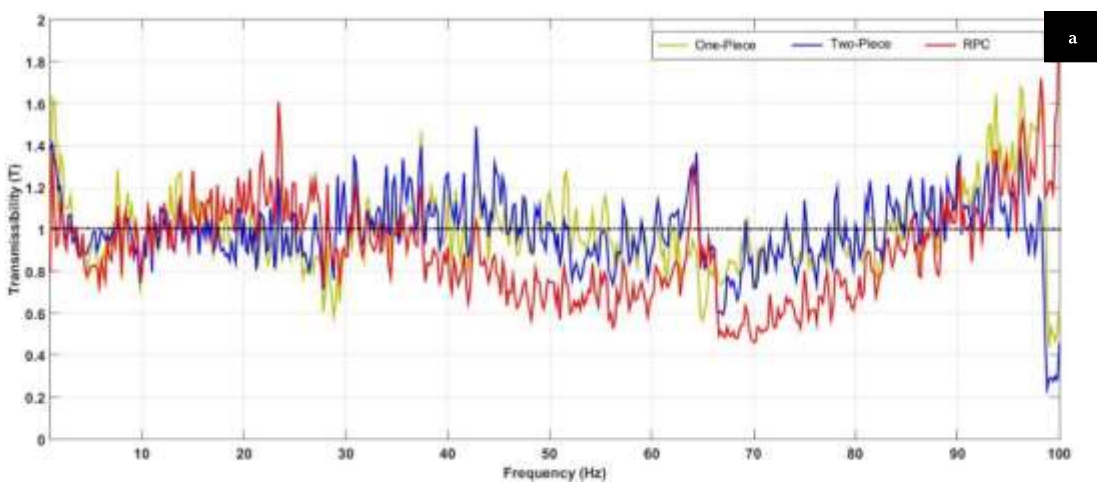


Figure 6.9: Comparison of the PSD Curves in the (a) Bottom (b) Middle and (c) Top Positions for Different Package Types



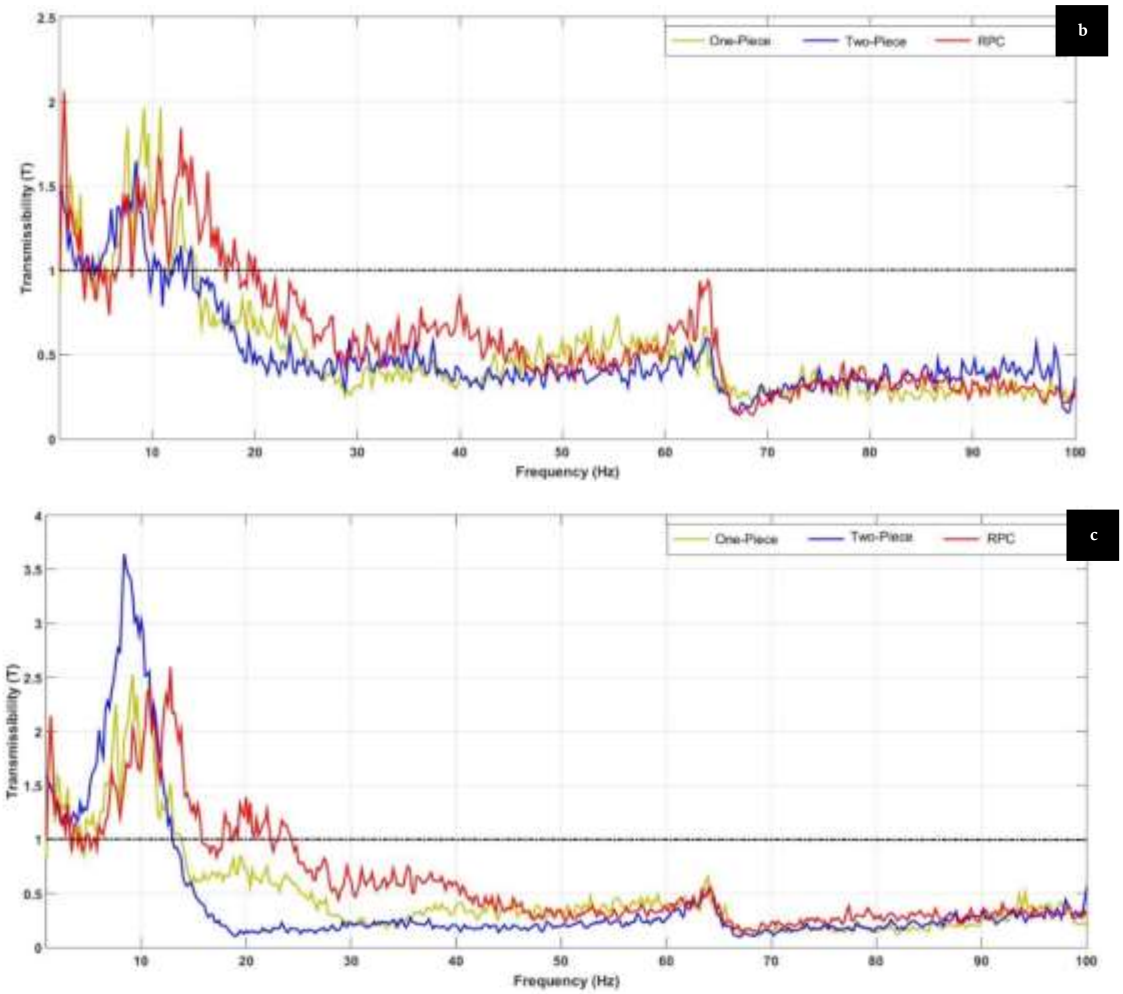


Figure 6.10: Vibration Transmissibility in the (a) Bottom, (b) Middle and (c) Top Positions

6.1.4. **Conclusion**

This study evaluated the effectiveness of three packaging types for the protective performance of bananas under simulated transport vibration and the effectiveness of vacuum tightening individual banana clusters to minimize damage caused by vibration. The results show that the mechanical damage to bananas was affected by the vibration transmissibility of the column, the freedom of movement of fruits, the dampening properties of the packaging, and the construction material of packaging. The bruising of the banana clusters in the top-tiers against the rigid sidewalls of RPCs has caused a multifold increase in damage compared to the two-piece corrugated cartons, emphasizing the need for non-rigid packaging material to pack soft fruits such as bananas. Based on the overall protective performance, the one-piece corrugated cartons performed the best in reducing the damage levels in bananas caused by in-transit vibration and thus, can be recommended for the interstate transport of bananas in Australia. The freedom of movement of fruits in packages was effectively restricted by vacuum tightening of banana clusters and reducing damage levels. However, further research is warranted to confirm that the clusters can be effectively tightened by using vacuum assisted packing or tensioned plastic wrapping for the long interstate transport. The effectiveness of micro-proliferated plastic bags can be investigated for their capability for further tightening the clusters with vacuuming, while facilitating a reasonable level of respiration for the fruits to avoid anaerobic respiration of bananas in-transit.

PART B

Evaluation of Packaging for the Distribution of Ripe Bananas in Consolidated Pallets by Simulated Vibration

Abstract

Mechanical damage is a prominent cause of fruit quality deterioration and wastage during distribution. Consolidation of different packaged fruits into pallets is used at the distribution centers (DC) to dispatch appropriate produce combinations to retail stores. Different stacking arrangements can affect the stability and the transmission of forces such as vibration and compression to the stacked packages in the pallet. The use of mixed packaging types, such as corrugated paperboard cartons mixed together with reusable plastic crates (RPC), may also result in increased risk for mechanical damage in packaged fruits due to miss-matching of package stacking properties. Therefore, this study used a four-tier prototypical consolidated pallet subjected to simulated transport vibration in a temperature-controlled environment to evaluate the influence of package height, position, and type on the development of mechanical damage in packaged bananas. The compression strength and base-sagging levels in different package types under high relative humidity (RH) ripening conditions were experimentally tested. Fruit packed in RPC showed the highest level of damage (3.5%) followed by the two-piece paperboard carton (3.3%) and the one-piece paperboard carton (2.5%). The structural integrity of the corrugated cartons was weakened, and the sagging levels were exacerbated due to the moisture absorption in the high RH environment. This loss of structural integrity and base-sagging was observed to be associated with mechanical damage in packaged bananas. The one-piece carton exhibited a higher compression strength and limited base-sagging levels under high RH conditions compared to the two-piece carton. Furthermore, column stacking of packages in the consolidated pallet, instead of flat-tier stacking, was shown to reduce overall damage in bananas. It was therefore found that, the column-stacked one-piece corrugated carton can be considered as a better packaging alternative to minimize fruit damage in consolidated pallets, compared to the widely used two-piece carton or RPCs for the distribution of bananas in Australia.

Key Words: Packaging, Post-harvest, Supply Chain, Fruit, Quality, Simulation

6.2. Evaluation of Packaging for the Distribution of Ripe Bananas in Consolidated Pallets by Simulated Vibration

6.2.1. Introduction

Fresh produce are vulnerable to diverse logistical risks (Ali, Nagalingam & Gurd 2018), resulting in produce contamination, reduced quality and shelf-life along post-harvest supply chains (SC). Bruising due to impact or compression, and abrasion injuries caused by friction, have been identified as the key causes of damage in fresh fruits (Li & Thomas 2014; Opara & Pathare 2014). Modern fruit SCs use corrugated paperboard cartons for storage and transport of produce from farm-gate to retail market. With increasing emphasis on environmental sustainability and costs of packaging, reusable plastic crates (RPC) have been introduced into fruit distribution systems (Accorsi et al. 2014). Despite efforts in improving packaging, products are still exposed to hazards during transport and handling that result mechanical damage to fruits (Fernando et al. 2018a; Slaughter, Thompson & Hinsch 1998).

Banana is one of the major internationally traded fruits and also the most sold fresh produce by volume in Australian supermarkets (ABGC 2016; FAO 2019). Packaged bananas can be highly susceptible to cosmetic damage along the SC (Ekman et al. 2011; Macheka et al. 2013; Wasala et al. 2014). The damage susceptibility of bananas increases with the degree of ripening and maturity level (Banks & Joseph 1991; Yuwana 1997). Visual damage in bananas can be categorized into bruising, neck injuries and abrasion caused by scuffing and rubbing (i.e. blackened rubs and fruit rubs) (Fig. 6.11). Mechanical damage in bananas can be influenced by the position of the package in a stacked pallet, the position of the cluster of bananas inside the package and the stacking arrangement of packages on a pallet (Ekman et al. 2011; Fernando, Fei & Stanley 2019). In addition, strength and integrity of packaging can be important for protecting delicate fruits such as bananas during the distribution.

The supply chains of most produce, including bananas, generally includes arrival at a centralized distribution centre (DC) in major metropolitan areas. The DCs are where different types of produce are temporarily stored, and then consolidated into required mixed types and quantities for dispatch to respective retail stores within the area. The demand for bananas in each retail store is usually less than a full-pallet load (i.e. 60 packages). Therefore, partial pallet loads need to be arranged. However, to utilise the space during transport, a partial pallet load of banana packages often consolidated with other different produce packages for delivery to retail stores. The consolidation process may require different produce packages being mixed onto a single ‘consolidated pallet’. The greater demand for bananas, compared to other produce, often results in banana cartons being stacked in the bottom or lower tier(s) of the consolidated pallets to stabilize the pallet. A consolidated pallet is often stacked with different types of packages with different dimensions, including RPCs. Stacking rigid RPCs on top of the corrugated cartons can potentially result in excessive mechanical stresses to fruits stacked below. For ripe bananas, further damage may be caused by the transmission of vibration stresses during the distribution process to retail stores.

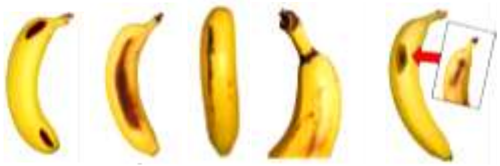


Figure 6.11: Different Types of Mechanical Damages in Bananas (Left to Right: Fruit-rub/Scuffing/ Blacked Rub, Neck-breaks and Bruising) (Ekman et al. 2011)

Exposure to vibration during transport is a well-known cause for fruit damage in post-harvest SCs. The development of mechanical damage during road transport of a variety fruits, such as apples, pears and strawberries, has been extensively studied (Nakamura et al. 2015; Slaughter, Thompson & Hinsch 1998; Soleimani & Ahmadi 2015). The type of packaging was an influential factor in reducing damage in fruits (Chonhenchob, Kamhangwong & Singh 2008b; Chonhenchob & Singh 2003a, 2005b; Fadiji, Coetzee, Chen, et al. 2016) and therefore, improvements to packaging have been widely researched to minimizing fruit damage. However, the occurrence of mechanical damage in fruits within consolidated pallets during distribution has not been previously studied or well understood.

The strength of a corrugated carton is an important determinant of the protection provided by a package to its contents (Pålsson & Hellström 2016). The structural integrity of the corrugated paperboard cartons can be significantly compromised by the humidity. Bananas are ripened in sealed temperature-controlled ripening chambers with over 90% of relative humidity (RH). A corrugated paperboard carton held at 90% RH equilibrium for a short exposure period may lose up to 60% of its original strength (Vigneault et al. 2009). Package failure during distribution can result in top-load compression on fruits causing compression bruising. Corrugated packages also exhibit base sagging (Niskanen 2012) due to the concentration of weight at the centre of the package. Base-sagging can be worsened after excessive moisture absorption of the paperboard cartons during the ripening. Increased base-sagging can result in rubbing damages in bananas due to the bruising of the base of the carton against the top-layers of fruit stacked in the packages underneath. Bananas also have increased damage susceptibility after the ripening (Bugaud et al. 2014; Yuwana 1997). It is therefore important to maintain the strength and structural integrity of the package, especially in the latter part of the produce SCs.

The final stages of distribution, towards point of sale or the consumer, is identified as the 'last-mile' of a SC. The last-mile distribution is usually regarded as one of the most critical, and expensive 'legs' in a post-harvest SC (Hsiao et al. 2018). The exposure of produce to mechanical stresses during this "last-mile" of the SC needs to consider the stacking dynamics of the consolidated pallets and the hazardous vibration excitation in-transit. Quality deterioration of bananas in the final stage of the SC can be substantial. Packaging for bananas need to maintain a reasonable structural integrity after the exposure to highly humid ripening conditions. Therefore, this study aimed to: (1) examine how the mechanical damage levels in packaged bananas are affected by stacking positions on a consolidated pallet subjected to simulated transport vibration, (2) determine the effect of highly- humid ripening conditions on the structural integrity of corrugated cartons; and (3) recommend the most effective packaging type for reducing mechanical damages to ripe bananas during the last-mile distribution.

6.2.2. Materials and Methods

6.2.2.1. Measurement of Vibration and Analysis

Simulation of road transport vibration can be performed by using existing simulation standards such as American Society of Testing and Materials (ASTM 2016b). However for a more realistic simulation, vibration levels in the actual transport environment need to be characterized and replicated (Fernando et al. 2018a). For this purpose, vibration data during the actual field transport of a semi-truck was recorded. A semi-trailer truck (*Mercedes Benz Actros* 2644) with air-ride suspension was used to collect the field vibration data during the distribution of palletised banana cartons. The temperature-controlled truck (13-15 °C) was fully loaded with 20 consolidated pallets containing different packaged produce.

A piezoelectric accelerometer data logger device (Slam Stick Logger MIDE Technology Inc., Massachusetts, USA) was placed in the rear-position of the semi-truck (attached to the pallet base) to measure the vibration during the transit from the DC to the retail store (Fig. 6.12). The accelerometer had a range of ±25 g and was configured for sampling at 400 Hz. A GPS data logger was placed in the cabin of the truck to capture the transport route from the DC to retail store. The transport route from the DC (East-Melbourne, Australia) to the retail store (West-Melbourne) via the Monash Freeway is given in Fig.6.12. Monash freeway is an A-grade bitumen sealed triple-lane highway spanning from east to west of Melbourne.

The captured time-series accelerometer data were analysed by the SlamStick Labs software (ver1.6) and converted to the frequency domain by the Fast-Fourier-Transform (FFT) (Smith 1997), using the Matlab signal processing toolbox (Simulink, Massachusetts ,USA). The post-processing of time-series data in the frequency domain generated the averaged power spectral density (PSD) plot for the truck journey. PSD plots indicate the concentration of vibration energy across a spectrum of frequencies. This contributes to understand in which frequencies the vibration energy is concentrated in and also provides a better characterization of the real distribution environment. The PSD based on field data was used to perform laboratory based vibration simulation experiments (Fernando, Fei & Stanley 2019; Fernando et al. 2018a).

Figure 6.12: Transport Route, Truck and the Accelerometer Device

6.2.2.2. Fruit Samples, Conditioning and Stacking of Packages

Forty-eight packages (gross-weight of 15.5-16.5 kg) of ripe bananas were used for package testing experiments. The packages were transferred to the nearby testing facility (< 5 km) in a temperature-controlled truck (13-15 °C) immediately after the ripening process. Bananas (c.v *Cavendish*) in the sample cartons were extra-large (‘*premium*’) category (length: 200-260mm; girth 30-40 mm) and were ripened to stage six (All yellow; light-green necks; no green tips) as per the visual ripeness chart (Ekman et al. 2011) used in the Australian banana industry. All clusters were inspected for existing cosmetic damages at the testing laboratory and the clusters with minor existing damages were photographed and marked with a sticker. The clusters with severe damages were replaced during the pre-experimental inspection.

Figure 6.13: Different Packaging Types for Bananas – RPC (left)\One-Piece Corrugated Carton (middle)\ Two-Piece Corrugated Carton (right)

Figure 6.14: Bananas Packed in Three Layers inside the RPC with the use of Plastic Liner

All inspected banana clusters were re-packed into three different package types (Fig. 6.13) and the details of the package types are provided in Table 6.2. The gross weight of the corrugated packages ranged from 15.5-16.5 kg and the RPCs ranged from 17.0-18.0 kg. The RPCs had an increased gross weight due to the higher tare weight than that of the corrugated cartons. All banana clusters were packed in three layers inside the package in "hands down" orientation and covered with a plastic liner bag and a liner between the bottom and top two layers (Fig. 6.14). The inspected banana packages were arranged in 'L' shape on a wooden pallet (Fig. 6.15). The rest of the empty spaces on the pallet were filled with re-usable plastic crates (RPC) each with an equal weight of bananas up to a height of four tiers. This pallet arrangement was used to (1) examine the differences in mechanical damage between the flat-stacking and column stacking of banana packages; and (2) to build a model of a consolidated pallet for simulation that resembles the actual stacking during the distribution of bananas from DC to retail stores.

6.2.2.3. Vibration Simulation Experiment

The consolidated pallet of bananas was triple wrapped with stretch film, in a manner similar to the actual industrial dispatch conditions, and stacked on a computer controlled electro- hydraulic vibration simulator (Fig. 6.15). The pallet was guided and kept in place by the vertical steel column fixtures to avoid sliding movement during the test. The consolidated pallet was subjected to 0.24 g root-mean-square (RMS) acceleration for two hours. The test used a custom-made vibration profile (Table 6.5) that was developed based on the field data collected during the transit (Fig. 6.18) which is further discussed in Section 6.2.3.1. The averaged vibration intensity during the field transport was 0.082 g.

However, previous studies showed that testing at the averaged acceleration intensity of the journey would result in an under-test during the transport vibration simulation experiments (Griffiths 2011; Griffiths et al. 2013; Shires 2011). Therefore, the vibration intensity was increased during the simulation and the duration of the test was determined in correspondence with the maximum duration of transport of ripe bananas to the furthest suburbs of Melbourne, covered by the central DC. Each test was conducted in quadruplicate and all experiments were performed in a temperature controlled (13-15 °C) enclosed simulation environment. The vibration simulation chamber had no mechanism to control the humidity level however, it can be expected that the effect of variations in humidity during the short duration simulation testing (<2 hours) was negligible.

To measure the vibration transmissibility characteristics in each package, six accelerometer devices (Slam Stick Logger- MIDE Technology Inc., Massachusetts, USA) were placed inside packages stacked in the bottom tier (POS 3) and third tier (POS 1) and an additional accelerometer device was placed on the simulator table (Fig.6.15). The acceleration data in each of these devices were analysed in the frequency domain to develop the PSD profiles using the same transformation (FFT) method described in Section 6.2.2.1. Vibration transmissibility was calculated as the ratio between the input (table), A_E and excited (output) acceleration A_T by Eq. 6.3 (Vursavus & Ozguven 2004).

$$\text{Transmissiblity } (T) = {A_E}/{A_T} \qquad \text{(Eq.6.3)}$$

T- Transmissibility Ratio; A_E – Acceleration on the Package A_T- Acceleration on the Simulator Table

Figure 6.15: The Model Consolidated-Pallet on the Vibration Simulation Table

Table 6.2: Package Types Evaluated in the Simulation Testing

Package Type	Package Material	Package Design	Tare Weight	Inner Dimensions of the Tray
Two-Piece	Corrugated	Telescope	1.0 kg	547 x 360 x 175 (L x W x D) (mm)
One-Piece	Corrugated	HSC*	0.9 kg	542 x 365 x 175 (L x W x D) (mm)
RPC†	Plastic	Tray	1.8 kg	553 x 357 x 203 (L x W x D) (mm)
*HSC – Half Slotted Container †RPC- Reusable Plastic Crate				

6.2.2.4.Measurement and Analysis of Damage

The mechanical damage level in bananas in each package was assessed 24 hours after the experiment (stored at 13-15°C). A transparent damage area measurement sheet was used to objectively measure the damage area in each banana cluster (Fernando, Fei & Stanley 2019). A Mechanical Damage Index (MDI) score for each package was calculated (Eq.6.4) for damage comparison, similarly to the Equivalent Bruise Index (EBI) (Vursavus & Ozguven 2004). The difference in MDI scores was calculated by Eq. 6.5 to derive the increment of mechanical damage (Δ MDI).

MDI (%) = 0.1 x Trace Damages (%) + 0.2 x Slight Damages (%) + 0.7 x Moderate Damages (%) + 1.0 x Severe Damages (%) (Eq.6.4)

(Damage Area (A) ≥3 cm² – Severe; 2 cm²≤A<3 cm² – Moderate; 1 cm²≤A<2 cm² – Slight; 0.5 cm²≤A<1 cm² - Trace)

Δ MDI (%) = MDI_A (%) - MDI_B (%) (Eq.6.5)

(MDI_A \ MDI_B – Damage level after \ before the simulated vibration treatment)

The MDI scores for each type of banana package were analysed for statistical significance with one-way ANOVA and Turkey's Honest Significance Difference (HSD) Tests using the GraphPad® Prism 8 statistical analysis package (GraphPad® Software, San Diego, CA, USA).

6.2.2.5.Properties of Corrugated Cartons

The paperboard specifications of the two types of double-wall corrugated packaging (i.e. One-piece carton and two-piece carton) are given in Table 6.3. In each double-wall corrugated carton, the sandwich structure (Fig.6.16) consists of three liners and two corrugated mediums. The liners are manufactured with Kraft paper or recycled paper. The corrugated medium of each package is produced with recycled paper material.

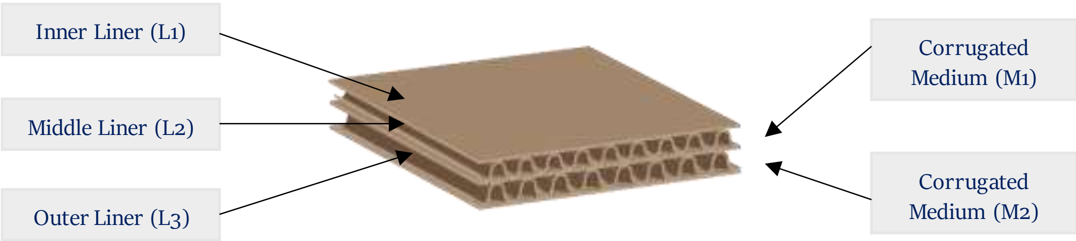


Figure 6.16: Sandwich Structure of the Corrugated Paperboard

Table 6.3: Grammage (g/m2) and Specifications of Paperboard Components in Corrugated Packaging

Package	One-Piece Carton	Two-Piece Carton	
	Tray	Lid	Tray
Total Grammage	999	611	938
Inner Liner (L1)	230 PL-KLR	186 RL	190 KLR
Corrugated Medium (M1)	RM (Flute E)	RM (Flute C)	RM (Flute E)
Middle Liner (L2)	192 KLR	-	179 RL
Corrugated Medium (M2)	RM (Flute B)	-	RM (Flute B)
Outer Liner (L3)	188 WT-RL	213 WT-KLR	195 KLR
* PL- Poly-Laminated; KL- Kraft Liner; KLR – KL with Recycled Fibre in Back Plies; RL –Recycled Liner; WT- White Top; RM- Recycled Medium			

6.2.2.6.Testing for Structural Integrity and Base Sagging

The three package types (Fig.6.13) were subjected to compression resistance testing and base-sag testing under ambient and simulated ripening conditions. For the pre-test conditioning, three corrugated cartons from each type and RPCs were stored in ambient conditions at 23 °C and 50 -60% RH for 120 hours. To determine the effect of the ripening conditions on the structural integrity of the corrugated cartons, another set of three cartons from each type were stored in simulated ripening conditions at 15 °C and 90-95% RH for 120 hours. The conditioning period of 120 hours was determined with respect to the ripening duration for packaged bananas which can range from 4-5 days depending on the desired level of ripeness. After the storage period, the moisture content of paperboard samples of each packaging type was measured using the method 1301-457s of AS/NZ standard (Aus-Std. 2006). For the compression strength testing, RPCs were only conditioned in ambient conditions as the construction material of the crates (i.e. plastic) is resistant to moisture absorption.

The pre-conditioned packages were subjected to top-load compression generated by a compression testing machine (Instron Model 1185) with a pre-load of 222 N. The moving platen of the tester was configured at 12.7 ± 2.5 mm/min and the packages were compressed until the failure point of each package was reached. The failure point of each package was determined by the load-deflection curve generated during the experiment. The compression resistance test for each package type was conducted in triplicates.

For the base-sag testing, packages from each type were stacked with 15 kg of dummy iron weights which were placed at the base of each package, filled up with solid rubber balls (Fig. 6.17) and the experiment was conducted in duplicates. The weights were evenly distributed in the base of each package and a vertical depth measurement gauge (mm/cm) was placed at the centre of the package to measure the level of base-sagging. Two sets of packages from each package type was stored under the ambient conditions (23 ±3 °C, 50-60% RH) and simulated ripening conditions (13± 3°C, 90% RH) for 120 hours. The base-sag measurements in each package were taken continuously for 14 days from the test date as per the measurement schedule given in Table 6.4.

Table 6.4: Base-sagging Measurement Schedule

Measurement	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th
Time	T*	T+ 5m	T+ 1h	T+ 2h	T+ 4h	T+ 24h	T+ 36h	T+ 2d	T+ 3d	T+ 5d	T+ 7d	T+ 12d	T+ 14d
***T- Time of the measurement in empty carton\packaging; m- minutes; h- hours; d- days**													

Figure 6.17- Testing for Base-sagging in Two-piece Carton filled with 15 kg Iron Weights and Solid Rubber Balls

6.2.3. **Results and Discussion**

6.2.3.1. Measurement and Analysis of Vibration

A segment of the acceleration-time data recorded during the actual distribution and the corresponding PSD is given in Fig.6.18. The root means square (RMS) acceleration for the semi-truck was 0.082 g, which corresponds to the area under the PSD curve during the field transport. RMS acceleration can be influenced by the road-vehicle-load interaction which cause the truck floor excitation and the energy transferred onto the pallets stacked on the floor can result in mechanical damage in packaged produce (Fernando, Fei & Stanley 2019; Fernando et al. 2018a). The findings of this study are in agreement with previous studies on the transport vibration levels for semi-trailer trucks with air-ride suspension (Garcia-Romeu-Martinez, Singh & Cloquell-Ballester 2008; Paternoster et al. 2018). The shape of a PSD curve can be influenced by the characteristics of the transport vehicle (i.e. semi-truck). In this study, the PSD peak with the highest vibration energy was exhibited in the lower frequency range at 1.6 Hz. This is in reasonably in agreement with previous studies that revealed analogues results showing that the PSD peaks for road truck transport were concentrated in the lower frequency range (Jarimopas, Singh & Saengnil 2005; Soleimani & Ahmadi 2015). A secondary peak was revealed between 15-20 Hz, which is in agreement with Slaughter, Thompson and Hinsch (1998). A narrow band spectral peak was revealed at 42-44 Hz in the refrigerated semi-trailer which could be generated by the vibration of the refrigeration (cooler) unit at a 2400-2600 RPM (Rotations-per-minute).

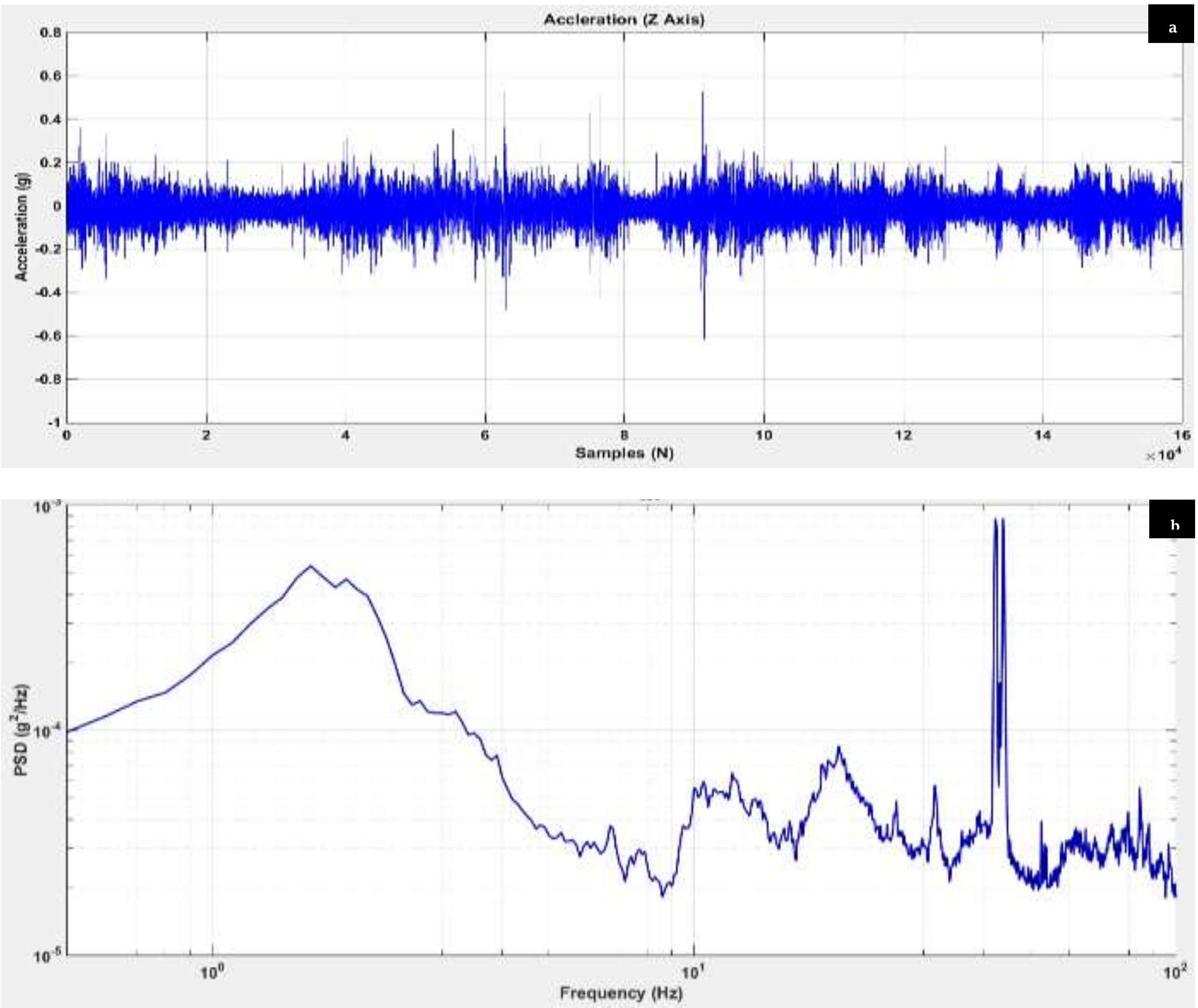


Figure 6.18: (a) A Segment of Time-history Acceleration and (b) the Averaged PSD Profile during the Actual Road Transport

Table 6.5: Break-points of the PSD Profile used for Simulation

F(Hz)	INTENSITY (g^2/Hz)	F(Hz)	INTENSITY (g^2/Hz)
1 Hz	0.0001	16 Hz	0.001
2 Hz	0.01	25 Hz	0.001
3 Hz	0.01	30 Hz	0.0001
6 Hz	0.0001	100 Hz	0.00004
12 Hz	0.0001		

6.2.3.2. Damage in Packaged Bananas caused by Simulated Vibration

The averaged mechanical damage increment (Δ MDI %) of different damage types in bananas was different for each package position (Table 6.6). Each sample package was also evaluated for physical damage after the simulated vibration test. No significant damage or deformation was observed. The mechanical damage in bananas often appeared as bruising, blacked rub and scuffing (including fruit-rub) as represented by the Δ MDI scores. Overall mechanical damage level was the highest in RPCs (3.6%) followed by the two-piece carton (3.4%) and the one-piece carton (2.5%). The damage level in RPCs was predominantly shown by increased bruise damage. Bruise damage in RPCs was found mostly in the first two layers of bananas inside the package. Similarly, the bruise damage in both types of corrugated cartons was also localized to the bottom layer of bananas inside the carton. The least levels of bruise damages occurred in the one-piece carton (0.9 %) and a moderate level of bruise damage revealed in the two-piece carton (1.2%). Similar results were reported for pineapples subjected to simulated vibration, suggesting that there was a higher incidence of bruising damage for the fruit stacked in RPC compared to corrugated cartons (Chonhenchob, Kamhangwong & Singh 2008b). It was observed that the causes of bruising inside RPCs and corrugated cartons were different. For RPCs, bruising occurred due to the contact of the clusters in the top two layers inside the crate impacting and rubbing against the side walls (Fig. 6.19). For the corrugated cartons, bruising occurred due to the compression placed on the bottom clusters.

Increased levels of bruising in the first-tier corrugated packages (POS 3/4) revealed that transmission of the weight from the upper tier cartons may have contributed to the bruising in bananas in the lower tiers of the pallet. This can occur due to the sagging of the base of the corrugated cartons resulting in bananas in the bottom-tiers having to sustain part of the weight from upper tiers. Even though the corner posts of a carton and the side walls are intended to support the load from the upper tiers of the carton, the unavoidable base sagging (Niskanen 2012) can cause partial transmission of the weight in the form of compression on ripe bananas. Similar results were reported by Ekman et al. (2011), suggesting that the extent of bruising in ripe bananas was significantly higher in the first layer of the fruits inside the corrugated package (two-piece). The packages in the lower tiers revealed elevated levels of bruise damage compared to the top-tier packages during the distribution, which was in concurrence with the results of this study.

Compromised structural integrity of the corrugated cartons due to moisture absorption over several days of ripening can exacerbate the base sagging in corrugated cartons. This results in even more mechanical damages due to the transmission of weight from the upper tiers and due to the brushing of the base against the fruit. The effect of moisture absorption by the corrugated cartons on the compression strength and base-sagging during the highly humid ripening conditions is further discussed in Section 6.2.3.3.

Table 6.6: Damage Levels (MDI %) for Each Package Type

Two-Piece Carton		BR*	SC*	BL*	**TD***
POS 1	Tier 3	0.2a ±0.06	0.2a ±0.10	0.2a ±0.08	**0.6**
POS 2	Tier 2	0.3ab ±0.08	0.2a ±0.10	0.2a ±0.10	**0.4**
POS 3	Tier 1	0.3ab ±0.17	0.4b ±0.05	0.3a ±0.15	**0.9**
POS 4	Tier 1	0.4b ±0.08	0.3a ±0.10	0.4a ±0.10	**1.2**
Mean Accumulated Damage		**1.2**	**1.1**	**1.1**	**3.4**
One-Piece Carton		BR	SC	BL	**TD**
POS 1	Tier 3	0.2ab ±0.08	0.1a ±0.08	0.2a ±0.08	**0.4**
POS 2	Tier 2	0.1a ±0.10	0.2ad ±0.06	0.1a ±0.08	**0.5**
POS 3	Tier 1	0.4 a ±0.06	0.4bc ±0.10	0.2a ±0.08	**0.8**
POS 4	Tier 1	0.3b ±0.10	0.3cd ±0.08	0.3a ±0.14	**0.9**
Mean Accumulated Damage		**0.9**	**1**	**0.8**	**2.7**
RPC		BR	SC	BL	**TD**
POS 1	Tier 3	0.5a ±0.10	0.2a ±0.05	0.1a ±0.05	**0.8**
POS 2	Tier 2	0.4a ±0.08	0.3a ±0.10	0.2a ±0.05	**0.9**
POS 3	Tier 1	0.6a ±0.13	0.2a ±0.06	0.2a ±0.08	**0.7**
POS 4	Tier 1	0.5a ±0.13	0.3a ±0.08	0.1a ±0.10	**0.9**
Mean Accumulated Damage		**2**	**1**	**0.6**	**3.6**
*BR-Bruising\ SC- Scuffing\ BL- Blackened Rub\ TD-Total Damage					

RPCs showed the least blackened rub damages (0.6%) followed by the one-piece cartons (0.8%) and two-piece carton (1.1%). Blackened rub damages did not show a significant association with the stacking height of packages in the consolidated pallet for any package type (P>0.01). It was observed that rubbing of the base against the fruit was associated with the development of blackened rub damages in corrugated packages but has not occurred in RPCs in a similar manner. In RPC, increased height of the plastic crates allows more head-space between the fruit and the base of the RPC stacked on top, preventing rubbing of the base against the fruit and avoiding transmission of weight as quasi-static compression to the bananas in the lower tiers. However, in RPCs, more blackened rub occurred in the first and second layers of fruits, possibly as an effect of vibration, resulting in rubbing of the clusters against each other within the package. A marginally higher (P>0.01) level of blackened rub in bananas occurred in both types of corrugated cartons in POS 4 (stacked underneath RPC) compared to POS 3 (stacked underneath same type of cartons) (Table 6.6). Brushing of the base of the RPC against the fruit in the top layer has caused blackened rub damages in fruits inside the one-piece carton stacked in POS 4. However, when the RPCs were stacked in POS 4, instead of corrugated cartons, a reduced level of blackened rub damages was exhibited in the same position, suggesting that increased height of the RPC (compared to the corrugated cartons) was an important factor for preventing such damages in the consolidated pallet.

Scuffing damages (Fig.6.19) in bananas were affected by the vibration characteristics of the fruits and the vibration transmissibility from the simulation table in the consolidated pallet. It was found that scuffing damage levels including fruit rub, were similar in all types of packages. As illustrated in Fig. 6.20, all packages exhibited similar vibration transmissibility from the simulator table up to the third tier with the first resonance between 10-15 Hz. At the first resonance the input vibration from the table was significantly amplified in the third tier by 4.5 times in RPC and about three times in corrugated cartons. Vibration above 15 Hz from the table was attenuated in the third-tier packages for all package types, probably due to the vibration dampening effect of the banana clusters stacked in the lower tiers. This could be a reason for the slightly reduced (P>0.01) scuffing damages in the upper tier corrugated cartons (POS 1/2) compared to the bottom tiers (POS 3/4). Majority of the scuffing and rubbing damages occurred in the top two layers of bananas inside the packages, irrespective of the package type. Similar findings were reported by Ekman et al. (2011).

Figure 6.19: Mechanical Damages in Bananas after the Simulated Vibration Test of the Consolidated Pallet: (A) Shoulder Bruising Occurred in RPC (B) Scuffing\Rubbing (C) Blackened Rub

In RPCs, the total damage in the first tier (POS 3/4) was similar to that of the second and third tiers (POS 1/2). This is because of the higher bruising damage compared to the other types of damages in each tier of RPCs. For corrugated packages the overall damage in the bottom tier (POS 3/4) was higher than that of the second and third tier packages (POS 1/2). This was mainly due to the increased bruising and scuffing damage in the lower tiers as a result of top-load compression and direct vibration transmissibility (Fig.6.20). Therefore, column stacking of corrugated packages, rather than flat-stacking on the pallet may reduce damage to bananas on the consolidated pallet. However, the stacking arrangement may not have any effect on the overall damage levels in RPCs during the distribution of ripe bananas. Despite the reduced scuffing and rubbing damages in RPCs in the bottom tiers compared to that of the corrugated packages, high bruising damage in almost every package position from the bottom to top is considered a critical disadvantage of RPCs.

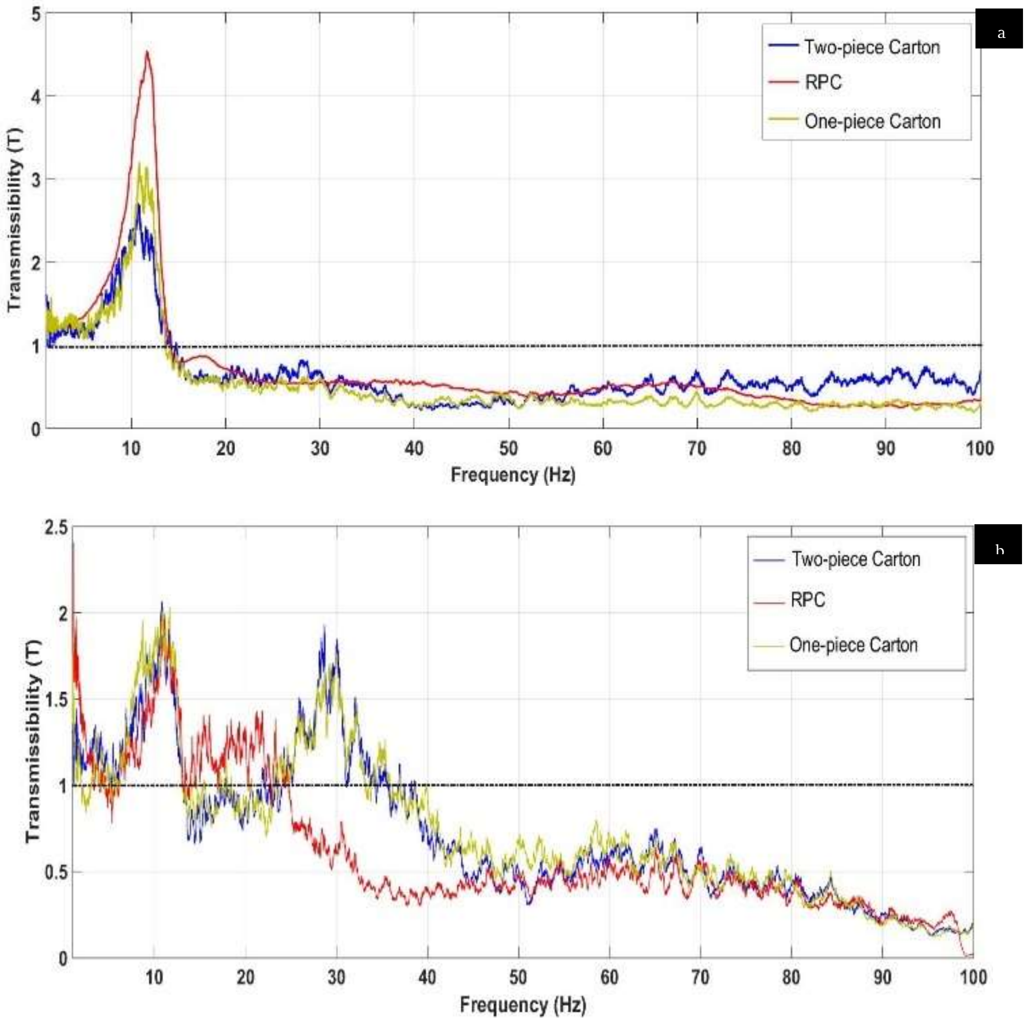


Figure 6.20: Transmissibility of Vibration for Different Package Types (a) Top (POS1) and (b) Bottom (POS3) Packages Stacked in the Consolidated Pallet

6.2.3.3.Compression Resistance and Base-sag in Packaging

The moisture content of the corrugated cartons stored in the ambient and simulated ripening conditions is given in Table 6.7. The moisture content in both corrugated cartons increased by 4.4-6% due to the moisture absorption in the highly humid (90% -95% RH) ripening conditions. Figure 6.21 presents the load-deflection curves for each package type under the ambient and simulated ripening conditions. Table 6.8 summarises the maximum loading at the failure of each package and the deflection at the failure point of the package. The corrugated cartons exhibited visible deformation as they collapsed, and the RPC crates revealed visible cracks in the side walls at the package failure point.

Table 6.7: Moisture Content of Corrugated Packaging at Different Conditioning Treatments

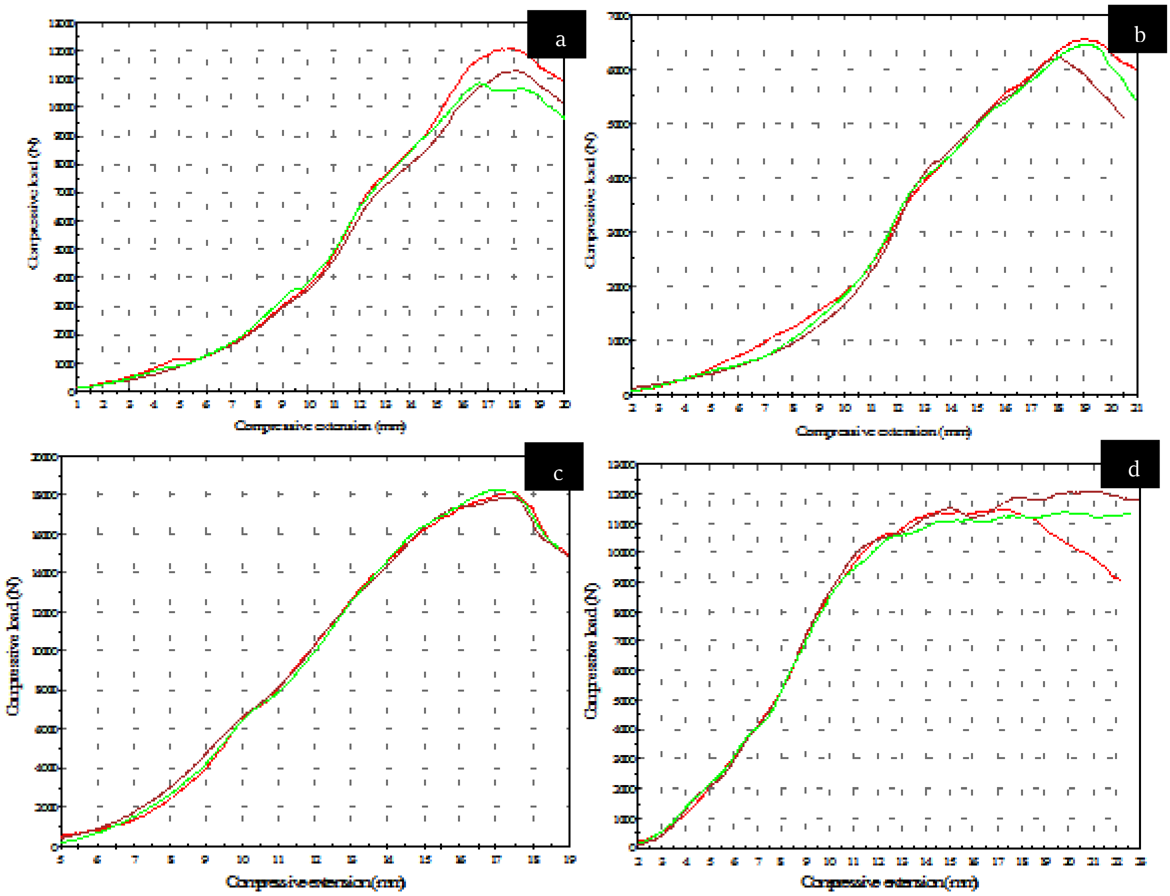
Package	Ambient Condition (%)	Ripening Condition (%)	Difference (%)
One-piece carton	8.2 ± 0.05	12.6 ± 0.17	4.4 ± 0.17
Two-piece carton - Tray	7.3 ± 0.06	12.7 ± 0.15	5.4 ± 0.11
Two-piece carton - Lid	7.6 ± 0.07	13.3 ± 0.12	6.0 ± 0.15

Table 6.8: Package Failure Load and the Displacement after Storage in Different Conditioning Treatments

Conditioning	Ambient Conditions (23C, 50-60% RH)		Simulated Ripening Conditions (15 C, 90-95% RH)	
Package	Maximum Load (Mean)	Displacement at Failure (Mean) ± SD	Maximum Load (Mean)	Displacement at Failure (Mean) ± SD
One-piece Carton	18,093 N	12.99 mm ± 1 mm	11,640 N	17.11 mm ± 1.7 mm
Two-piece Carton	11,418 N	15.31 mm ± 0.5 mm	6, 407 N	15.88 mm ± 0.9 mm
RPC	27,263 N	7.02 mm ± 0.1 mm	-	-

In ambient conditions, the RPCs had the highest compression strength (~27 kN) which was more than 50% higher than the one-piece corrugated carton (~18 kN) and more than double the compression strength (~139%) of the two-piece corrugated carton (~11.5 kN). The one-piece carton showed 59% higher compression resistance compared to the two-piece carton at the ambient conditions. Both corrugated cartons significantly lost structural strength when exposed to simulated ripening conditions. In the highly humid ripening conditions, the compression resistance of the two-piece carton was reduced by 43% from 11.4 kN to 6.4 kN and the one-piece carton by 36% from 18.1 kN to 11.6 kN. The compression strength of the one-piece carton was still shown to be 81% higher than that of the two-piece carton after exposed to high humidity. The findings of this study correspond with Junli and Quancheng (2006) that showed the strength of a corrugated paperboard carton can be reduced by 52% when the moisture content is increased from 7.7% to 16%. The mean compressive deflection at the failure point was 15.3 mm in the two-piece carton stored in the ambient conditions. The value slightly increased to 15.8 mm after exposed to the simulated ripening condition. Similarly, the mean deflection in one-piece carton was 13 mm and increased to 17 mm in the simulated ripening conditions. The minimal deflection at the collapse of the package was exhibited by RPCs at 7 mm in the ambient conditions.

The results suggest that the moisture absorption of the corrugated cartons weakened their structural strength in the highly-humid simulated ripening conditions compared to the storage in the ambient conditions. From the results, it can be expected that if a package incidentally collapses during the post-harvest handling, more compression damage may occur to the contents (i.e. bananas) in one-piece cartons than in the two-piece carton due to the increased deflection at the failure point. However, due to the much-increased compression strength of the one-piece carton compared to the two-piece carton in both environmental conditions, one-piece carton can still be expected to withstand a higher compression load at any given point and have reduced possibility of package failure in the post-harvest SC.



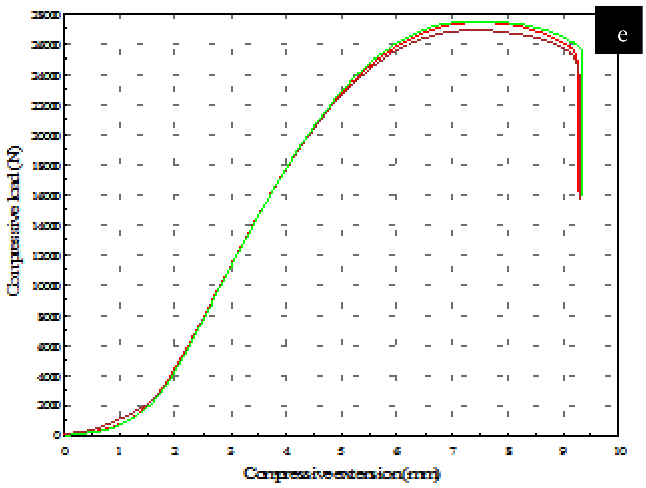


Figure 6.21: Load-deflection Curves for (a) One-piece carton and (b) Two-piece carton in ambient conditions, (c) One-piece carton and (d) Two-Piece carton in simulated ripening conditions (e) RPC in ambient conditions (Each curve represents a single test-run for a package)

Figure 6.22 presents base-sagging for each type of packaging stored in different temperature and humidity conditions over a period of 14 days. Under the ambient conditions, the base-sagging gradually increased in all types of packaging. At the intervals of 24 hours, 48 hours and 3 to 14 days of storage in the ambient conditions, RPC had the highest level of sagging, followed by the one-piece carton and then the two-piece carton (Fig. 6.22). However, when the packages were stored in simulated ripening conditions, an exponential increment in base-sagging was exhibited by the corrugated cartons after the first few hours. In the first two hours of storage in the simulated ripening conditions, the highest level of sagging was exhibited in the one-piece carton followed by the RPC and the least level of sagging was revealed in the two-piece carton. However, after two hours of storage in the simulated ripening conditions, all packaging exhibited similar level of base sagging (~12 mm) and from two hours onwards the two-piece carton showed much exacerbated levels of sagging (Fig. 6.22) compared to the other two packaging alternatives. Therefore, it can be concluded that after several days of ripening of bananas in highly-humid enclosed chambers, two-piece cartons are expected to have greater base-sagging than the other two packaging alternatives. The best control of base-sagging was revealed in RPC during the storage at high-RH simulated ripening conditions.

These results reveal that base-sagging was exacerbated in corrugated cartons due to the moisture absorption during ripening conditions. The differences or 'gap' between the base-sagging levels under different environmental conditions are given in Fig. 6.23. The 'gap' was calculated by subtracting the base-sagging level in ambient conditions from the base-sagging level in simulated ripening conditions for each package type. Therefore, a positive 'gap' value indicates that the base-sagging under the simulated ripening conditions was higher than the sagging level under the ambient conditions and viceversa. In one-piece carton the gap increased by 6.3 mm while the gap in two-piece carton increased by 13.1 mm over the period of 14 days. This indicates that the effect of the moisture absorption on the base-sagging is much critical for the two-piece carton compared to the one-piece carton.

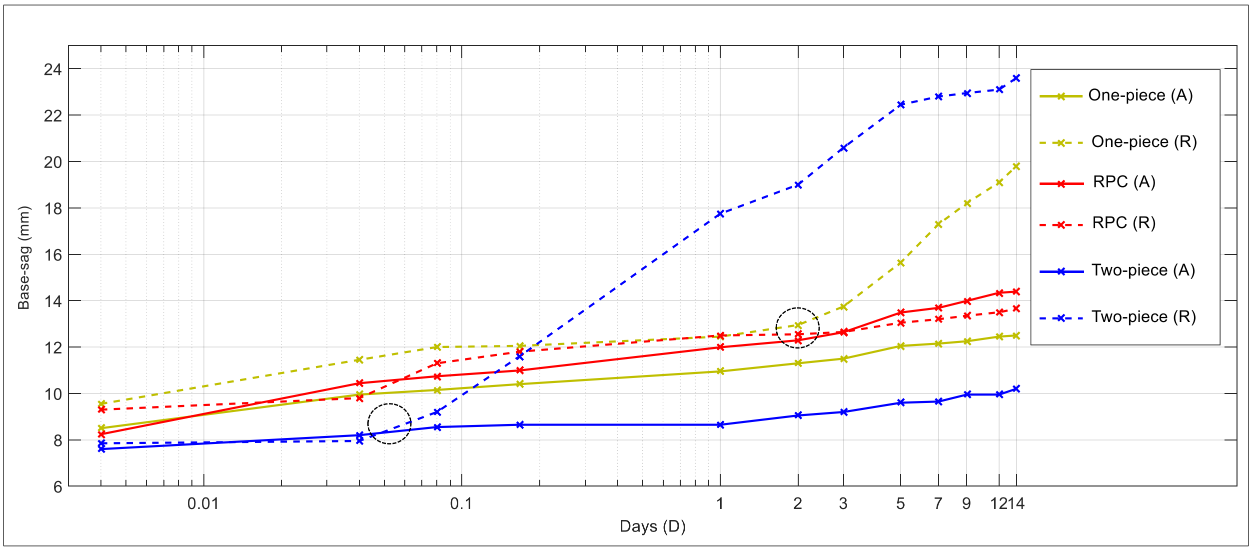


Figure 6.22: Development of Base-sagging in Packages under (A) Ambient conditions and (R) Simulated ripening conditions (Point at which exponential Base-sagging start to occur in corrugated cartons are circled)

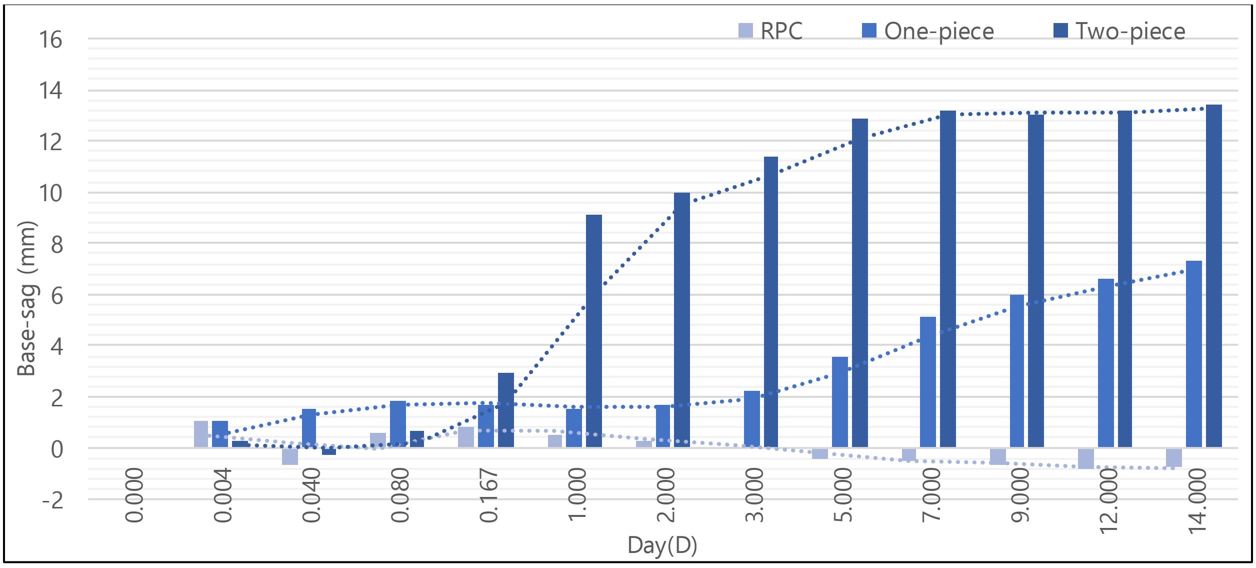


Figure 6.23: The Calculated Gap in Base-sagging Levels (This 'Gap' is calculated as the difference between the Base-sagging level in ambient conditions and simulated-ripening conditions)

Plastic crates are moisture-resistant and can be expected to have negligible effect on base-sagging caused by moisture absorption. At the start of the experiment a 1 mm gap was observed in RPC under the ambient conditions and simulated ripening conditions. This could be due to the slight variations in the weight of bananas in each crate, as each package was packed with 15 kg ± 0.5 kg of bananas. Over a period of 14 days, the base-sagging level of RPC increased from 8 ± 1 mm to 14 ± 1 mm under both conditions and the gap between the sagging levels has oscillated between + 1 mm to -0.74 mm over the observation period. The negative value indicates that the base-sagging level in RPC under ambient condition was higher than the base-sagging level under the simulated ripening condition. This may have occurred due to a couple of reasons. First as mentioned, the slight variation of fruit weight packed in each crate and second, the different rates of respiration of bananas during the storage period may result in minor net weight differences, causing an error of ± 1 mm in the base-sagging measurements in RPC. This error may have also affected the base-sagging levels in corrugated cartons however, the effect of the error could be negligible compared to the extent of sagging levels measured in both types of cartons (>7 mm).

The simulated vibration testing of packages in a consolidated pallet revealed that some damages in bananas, such as blackened rub, occurred due to the rubbing of the base of the packaging against the fruit stacked in the package underneath. The base-sagging may also transfer the weight of the top-tiers partially to the fruit stacked in lower-tier packages which may lead to compression damage in bananas. Therefore, it is important that packaging used in the distribution of bananas has minimal level of base-sagging, especially in the highly-humid ripening environments. Even though RPCs showed the best control for base sagging in the simulated ripening conditions, the bruise damage levels occurred in RPC during the simulated vibration testing was much higher compared to the corrugated cartons. Therefore, RPC's cannot be considered as an alternative for the distribution of ripe bananas, despite their controlled base-sagging performance in the high-RH environment. Out of the two types of corrugated cartons, one-piece carton exhibited relatively less damage levels (26%) in bananas and a better control of base-sagging at highly humid environments, compared to that of the two-piece carton. Increased base sagging in two-piece cartons compared to the one-piece cartons may have caused slightly increased rubbing (~28 %) and compression damages (~25 %) in bananas, when stacked in the consolidated pallet (Table 6.6).

There are two limitations in this study. First, the model of the consolidated pallet used for the experiment was a representative case of the distribution pallet arrangement for bananas. However, in practice the pallet height normally exceeds four tiers and there can be an infinite number of combinations of packaging, produce, and pallet arrangements. It is impractical to simulate all such different stacking arrangements and therefore, the generalisation of the results needs to be made with caution. The other limitation is the number of tests performed. Constrained by time and resources, the simulation tests were conducted in quadruplicates. A higher number of repetitive tests can enhance the reliability of the results.

6.2.4. Conclusion

This study analysed the occurrence of mechanical damage in bananas packed in different types of packages and stack positions in a consolidated pallet, subjected to simulated vibration under controlled temperature environment. The significance of this study is that it examined the occurrence of different types of mechanical damage in packaged bananas to determine the mechanism of damage occurrence. Additionally, the experimental validation of the best packaging alternative for the distribution of bananas will benefit the banana industry by reducing wastage levels caused by mechanical damage and improving perceived quality of fruits in the retail stores for a better marketability. The one-piece corrugated carton showed relatively reduced overall damage levels for ripe bananas in a consolidated pallet under simulated vibration. Moisture absorption during the simulated ripening conditions weakened the structural integrity of the corrugated paperboard cartons, resulting in reduced compression strength and increased level of base-sagging. The one-piece carton also revealed increased compression strength and reduced levels of base-sagging under the simulated ripening conditions compared to the two-piece counterpart. Therefore, one-piece carton can be considered as a better alternative to the two-piece corrugated carton which is widely used for the banana distribution in Australia. Even though RPCs are resistant to moisture absorption and exhibited much higher compression strength, the occurrence of higher levels of bruising caused by brushing of fruits against the side-walls under simulated vibration, remains a major factor for preventing their use for distribution of ripe bananas. The occurrence of bruising in RPCs could potentially be reduced with thicker inner-liners and side-wall cushioning mechanisms. Therefore, further research is warranted to further improve RPCs before the plastic crates are recommended as an appropriate alternative for the distribution of packaged bananas in Australia.

7. CHAPTER VII

General Discussion and Conclusion

This chapter synthesizes the key results and findings of the research chapters and explains the extent to which the research questions has been addressed towards achieving the research objectives. The final chapter of the thesis highlights the key conclusions of the study and presents the contributions of this research to the focal research fields and implications to the industry. The interventions and recommendations for improving the quality of bananas in the post-harvest SC are discussed. Finally, the chapter discusses the limitations of this research and provides future research direction.

Chapter VII

General Discussion and Conclusion

This research study was focused on investigating and improving the quality of bananas in post-harvest supply chains. The purpose of this chapter is to discuss how the various parts of the thesis are integrated to address the main research question: '*What are the causes of mechanical damage in packaged bananas and what interventions can be recommended to improve their appearance quality in the post-harvest supply chain?*' Three research objectives were framed as elaborated in Section 1.4 of this thesis and for convenience, the key objectives of this research are restated here

- Objective 1: Evaluate mechanical damage in packaged bananas and identify the causes of damage from the farm-gate to retail stores.
- Objective 2: Characterize the relationship between mechanical forces and the consequential mechanical damages in packaged bananas.
- Objective 3: Evaluate the protective performance of packaging for minimizing mechanical damage in bananas and recommend potential interventions for improving banana quality in the post-harvest supply chain.

The phases that were adopted to address the research questions can be illustrated in Fig. 7.1 as damage Evaluation, Characterization and Minimization.

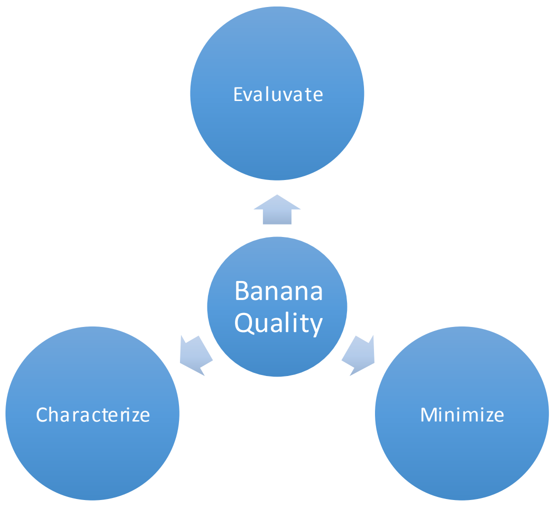


Figure 7.1- Key Research Phases used in this Study

7.1. Summary of the Research Findings

The main findings of this study are summarised in this section. These findings were derived from the key results and conclusions drawn from each of the results chapters (i.e. Chapters 4-6) and summarized in relation to the key research phases (i.e. Evaluate, Characterize and Minimize) in this study. The collective implications of these findings are discussed in Sections 7.2-7.4 and the limitations are further discussed in Section 7.5.

7.1.1. Evaluate: Evaluate the mechanical damage levels and identifying the causes

- Quality deterioration of bananas caused by mechanical damage was progressive along the post-harvest SC, resulting in diminished appearance quality in the retail stores.
  - Significantly different damage levels were revealed in pack house, Distribution Centre (DC) and retail stores for all damage types in packaged bananas.
  - Abrasion was the mostly revealed damage type in bananas from pack-house to DC (ΔVDI% = 5.5) which further exacerbated from DC to retail stores (ΔVDI% = 1.1).
  - Bruising and neck injuries more than doubled with 130% and 134% increments between the DC and retail stores respectively.
  - The stack height of the package during the transport from pack house to DC was associated with the levels of neck and bruising damage in packaged bananas (i.e. Damage levels decreased from the bottom to top).
  - Despite the shorter transport distance, the last-mile distribution from DC to retail stores had a disproportionate impact on the quality deterioration of bananas, where over 30% of the overall damages occurred.
  - Significantly different levels of abrasion damage were revealed in packaged bananas delivered to the retail store located farthest away from the DC compared to the other closer stores.

- A range of work practices related to the industry were identified as risk factors for mechanical damage across the SC.
  - Damaged cushioning or lack of cushioning in field tractors caused severe abrasion damage to bananas in the early stages of the SC.
  - Under-filling of cartons was associated with abrasion damage caused by vibration.
  - Over-filling of clusters in the cartons influenced bruising due to top-load compression, especially in the latter stages of the SC.

- Package handling during the pallet consolidation in the DC was a major cause for the neck injuries and bruising in ripe bananas.
- Inappropriate stacking arrangements for air-cooling of the clusters and other handling practices at the retail stores caused further damage to bananas at the last stage of the SC.

7.1.2. **Characterize: Characterize mechanical damage in packaged bananas**

- Different mechanical stresses exerted on packages, such as top-load compression, transient impact and vibration resulted in markedly different types of mechanical damage in bananas.
  - Exposure to vibration resulted in abrasion damages among the top two layers (88%) of bananas inside the package.
  - Abrasion damage caused by vibration increased proportionally to the exposure duration and escalated exponentially with increased vibration intensity (RMS acceleration).
  - Package drop or impact resulted in severe neck injuries in bananas mostly concentrated in the top two layers (91-94%) inside the package.
  - The neck damage levels increased with the package drop height from 0.3 m to 0.5 m, however the results were not statistically significant ($p>0.05$).
  - Top-load compression on packaged bananas resulted in bruising damage in the most bottom layer (72-84%) of fruits inside the package.
  - Bruise damage levels increased with the deflection of the package from 16mm to 25 mm due to the top-load compression.
- Mechanical damage caused by vibration during the long interstate transport was associated with the stack-height of the package in a pallet and the pallet position in the truck.
  - Packages in the most bottom and top tiers of the pallets suffered significantly increased levels of abrasion damage caused by vibration.
  - Vibration induced damage in bananas was affected by the pallet position in the truck as a function of the input RMS acceleration intensity (G_{rms}), where the highest damage levels were revealed in the most rear pallet-position.
  - Differences in transmissibility were found between the cross- and column-stack pallet stacking arrangements from the middle to top tiers of the pallet.
  - Accelerated vibration testing based on Single Degree of Freedom (SDOF) simulation with a RMS acceleration of 0.36 g for a duration of 3 hours in the laboratory reasonably replicated the field damage levels in packaged bananas.

7.1.3. **Minimize: Minimize mechanical damage by improved packaging and other potential interventions**

- Package type and the freedom of movement of bananas inside the package was associated with the level of mechanical damage.
  - One-piece corrugated cartons showed the least damage levels and the best protective performance for packaged unripe bananas during the long-distance interstate transport.
  - The vibration dampening characteristics and the construction material of packaging influenced the mechanical damage levels.
  - RPC had the highest damage levels in bananas followed by the currently used two-piece corrugated carton.
  - Vacuum-tightening of clusters reduced the vibration damage, especially in the most bottom- and top- tier packages of the pallet.

- Packaging type and the stacking arrangement within a consolidated pallet together with the exacerbated base-sagging levels, influenced the mechanical damage levels in ripe bananas.
  - The damage level in the one-piece carton was lower ($p>0.05$) than other package types, however the results were not statistically significant.
  - Column-stacking of packages showed reduced mechanical damage to ripe bananas in consolidated pallets compared to flat-tier stacking.
  - Exposure to high RH during ripening reduced the strength of both types of corrugated cartons and resulted exacerbated base-sagging levels .
  - Base-sagging and package failure due to top-load compression was associated with mechanical damage in ripe bananas.
  - RPCs showed the least base-sagging, followed by the one-piece carton but the two-piece carton had the highest increment in sagging levels after moisture absorption during the ripening process.
- Several modifications to work practices in the industry are proposed as potential interventions to minimize mechanical damage to bananas and improve their quality in the post-harvest SC. These implications and recommendations to the industry are discussed in Section 7.4.

7.2. The Effectiveness of the Study in Achieving the Research Objectives

The overarching goal of this research was to understand the causes of mechanical damage in packaged bananas and determine the interventions to improve their quality in the post-harvest SC. There were three phases (i.e. Evaluate, Characterize and Minimize) in this study with each research phase being corresponding to its research objective and aimed at achieving the overarching research goal. This section elaborates how the three research phases collectively addressed the research question and achieved the three objectives in this study.

The first phase aimed at evaluating the damage levels across the SC and identifying the causes of damage in packaged bananas. Damage evaluation along the SC was an essential first step to determining the extent of mechanical damage and how it progressed along the SC. This study used two approaches (i.e. random inspection and follow-up inspection) to understand the appearance quality deterioration in bananas along the SC. The two approaches were reinforced by a qualitative observation study across the SC to understand the risk factors for damage development. Both random and follow-up inspections (Section 4.1.3 and Section 4.2.3) contributed to determining when and where the damages occurred along the SC and, the extent and type of damages in each stage of the SC. The assessment of damage in randomly selected packages was important to quantify the level of different types of mechanical damages in bananas at each node of the SC. In addition, the follow-up inspections further enhanced the knowledge of damage development by tracking each package from their origins to the destinations. Therefore, follow-up inspections further contributed to understanding how the damage levels in each damage category (i.e. bruising, abrasion and neck damage) progressed along the SC. Despite of the discrepancies found between the two approaches, both methods effectively assessed the damage levels along the SC. The damage levels were quantified by Visual Damage Index (VDI) which was effective in converting the frequency and severity of all damage types in packaged bananas to an aggregated score. This allowed the comparison of different types damages in packaged bananas by VDI score to determine the incremental damage between the SC nodes.

The first phase included the observation study along the SC to identify the risk factors for mechanical damage to bananas. This qualitative study provided much useful knowledge on the causes of damage development attributed to the work practices which would have otherwise been undisclosed. The collection of first-hand qualitative data on the work practices and the industrial conditions allowed the identification of the areas requiring further study (which were investigated in the latter phases of the study) and improvements on industry practice (Section 7.4). The observation study identified the risk factors for mechanical damage however the observation findings alone could not determine the mechanisms of damage development in packaged bananas. Therefore, the second research phase (i.e. Characterizing damage) was conducted.

Several different types of damages were identified during the first phrase including bruising, abrasion and neck injuries as discussed in Section 2.5.1. However, their mechanism of occurrence in packaged bananas was unclear. There is limited research on the development of damage to fruits caused by compression, vibration and impact when they are packaged inside corrugated paperboard cartons (Opara & Fadiji 2018). The second phase of this study characterized different damages in packaged bananas by subjecting the packages to mechanical stresses in a laboratory environment. The second phase of the study successfully characterized the occurrence of damage in packaged bananas. The results from the first phase revealed that abrasion damage (i.e. rubbing) in bananas during transport was a major factor for the poor appearance quality. Consequently, the occurrence of abrasion damage to bananas caused during transport was further characterized. For this purpose, this study collected vibration data along the entire post-harvest SC (from farm-gate to retail store) and simulated vibration using an electro-hydraulic vibration simulator, which allowed a thorough investigation of mechanical damage to packaged bananas in-transit. The second phase of the study further established the relationship between the level of mechanical damage in packaged bananas and the vibration 'dose' as a function of exposure duration and vibration intensity. This led to the development of a 'vibration simulation test' which allowed laboratory simulation to replicate equivalent field experience. The derived test was used in package testing experiments in the final phase of the study resulting in a better understanding of how the exposure to such stresses affected the damage development. Therefore, the first two phases of the research and their resulted outcomes have adequately achieved the first two research objectives.

The third phase of this research was aimed at improving the appearance quality of bananas. To achieve this, the protective performance of various packaging was examined. The empirical study identified that ripening of bananas in high RH enclosed chambers increased their vulnerability to damage during the subsequent storage and handling. This study found that weakened structural strength was a major cause of bruising due to the sporadic failure of packaging and base-sagging is associated with a variety of damages (i.e. blackened rub and bruising) during the distribution of ripe bananas. A series of experiments on the compression strength and base-sagging levels in the final phase of this study was used to recommend an improved packaging alternative (i.e. One-piece carton) for bananas with enhanced protective performance. Additionally, the final phase of the study also assessed the effectiveness of column-stacking of banana packages instead of cross-stacking (i.e. in full-pallet loads) during the interstate transport. Furthermore, the study continued to assess the effectiveness of column-stacking of packaged bananas in consolidated pallets during the distribution of ripe bananas and, vacuum-tightening of the clusters to further minimizing the damage caused by vibration. Therefore, the final objective of this study has been achieved through the experimentally validated results on packaging alternatives, packing and stacking methods for packaged bananas and, suggesting several work-practice improvements (further discussed in Section 7.4).

7.3. Contributions to the Field of Research

Firstly, a novel mechanism to objectively estimate the area of fruit-mechanical damage was developed. This was proven an accurate and efficient damage quantification mechanism for bananas and can be potentially applied to a variety of horticultural produce that requires objective damage measurement. Similar to the Equivalent Bruise Index (EBI) for apples (Vursavus & Ozguven 2004), this study developed a Mechanical Damage Index (MDI) which not only assessed bruise damage but also quantified a range of abrasion damages on fruits such as fruit rub, scuffing and scars in various shapes. MDI score in this study was successfully used as a tool for damage comparison along the SC and in simulation experiments. Similarly, MDI can be used to quantify damages in a variety of fruits for research on mechanical damage comparison in the field or in the laboratory, in a robust, rapid and objective manner.

Numerous studies assessed the quality of fresh fruits in different segments of the post-harvest SC (dos Santos & Ferraz 2007; Gambella, Paschino & Dimauro 2013; Mazhar 2015; Peterson & Bennedsen 2005; Zhou et al. 2014). These studies were limited to the damage development in a particular SC node such as the farm and pack house or during transport. Complete assessment of damage in the entire post-harvest SC is rare (Da Costa et al. 2010; Ekman et al. 2011). The uniqueness of this study was the use of several qualitative and quantitative methods including damage assessments, field observation, vibration data collection and analysis and laboratory simulations to comprehensively identify the causes of damage development and develop recommendations for each stage of the SC, with the ultimate objective of improving the quality of the fruits at the retail end.

Characterizing different damages in packaged bananas through simulation of the field conditions contributed to a better understanding the causes of each type of damage. The susceptibility of fruit by mechanical loads has been extensively studied however, little knowledge exists on the occurrence of damage in packaged fruit (Fadiji et al. 2018). Damage characterization helped to understand why some types of damages were prominent in certain parts of the SC. Improved knowledge of the factors affecting damage was vital for recommending measures to reducing mechanical damage. Further experiments using simulated vibration provided knowledge on the influence of vibration transmissibility and stacking-arrangements on the damage occurrence. The package testing experiments contributed to determining the vibration dampening properties, compression strength and base-sagging of packages, which were associated with a variety of mechanical damages in bananas.

This study has found that exposure of packaged bananas to vibration during transport is one of the most critical causes of the frequent damage in bananas across the SC. Vibration levels during road truck transport were investigated across the world including Japan, Thailand, Spain, Iran, United States, Brazil and multiple other countries. (Chonhenchob et al. 2009; Garcia-Romeu-Martinez, Singh & Cloquell-Ballester 2008; Lu et al. 2008; Rissi et al. 2008; Singh 2006; Soleimani & Ahmadi 2014, 2015). However, there is a lack of studies focused on characterizing vibration levels during produce transport in Australia. In fact, almost all most previous studies measured and characterized vibration in single semi-trailer truck. There has been a lack of research on the vibration characteristics of multi-trailer road trains and how it affects the damage development in packaged produce. This study contributes to enhancing the knowledge on vibration characteristics in multi-trailer road trains and also providing an insight on the vibration levels on Australian road highways in comparison to standard vibration testing methods such as ASTM (Fernando, Fei & Stanley 2019).

One of the main constraints in field vibration data collection was the power and memory capacity restrictions in the data recording devices. For vibration data collection during field transport previous researchers used time triggered or event triggered settings to record vibration and shock data (Barchi et al. 2002; Berardinelli et al. 2005; Jarimopas, Singh & Saengnil 2005; Timm, Brown & Armstrong 1996). This resulted in capturing only few parts of the journey or shock events above a specified threshold which did not provide an accurate characterization of the transport environment (Dunno 2014; Fernando et al. 2018a). This research used piezoelectric accelerometers with improved memory capacity, coupled with external battery packs, which extended the effective operating time of the devices to over 100 hours of continuous sampling. This helped to record vibration and shock signals from end-to-end of the long- distance transport journeys. Time synchronized GPS data recorders were used to identify the position of the truck and remove the non-useful data along the route during the analysis stage. Capturing vibration and shock data throughout the journey contributed to accurately characterize the transport environment and the development of Power-Spectral Density (PSD) profiles for laboratory vibration simulation.

This study developed a simulation test that replicated field experience of packaged bananas during the long-distance road transport in a compressed timeframe, making laboratory experiments for long-distance transport simulation possible and repeatable. A significant challenge in vibration simulation studies is the realistic replication of the field conditions in a laboratory environment. For package testing purposes, the approach based on a test setting derived from the actual field data can considered superior (Fernando et al. 2018a; Kipp 2008; Kipp 2001a; Kipp 2001b) than relying on a standard test protocol such as ASTM or ISTA (ASTM 2016b; ISTA 2017b). This is because the PSD profiles and the vibration doses prescribed in these standards may significantly deviate from the actual field transport conditions. An equivalent test setting that produces damage in bananas comparable to the field damage levels was determined by carefully modelling the vibration intensity and exposure duration. The vibration test profiles developed in this study can be used in extended studies for a variety of fresh produce and other products in packaging research to simulate similar road truck transport conditions in Australia.

Time compressed vibration testing has been a topic of interest in the field of packaging research. However limited research has been conducted on the accuracy of accelerated vibration testing. Previous studies showed that using an erroneous power factor (k) for a given product under the test can lead to significant errors in simulation (Griffiths 2011; Griffiths et al. 2013; Shires 2011). Due to lack of research in this area the value of k is usually assumed in most vibration experiments. This study revealed that for packaged bananas, using an appropriate power factor (k =2.3) provides the closest correlation of field damage levels during laboratory simulation. Firstly, this finding further strengthens the previous argument that an erroneous power factor may result in significant errors in accelerated simulation testing. Secondly, this implies the importance of using a reasonable value for the power factor in package testing experiments, with reference to similar products, packaging, packing and stacking arrangements. This can be of a great importance to packaging designers and researchers involved in transport vibration simulation studies.

The simulated vibration experiments investigated the vibration levels up the stacked column of banana cartons. It demonstrated three factors were associated with the damage occurrence in bananas including (1) attenuation of high frequency vibration up the column of packages, (2) resonance characteristics of the stacked column and (3) freedom of movement of bananas inside the packages. Although the behaviour of a single-unit packaging systems has been thoroughly researched, the vibrational performance of a stacked column of individual packaging units is much more complex (Rouillard, Sek & Crawford 2004; Wang & Fang 2016). Stacking of multiple packaging together as a column, and stacking multiple layers of products inside the package and the stacking arrangement can influence the vibrational characteristics of packaged products (Paternoster, Van Camp, et al. 2017). The laboratory vibration simulation experiments contributed to understanding why the damage levels were increased in the top tiers and bottom tiers of the pallets and reduced in the middle tiers. The attenuation or amplification of the vibration up a stacked column depends on the mechanical properties in each carton and also the properties, mass and the behaviour of its contents (i.e. the products)

(Berardinelli et al. 2005; Berry et al. 2019; Fischer et al. 1992; La Scalia, Enea, et al. 2015b). However, this finding needs to be cautiously extended to other fruits as the vibration characteristics and damage occurrence in palletised packages may be influenced by a variety of factors, such as the characteristics of fruits, properties of packaging and method of packing.

This research confirmed that the construction material and the transmissibility of vibration of packaging played a significant role for the development of mechanical damage in bananas. Palletised packages are often used in produce handling in post-harvest SCs. However, the vibration characteristics of palletised loads have not been fully explored (Rouillard, Sek & Crawford 2004; Wang & Fang 2016). The study broadened the understanding by investigating the vibration transmissibility in cross- and column-stacked pallet arrangements. Cross-stacking the sixth, ninth and tenth tier resulted in escalated vibration levels around the resonance frequencies in the top half of the pallet (i.e. sixth tier upwards), which can result in increased mechanical damage to fruits in the upper-tiers. This finding are useful in the industry practice and also for similar future studies to understand the behaviour of fruits in different stacking arrangements during transport.

7.4. Industry Implications and Recommendations

The recommendations to the industry for minimizing damages during the pre-packing and post-delivery of bananas will also require several changes in industry work practices, which are further discussed in this section. There are many causes for the appearance quality deterioration in bananas along the SC, as identified in this study. A broad understanding of the damage levels, the location of damages occurrence and the causes of damages will enable the industry to determine the level of intervention required in each stage of the SC. The key focus of this research was to understand the damage development in packaged bananas. However, the empirical industry study (included in Section 4.1.3) also revealed potential causes for mechanical damage when bananas are handled in clusters at either ends of the SC (i.e. farms and pack houses and, retail stores). Therefore, the interventions for addressing the identified risk factors when bananas are handled in bunches or clusters (i.e. before packaging and post-delivery of packages) are also incorporated to the discussion in this section to cover the entire post-harvest SC. The following recommendations can be derived from this study are made to assist the industry to preserve the quality of bananas in the post-harvest SCs in Australia.

7.4.1. Improve Field Transport Conditions

The experimental characterization of various types of mechanical damage in bananas was important to understand the mechanism of damage development, especially in packaged bananas. However, none of the simulation experiments caused the development of ‘scar’ injuries in bananas, which have been frequently reported in the early stages of the SC, specifically in the farms and pack houses. In the early stages of the post-harvest SC, field transport in the farm was found to be a major source of mechanical damage (i.e. bruising and scars), especially for bananas in the most bottom of the bunch. Bunches are placed vertically on the tractor-trailers and the unpaved field-tracks in most of the visited farms were often uneven and muddy. This essentially requires the bunches to be properly secured to avoid excessive bumping on trailers. During the farm visits it was observed that the securing of the bunches can be improved with proper lashing-straps. In addition, it is essential to improve the cushioning of the trailers with thicker and softer foam materials. In the medium to long term improving the field tracks to avoid accumulation of mud and rainwater will also be important. The tractor-trailers that have been used for the field transport of bunches did not have a suspension mechanism and thus, installation of a suspension mechanism (e.g. leaf-springs or shock absorbers) should be considered. However, there will be an initial capital cost for the growers specially for the major improvements such as improving the roads or upgrading the suspension systems of the tractor tailors.

7.4.2. **Modifications to Packing-lines**

Even though most packing-lines were similar there were some lines with level-drops, rough or worn-out conveyer belts as identified during the observation study (Section 4.1.4). Presence of level-drops in a packing-line may cause the fruit to drop from one-level to another, resulting in impact damage to the clusters. Even though the level separation is short, bruising can occur due to impact of the cluster with another hard surface and thus, packing lines can be modified to eliminate such level-drops. Rough and worn-out conveyer belts can cause abrasion damage such as scars due to the friction which can be upgraded with smoother conveyer belts to eliminate the risk of damage.

7.4.3. **Firm-packing of Clusters**

Both under-filling and over-filling of the cartons need to be avoided as both were associated with vibration-induced abrasion and bruising in bananas in the latter stages of the SC. Vibration simulation experiments revealed that the tightness of filling is an important factor for controlling the abrasion damage in bananas. Therefore, firm-packing of the clusters inside each carton is important for minimizing abrasion damage. Over-filling results in supporting a significant share of the weight from above by bananas rather than the package corner posts, resulting in compression bruising. In addition, over-filling causes the top layer clusters brush against the lid of the carton resulting in abrasion damages during the distribution. Therefore, both over-filling and under-filling the cartons must be avoided which may require training of the fruit packers in the industry.

Vacuum-tightening significantly reduced abrasion damage levels in packaged bananas. This can be attributed to the increased fill-tightness (Slaughter, Hinsch & Thompson 1993; Slaughter, Thompson & Hinsch 1998) of bananas which restricts their relative movement of fingers when exposed to vibration. The experiments revealed that restricting the relative movement of fingers of bananas is an effective measure to reduce vibration damage in packaged bananas. However, further research is required to address several limitations of this method before this solution can be practically considered which is further discussed in the Section 7.5.

7.4.4. Stacking and Palletising

It was observed that manual palletizing occasionally results in miss-aligned stacking. Miss-aligned stacking was found to be a major cause of package collapsing especially in the lower tiers of the pallet during and after the ripening process. It was evident that the weakening of the corrugated cartons due to moisture absorption during the ripening, and the miss-aligned stacking of packaging can trigger sporadic package failures during the post-ripening distribution, resulting in severe bruising damage and neck injuries in ripe bananas. The current industry practice is to stack banana packages in a cross-stack formation with the sixth, ninth and tenth tiers being cross-stacked. This is to increase the stability of the pallet however, there are several disadvantages with this stacking arrangement. The most obvious one is that in cross-stacked tiers, the corner posts of the packages cannot be used as intended to transfer the weight of the top-tiers to the bottom tiers. Instead, the weight is distributed onto the top-surface of the packages below where there is lack of reinforcement to support the weight. This not only compromises the strength of packaging, especially in the mid-tiers but also compresses the fruits. Compared to the cross-stacked pallets, column-stacking of packages exhibited reduced vibration levels, especially in the mid-frequency range and around the resonance frequencies. Therefore, column-stacking of packages can be expected to reduce vibration damage in the top-half of the pallet and minimize the risk of bruising in the bottom-half of the pallet. However, the stability of the column-stacked pallet must be improved with stretch-wrapping or pallet corner-post supporters to ensure that the pallet is not collapsed during the post-harvest transport and handling.

7.4.5. Pallet Consolidation

Consolidation of produce packages at the DC for dispatching to retail stores is a crucial step in the latter part of the SC, with an increased risk of damage to bananas. This is due to the consolidation of the produce packages with different sizes and dimensions stacked together in a consolidated pallet to be dispatched to retail stores. This research found that drop impact which simulated the rough handling of packages was the major source of neck injuries in bananas. Consolidation of packages immediately after the ripening processes, while the corrugated packaging has lost its original strength, can cause significant damage to bananas and thus, careful handling during the manual package consolidation process is essential to minimize the risk of damage during the last-mile distribution.

Numerous factors affect the structural strength of a package including the dimensions, direction of the flaps, storage conditions and paperboard material properties (Fadiji et al. 2018; Kirwan 2012). After the ripening process, bananas packages are usually stored in the ambient atmosphere (23 °C, 60±20% RH) in the DC until they are consolidated onto dispatch pallets. Storage of the packages in the ambient condition for several hours before consolidation will allow the corrugated cartons to regain a certain degree of their structural strength with the evaporation of moisture from the paperboards. Therefore, practicing First-in-Frist out (FIFO) in the receiving area of the DC for ripen bananas is helpful in minimizing further damage in the distribution process. Simulated vibration experiments of the consolidated pallets also revealed that mix-stacking of banana cartons with RPCs can lead to elevated damage in bananas. Additionally, column-stacking of packages was shown to be reducing mechanical stresses such as compression on bananas compared to the flat-stacking on the pallets. Column-stacking allows the packages in the bottom tiers to support the weight by the corner-posts as intended. Therefore, the current industry practice of stacking voluminous and heavy banana cartons at the bottom of the consolidated pallet needs to be changed by possibly column-stacking the banana packages on the consolidated pallets and, also avoiding the stacking of RPCs on banana cartons.

7.4.6. **Switching to the One-piece carton**

Several factors together with the inner packing and stacking arrangement affected the behavior of each type of packaging under simulated vibration. A corrugated carton is often considered as a single structure however, the stiffness of a package is a function of the stiffness of the different parts of the package, with the top and bottom sections usually having a lower stiffness compared to the middle section (Meng, Trost & Östlund 2007). The performance of corrugated cartons depends on function of factors such as the quality of the input cellulose fiber, mechanical properties of the components, board grades, machine precision and the human factors involved in the corrugation process (Fadiji et al. 2018).

A package is deemed to have failed if the package itself, internal packing or the packaged contents are scratched, damaged or deformed (Fadiji et al. 2018). The one-piece corrugated carton exhibited reduced damage levels in bananas compared to the two-piece carton. Even though both use corrugated paperboard for construction, the package design, length-height ratio, paperboard grades, and fluting were important for packaging performance (Fadiji et al. 2017; Fadiji et al. 2018; Fadiji, Coetzee, Chen, et al. 2016; Fadiji, Coetzee, Pathare, et al. 2016; Opara & Fadiji 2018). This resulted in differences in compression strength, base-sagging levels, moisture resistance and vibration dampening characteristics of packaging. One-piece carton, which had a slightly increased height-length ratio and reduced vibration transmissibility around the resonance frequencies exhibited higher compression strength and decreased base-sagging levels under high RH ripening conditions. These performance characteristics were important not only during the interstate transport of bananas in full pallets but also during the distribution of ripe bananas in partial and consolidated pallets. Therefore, one-piece cartons can be considered as a better alternative compared to the currently used two-piece carton in Australia.

There are natural variations of banana size in different growing regions. The current height of the corrugated cartons can be challenging to some growers, given that clusters with large bananas make it difficult to optimally fill the carton during the packing process. This may result in over-filling of cartons which causes bruising especially in the bottom tiers of the pallets due to the top-load. For such growers, the protective performance of one-piece carton can be improved through adjusting package height for optimal head-space. Too little headspace can cause fruits to be compressed due to base sagging. Too much headspace may cause fruits to move freely due to vibration. Therefore, ensuring an optimum level of headspace to maintain quasi-static compression on bananas has the best ability to minimize both types of damage (i.e. bruising and abrasion). However, it will be practically impossible for the fruit packers to determine the headspace during the packing process without a tool or a visual aid. For this purpose, a pre-printed mark on the inner insides of the cartons to indicate the highest fill level can be beneficial for the packers. This study has shown that the optimal headspace can vary depending on the level of base-sagging in cartons and the base-sagging levels increase with the highly humid ripening conditions. The base sagging level for one-piece carton varied between 9-12 mm during the first two days of ripening. Therefore, at least a mean headspace of 9 mm can be recommended during packing of clusters in the one-piece cartons to ensure a firm filling of bananas inside the cartons.

The ideal package should provide sufficient protection to the produce at the lowest possible overall cost (Fadiji et al. 2018; Robertson 2005). Switching to the one-piece carton as recommended can be slightly costly for the growers (i.e. AU $ 0.001 per carton) due to the better-quality paperboard used in their production (refer to Appendix A2), which is also exhibited by the increased compression strength (i.e. 81% higher) compared to the two-piece carton. However, Kitchener (2015) demonstrated that there is a significant cost saving (i.e. AU $ 0.01 per carton) when the total cost of packing material, labour and palatizing are considered (refer Appendix A1.). The main cost savings by using the one-piece carton is apportioned to the reduction in total labour costs since there is no requirement to place the carton lids in a one-piece carton. However, Kitchener (2015) further elaborated that there will be a premium of

AU $ 0.2 to $ 0.3 per one-piece carton due to the low volumes demanded during the early stages of switching. Therefore, for the growers there is a net cost saving by switching to the one-piece carton will be realistic in the long-term with the switching of majority of growers. However, the other factors including the environmental sustainability may also need to be considered for an industry-wide switch to one-piece carton in Australia.

Carton manufacturers can also consider recycled paper material instead of the virgin paperboards, reinforced by water-resistant waxing to further minimize the cost of the one-piece carton while controlling the effect of moisture absorption in the high RH ripening environment. However, this may affect the dampening properties and the protective performance for bananas during the exposure to vibration, which need to be re-evaluated with the changes in materials for manufacturing.

7.4.7. Re-arranging the Back-store Storage and On-shelf Displays

Several retail stores that were visited during the study had limited back-store storage area, especially the stores in the metropolitan areas in Melbourne. Stacking packages on top of each other with open-lids for air cooling was found to be a prime cause of the last-mile quality deterioration of the packaged bananas. Partitioned steel trolley racks can be considered for air-cooling banana packages, which allows high-capacity storage of the packages in a limited space. The repetitive handling of banana clusters by consumers unavoidably results in damages such as scuffing and blackened rub in bananas. The repetitive handling of the clusters can be minimized by cutting clusters in different number of fingers or weight range. The on-shelf displays are mostly constructed from hard-plastic which can exacerbate the abrasion damage in bananas during the handling. Therefore, improve shelf-displays with soft cushioning can be considered to minimize such abrasion damages in bananas.

7.4.8. Other Recommendations

The field observation study found that manual palletising of packages was one of the most labour-intensive, repetitive and manual work processes in the entire SC. Each banana package weighs more than 15 kg and a full pallet contains 60 packages, which amounts to 60 heavy lifting stacking-moves by the pallet stacker. The fatigue due to the repetitive and heavy nature of the pallet stacking process means the handling of packages can be rough or rapid at times. Therefore, frequent breaks are advisable for the pallet stackers, however sourcing labour to a role of this nature can be challenging for the growers in remote areas such as far north Queensland. The feasibility of mechanical palletising can be explored to overcome this challenge however, the industry may need to bear the initial cost of mechanization.

Accurate forecasting of demand from buyers and retail markets facilitating a smooth production planning for the pack house is important to minimize the urgency and the unnecessary pressure on the pack house staff. During the field observations, few occasions of abrupt demand emerged and the rapid nature of packing process and the pressure on the production staff inevitably meant rapid packing of the cartons and handling of packages. Previous studies confirmed that accurate forecasting of demand is necessary to ensure a smooth supply of bananas which may also affect their quality in the post-harvest SC (Mvumi, Matsikira & Mutambara 2016; Vidanagama & Piyathilaka 2011). Therefore, accurate forecasting and effective communication between the retailers, ripeners, transporters and the growers can be important to reduce mechanical damage to bananas caused by rapid handling across the SC.

Cosmetic defects caused by mechanical stresses on packaged bananas across the SC are usually detected at the retail stores upon the unpacking of cartons however, the unpacking process itself can cause damage such as neck injuries and bruising in ripe bananas. The market observations showed that some retail staff unpack the two-piece carton from the top by removing the lid and reaching for the clusters. While unpacking from the top by removing the lid has been the conventional method, taking the clusters from the top can be difficult due to the three-layer inter-locking arrangement of the clusters during the packing process. Therefore, reaching the clusters from the bottom of the package by flipping the carton up-side-down and first removing the base of the carton is the easiest and the safest method of unpacking. Training the retail staff to properly unpack the carton can help prevent further damage to ripe bananas in retail stores.

7.4.9. Extendibility of the Findings

This research identified a range of factors affecting damage development in bananas, along the selected post-harvest SC. Due to the nature of banana plantation and consumption in Australia, the selected SC is a good representation of about three quarters of total bananas sold in Australia (Day 2018). The prevalent factors that are associated with mechanical damage development as identified in this research can be common to a majority of post-harvest banana SCs in Australia. However, the specific causes of damage such as the incidental factors can be unique to each SC. Therefore, extending the findings of the study to other banana SCs needs careful consideration of the processes, nodes, channels and the overall design in each SC. It can be reasonably established that the majority of these findings and recommendations are applicable to similar post-harvest banana SCs in Australia (refer the Fig. 1.2 for the stages in a typical post-harvest banana SC in Australia). Extending those specific findings related to industry practices to a global context can be challenging due to the differences in packing, stacking, handling and transporting procedures. For example, the production methods and shipping process in export-oriented SCs can be very different from those in domestic-focused SCs. However, the findings and recommendations may be carefully extended to similar post-harvest SCs specially in countries with similar post-harvest operations and handling conditions. In addition, the damage occurrence during transport in similar global SCs need to be comparatively considered especially with respect to the distance, duration and the road conditions and the type of vehicles used to transport packaged bananas from the farm-gates to the retail stores.

7.5. Limitations and Future Research

Several limitations existed in this study, which need consideration when interpreting the results and generalizing the findings. These limitations were mostly due to the resource and time constraints. The number of interstate trips in this study was restricted by the resource constraints such as the cost associated with each data collection trial and the associated logistical complexities. The interstate trip was over 3000 km in distance by road. It has been a common practice in this field of research to characterize the transport environment in a limited number of field trips (Barchi et al. 2002; Berardinelli et al. 2003, 2005; Rissi et al. 2008; Singh & Marcondes 1992; Singh, Burgess & Xu 1992; Singh et al. 2007). This study was also restricted to the investigation of damage occurrence in bananas transported in road trucks as this has been the only method of interstate transport of packaged bananas in Australia. Future research can consider other modal variations and comparisons such as rail and costal shipping for the long-distance transport of packaged bananas.

The simulated vibration experiments for package testing were based on the PSD spectra, constructed from the vertical acceleration data during the transport of bananas from Tully in Queensland to Melbourne, Victoria. The PSD used in these experiments was the averaged spectra calculated by averaging each PSD derived from one-million acceleration data points at 400 Hz sampling frequency. Averaging the PSDs can cause transit shocks to be smoothened and thus, not represented in the final PSD spectra used in the vibration simulation experiments (Fernando et al. 2018a). Additionally, the capability of vibration simulators to simulate intermittent transient shocks during the transport vibration simulation was also limited. Consequently, transient shocks encountered along the road route during transport were not adequately simulated in this study and thus, the impact of intermittent shocks on the damage development in packaged bananas needs further investigation. More research can be conducted by subjecting palletised and packaged bananas to simulated transient shocks, to confirm how the damage levels will be further influenced due to the high energy shocks during transport.

The initial phases of this study used the visual inspection method to assess the damage levels in bananas by a widely used damage assessment chart (Ekman et al. 2011) in the Australian banana industry. However, this is a subjective damage assessment method and therefore the accuracy can be lower compared to the other objective damage assessment methods. To minimize the discrepancies and to improve the accuracy of the VDI method, the damages were assessed by the same assessor and a large number of fruits (i.e. over 30,000 bananas) were assessed along the post-harvest SC.

Testing of different package types confirmed that the transmission of this lower frequency energy with high spectral peaks could not be effectively dampened alone by corrugated packaging or RPCs. Paternoster, Van Camp, et al. (2017) similarly showed that high frequency vibration will decrease by 50% caused by the dampening properties of packaging material, however the transmission of low frequency vibration could not be reduced. Therefore, alternate mechanisms to reduce this transmission increased vibration energy in the lower frequency range need to be further researched. These may include improved shock-absorbent packaging and dampening mechanisms embedded in the base of the pallet structure.

Regardless of the package design, packaged bananas in the most bottom tiers of the stacked pallet exhibited moderate levels of damage caused by vibration. Minimizing the mechanical damage in the bottom tiers was much effective with the vacuum-tightening of the clusters. However, the vacuum-tightening solution requires further testing to determine the influence on the ripening of bananas after packing inside plastic wrapping. If the vacuumed bag is sealed, it may effectively restrict the relative movement for a longer period during transport but will also cause anaerobic respiration in bananas. In contrast, if the bags are unsealed, the vacuum-tightened status may not last for long. Therefore, further research on tensioned-wrapping of the clusters can be considered to overcome these challenges while effectively restricting the relative movement of the banana fingers. In addition, investigations on polymer-based vibration dampening solutions for pallets can be further researched to effectively reduce the transmission of high frequency vibration into the bottom tiers of the pallet. These potential solutions may also need further testing and evaluation in relation to environmental and economic feasibility before practical implementation in the post-harvest SCs in Australia.

7.6. Conclusion

The goal of this thesis was to understand the damage development packaged bananas along the post-harvest SCs with the intention of proposing interventions to improve the appearance quality banana at the retail stores. With the knowledge accumulated throughout the research it was possible to determine when, where, to what extent and why the damages developed. The improved understanding of the extent and the mechanism of damage development contributed to addressing several work practice issues in the industry and recommending more suitable packaging, stacking and packing methods for reducing the risk of damage in the post-harvest SC. Overall, the research objectives of this research have been systematically achieved although subjected to several practical constraints which have been highlighted. Finally, it is expected this work will benefit the industry while providing a foundation for similar academic and industry-based research projects into the future.

Bibliography

Aba, IP, Gana, YM, Ogbonnaya, C & Morenikeji, O 2012, 'Simulated transport damage study on fresh tomato (Lycopersicon esculentum) fruits', *Agricultural Engineering International: CIGR Journal*, vol. 14, no. 2, pp. 119-126.

Abbott, JA 1999, 'Quality measurement of fruits and vegetables', *Postharvest Biology and Technology*, vol. 15, no. 3, pp. 207-225.

Abedi, G & Ahmadi, E 2014, 'Bruise susceptibilities of Golden Delicious apples as affected by mechanical impact and fruit properties', *The Journal of Agricultural Science*, vol. 152, no. 3, pp. 439-447.

ABGC 2016, *Australian Banana Grower's Council* Australian Banana Grower's Council viewed 30/11/2016, <http://abgc.org.au/banana-industry-2/our-industry/key-facts/>.

ABS 2017, *Australian Demographic Statistics, Dec 2017*, Australian Bureau of Statistics, viewed 14/09/2018, <http://www.abs.gov.au/ausstats/abs@.nsf/0/D56C4A3E41586764CA2581A70015893E?Opendocument>.

Accorsi, R, Cascini, A, Cholette, S, Manzini, R & Mora, C 2014, 'Economic and environmental assessment of reusable plastic containers: A food catering supply chain case study', *International Journal of Production Economics*, vol. 152, pp. 88-101.

Acican, T, Alibaş, K & Özelkök, I 2007, 'Mechanical damage to apples during transport in wooden crates', *Biosystems Engineering*, vol. 96, no. 2, pp. 239-248.

Ahmadi, E 2012, 'Bruise susceptibilities of kiwifruit as affected by impact and fruit properties', *Research in Agriculture Engineering*, vol. 58(2012), 107-113.

Ahmadi, E, Ghassemzadeh, HR, Sadeghi, M, Moghaddam, M & Neshat, SZ 2010, 'The effect of impact and fruit properties on the bruising of peach', *Journal of Food Engineering*, vol. 97, no. 1, pp. 110-117.

Akkaravessapong, P, Joyce, D & Turner, D 1992, 'The relative humidity at which bananas are stored or ripened does not influence their susceptibility to mechanical damage', *Scientia Horticulturae*, vol. 52, no. 3, pp. 265-268.

Al-Hosni, A, Al-Busaidi, K, Al-Farsi, K, Al-Jabri, M & Al-Azri, H 2008, 'Postharvest characteristics and qualities of selected banana (Musa spp.) cultivars in Oman', in *IV International Symposium on Banana: International Conference on Banana and Plantain in Africa: Harnessing International 879*, pp. 407-411.

Alayunt, F, Cakmak, B, Can, H & Aksoy, U 1997a, 'Vibration damage trial on some fig cultivars', in *I International Symposium on Fig* pp. 305-310.

Alayunt, F, Cakmak, B, Can, H & Aksoy, U 1997b, 'Vibration damage trial on some fig cultivars', in *I International Symposium on Fig 480*, pp. 305-310.

Ali, I, Nagalingam, S & Gurd, B 2018, 'A resilience model for cold chain logistics of perishable products', *The International Journal of Logistics Management*, vol. 29, no. 3, pp. 922-941.

Arazuri, S, Arana, I & Jaren, C 2010, 'Evaluation of mechanical tomato harvesting using wireless sensors', *Sensors (Basel)*, vol. 10, no. 12, pp. 11126-11143, doi:10.3390/s101211126.

Ariana, DP, Lu, R & Guyer, DE 2006, 'Near-infrared hyperspectral reflectance imaging for detection of bruises on pickling cucumbers', *Computers and Electronics in Agriculture*, vol. 53, no. 1, pp. 60-70.

ASTM 2016a, *Packaging and Shipping Container Standards*, ASTM International, West Conshohocken, PA.

ASTM 2016b, *Standard Practice for Performance Testing of Shipping Containers and Systems*, ASTM International, West Conshohocken, PA: ASTM International.

Aus-Std. 2006, *Methods of test for pulp and paper* Standards Aus. , Australia, viewed 30/11/2019, <https://www.standards.org.au/standards-catalogue/sa-snz/manufacturing/pk-019/as-slash-nzs--1301-dot-457s-2006>.

Babarinsa, F & Ige, M 2012, 'Young's Modulus for packaged Roma tomatoes under compressive loading', *Int. J. Sci. Eng. Res*, vol. 3, no. 10, pp. 314-320.

Bajema, RW & Hyde, G 1998, 'Instrumented pendulum for impact characterization of whole fruit and vegetable specimens', *Transactions of the ASAE*, vol. 41, no. 5, p. 1399-1405.

Banks, NH, Borton, CA & Joseph, M 1991, 'Compression bruising test for bananas', *Journal of the Science of Food and Agriculture*, vol. 56, no. 2, pp. 223-226.

Banks, NH & Joseph, M 1991, 'Factors affecting resistance of banana fruit to compression and impact bruising', *Journal of the Science of Food and Agriculture*, vol. 56, no. 3, pp. 315-323.

Baranowski, P, Mazurek, W, Wozniak, J & Majewska, U 2012, 'Detection of early bruises in apples using hyperspectral data and thermal imaging', *Journal of Food Engineering*, vol. 110, no. 3, pp. 345-355.

Barchi, GL, Berardinelli, A, Guarnieri, A, Ragni, L & Fila, CT 2002, 'Damage to Loquats by Vibration-simulating Intra-state Transport', *Biosystems Engineering*, vol. 82, no. 3, pp. 305-312, doi: 10.1006/bioe.2002.0067.

Berardinelli, A, Donati, V, Giunchi, A, Guarnieri, A & Ragni, L 2003, 'Effects of Transport Vibrations on Quality Indices of Shell Eggs', *Biosystems Engineering*, vol. 86, no. 4, pp. 495-502. doi: 10.1016/j.biosystemseng.2003.08.017

Berardinelli, A, Donati, V, Giunchi, A, Guarnieri, A & Ragni, L 2005, 'Damage to pears caused by simulated transport', *Journal of Food Engineering*, vol. 66, no. 2, pp. 219-226. doi: 10.1016/j.jfoodeng.2004.03.009

Berry, TM, Ambaw, A, Defraeye, T, Coetzee, C & Opara, UL 2019, 'Moisture adsorption in palletised corrugated fibreboard cartons under shipping conditions: A CFD modelling approach', *Food and Bioproducts Processing*, vol. 114, pp. 43-59.

Besada, C, Arnal, L, Salvador, A & Martínez-Jávega, JM 2009, 'Flesh browning of persimmon caused by mechanical damage in packing line', in *VI International Postharvest Symposium 877*, pp. 555-560.

Blahovec, J 1999, 'Bruise resistance coefficient and bruise sensitivity of apples and cherries', *International agrophysics*, vol. 13, pp. 315-322.

Blahovec, J, Mareš, V & Paprštein, F 2004, 'Static and dynamic tests of pear bruise sensitivity', *Research in Agricultural Engineering*, vol. 50, no. 54, p. e60.

Blanke, MM 2014, 'Reducing ethylene levels along the food supply chain: a key to reducing food waste?', *Journal of the Science of Food and Agriculture*, vol. 94, no. 12, pp. 2357-2361.

Bollen, A, Nguyen, H & Rue, BD 1999, 'Comparison of methods for estimating the bruise volume of apples', *Journal of Agricultural Engineering Research*, vol. 74, no. 4, pp. 325-330.

Bollen, A, Timm, E & Rue, BD 2001, 'Relation of individual forces on apples and bruising during orchard transport of bulk bins', *Applied Engineering in Agriculture*, vol. 17, no. 2, p. 193-200.

Bonnin, AS, Nolot, JB, Huart, V, Pellot, J, Krajka, N, Odof, S & Erre, D 2018, 'Decomposition of the acceleration levels distribution of a road transport into a sum of weighted Gaussians: Application to vibration tests', *Packaging Technology and Science*.

Boote, J & Mathews, A 1999, '“Saying is one thing; doing is another”: the role of observation in marketing research', *Qualitative Market Research: An International Journal*, vol. 2, no. 1, pp. 15-21.

Brusewitz, G & Bartsch, J 1989, 'Impact parameters related to post harvest bruising of apples', *Transactions of the ASAE*, vol. 32, no. 3, p. 953.

Brusewitz, G, McCollum, T & Zhang, X 1991, 'Impact bruise resistance of peaches', *Transactions of the ASAE*, vol. 34, no. 3, pp. 962-0965.

Bugaud, C, Daribo, MO & Dubois, C 2007, 'Climatic conditions affect the texture and colour of Cavendish bananas (Grande Naine cultivar)', *Scientia Horticulturae*, vol. 113, no. 3, pp. 238-243.

Bugaud, C, Ocrisse, G, Salmon, F & Rinaldo, D 2014, 'Bruise susceptibility of banana peel in relation to genotype and post-climacteric storage conditions', *Postharvest Biology and Technology*, vol. 87, pp. 113-119.

Çakmak, B, Alayunt, F, Akdeniz, C, Can, Z & Aksoy, U 2010, 'The Assessment of the Quality Losses of Fresh Fig Fruits during Transportation', *Tarım Bilimleri Dergisi*, vol. 16, no. 3, 180-193.

Cantwell, AAKM 2007, *Produce quality rating scales and colour charts.* , UC Davis University;CA, USA.

Chaiwong, S & Bishop, CF 2015, 'Effect of vibration damage on the storage quality of 'Elsanta' strawberry', *Australian Journal of Crop Science*, vol. 9, no. 9, p. 859-864.

Charles, D 1993, 'Derivation of environment descriptions and test severities from measured road transportation data', *Journal of the IES*, vol. 36, no. 1, pp. 37-42.

Chen, P & Sun, Z 1981, 'Impact parameters related to bruise injury in apples', *Paper-American Society of Agricultural Engineers (Microfiche collection)(USA), ASAE 81-3041*.

Chonhenchob, V, Kamhangwong, D & Singh, SP 2008a, 'Comparison of reusable and single ‐ use plastic and paper shipping containers for distribution of fresh pineapples', *Packaging Technology and Science*, vol. 21, no. 2, pp. 73-83.

Chonhenchob, V, Kamhangwong, D & Singh, SP 2008b, 'Comparison of reusable and single ‐ use plastic and paper shipping containers for distribution of fresh pineapples', *Packaging Technology and Science: An International Journal*, vol. 21, no. 2, pp. 73-83.

Chonhenchob, V & Singh, SP 2003a, 'A comparison of corrugated boxes and reusable plastic containers for mango distribution', *Packaging Technology and Science: An International Journal*, vol. 16, no. 6, pp. 231-237.

Chonhenchob, V & Singh, SP 2003b, 'A comparison of corrugated boxes and reusable plastic containers for mango distribution', *Packaging Technology and Science*, vol. 16, no. 6, pp. 231-237.

Chonhenchob, V & Singh, SP 2005a, 'Packaging performance comparison for distribution and export of papaya fruit', *Packaging Technology and Science*, vol. 18, no. 3, pp. 125-131.

Chonhenchob, V & Singh, SP 2005b, 'Packaging performance comparison for distribution and export of papaya fruit', *Packaging Technology and Science: An International Journal*, vol. 18, no. 3, pp. 125-131.

Chonhenchob, V, Sittipod, S, Swasdee, D, Rachtanapun, P, Singh, S & Singh, JA 2009, 'Effect of truck vibration during transport on damage to fresh produce shipments in Thailand', *Industrial Technology*, vol. 3, pp. 27-38.

Chukwu, U., Olorunda, A., & Ferris, R. 1998. Effect of postharvest injury on weight loss, ripening period, and pulp loss on Musa spp. fruits. Postharvest Technology and Commodity Marketing:Proceedings of a Postharvest Conference IITA, 29 November–1 December1995, Accra.

Crisosto, CH, Garner, D, Doyle, J & Day, KR 1993, 'Relationship between fruit respiration, bruising susceptibility, and temperature in sweet cherries', *HortScience*, vol. 28, no. 2, pp. 132-135.

Crisosto, CH, Johnson, RS, Luza, J & Day, K 1993, 'Incidence of physical damage on peach and nectarine skin discoloration development: Anatomical studies', *Journal of the American Society for Horticultural Science*, vol. 118, no. 6, pp. 796-800.

Crisosto, CH, Mitchell, FG & Johnson, S 1995, 'Factors in fresh market stone fruit quality', *Postharvest News and Information*, vol. 6, no. 2, pp. 17-21.

Da Costa, FB, Puschmann, R, Moreira, SI, Junior, JIR & Finger, FL 2010, 'Survey of mechanical injury in 'Prata Ana'banana during shipping', *Revista Verde de Agroecologia e Desenvolvimento Sustentável*, vol. 5, no. 1, pp. 72-78.

Dadzie, BK & Orchard, JE 1997, *Routine post-harvest screening of banana/plantain hybrids: criteria and methods*, International Plant Genetic Resources Institute (IPGRI).

Dang, H-Q, Kim, I, Cho, B-K & Kim, MS 2012, 'Detection of bruise damage of pear using hyperspectral imagery', in *Control, Automation and Systems (ICCAS), 2012 12th International Conference on*, pp. 1258-1260.

Dantas, TB, Ferraz, ACdO, Honório, SL & Lima, GP 2013, 'Polyphenoloxidase activity in peaches after vibration', *Engenharia Agrícola*, vol. 33, no. 2, pp. 312-318.

Day, C 2018, 'Despite Higher Prices, Aussies Still Love their Bananas', viewed 14/09/2018, <https://www.nielsen.com/au/en/insights/news/2018/despite-higher-prices-aussies-still-love-their-bananas.html>.

Defilippi, BG, Whitaker, BD, Hess-Pierce, BM & Kader, AA 2006, 'Development and control of scald on wonderful pomegranates during long-term storage', *Postharvest Biology and Technology*, vol. 41, no. 3, pp. 234-243.

Del Aguila, JS, Heiffig-del Aguila, LS, Sasaki, FF, Tsumanuma, GM, das Graças Ongarelli, M, Spoto, MHF, Jacomino, AP, Ortega, EMM & Kluge, RA 2010, 'Postharvest modifications of mechanically injured bananas', *Revista Iberoamericana de Tecnología Postcosecha, Hermosillo*, vol. 10, no. 2, pp. 73-85.

Demir, F, Kara, Z & Carman, K 2010, 'Table Grapes Transport Simulation Study by Bardas (Vitis vinifera L.) Cultivar Grown in Karaman Turkey'. Retrieved from http://eprints.ibu.edu.ba/546/1/issd2010_science_book_p456-p463.pdf (Accessed 29/10/2017)

Diener, R, Elliott, K, Nesselroad, P, Ingle, M, Adams, R & Blizzard, S 1979, 'Bruise energy of peaches and apples', *Transactions of the ASAE*, vol. 22, no. 2, pp. 287-0290.

Dos Santos, J & Ferraz, A 2007, 'Mechanical damage caused to banana fruits by manual harvesting', *Revista Brasileira de Armazenamento*, vol. 32, no. 2, pp. 141-151.

Dunno, K 2014, 'Experimental Evaluation of Techniques Designed to Reduce Vibration Simulation Test Time', *Journal of Applied Packaging Research*, vol. 6, no. 2, p. 1-10.

Eissa, A & Hafiz, A 2012, 'Comparison of package cushioning materials to protect vibration damage to golden delicious apples', *International Journal of Latest Trends in Agriculture and Food Sciences*, vol. 2, no. 1, PP. 36-57.

Eissa, AHA, Albaloushi, NS & Azam, MM 2013, 'Vibration analysis influence during crisis transport of the quality of fresh fruit on food security', *Agricultural Engineering International: CIGR Journal*, vol. 15, no. 3, pp. 181-190.

Ekanayake, S & Bandara, L 2002, 'Development of banana fruit leather', *Annals of the Sri Lanka Department of Agriculture*, vol. 4, pp. 353-358.

Ekman, J, King, N, Lindsay, S & Gething, K 2011, *Improved handling in banana supply chains*, Department of Primary Industries, Queensland.

Ellram, LM 1996, 'The use of the case study method in logistics research', *Journal of business logistics*, vol. 17, no. 2, p. 93-138.

ElMasry, G, Wang, N, Vigneault, C, Qiao, J & ElSayed, A 2008, 'Early detection of apple bruises on different background colors using hyperspectral imaging', *LWT-Food Science and Technology*, vol. 41, no. 2, pp. 337-345.

Fadiji, T, Berry, T, Coetzee, CJ & Opara, L 2017, 'Investigating the mechanical properties of paperboard packaging material for handling fresh produce under different environmental conditions: experimental analysis and finite element modelling', *Journal of Applied Packaging Research*, vol. 9, no. 2, p. 20-34.

Fadiji, T, Berry, TM, Coetzee, CJ & Opara, UL 2018, 'Mechanical design and performance testing of corrugated paperboard packaging for the postharvest handling of horticultural produce', *Biosystems Engineering*, vol. 171, pp. 220-244.

Fadiji, T, Coetzee, C, Chen, L, Chukwu, O & Opara, UL 2016, 'Susceptibility of apples to bruising inside ventilated corrugated paperboard packages during simulated transport damage', *Postharvest Biology and Technology*, vol. 118, pp. 111-119.

Fadiji, T, Coetzee, C, Pathare, P & Opara, UL 2016, 'Susceptibility to impact damage of apples inside ventilated corrugated paperboard packages: Effects of package design', *Postharvest Biology and Technology*, vol. 111, pp. 286-296.

FAO 2019, *FAO(Food and Agriculture Organization of the United Nations)*. viewed 23/01/2019], <http://www.fao.org/faostat/en/>.

Fei Lu, Ys & Satake, H, Kitazawa Takaaki 2008, 'Effect of Sampling Parameters on Shock and Vibration Levelsin Truck Transport'. Paper presented at the Proceedings of the 17th IAPRI World Conference on Packaging 2008.

Fei, X, Chuanri, L, Tongmin, J & Ahlin, K 2014, 'Synthesis of running rms-induced non-Gaussian random vibration based on Weibull distribution', *Vibroengineering PROCEDIA*, vol. 4, pp. 40-45.

Feng, X, Biasi, B & Mitcham, EJ 2004, 'Effects of various coatings and antioxidants on peel browning of 'Bartlett'pears', *Journal of the Science of Food and Agriculture*, vol. 84, no. 6, pp. 595-600.

Fernando, I, Fei, J & Stanley, R 2019, 'Measurement and analysis of vibration and mechanical damage to bananas during long-distance interstate transport by multi-trailer road trains', *Postharvest Biology and Technology*, vol. 158, 110977.

Fernando, I, Fei, J, Stanley, R & Enshaei, H 2018a, 'Measurement and evaluation of the effect of vibration on fruits in transit', *Packaging Technology and Science*, vol. 31, no. 11, pp. 723-738.

Fernando, I, Fei, J, Stanley, R & Enshaei, H 2018b, 'Measurement and evaluation of the effect of vibration on fruits in transit—Review', *Packaging Technology and Science*, pp. 1-16.

Ferreira, M, Ferraz, A & Franco, A 2004, 'Tomato packing lines studies with an instrumented sphere in Brazil', in *V International Postharvest Symposium 682*, pp. 1753-1760.

Ferris, R, Hotsonyame, G, Wainwright, H & Thompson, A 1993, 'The effects of genotype, damage, maturity, and environmental conditions on the postharvest life of plantain', *Tropical Agric.*, vol. 70, pp. 45-45.

Fischer, D, Craig, W, Watada, A, Douglas, W & Ashby, B 1992, 'Simulated in-transit vibration damage to packaged fresh market grapes and strawberries', *Applied Engineering in Agriculture*, vol. 8, no. 3, pp. 363-366.

Gambella, F, Paschino, F & Dimauro, C 2013, 'Evaluation of fruit damage caused by mechanical harvesting of table olives', *Transactions of the ASABE*, vol. 56, no. 4, pp. 1267-1272.

Gamble, J, Harker, FR, Jaeger, SR, White, A, Bava, C, Beresford, M, Stubbings, B, Wohlers, M, Hofman, PJ & Marques, R 2010, 'The impact of dry matter, ripeness and internal defects on consumer perceptions of avocado quality and intentions to purchase', *Postharvest Biology and Technology*, vol. 57, no. 1, pp. 35-43.

Garcia-Ramos, F, Ortiz-Canavate, J & Ruiz-Altisent, M 2004, 'Analysis of the factors implied in the fruit-to-fruit impacts on packing lines', *Applied engineering in agriculture*, vol. 20, no. 5, p. 671.

Garcia-Romeu-Martinez, M-A, Singh, SP & Cloquell-Ballester, V-A 2008, 'Measurement and analysis of vibration levels for truck transport in Spain as a function of payload, suspension and speed', *Packaging Technology and Science*, vol. 21, no. 8, pp. 439-451.

García Fernández, JL, Ruiz-Altisent, M & Barreiro Elorza, P 1995, 'Factors influencing mechanical properties and bruise susceptibility of apples and pears', *Journal of Agricultural Engineering Research*, vol. 61, no. 1, pp. 11-17.

Ge, C & Pan, L 2018, 'Vibration damage rate curves for quantifying abrasion of printed packaging in accelerated random vibration test', *Packaging Technology and Science*, vol. 31, no. 2, pp. 71-81.

Gebresenbet, G, Aradom, S, Bulitta, FS & Hjerpe, E 2011, 'Vibration levels and frequencies on vehicle and animals during transport', *Biosystems Engineering*, vol. 110, no. 1, pp. 10-19.

Geyer, M, Herold, B, Oberbarnscheidt, B, Borsa, B, Kovacs, L & Jakovac, F 2002, 'Detection of mechanical load and damage of industrial tomatoes during transport', in *International Conference: Postharvest Unlimited* pp. 273-280.

Godshall, WD 1971, *Frequency Response Damping, and Transmissibility Characteristics of Top-Loaded Corrugated Containers*, DTIC Document. United States Department of Agriculture, Forest Service, Forest Products Laboratory, Research Paper FPL 160, 1971.

Gómez-Sanchis, J, Blasco, J, Soria-Olivas, E, Lorente, D, Escandell-Montero, P, Martínez-Martínez, J, Martínez-Sober, M & Aleixos, N 2013, 'Hyperspectral LCTF-based system for classification of decay in mandarins caused by Penicillium digitatum and Penicillium italicum using the most relevant bands and non-linear classifiers', *Postharvest Biology and Technology*, vol. 82, pp. 76-86.

Grant, J & Thompson, J 1997, 'Packing-line modifications reduce pitting and bruising of sweet cherries', *California Agriculture*, vol. 51, no. 2, pp. 31-35.

Griffiths, K 2012, 'An improved method for simulation of vehicle vibration using a journey database and wavelet analysis for the pre-distribution testing of packaging', Doctoral Thesis, University of Bath Bath, UK.

Griffiths, K, Hicks, B, Keogh, P & Shires, D 2016, 'Wavelet analysis to decompose a vibration simulation signal to improve pre-distribution testing of packaging', *Mechanical Systems and Signal Processing*, vol. 76, pp. 780-795.

Griffiths, K, Hicks, B., Keogh, P., Shires, D. and Sheppard-Fidler, S., 2011, 'Simulating the transport environment for packaging testing using a multi degree of freedom method', paper presented to International Safe Transit Association, 2011 International Transport Packaging Forum, , Florida, USA.

Griffiths, K, Shires, D, White, W, Keogh, PS & Hicks, BJ 2013, 'Correlation study using scuffing damage to investigate improved simulation techniques for packaging vibration testing', *Packaging Technology and Science*, vol. 26, no. 7, pp. 373-383.

Guillermin, P, Camps, C & Bertrand, D 2004, 'Detection of bruises on apples by near infrared reflectance spectroscopy', in *V International Postharvest Symposium 682*, pp. 1355-1362.

Guyer, D, Schulte, N, Timm, E & Brown, G 1991, 'Minimizing apple bruising in the packingline', *Tree Fruit Postharvest Journal*, vol. 2, no. 4, pp. 14-20.

Hadi, S, Ahmad, D & Akande, FB 2009, 'Determination of the bruise indexes of oil palm fruits', *Journal of Food Engineering*, vol. 95, no. 2, pp. 322-326.

Hailu, M, Workneh, TS & Belew, D 2013, 'Review on postharvest technology of banana fruit', *African Journal of Biotechnology*, vol. 12, no. 7, pp. 635-647.

Harker, R 2009, 'Consumer preferences and choice of fruit: the role of avocado quality', in *4th Australian and New Zealand Avocado Growers Conference 21-24 July 2009*.

Harvey, JM 1978, 'Reduction of losses in fresh market fruits and vegetables', *Annual Review of Phytopathology*, vol. 16, no. 1, pp. 321-341.

Herold, B, Geyer, M & Studman, CJ 2001, 'Fruit contact pressure distributions—equipment', *Computers and Electronics in Agriculture*, vol. 32, no. 3, pp. 167-179.

HIA 2019, *All About Bananas*, Horticulture Innovation Australia viewed 28/02/2019, <https://australianbananas.com.au/>.

Hinsch, R, Slaughter, D, Craig, W & Thompson, J 1993, 'Vibration of fresh fruits and vegetables during refrigerated truck transport', *Transactions of the ASAE*, vol. 36, no. 4, pp. 1039-1042.

Hofman, PJ 2003, *Bruising of 'Hass' Avocado from Harvest to the Packhouse*, Horticulture Australia.

Holt, J & Schoorl, D 1977, 'Bruising and energy dissipation in apples', *Journal of Texture Studies*, vol. 7, no. 4, pp. 421-432.

Hosoyama, A, Saito, K & Nakajima, T 2013, 'Effect of non-Gaussian random vibration on packaging response using numerical simulation', *Journal of Packaging Science and Technology, Japan*, vol. 22(4): , pp. 269-278. .

Hsiao, Y-H, Chen, M-C, Lu, K-Y & Chin, C-L 2018, 'Last-mile distribution planning for fruit-and-vegetable cold chains', *The International Journal of Logistics Management*, vol. 29, no. 3, pp. 862-886.

Hu, MH, Dong, Q-L, Malakar, PK, Liu, B-L & Jaganathan, GK 2015, 'Determining banana size based on computer vision', *International Journal of Food Properties*, vol. 18, no. 3, pp. 508-520.

Hu, MH, Dong, Ql, Liu, Bl & Malakar, PK 2014, 'The Potential of Double K - Means Clustering for Banana Image Segmentation', *Journal of Food Process Engineering*, vol. 37, no. 1, pp. 10-18.

Hu, MH, Dong, QL, Liu, BL, Pan, LQ & Walshaw, J 2015, 'Image Segmentation of Bananas in a Crate Using a Multiple Threshold Method', *Journal of Food Process Engineering*, 39(5), 427-432.

Huang, W, Zhang, B, Li, J & Zhang, C 2013, 'Early detection of bruises on apples using near-infrared hyperspectral image', in *Third International Conference on Photonics and Image in Agriculture Engineering (PIAGENG 2013)*.

Huang, W, Zhao, C, Wang, Q, Li, J & Zhang, C 2013, 'Development of a multi-spectral imaging system for the detection of bruises on apples', Paper presented at the SPIE Defense, Security, and Sensing.

Idah, P, Visa, M, Ajisegiri, E & Okpala, O 2009, 'Resonance frequency of Nigerian tomato fruit as related to prevention of damage during transportation', *Journal of Food Science and Technology (Mysore)*, vol. 46, no. 2, pp. 153-155.

Ishikawa, Y, Kitazawa, H & Shiina, T 2009, 'Vibration and shock analysis of fruit and vegetables transport-Cherry transport from Yamagata to Taipei', *Japan Agricultural Research Quarterly: JARQ*, vol. 43, no. 2, pp. 129-135.

ISTA 2017, *ISTA-2017 Resource Book*, International Safe Transit Association, MI, USA.

Jaeger, SR, Antúnez, L, Ares, G, Johnston, JW, Hall, M & Harker, FR 2016, 'Consumers’ visual attention to fruit defects and disorders: A case study with apple images', *Postharvest Biology and Technology*, vol. 116, pp. 36-44.

Jarimopas, B, Singh, SP & Saengnil, W 2005, 'Measurement and analysis of truck transport vibration levels and damage to packaged tangerines during transit', *Packaging Technology and Science*, vol. 18, no. 4, pp. 179-188.

Jarimopas, B, Singh, SP, Sayasoonthorn, S & Singh, JA 2007, 'Comparison of package cushioning materials to protect post-harvest impact damage to apples', *Packaging Technology and Science*, vol. 20, no. 5, pp. 315-324.

Ji, W, Koutsidis, G, Luo, R, Hutchings, J, Akhtar, M, Megias, F & Butterworth, M 2013, 'A digital imaging method for measuring banana ripeness', *Color Research & Application*, vol. 38, no. 5, pp. 364-374.

Jiménez-Jiménez, F, Castro-Garcia, S, Blanco-Roldán, G, González-Sánchez, E & Gil-Ribes, J 2013, 'Isolation of table olive damage causes and bruise time evolution during fruit detachment with trunk shaker', *Spanish Journal of Agricultural Research*, vol. 11, no. 1, pp. 65-71.

Jiménez-Jiménez, F, Castro-García, S, Blanco-Roldán, GL, Agüera-Vega, J & Gil-Ribes, JA 2012, 'Non-destructive determination of impact bruising on table olives using Vis–NIR spectroscopy', *Biosystems Engineering*, vol. 113, no. 4, pp. 371-378.

Jiménez-Jiménez, F, Castro-García, S, Blanco-Roldán, GL, Ferguson, L, Rosa, UA & Gil-Ribes, JA 2013, 'Table olive cultivar susceptibility to impact bruising', *Postharvest Biology and Technology*, vol. 86, pp. 100-106.

Jiménez, R, Rallo, P, Suárez, M, Morales-Sillero, A, Casanova, L & Rapoport, H 2010, 'Cultivar susceptibility and anatomical evaluation of table olive fruit bruising', in *XXVIII International Horticultural Congress on Science and Horticulture for People (IHC2010): Olive Trends Symposium-From the 924*, pp. 419-424.

Jones, C, Holt, J & Schoorl, D 1991, 'A model to predict damage to horticultural produce during transport', *Journal of Agricultural Engineering Research*, vol. 50, pp. 259-272.

Jung, HM & Park, JG 2012, 'Effects of Vibration Stress on the Quality of Packaged Apples during Simulated Transport', *Journal of Biosystems Engineering*, vol. 37, no. 1, pp. 44-50.

Junli, W & Quancheng, Z 2006, 'Effect of Moisture Content of Corrugated Box on Mechanical Properties', *Journal of Lanzhou Jiaotong University*, vol. 25(3).134-136..

Kader, AA 2002, *Postharvest technology of horticultural crops*, 3rd ed. edn, Oakland, University of California, Division of Agriculture and Natural Resources, CA.

Kajuna, S, Bilanski, W & Mittal, G 1997, 'Response of bananas and plantains to impact forces', *Journal of Texture Studies*, vol. 28, no. 1, pp. 71-85.

Kappel, F, MacDonald, RA, Cliff, M & Mckenzie, D-L 2009, '13N0770 (Stardust™) sweet cherry', *Canadian Journal of Plant Science*, vol. 89, no. 4, pp. 713-716.

Kays, SJ 1999, 'Preharvest factors affecting appearance', *Postharvest Biology and Technology*, vol. 15, no. 3, pp. 233-247.

Keresztes, JC, Goodarzi, M & Saeys, W 2016, 'Real-time pixel based early apple bruise detection using short wave infrared hyperspectral imaging in combination with calibration and glare correction techniques', *Food Control*, vol. 66, pp. 215-226.

Kim, JN, Sim, JM, Park, MJ, Kim, GS, Kim, J & Park, JM 2013, 'Analysis and Modelling of Vibration Performance for Multi-layered Corrugated Structure', *Journal of Biosystems Engineering*, vol. 38, no. 4, pp. 327-334.

Kipp, B 2008, 'Environmental data recording, analysis and simulation of transport vibrations', *Packaging Technology and Science*, vol. 21, no. 8, pp. 437-438.

Kipp, W 2001a, 'Accelerated Random Vibration with Time-history Shock', in *IoPP 2001 Annual Membership Meeting*.

Kipp, W 2001b, 'Accelerated Random Vibration with Time-History Shock for Improved Laboratory Simulation', in *IoPP Annual Meeting*.

Kirwan, MJ 2012, *Handbook of paper and paperboard packaging technology*, John Wiley & Sons.

Kitazawa, H, Ishikawa, Y, Nakamura, N, Lu, F & Shina, T 2008, 'Improvement of packaging to reduce deterioration of peach fruit caused by vibration', *Food Preservation Science*, vol. 34, no. 6, pp. 331-336.

Kitchener, T 2015, *Project BA13019 :Carton Management inthe Banana Industry*, Kitchener Partners Pty Ltd.

Kitthawee, U, Pathaveerat, S, Srirungruang, T & Slaughter, D 2011, 'Mechanical bruising of young coconut', *Biosystems Engineering*, vol. 109, no. 3, pp. 211-219.

Kleynen, O, Leemans, V & Destain, M-F 2005, 'Development of a multi-spectral vision system for the detection of defects on apples', *Journal of Food Engineering*, vol. 69, no. 1, pp. 41-49.

Kondo, N, Chong, VK, Ninomiya, K, Nishi, T & Monta, M 2005, 'Application of NIR-color CCD camera to Eggplant Grading Machine', in *2005 ASAE Annual Meeting*, Paper No. 056073, Tampa, FL.

Konya, T, Kainuma, H, Fujioka, O & Tanaka, H 2016, 'Development and adaptability of individual packaging containers for strawberries', *Japan Agricultural Research Quarterly: JARQ*, vol. 50, no. 3, pp. 183-186.

La Scalia, G, Aiello, G, Miceli, A, Nasca, A, Alfonzo, A & Settanni, L 2015, 'Effect of vibration on the quality of strawberry fruits caused by simulated transport', *Journal of Food Process Engineering*, 39(2), 140-156.

La Scalia, G, Enea, M, Micale, R, Corona, O & Settanni, L 2015a, 'Damage to strawberries caused by simulated transport', *World Academy of Science, Engineering and Technology, International Journal of Biological, Biomolecular, Agricultural, Food and Biotechnological Engineering*, vol. 9, no. 5, pp. 480-485.

La Scalia, G, Enea, M, Micale, R, Corona, O & Settanni, L 2015b, 'Damage to Strawberries Caused by Simulated Transport', in *ICSCLE 2015: 17th International Conference on Supply Chain and Logistics Engineering*.

Labavitch, J, Greve, L & Mitcham, E 1998, 'Fruit bruising: It is more than skin deep', *Perishables Handling Quarterly*, vol. 95, pp. 7-9.

Lalanne, C 2002, *Mechanical vibration & shock*: Fatigue Damage, vol. IV. Hermes Penton Ltd, London (2002).

Lallu, N, Rose, K, Wiklund, C & Burdon, J 1999, 'Vibration induced physical damage in packed Hayward kiwifruit', in *IV International Symposium on Kiwifruit 498*, pp. 307-312.

Lepine, J, Rouillard, V & Sek, M 2015a, 'Review paper on road vehicle vibration simulation for packaging testing purposes', *Packaging Technology and Science*, vol. 28, no. 8, pp. 672-682.

Lepine, J, Rouillard, V & Sek, M 2015b, 'Wavelet transform to index road vehicle vibration mixed mode signals', in *ASME 2015 Noise Control and Acoustics Division Conference at InterNoise 2015*.

Lepine, J, Rouillard, V & Sek, M 2017, 'On the use of machine learning to detect shocks in road vehicle vibration signals', *Packaging Technology and Science*, vol. 30, no. 8, pp. 387-398.

Lewis, R, Yoxall, A, Canty, L & Romo, ER 2007, 'Development of engineering design tools to help reduce apple bruising', *Journal of Food Engineering*, vol. 83, no. 3, pp. 356-365.

Li, C, Cao, B & You, SZ 2011, 'Simulation of Huangguan pear vibration damage during transportation', in *Applied Mechanics and Materials* vol. 63, pp. 453-456.

Li, J, Rao, X & Ying, Y 2011, 'Detection of common defects on oranges using hyperspectral reflectance imaging', *Computers and Electronics in Agriculture*, vol. 78, no. 1, pp. 38-48.

Li, Z, Liu, J & Li, P 2010, 'Relationship between mechanical property and damage of tomato during robot harvesting', *Transactions of the Chinese Society of Agricultural Engineering*, vol. 26, no. 5, pp. 112-116.

Li, Z & Thomas, C 2014, 'Quantitative evaluation of mechanical damage to fresh fruits', *Trends in Food Science & Technology*, vol. 35, no. 2, pp. 138-150.

Lorente, D, Aleixos, N, Gómez-Sanchis, J, Cubero, S, García-Navarrete, OL & Blasco, J 2011, 'Recent advances and applications of hyperspectral imaging for fruit and vegetable quality assessment', *Food and Bioprocess Technology*, vol. 5, no. 4, pp. 1121-1142.

Lu, F, Ishikawa, Y, Kitazawa, H & Satake, T 2010a, 'Effect of vehicle speed on shock and vibration levels in truck transport', *Packaging Technology and Science*, vol. 23, no. 2, pp. 101-109.

Lu, F, Ishikawa, Y, Kitazawa, H & Satake, T 2010b, 'Measurement of impact pressure and bruising of apple fruit using pressure-sensitive film technique', *Journal of Food Engineering*, vol. 96, no. 4, pp. 614-620.

Lu, F, Ishikawa, Y, Shiina, T & Satake, T 2008, 'Analysis of shock and vibration in truck transport in Japan', *Packaging Technology and Science*, vol. 21, no. 8, pp. 479-489.

Lü, Q & Tang, M 2012, 'Detection of hidden bruise on kiwi fruit using hyperspectral imaging and parallelepiped classification', *Procedia Environmental Sciences*, vol. 12, pp. 1172-1179.

Lü, Q, Tang, MJ, Cai, JR, Zhao, JW & Vittayapadung, S 2011, 'Vis/NIR hyperspectral imaging for detection of hidden bruises on kiwifruits', *Czech Journal of Food Sciences*, vol. 29, no. 6, pp. 595-602.

Lu, R 2003, 'Detection of bruises on apples using near–infrared hyperspectral imaging', *Transactions of the ASAE*, vol. 46, no. 2, p. 523.

Luo, R, Lewis, KM, Zhang, Q & Wang, S 2012, 'Assessment of bruise damage by vacuum apple harvester using an impact recording device', in *2012 Dallas, Texas, July 29-August 1, 2012*.

Luo, X, Takahashi, T, Kyo, K & Zhang, S 2012, 'Wavelength selection in vis/NIR spectra for detection of bruises on apples by ROC analysis', *Journal of Food Engineering*, vol. 109, no. 3, pp. 457-466.

Luyckx Audrey, LM, Hubert O, Salmon F, Brat P 2016, 'Banana Peel Physiological Post-Harvest Disorders: A Review.', *MOJ Food Processing & Technology*, vol. 3(1), pp. 226-231.

Ma, S, Karkee, M, Han, F, Sun, D & Zhang, Q 2017, 'Effect of Air Pressure and shaking Frequency on Fruit Damage in Mechanical Harvesting of Apples', in *2017 ASABE Annual International Meeting*. doi:10.13031/aim.201700727.

Macheka, L, Ngadze, RT, Manditsera, FA, Mubaiwa, J & Musundire, R 2013, 'Identifying causes of mechanical defects and critical control points in fruit supply chains: an overview of a banana supply chain', *International Journal of Postharvest Technology and Innovation*, vol. 3, no. 2, pp. 109-122.

Macleod, R, Kader, A & Morris, L 1976, 'Damage to fresh tomatoes can be reduced', *California Agriculture*, vol. 30, no. 12, pp. 10-12.

Maia, LCB, Maia, VM, Salomão, LCC, Salles, BPA & Pegoraro, RF 2015, 'Metabolic alterations in banana induced by mechanical damage', *Unimontes Científica*, vol. 17, no. 2, pp. 27-34.

Maia, VM, Salomão, LCC, Siqueira, DL, Puschman, R, Mota Filho, VJG & Cecon, PR 2011, 'Physical and metabolic alterations in" Prata Anã" banana induced by mechanical damage at room temperature', *Scientia Agricola*, vol. 68, no. 1, pp. 31-36.

Maia, VM, Salomão, LCC, Siqueira, DL, Puschmann, R, Mota Filho, VJG & Cecon, PR 2008, 'Types and intensity of mechanical damages on'prata anã'bananas along the commercialization chain', *Revista Brasileira de Fruticultura*, vol. 30, no. 2, pp. 365-370.

Manetto, G, Cerruto, E, Pascuzzi, S & Santoro, F 2017, 'Improvements in citrus packing lines to reduce the mechanical damage to fruit', *Chem. Eng. Trans. 2017, 58, 391*, vol. 396.

Mao, L, Ying, T, Xi, Y & Zhen, Y 1995, 'Respiration rate, ethylene production, and cellular leakage of fig fruit following vibrational stress', *HortScience*, vol. 30, no. 1, pp. 145-145.

Margetts, J 2014, *Australian Banana Industry- Strategic Investment Plan*, Plant & Food Research Australia Pty Ltd.

Martinez-Romero, D, Serrano, M, Carbonell, A, Castillo, S, Riquelme, F & Valero, D 2004, 'Mechanical damage during fruit post-harvest handling: technical and physiological implications', in *Production practices and quality assessment of food crops*, Springer, pp. 233-252.

Martinez, MV & Whitaker, JR 1995, 'The biochemistry and control of enzymatic browning', *Trends in Food Science & Technology*, vol. 6, no. 6, pp. 195-200.

Mazhar, M, Joyce, D, Cowin, G, Brereton, I, Hofman, P, Collins, R & Gupta, M 2015, 'Non-destructive 1H-MRI assessment of flesh bruising in avocado (Persea americana M.) cv. Hass', *Postharvest Biology and Technology*, vol. 100, pp. 33-40.

Mazhar, MS 2015, 'Bruising in avocado (Persea americana M.) cv.'Hass' supply chains: from the ripener to the consumer'.

McCabe, M 2014, *Aussies go bananas for bananas*, 14/09/02018, Nielsen, <https://www.nielsen.com/au/en/insights/news/2014/aussies-go-bananas-for-bananas.html>.

Menesatti, P & Paglia, G 2001, 'Development of a Drop Damage Index of Fruit Resistance to Damage', *Journal of Agricultural Engineering Research*, vol. 80, no. 1, pp. 53-64.

Meng, G, Trost, T & Östlund, S 2007, 'Stacking misalignment of corrugated boxes-a preliminary study', in *23rd IAPRI Symposium on Packaging, September 3-5, Windsor, UK, 2007*.

Miller, W & Wagner, C 1991, 'Florida citrus packing line studies with an instrumented sphere', *Applied Engineering in Agriculture*, vol. 7, no. 5, pp. 577-581.

Mohammad Shafie, M, Rajabipour, A, Castro-García, S, Jiménez-Jiménez, F & Mobli, H 2015, 'Effect of fruit properties on pomegranate bruising', *International Journal of Food Properties*, vol. 18, no. 8, pp. 1837-1846.

Mohsenin, Jindal, V & Manor, A 1978, 'Mechanics of impact of a falling fruit on a cushioned surface', *Transactions of the ASAE*, vol. 21, no. 3, pp. 594-600.

Mohsenin, N 1986, *Physical Properties of Plant and Animal Materials: Structure, Physical Characteristics, and Mechanical Properties*, Gordon and Breach.

Mohsenin, N, Goehlich, H & Tukey, LD 1962, 'Mechanical behaviour of apple fruits as related to bruising', in *Proc Am Soc Hortic Sci*, vol. 81, pp. 67-77.

Mohsenin, NN 1970, 'Physical properties of plant and animial materials. Vol. 1. Structure, physical characterisitics and mechanical properties', *Physical properties of plant and animial materials.* doi: 10.1002/ food.19870310724

Mokkila, M, Randell, K, Sariola, J, Hägg, M & Häkkinen, U 1996, 'Improvement of the postharvest quality of strawberries', in *III International Strawberry Symposium* pp. 553-558.

More, P, Behere, D, Housalmal, S, Khodke, S, Jadhav, S & Kakade, A 2015, 'Assessment of vibration damage to banana bunches simulated by vibration tester', *International Journal of Tropical Agriculture*, vol. 33, no. 2 (Part III), pp. 1419-1422.

Morgan, R 2018, 'Woolworths increases lead in $100b+ grocery war', viewed 01/07/2019, <http://www.roymorgan.com/findings/7537-woolworths-increases-lead-in-$100b-plus-grocery-war-201803230113>.

Morris, KJK & Kamarulzaman, NH 2014, 'Conceptual framework for estimating postharvest losses in food supply chains: the case of plantain fruits in Nigeria', *International Journal of Business and Economics Research*, vol. 3, no. 6-1, pp. 31-37.

Müller, I, Basso, D, Brusamarello, V & Pereira, CE 2012, 'Three-independent axis instrumented sphere for compression measurement based on piezoelectric transducers', in *Instrumentation and Measurement Technology Conference (I2MTC), 2012 IEEE International*, pp. 628-632.

Muller, I, de Brito, RM, Pereira, CE & Bender, RJ 2009, 'Wireless instrumented sphere for three-dimensional force sensing', in *Sensors Applications Symposium, 2009. SAS 2009. IEEE*, pp. 153-157.

Mvumi, B, Matsikira, LT & Mutambara, J 2016, 'The banana postharvest value chain analysis in Zimbabwe', *British Food Journal*, vol. 118, no. 2, pp. 272-285.

Nagata, M, Tallada, JG & Kobayashi, T 2006, 'Bruise detection using NIR hyperspectral imaging for strawberry (Fragaria* ananassa Duch.)', *Environmental Control in Biology*, vol. 44, no. 2, pp. 133-142.

Nakamura, N, Inatsu, Y, Kawamoto, S, Okadome, H, Nakano, K, Maezawa, S & Shiina, T 2007, 'Effect of vibration on the bacterial growth on strawberry fruits', *Journal of Food Agriculture and Environment*, vol. 5, no. 1, p. 44-48.

Nei, D, Nakamura, N, Roy, P, Orikasa, T, Ishikawa, Y, Kitazawa, H & Shiina, T 2008, 'Wavelet analysis of shock and vibration on the truck bed', *Packaging Technology and Science*, vol. 21, no. 8, pp. 491-499.

NHVR 2019, *National Heavy Vehicle Regulator (NHVR) Journey Planner*, <http://gis.nhvr.gov.au /journeyplanner/>.

Niskanen, K 2012, *Mechanics of paper products*, 1st ed. edn, Walter de Gruyter, Hawthorne, NY.

Opara, LU 2007, 'Bruise susceptibilities of 'Gala'apples as affected by orchard management practices and harvest date', *Postharvest Biology and Technology*, vol. 43, no. 1, pp. 47-54.

Opara, UL & Fadiji, T 2018, 'Compression damage susceptibility of apple fruit packed inside ventilated corrugated paperboard package', *Scientia Horticulturae*, vol. 227, pp. 154-161.

Opara, UL & Pathare, PB 2014, 'Bruise damage measurement and analysis of fresh horticultural produce—A review', *Postharvest Biology and Technology*, vol. 91, pp. 9-24.

Pålsson, H & Hellström, D 2016, 'Packaging logistics in supply chain practice–current state, trade-offs and improvement potential', *International Journal of Logistics Research and Applications*, vol. 19, no. 5, pp. 351-368.

Pang, D, Studman, C & Banks, N 1994, 'Apple bruising thresholds for an instrumented sphere', *Transactions of the ASAE (USA),* 37(3), 893-897.

Pang, DW, Studman, CJ, Banks, NH & Baas, PH 1996, 'Rapid assessment of the susceptibility of apples to bruising', *Journal of Agricultural Engineering Research*, vol. 64, no. 1, pp. 37-47.

Pang, W, Studman, C & Ward, G 1992, 'Bruising damage in apple-to-apple impact', *Journal of Agricultural Engineering Research*, vol. 52, pp. 229-240.

Parfitt, J, Barthel, M & Macnaughton, S 2010, 'Food waste within food supply chains: quantification and potential for change to 2050', *Philosophical transactions of the royal society B: biological sciences*, vol. 365, no. 1554, pp. 3065-3081.

Paternoster, A, Van Camp, J, Vanlanduit, S, Weeren, A, Springael, J & Braet, J 2017, 'The performance of beer packaging: Vibration damping and thermal insulation', *Food Packaging and Shelf Life*, vol. 11, pp. 91-97.

Paternoster, A, Vanlanduit, S, Springael, J & Braet, J 2017, 'Measurement and analysis of vibration and shock levels for truck transport in Belgium with respect to packaged beer during transit', *Food Packaging and Shelf Life*.

Paternoster, A, Vanlanduit, S, Springael, J & Braet, J 2018, 'Measurement and analysis of vibration and shock levels for truck transport in Belgium with respect to packaged beer during transit', *Food Packaging and Shelf Life*, vol. 15, pp. 134-143.

Pathare, PB & Opara, UL 2014, 'Structural design of corrugated boxes for horticultural produce: A review', *Biosystems Engineering*, vol. 125, pp. 128-140.

Peterson, D & Bennedsen, B 2005, 'Isolating damage from mechanical harvesting of apples', *Applied Engineering in Agriculture*, vol. 21, no. 1, pp. 31-34.

Pholpho, T, Pathaveerat, S & Sirisomboon, P 2011, 'Classification of longan fruit bruising using visible spectroscopy', *Journal of Food Engineering*, vol. 104, no. 1, pp. 169-172.

Pierce, CD, Singh, SP & Burgess, G 1992, 'A comparison of leaf - spring with aircushion trailer suspensions in the transport environment', *Packaging Technology and Science*, vol. 5, no. 1, pp. 11-15.

Piersol, AG & Harris, CM 2017, *Harri's Shock and Vibration Handbook Fifth Edition*, Mcgraw-hill.

Pillay, M & Tenkouano, A 2011, *Banana breeding: progress and challenges*, CRC Press, Taylor & Francis Group, New York.

Prabha, DS & Kumar, JS 2015, 'Assessment of banana fruit maturity by image processing technique', *Journal of Food Science and Technology*, vol. 52, no. 3, pp. 1316-1327.

Prange, R & Delong, J 1998, 'Bruising reduction: effect of storage humidity and post storage handling on compression bruising of CA stores apples', in *14th Annual Postharvest Conference, Yakima, Washington*.

Prusky, D 2011, 'Reduction of the incidence of postharvest quality losses, and future prospects', *Food Security*, vol. 3, no. 4, pp. 463-474.

QDAFF 2017, *Queensland AgTrends 2017–18: Forecasts and trends in Queensland agricultural, fisheries and forestry production*.

Quintana, MEG & Paull, RE 1993, 'Mechanical injury during postharvest handling of 'solo'papaya fruit', *Journal of the American Society for Horticultural Science*, vol. 118, no. 5, pp. 618-622.

Raghav, P & Gupta, A 2003, 'Simulated transportation of individually shrink wrapped kinnow fruits', *Journal of Food Science and Technology*, vol. 40, no. 4, pp. 389-397.

Rajkumar, P, Wang, N, Eimasry, G, Raghavan, GSV & Gariepy, Y 2012, 'Studies on banana fruit quality and maturity stages using hyperspectral imaging', *Journal of Food Engineering*, vol. 108, no. 1, pp. 194-200.

Ranathunga, C, Jayaweera, HH, Suraweera, S, Wattage, S, Ruvinda, K & Ariyaratne, T 2010, 'Vibration effects in vehicular road transportation', in *Proceedings of the Technical Sessions - Institute of Physics – Sri Lanka*.

Randall, RB & Tech, B 1987, *Frequency analysis*, Brüel & Kjær, Denmark.

Richards, D 1990, 'Review of analysis and assessment methodologies for road transportation vibration and shock data', *Environmental Engineering*, vol. 3, pp. 23-26.

Rissi, GO, Singh, SP, Burgess, G & Singh, J 2008, 'Measurement and analysis of truck transport environment in Brazil', *Packaging Technology and Science*, vol. 21, no. 4, pp. 231-246.

Robertson, GL 2005, *Food packaging: principles and practice*, CRC press, Taylor & Francis Group, New York.

Rouillard, V 2007, 'The synthesis of road vehicle vibrations based on the statistical distribution of segment lengths', in *Proceedings of the 5th Australasian congress on applied mechanics*, p. 614.

Rouillard, V 2008, 'Generating road vibration test schedules from pavement profiles for packaging optimization', *Packaging Technology and Science*, vol. 21, no. 8, pp. 501-514.

Rouillard, V 2009, 'Statistical Models for Nonstationary and Non-Gaussian Road Vehicle Vibrations', *Engineering letters*, vol. 17, no. 4, 227-237.

Rouillard, V & Lamb, M 2008, 'On the effects of sampling parameters when surveying distribution vibrations', *Packaging Technology and Science*, vol. 21, no. 8, pp. 467-477.

Rouillard, V & Sek, M 2013, 'Creating transport vibration simulation profiles from vehicle and road characteristics', *Packaging Technology and Science*, vol. 26, no. 2, pp. 82-95.

Rouillard, V & Sek, MA 2010, 'Synthesizing nonstationary, non - Gaussian random vibrations', *Packaging Technology and Science*, vol. 23, no. 8, pp. 423-439.

Rouillard, V, Sek, MA & Crawford, S 2004, 'The dynamic behaviour of stacked shipping units during transport. Part 1: model validation', *Packaging Technology and Science: An International Journal*, vol. 17, no. 5, pp. 237-247.

Rouillard, V, Sek, MA & Perry, T 1996, 'Analysis and simulation of road profiles', *Journal of Transportation Engineering*, vol. 122, no. 3, pp. 241-245.

Santana Llado, J & Marrero Dominguez, A 1997, 'The effects of peel abrasion on the postharvest physiology and commercial life of banana fruits', in *II International Symposium on Banana: I International Symposium on Banana in the Subtropics 490*, pp. 547-554.

Schröder, MJ 2003, *Food quality and consumer value: Delivering food that satisfies*, Springer Science & Business Media.

Scott, KJ 1971, *Simple Low Cost Ways to Reduce Wastage and Extend the Life of Bananas after Harvest*, Department of Primary Industries, QLD, Australia.

Sek, MA 1996, 'A modern technique of transportation simulation for package performance testing', *Packaging Technology and Science*, vol. 9, no. 6, pp. 327-343.

Shahbazi, F, Rajabipour, A, Mohtasebi, S & Rafie, S 2010, 'Simulated in-transit vibration damage to watermelons', *Journal of Agricultural Science and Technology*, vol. 12, pp. 23-34.

Shewfelt, RL 1987, 'Quality of minimally processed fruits and vegetables', *Journal of Food Quality*, vol. 10, no. 3, pp. 143-156.

Shires, D 2011, 'On the time compression (test acceleration) of broadband random vibration tests', *Packaging Technology and Science*, vol. 24, no. 2, pp. 75-87.

Sila, DN, Duvetter, T, De Baerdemaeker, J & Hendrickx, M 2008, 'Effect of mechanical impact-bruising on polygalacturonase and pectinmethylesterase activity and pectic cell wall components in tomato fruit', *Postharvest Biology and Technology*, vol. 47, no. 1, pp. 98-106.

Simmonds, NW 1966, *Bananas (2nd edn).* Longman Publishers, London.

Singh & Marcondes, J 1992, 'Vibration Levels in Commercial Truck Shipments as a Function of Suspension and Payload'.

Singh, JS, S. Paul; Joneson, Eric 2006, 'Measurement and analysis of US truck vibration for leaf spring and air ride suspensions, and development of tests to simulate these conditions', *Packaging Technology and Science*, vol. 19, no. 6, pp. 309-323.

Singh, S & Xu, M 1993, 'Bruising in apples as a function of truck vibration and packaging', *Applied Engineering in Agriculture*, vol. 9, no. 5, pp. 455-460.

Singh, SP, Burgess, G & Xu, M 1992, 'Bruising of apples in four different packages using simulated truck vibration', *Packaging Technology and Science*, vol. 5, no. 3, pp. 145-150.

Singh, SP, Sandhu, A, Singh, J & Joneson, E 2007, 'Measurement and analysis of truck and rail shipping environment in India', *Packaging Technology and Science*, vol. 20, no. 6, pp. 381-392.

Slaughter, D, Hinsch, R & Thompson, J 1993, 'Assessment of vibration injury to Bartlett pears', *Transactions of the ASAE*, vol. 36, no. 4, pp. 1043-1047.

Slaughter, D, Thompson, J & Hinsch, R 1995, 'Packaging Bartlett pears in polyethylene film bags to reduce vibration in transit', *Transactions of the ASAE*, vol. 41, pp. 107-114.

Slaughter, D, Thompson, J & Hinsch, R 1998, 'Packaging Bartlett pears in polyethylene film bags to reduce vibration injury in transit', *Transactions of the ASAE*, vol. 41, no. 1, p. 107.

Smith, SW 1997, 'The scientist and engineer's guide to digital signal processing', California Technical Pub, USA.

Smith, SW 2006, *The scientist and engineer's guide to digital signal processing*, California Technical Publishing, San Diego, CA.

Sober, S, Zapp, H & Brown, G 1990, 'Simulated packing line impacts for apple bruise prediction', *Transactions of the ASAE*, vol. 33, no. 2, pp. 629-0636.

Soleimani, B & Ahmadi, E 2014, 'Measurement and analysis of truck vibration levels as a function of packages locations in truck bed and suspension', *Computers and Electronics in Agriculture*, vol. 109, pp. 141-147.

Soleimani, B & Ahmadi, E 2015, 'Evaluation and analysis of vibration during fruit transport as a function of road conditions, suspension system and travel speeds', *Engineering in Agriculture, Environment and Food*, vol. 8, no. 1, pp. 26-32.

Soltani, M, Alimardani, R & Omid, M 2010, 'Comparison of some chromatic, mechanical and chemical properties of banana fruit at different stages of ripeness', *Modern Applied Science*, vol. 4, no. 7, pp. 34-41.

Sommer, NF, Laude, HM, Berry, LJ, Madsen, HF, Hoyt, SC, Luthin, JN, Hall, H, Harding, RB, Miller, MP & Fireman, M 1957, 'Surface discoloration of pears: Compression pads between fruit and carton lid effectively prevent transit bruising of jumble-packed Bartlett pears', *Calif.Agric. 1957; 11(1): 3–4*.

Stopa, R, Komarnicki, P & Młotek, M 2014, 'Distribution of surface thrusts on avocado fruit at the constant load value', *Inżynieria Rolnicza*, no. 1 (149), pp. 209-220.

Studman, C 1995, 'A model of fruit bruising', in *2nd Australasian Postharvest Conference, Melbourne, Monash University*.

Tabatabaekoloor, R, Hashemi, S & Taghizade, G 2013, 'Vibration damage to kiwifruits during road transportation', *Int. J. Agric. Food Sci. Technol.*, vol. 4, no. 5, pp. 467-474.

Thompson, J, Slaughter, D & Arpaia, M 2008, 'Suspended tray package for protecting soft fruit from mechanical damage', *Applied Engineering in Agriculture*, vol. 24, no. 1, pp. 71-75.

Thomson, WT 1953, *MECHANICAL VIBRATIONS*, *Prentice-Hall, Englewood Cliffs,NJ, 1953*.

Timm, E & Brown, G 1991, 'Impacts recorded on avocado, papaya, and pineapple packing lines', *Applied Engineering in Agriculture*, vol. 7, no. 4, pp. 418-422.

Timm, E, Brown, G & Armstrong, P 1996, 'Apple damage in bulk bins during semi-trailer transport', *Applied Engineering in Agriculture*, vol. 12, no. 3, pp. 369-377.

Toivonen, PM, Hampson, C, Stan, S, McKenzie, D-L & Hocking, R 2007, 'Factors affecting severity of bruises and degree of apparent bruise recovery in a yellow-skinned apple', *Postharvest Biology and Technology*, vol. 45, no. 2, pp. 276-280.

Turczyn, M, Grant, S, Ashby, B & Wheaton, F 1986, 'Potato shatter bruising during laboratory handling and transport simulation', *Transactions of the ASAE*, vol. 29, no. 4, pp. 1171-1175.

Twede, D, Selke, SE, Kamdem, D-P & Shires, D 2014, *Cartons, crates and corrugated board: handbook of paper and wood packaging technology*, DEStech Publications, Inc. Lancaster.

Urbanik, T. J. 1978, Transportation vibration effects on unitized corrugated containers, United States Department of Agriculture,Forest Service, Forest Products Laboratory, Research Paper FPL 322, 1978.

Usuda, H., Shiina, T., Ishikawa, Y., & Satake, T. 2006, Basic study on the vibration analysis for development of three dimensional transport simulation model for produce. Journal of the Society of Agricultural Structures (Japan), 36(2006), 215-222.

Van Baren, J. 2005. Kurtosis-the missing dashboard knob. TEST Engineering & Management magazine, October/November 2005.

Van, L, De Ketelaere, B, Desmet, M & De Baerdemaeker, J 2006, 'Determination of bruise susceptibility of tomato fruit by means of an instrumented pendulum', *Postharvest Biology and Technology*, vol. 40, no. 1, pp. 7-14.

Van Zeebroeck, M, Darius, P, De Ketelaere, B, Ramon, H & Tijskens, E 2007a, 'The effect of fruit factors on the bruise susceptibility of apples', *Postharvest Biology and Technology*, vol. 46, no. 1, pp. 10-19.

Van Zeebroeck, M, Darius, P, De Ketelaere, B, Ramon, H & Tijskens, E 2007b, 'The effect of fruit properties on the bruise susceptibility of tomatoes', *Postharvest Biology and Technology*, vol. 45, no. 2, pp. 168-175.

Van Zeebroeck, M, Tijskens, E, Dintwa, E, Kafashan, J, Loodts, J, De Baerdemaeker, J & Ramon, H 2006a, 'The discrete element method (DEM) to simulate fruit impact damage during transport and handling: case study of vibration damage during apple bulk transport', *Postharvest Biology and Technology*, vol. 41, no. 1, pp. 92-100.

Van Zeebroeck, M, Tijskens, E, Dintwa, E, Kafashan, J, Loodts, J, De Baerdemaeker, J & Ramon, H 2006b, 'The discrete element method (DEM) to simulate fruit impact damage during transport and handling: Model building and validation of DEM to predict bruise damage of apples', *Postharvest Biology and Technology*, vol. 41, no. 1, pp. 85-91.

Van Zeebroeck, M, Van linden, V, Ramon, H, De Baerdemaeker, J, Nicolaï, BM & Tijskens, E 2007, 'Impact damage of apples during transport and handling', *Postharvest Biology and Technology*, vol. 45, no. 2, pp. 157-167.

Vélez Rivera, N, Gómez-Sanchis, J, Chanona-Pérez, J, Carrasco, JJ, Millán-Giraldo, M, Lorente, D, Cubero, S & Blasco, J 2014, 'Early detection of mechanical damage in mango using NIR hyperspectral images and machine learning', *Biosystems Engineering*, vol. 122, pp. 91-98.

Vergano, P, Testin, R & Newall, W 1991, 'Peach bruising: susceptibility to impact, vibration, and compression abuse', *Transactions of the ASAE*, vol. 34, no. 5, pp. 2110-2116.

Verghese, K, Lewis, H, Lockrey, S & Williams, H 2015, 'Packaging's role in minimizing food loss and waste across the supply chain', *Packaging Technology and Science*, vol. 28, no. 7, pp. 603-620.

Vidanagama, J & Piyathilaka, MD 2011, 'Enhancement of Product Quality and Resource Efficiency of Sri Lankan Banana Supply Chain', *10 th Asia Pacific Round Table for Sustainable Consumption and Production*, pp. 1-11.

Vigneault, C, Thompson, J, Wu, S, Hui, KC & LeBlanc, DI 2009, 'Transportation of fresh horticultural produce', *Postharvest Technologies for Horticultural Crops*, vol. 2, pp. 1-24.

Vursavus, K & Ozguven, F 2004, 'Determining the effects of vibration parameters and packaging method on mechanical damage in golden delicious apples', *Turkish Journal of Agriculture and Forestry*, vol. 28, no. 5, pp. 311-320.

Wang, LJ, Wang, ZW & Rouillard, V 2018, 'Investigation on vibration scuffing life curves', *Packaging Technology and Science*, 31(8), 523-531.

Wang, ZW & Fang, K 2016, 'Dynamic performance of stacked packaging units', *Packaging Technology and Science*, vol. 29, no. 10, pp. 491-511.

Wasala, CB, Dissanayake, C, Dharmasena, D, Gunawardane, C & Dissanayake, T 2014, 'Postharvest losses, current issues and demand for postharvest technologies for loss management in the main banana supply chains in Sri Lanka', *Journal of Post-Harvest Technology*, vol. 2, no. 1, pp. 80-87.

Wasala, W, Dharmasena, D, Dissanayake, C & Tilakarathne, B 2015, 'Feasibility Study on Styrofoam Layer Cushioning for Banana Bulk Transport in a Local Distribution System', *Journal of Biosystems Engineering*, vol. 40, no. 4, pp. 409-416.

Wasala, W, Dharmasena, D, Dissanayake, T & Thilakarathne, B 2015a, 'Vibration simulation testing of banana bulk transport packaging systems', *Tropical Agricultural Research*, vol. 26, no. 2, pp. 355-367.

Wasala, W, Dharmasena, D, Dissanayake, T & Thilakarathne, B 2015b, 'Vibration simulation testing of banana bulk transport packaging systems', *Tropical Agricultural Research*, vol. 26, no. 2.

White, A, Gallegos, D & Hundloe, T 2011, 'The impact of fresh produce specifications on the Australian food and nutrition system: a case study of the north Queensland banana industry', *Public Health Nutrition*, vol. 14, no. 08, pp. 1489-1495.

Widdup, JDA & Pedersen, TA 1981, 'The Development of Specifications and Control Conditions for Road Trains in Australia', SAE International ,DOI 10.4271/811395.

Wilson, L, Boyette, M & Estes, G 1995, 'Post harvest handling and cooling of fresh fruits, vegetables and flowers for small farms leaflets 800–804', *North Carolina Cooperative Extension Service*.

Wilson, T & Streatfield, DR 1981, 'Structured observation in the investigation of information needs', *Social Science Information Studies*, vol. 1, no. 3, pp. 173-184.

Wu, G & Wang, C 2014, 'Investigating the effects of simulated transport vibration on tomato tissue damage based on vis/NIR spectroscopy', *Postharvest Biology and Technology*, vol. 98, pp. 41-47.

Xing, J, Bravo, C, Jancsok, PT, Ramon, H & De Baerdemaeker, J 2005, 'Detecting bruises on 'Golden Delicious' apples using hyperspectral imaging with multiple wavebands', *Biosystems Engineering*, vol. 90, no. 1, pp. 27-36.

Xing, J, Saeys, W & De Baerdemaeker, J 2007, 'Combination of chemometric tools and image processing for bruise detection on apples', *Computers and Electronics in Agriculture*, vol. 56, no. 1, pp. 1-13.

Xu, R & Li, C 2015, 'Development of the Second Generation Berry Impact Recording Device (BIRD II)', *Sensors (Basel)*, vol. 15, no. 2, pp. 3688-3705.

Xu, R, Takeda, F, Krewer, G & Li, C 2015, 'Measure of mechanical impacts in commercial blueberry packing lines and potential damage to blueberry fruit', *Postharvest Biology and Technology*, vol. 110, pp. 103-113.

Yasunaga, E, Sardsud, V, Wanwarang, P, Yuge, K, Spreer, W & Fukuda, S 2010a, 'Effect of post-harvest distribution environment on quality deterioration of mango fruits', in *XXVIII International Horticultural Congress on Science and Horticulture for People (IHC2010): International Symposium on 934*, pp. 921-927.

Yasunaga, E, Sardsud, V, Wanwarang, P, Yuge, K, Spreer, W & Fukuda, S 2010b, 'Effect of post-harvest distribution environment on quality deterioration of mango fruits', in *XXVIII International Horticultural Congress on Science and Horticulture for People (IHC2010)* pp. 921-927.

Young, D & Williams, K 1990, 'Road trains in an urban environment: the Northern Territory experience', in *Workshop on Integration of Large Vehicles into Urban Networks, 1990, Darwin, Australia*.

Yu, P, Li, C, Takeda, F & Krewer, G 2014, 'Visual bruise assessment and analysis of mechanical impact measurement in southern highbush blueberries', *Applied engineering in agriculture*, vol. 30, no. 1, pp. 29-37.

Yuwana 1997, 'Impact Bruise Susceptabilities of Unripe Banana, Mango and Avacado', *Indonesian Food Nutrition and Progress (IFNP)*, vol. Volume 4,, no. Number 2, pp. 56-60.

Zarifneshat, S, Ghassemzadeh, HR, Sadeghi, M, Abbaspour-Fard, MH, Ahmadi, E, Javadi, A & Shervani-Tabar, MT 2010, 'Effect of impact level and fruit properties on golden delicious apple bruising', *American Journal of Agricultural and Biological Sciences*, vol. 5, no. 2, pp. 114-121.

Zarifneshat, S, Rohani, A, Ghassemzadeh, HR, Sadeghi, M, Ahmadi, E & Zarifneshat, M 2012, 'Predictions of apple bruise volume using artificial neural network', *Computers and Electronics in Agriculture*, vol. 82, pp. 75-86.

Zeithaml, VA 1988, 'Consumer perceptions of price, quality, and value: a means-end model and synthesis of evidence', *The Journal of Marketing*, pp. 2-22.

Zhang, L, Yang, C, Wang, Y, Pan, D, Meng, X & Tong, T 2011, 'Vibration and impact performance tests of cherry tomato transport packages', in *Trans. Chin. Soc. Agric. Mach*, vol. 42, pp. 125-130.

Zhang, S, Zhang, H, Zhao, Y, Guo, W & Zhao, H 2013, 'A simple identification model for subtle bruises on the fresh jujube based on NIR spectroscopy', *Mathematical and Computer Modelling*, vol. 58, no. 3, pp. 545-550.

Zhang, Y-l, Chen, J & Wu, Y 2011, 'Analysis on hazard factors of the use of corrugated carton in packaging low-temperature yogurt during logistics', *Procedia Environmental Sciences*, vol. 10, pp. 968-973.

Zhao, J, Ouyang, Q, Chen, Q & Wang, J 2010, 'Detection of bruise on pear by hyperspectral imaging sensor with different classification algorithms', *Sensor Letters*, vol. 8, no. 4, pp. 570-576.

Zhao, W, Yang, Z, Chen, Z, Liu, J, Wang, WC & Zheng, WY 2016, 'Hyperspectral Surface Analysis for Ripeness Estimation and Quick UV-C Surface Treatments for Preservation of Bananas', *Journal of Applied Spectroscopy*, vol. 83, no. 2, pp. 254-260.

Zhou, H & Wang, ZW 2018, 'Comparison study on simulation effect of improved simulation methods for packaging random vibration test', *Packaging Technology and Science*, https://doi.org/10.1002/pts.2421.

Zhou, J, He, L, Zhang, Q & Karkee, M 2014, 'Effect of excitation position of a handheld shaker on fruit removal efficiency and damage in mechanical harvesting of sweet cherry', *Biosystems Engineering*, vol. 125, pp. 36-44.

Zhou, R, Su, S & Li, Y 2008a, 'Effects of cushioning materials on the firmness of Huanghua pears (Pyrus pyrifolia Nakai cv. Huanghua) during distribution and storage', *Packaging Technology and Science: An International Journal*, vol. 21, no. 1, pp. 1-11.

Zhou, R, Su, S & Li, Y 2008b, 'Effects of cushioning materials on the firmness of Huanghua pears (Pyrus pyrifolia Nakai cv. Huanghua) during distribution and storage', *Packaging Technology and Science*, vol. 21, no. 1, pp. 1-11.

Zhou, R, Su, S, Yan, L & Li, Y 2007, 'Effect of transport vibration levels on mechanical damage and physiological responses of Huanghua pears (Pyrus pyrifolia Nakai, cv. Huanghua)', *Postharvest Biology and Technology*, vol. 46, no. 1, pp. 20-28.

Zhou, R, Wang, X, Hu, Y, Zhang, G, Yang, P & Huang, B 2015, 'Reduction in Hami melon (Cucumis melo var. saccharinus) softening caused by transport vibration by using hot water and shellac coating', *Postharvest Biology and Technology*, vol. 110, pp. 214-223.

Zhou, R, Yan, L, Li, B & Xie, J 2015, 'Measurement of Truck Transport Vibration Levels in China as a Function of Road Conditions, Truck Speed and Load Level', *Packaging Technology and Science*, vol. 28, no. 11, pp. 949-957,doi.org/10.1002/pts.2176.

Zwiggelaar, R, Yang, Q, Garcia-Pardo, E & Bull, CR 1996, 'Use of spectral information and machine vision for bruise detection on peaches and apricots', *Journal of Agricultural Engineering Research*, vol. 63, no. 4, pp. 323-331.

(This page was intentionally left blank)

Appendices

Appendix A1: Summary of costing for packing configurations for One-piece and Two-piece cartons (Source: Kitchener (2015))

Item	Material and Labour Cost	15kg 1-Piece Carton				15kg 2-Piece Carton			
		Minimum Specification		Optimum Specification		Minimum Specification		Optimum Specification	
		Cost Per Pallet (60 cartons/ pallet)	Cost Per Carton (15kg/ carton)	Cost Per Pallet (60 cartons/ pallet)	Cost Per Carton (15kg/ carton)	Cost Per Pallet (60 cartons/ pallet)	Cost Per Carton (15kg/ carton)	Cost Per Pallet (60 cartons/ pallet)	Cost Per Carton (15kg/ carton)
Corner Posts	Material Cost	$ 4.88	$ 0.081	$ 4.88	$ 0.081	$ 4.88	$ 0.081	$ 4.88	$ 0.081
	Labour Cost	$ 1.50	$ 0.025	$ 1.50	$ 0.025	$ 1.50	$ 0.025	$ 0.03	$ 0.000
Pallet Strapping	Material Cost	$ 0.58	$ 0.010	Not required if using automatic palletizer with stretch tape		$ 0.58	$ 0.010	Not required if using automatic palletizer with stretch tape	
	Labour Cost	$ 2.08	$ 0.035			$ 2.08	$ 0.035		
Pallet Stretch Tape	Material Cost	Not required if using hand-applied poly strapping		$ 1.76	$ 0.029	Not required if using hand-applied poly strapping		$ 1.76	$ 0.029
	Labour Cost			$ 0.08	$ 0.001			$ 0.08	$ 0.001
Pallet Locking Sheet	Material Cost	$ 0.46	$ 0.008	$ 0.46	$ 0.008	$ -	$ -	$ -	$ -
	Labour Cost	$ 0.08	$ 0.001	$ 0.08	$ 0.001	$ 0.08	$ 0.001	$ 0.08	$ 0.001
Pallet Cap	Material Cost	$ 0.65	$ 0.011	$ 0.65	$ 0.011				
	Labour Cost	$ 0.08	$ 0.001	$ 0.08	$ 0.001				
Bag (Slitted)	Material Cost	$ 10.80	$ 0.180	$ 10.80	$ 0.180	$ 10.80	$ 0.180	$ 10.80	$ 0.180
	Labour Cost	$ 4.00	$ 0.067	$ 4.00	$ 0.067	$ 4.00	$ 0.067	$ 4.00	$ 0.067
Slip-Sheets	Material Cost	$ 3.30	$ 0.055	$ 3.30	$ 0.055	$ 3.30	$ 0.055	$ 3.30	$ 0.055
	Labour Cost	$ 2.50	$ 0.042	$ 2.50	$ 0.042	$ 2.50	$ 0.042	$ 2.50	$ 0.042
Sap Paper	Material Cost	$ 3.20	$ 0.053	$ 3.20	$ 0.053	$ 3.20	$ 0.053	$ 3.20	$ 0.053
	Labour Cost	$ 2.50	$ 0.042	$ 2.50	$ 0.042	$ 2.50	$ 0.042	$ 2.50	$ 0.042
Bag Closure	Material Cost	$ 0.240	$ 0.004	$ 0.120	$ 0.002	$ 0.24	$ 0.004	$ 0.12	$ 0.002
	Labour Cost	$ 1.50	$ 0.025	$ 6.50	$ 0.1083	$ 1.50	$ 0.025	$ 6.50	$ 0.108
Placing Lid on Carton	Material Cost	Not required		Not required		No change		No change	
	Labour Cost					$ 0.03	$ 0.001	$ 0.03	$ 0.001
Taping Carton Lid to Base	Material Cost	Not required		Not required		$ 0.22	$ 0.004	$ 0.22	$ 0.004
	Labour Cost					$ 1.50	$ 0.025	$ 1.50	$ 0.025
Cross-Stack Top Layer	Material Cost	$ -	$ -			$ -	$ -		
	Labour Cost	$ -	$ -			$ -	$ -		
Glueing	Material Cost	Not required		Not required		Not required		Not required	
	Labour Cost								
Total Material Cost		$ 24.11	$ 0.40	$ 25.17	$ 0.42	$ 23.22	$ 0.39	$ 24.28	$ 0.40
Total Labour Cost		$ 14.25	$ 0.24	$ 17.25	$ 0.29	$ 15.70	$ 0.26	$ 17.23	$ 0.29
Grand Total		$ 38.36	$ 0.64	$ 42.42	$ 0.71	$ 38.92	$ 0.65	$ 41.50	$ 0.69
Total cost to pack per KG		$ 0.0426		$ 0.0471		$ 0.0432		$ 0.0461	

Appendix A2: Comparison between the cost of One-piece and Two-piece cartons (Source: Kitchener (2015)

Carton Weight	Configuration	Cartons Per Pallet	Weight Of Fruit Per Pallet	Carton Cost ($ per carton)			Carton Cost ($ Per KG of Fruit)		
				Min	Max	Av	Min	Max	Av
15kg	2-piece	60	900	$2.25	$2.55	$2.40	$0.150	$0.170	$ 0.160
	1-piece	60	900	$2.29	$2.55	$2.42	$0.153	$0.170	$ 0.161

Appendix B1: Cosmetic damage assessment and grading chart (Ekman et al. 2011)

Severity / Damage	0- None	1- Trace	2- Slight	3- Moderate	4- Severe
Bruising					
Description	No Damage	Barely Noticable (Approx.1% of Surface)	Bruise Area Beocming Obvious (Approx. 2% of Surface)	Obvious Bruise (Appox. 5% of Surface)	Extensive Bruise (5-10% or More of Surface)
Area Affected*	-	Approx. 1%	Approx. 2%	Approx. 5%	Approx. 5-10% or More
Fruit Rub/ Scars					
Description	No Damage	Barely Visible Crease Mark	Thin Brownish/ Black Line (Inner Neck Only)	Thick Dark Area/Line (Inner Neck Only)	Dark Ring Encircling Whole Neck
Area Affected*	-	Approx. 0.5 cm^2	Approx. 1.5 cm^2	Approx. 2.5 cm^2	Approx. 3 cm^2 or More
Scuffing					
Description	No Damage	Barely Noticeable/ Light and Localized	Distinct Rub Mark Becoming Obvious	Obvious Damage/ May be Dark Brown	Extensive Discoluration Darkening to Almost Black
Area Affected*	-	Approx. 1%	Approx. 5%	Approx. 15%	Approx. 20% or More

Blackened Rub					
Description	No Damage	Barely Visible Crease Mark	Thin Brownish/ Black Line (Inner Neck Only)	Thick Dark Area/Line (Inner Neck Only)	Dark Ring Encircling Whole Neck
Neck Injury					
Description	No Damage	Barely Visible Crease Mark	Thin Brownish/ Black Line (Inner Neck Only)	Thick Dark Area/Line (Inner Neck Only)	Dark Ring Encircling Whole Neck

* **Area Affected:** The affected area as a percentage (%) of the total surface or damage area (cm^2) in banans is mentioned as an approximation guide for visual damage and does not include damage area meassurement or estimation.

Appendix B2: Supermarket specifications for Cavendish bananas (Source- Woolworth's Produce Specifications)

GENERAL APPEARANCE CRITERIA	
COLOUR	*With receival colour (inner whorl) stage 4.0 Summer (01November-31 March), stage 5.0 Winter (01 April-31 October); uniform colour within cartons.*
VISUAL APPEARANCE	*With normal-bright bloom.*
SENSORY	*Firm, not soft; starchy flesh; nil foreign smells or tastes.*
SHAPE	*Slightly arched, with blunted butt end and intact, undamaged necks. Can have odd shapes (overarched, straight, and twisted).*
SIZE	*Finger length: 200-260mm (200-220 one layer allowed only), (measurement is over curvature, pulp to pulp, across the back of the Banana).* *Clusters - 3 to 9 fingers (ideal 5 to 9 fingers); Hands ->7 fingers.*
MATURITY	*Finger maturity thickness: measured at right angles to the curve of the fruit at a point one third from its flowering end. Girth 30-40 mm*
MAJOR DEFECTS	
INSECTS	*With obvious live insects or other pests.*
DISEASES	*With fungal diseases or soft rots e.g. Anthracnose, black end rot, crown rot.*
PHYSICAL / PEST DAMAGE	*With splits, holes, deep bruises or cuts through the peel into the pulp.*
	With severed / broken necks.
SKIN MARKS / BLEMISHES	*With excessive scattered brown spots/flecks (senescent spotting).*
TEMPERATURE INJURY	*With severe dull, greyish, or blackened peel, or brown under-peel discolouration (chilling injury).*
	With dark, water-soaked areas (freezing injury).
	With translucent pitting or blackening of skin, or translucent cores in fruit (heat damage).
MINOR DEFECTS	
PHYSICAL / PEST DAMAGE	*With dry brown scab / speckling (insect damage); or with scars (due to hail, bird damage) affecting areas > 2 sq cm (per cluster).*
	With reddish-brown blemishes (Banana rust) affecting areas > 2 sq cm (per cluster).
	With dark sap stains affecting > 4 sq cm (per cluster).
PHYSIOLOGICAL DISORDERS	*With reddish-brown discolouration (maturity bronzing) affecting >4 sq cm (per cluster).*
SKIN MARKS / BLEMISHES	*With superficial bruises (<1mm deep), abrasion or rub damage (tan/brown/black) affecting >4 sq cm (per cluster).*

Appendix B3: The checklist for Structured Observation Study

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?	☐ YES ☐ NO ☐ NA.
Notes:	
Cushions and adequate protective material are used when harvesting?	☐ YES ☐ NO ☐ NA.
Notes:	
Field tractors are well cushioned and covered to prevent possible mechanical damages to bunches during transport?	☐ YES ☐ NO ☐ NA.
Notes:	
Bunches are well secured to prevent bouncing and falling during field transport?	☐ YES ☐ NO ☐ NA.
Notes:	
Pack house workers wear protective gloves while handling the banana clusters?	☐ YES ☐ NO ☐ NA.
Notes:	
The conveyer belts have no level drops and rough surfaces that may harm bananas?	☐ YES ☐ NO ☐ NA.
Notes:	
The conveyer belts are free of any obstacles or sharp edges which might directly contact with the moving banana clusters?	☐ YES ☐ NO ☐ 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?	☐ YES ☐ NO ☐ NA.
Notes:	
The side walls of the water bath has no rough surfaces and no risk of abrasion injury to bananas?	☐ YES ☐ NO ☐ NA.

Notes:	
There is adequate level of lighting in banana sorting and the grading points?	☐ YES ☐ NO ☐ 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?	☐ YES ☐ NO ☐ NA.
Notes:	
There are no significant level drops in the package conveyer belts which may result in significant drop impact on the packages?	☐ YES ☐ NO ☐ NA.
Notes:	
The banana pallets are stacked with proper alignment and the pallets are well secured to minimise vibration especially in the upper tiers?	☐ YES ☐ NO ☐ NA.
Notes:	
The pallets are pre-cooled before transport and the temperature is maintained between 13-15 ºC?	☐ YES ☐ NO ☐ 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?	☐ YES ☐ NO ☐ 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?	☐ YES ☐ NO ☐ NA.
Notes:	
The machinery such as forklifts\ layer pickers have adequate protective mechanisms to avoid compression of the fruit packages during handling operations?	☐ YES ☐ NO ☐ NA.
Notes:	
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?	☐ YES ☐ NO ☐ NA.
Notes:	
Banana packages are not exposed to harmful low temperatures (below 13 ºC) which may result in chilling injury while stacked in the DC?	☐ YES ☐ NO ☐ NA.
Notes:	
Conditions\ Risk Factors	**Status**

Retail Stores

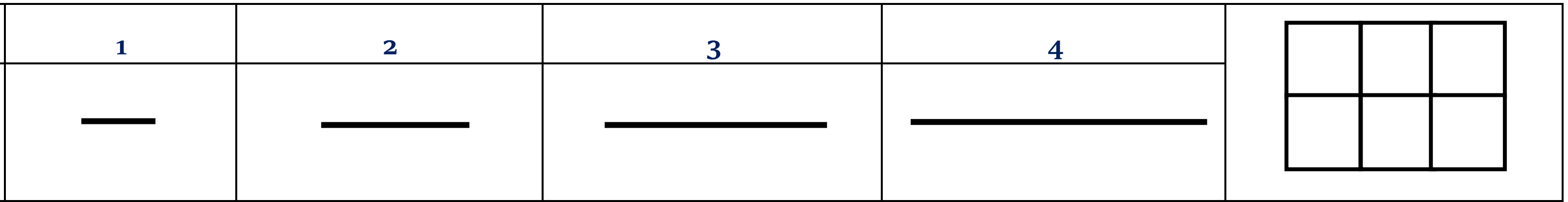
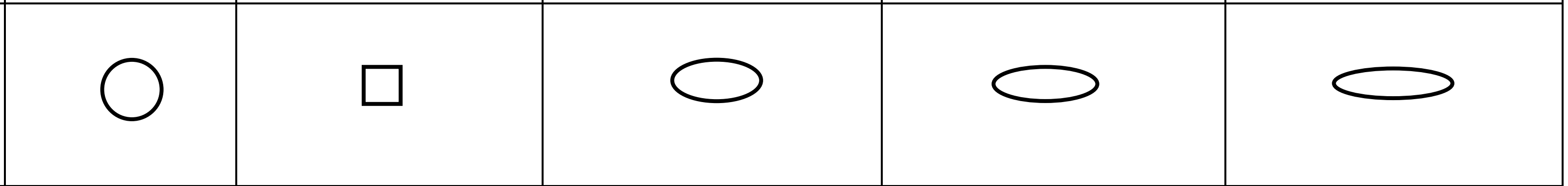
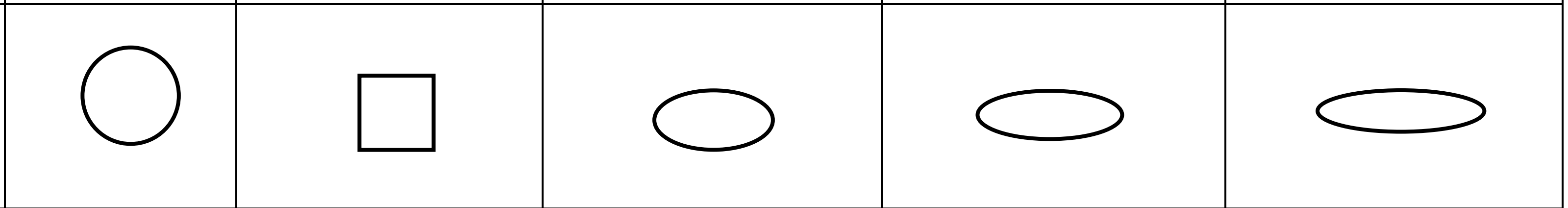
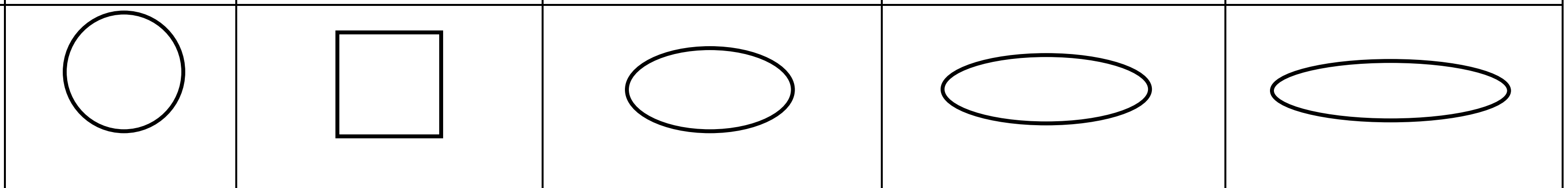
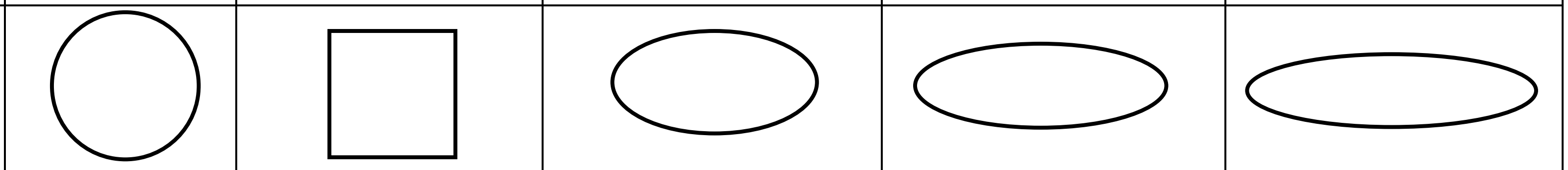
At the arrival in the retail stores, the integrity of the pallets are maintained without visible deformation of the banana packages?	☐ YES ☐ NO ☐ NA.
Notes:	
The pallets are stacked straight and no visible lean or inclination which may cause by compression of the packages in the lower layers?	☐ YES ☐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

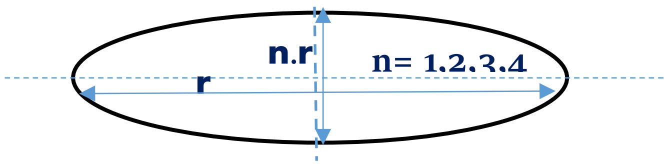
Conditions\Risk Factors	**Status**

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)	☐ YES ☐ NO ☐ NA.
Notes:	

Appendix C1: Damage area measurement sheet (Ver 4.0)

cm	1	2	3	4	
LINE					
0.5					
1.0					
2.0					
3.0					
cm²	$A = \pi r^2$	$A = x^2$	$A = \frac{\pi}{4}(2r^2)$	$A = \frac{\pi}{4}(3r^2)$	$A = \frac{\pi}{4}(4r^2)$



Appendix C2: Temperature and humidity conditions during the inter-state transport of bananas

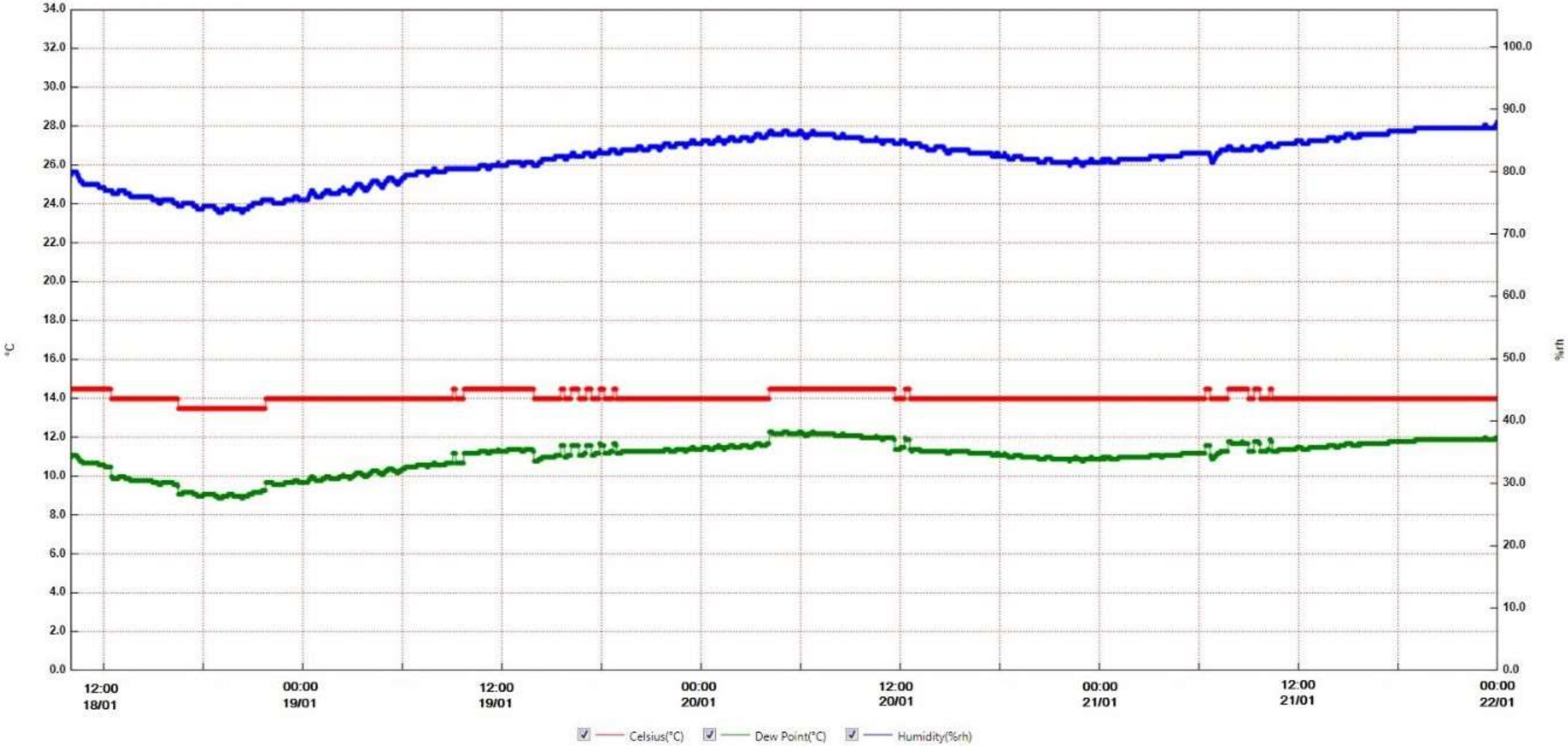


Figure C2 : Temperature, Relative Humidity (RH) and Dew Point during the Transport of Packaged Bananas

Appendix C3: Temperature and humidity conditions during the ripening of bananas

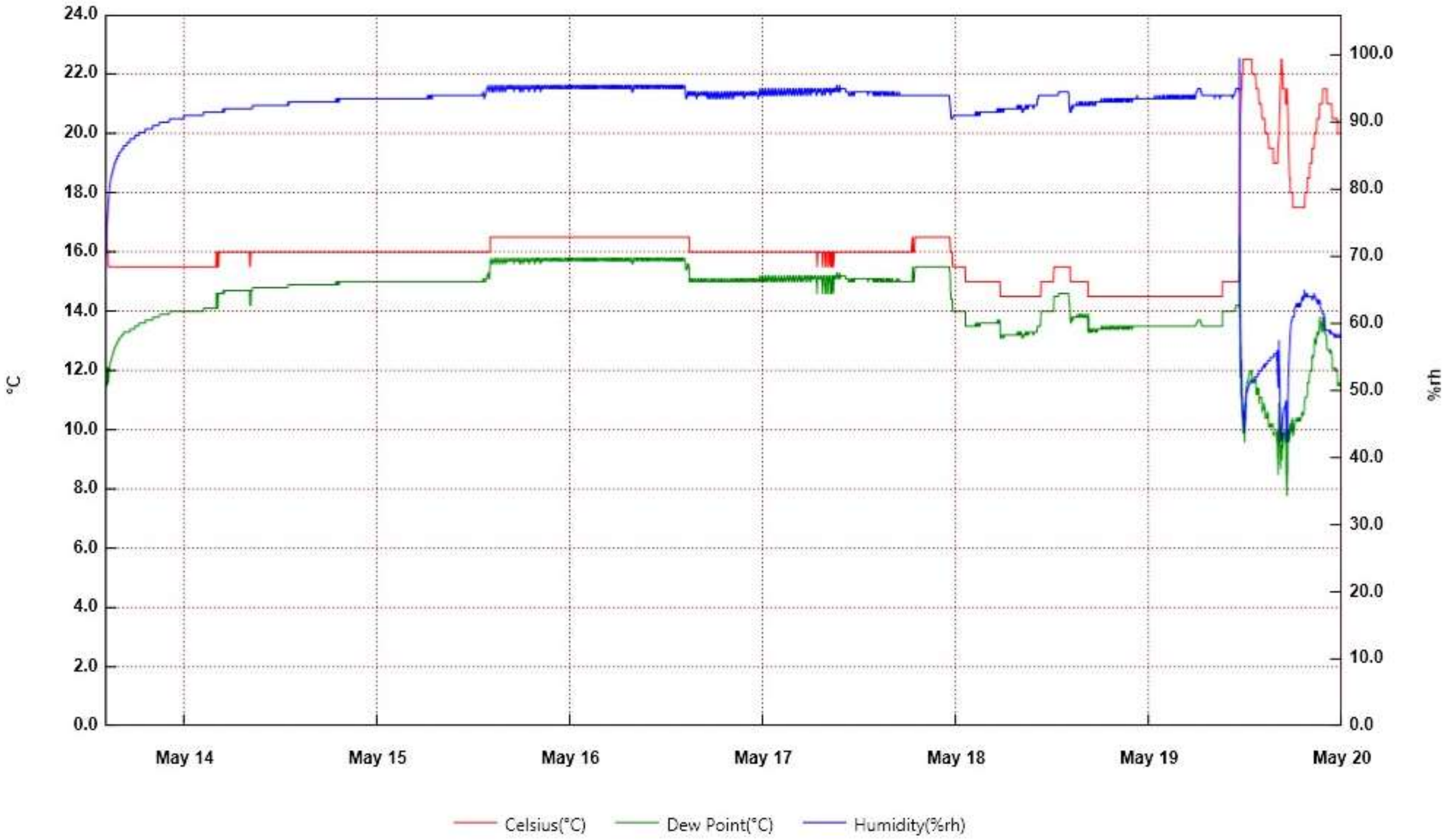


Figure C3: Temperature (°C), Relative Humidity (RH %) and Dew Point (°C) during the Ripening of Bananas