Technology and Raw Material Quality to Underpin the Irish Fresh-cut Fruit Industry

A dissertation presented by

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under the supervision of

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Abstract

The objective of this thesis was to contribute to improving the quality of fresh-cut fruits by identifying how raw material use, processing, packaging and storage might be optimised. Effects of intrinsic and extrinsic factor variables on the quality, microbiology and phytochemical content were determined.

Following comprehensive quality evaluations, principal component analysis (PCA) was employed, and the biplots generated were effective in characterising patterns of deterioration and in tracking differences in quality in terms of the rate and extent of change. Ripeness stage/physiological age, geographical origin, cut size and packaging type had large effects on quality (p<0.05) as did storage temperature and time (p<0.01).

There were significant effects of controlled and modified atmospheres on quality (p<0.05), but little effect on microbial growth or phytochemical (total phenolic, total carotenoid, total antioxidant activity) content (p>0.05). In general, product modified atmosphere (PMA) packs displayed a steadier rate of quality loss with more consistent end-product quality. A CA of 5%O₂+5%CO₂ was best at maintaining fresh-cut pineapple and cantaloupe melon quality, while a CA of 97%N₂+3%O₂ was best for fresh-cut kiwifruit. Exposure to sub-optimal atmospheres resulted in physiological disorders such as discoloration, loss of firmness and off-odour development.

Cut size (p<0.05) and storage time (p<0.01) had large effects on volatile aromatic compounds (VACs). VAC changes involved increased and/or decreased concentrations of existing volatiles rather than the emergence of new compounds. A total of 18, 16 and 20 odour-active compounds were detected and tentatively identified in the headspace of fresh-cut pineapple, cantaloupe melon and kiwifruit respectively. Based on PCA interpretation, the post cutting aroma life of fresh-cut pineapple and kiwifruit was adequate over 7 days for large cut pieces, and limited to less than 7 Days for smaller cut pieces. In contrast, fresh-cut melon aroma was limited to 4 and 7 Days for small and large cut pieces respectively. This was largely due to the presence of fermentative-like off-odours, which were more pronounced for smaller cut pieces.

The effects of intrinsic and extrinsic variables on the respiration rate (R_{CO₂}) of a number of fresh-cut fruits were determined. In general, the R_{CO₂} increased initially, peaked, and declined gradually to equilibrium within 24h. The high initial rate was highly dependent on fruit type, physiological age and processing (p<0.05). Using data for fresh-cut pineapple, a mathematical model based on exponential decay was developed in order to predict the R_{CO₂} over time. From this, the oxygen and carbon dioxide transmission rates required in package design were estimated and validated. The model parameters were found to be a good fit with experimental data and could be successfully applied to other fresh-cut fruits to aid in product-package compatibility.
Declaration

“I hereby declare that this dissertation is entirely my own work and effort and has not been submitted to any other institution for any other academic award. Where use has been made of the work of others, it has been fully acknowledged and referenced.”

Signature:       Date:

_______________________________________  _____________________

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To Granny Kelly ♥
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Finnegan, E., Ryan, S., Kilcawley, K. and O’Beirne, D. ‘Volatile aromatic compound (VAC) changes in fresh-cut fruits: effects of cutting size and storage time’. In preparation for submission in Journal of Agriculture and Food Chemistry.

Significant Achievements

List of Oral/ Poster Presentations

Finnegan, E. (2010). ‘Technology and Raw Material Quality to Underpin the Irish Fresh-cut Fruit Industry’, PhD Confirmation and Progression Seminar, Department of Life Sciences; Faculty of Science and Engineering, December 16th.


Finnegan, E. and O’Beirne, D. (2013). ‘Tracking Deterioration Patterns in Fresh-cut Fruits: Principal Component Analysis’, Abstract of the paper entitled “Characterising deterioration patterns in fresh-cut fruits using principal component analysis” presented to the Department of Life Sciences, 2\textsuperscript{nd} Annual Research Day, Radisson Blu Hotel and Spa, 17\textsuperscript{th} May.

Finnegan, E., Ryan, S., Kilcawley, K.N. and O’Beirne, D. (2014). “Volatile aromatic compound changes in fresh-cut fruits: effects of storage time and cut size”. Paper presented to the Department of Life Sciences, 3\textsuperscript{rd} Annual Research Day, Radisson Blu Hotel and Spa, 7\textsuperscript{th} May.
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List of Abbreviations/ Acronyms

% Percent
%SS Percent soluble solids
& And
β Beta
βs Selectivity
3Z, 2E-EI 3Z, 2E-enal isomerase
A Surface area, m²
AA Ascorbic acid
AAT Alcohol acyltransferase
ABTS 2,2'-azinobis(3-ethylbenzothiazoline)-6 sulfonic acid
ACC 1-aminocyclopropane-1-carboxylate
ADH Alcohol dehydrogenase
AEDA Aroma extract dilution analysis
AER Alkenal oxidoreductase
ALDH Aldehyde dehydrogenase
ANOVA Analysis of variance
AOC Allene oxide cyclise
AOS Allene oxide synthase
atm atmosphere
Aut Autumn
C₂H₄ Ethylene
CA Citric acid
CA Controlled atmosphere
Ca²⁺ Calcium ion
CCDs Carotenoid cleavage dehydrogenase
CCP Critical Control Point
CFU colony forming units
CHARM Combined hedonic aroma response measurement
CI Chilling injury
CL Climacteric
cm centimetres
cm² centimetre squared
cm³ centimetre cubed
CO₂ Carbon dioxide
Co-A Co-enzyme A
CS Clamshell container
CTR carbon dioxide transmission rate
DMAPP Dimethylallyl diphosphate
DMFH 2,5, dimethyl-4-hydroxy-3(2H)-furanone
DXP 1-deoxy-D-xylulose-5-phosphate
DXR DXP reductoisomerase
DXS  DXP synthase

e  external

EB  Enzymatic browning

ECK  Extended Craft Knife

EMA  Equilibrium modified atmosphere

EXP  exponential

FAD  Flavinadenine dinucleotide

FAO  Food and Agriculture Organization for the United Nations

FC  Fresh-cut

FCF  Fresh-cut fruit

FFA  Free fatty acids

FPP  Farnesyl diphosphate

FSAI  Food Safety Authority of Ireland

FW  Fresh weight

g  G force

g  Gram

G3P  Glyceraldehyde 3-phosphate

GAP  Good agricultural practices

GC-MS  Gas chromatography-mass spectrometry

GGPP  Geranyl geranyl diphosphate

GMP  Good manufacturing practices

GPP  Geranyl diphosphate

HACCP  Hazard Analysis Critical Control Point

HB  high barrier film

HDPE  High density polyethylene

HMGR  HMG-Co-A reductase

HPL  Hydroperoxide lyase

hr  hour

HS-SBSE  Headspace-SBSE

HS-SPME  Headspace-SPME

INDI  Irish Nutrition and Dietetic Institute

IPP  Isopentyl diphosphate

JMT  Jasmonate methyltransferase

kg  kilogram

L  Thickness, m

LAB  Lactic acid bacteria

LDPE  Low density polyethylene

Log  logarithm

LOx  Lipoxygenase

LOX  Lipid oxidation

LSA  Listeria selective agar

LSD  Least significant difference

M  mass, kg

MA  Modified atmosphere

xlvi
<table>
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<tr>
<td>MAP</td>
<td>Modified atmosphere packaging</td>
</tr>
<tr>
<td>MEA</td>
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<td>$P_{\text{min}}$</td>
<td>Minimum probe firmness, N</td>
</tr>
<tr>
<td>POx</td>
<td>Peroxidase</td>
</tr>
<tr>
<td>PP</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>PPO</td>
<td>Polyphenol oxidase</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinyl chloride</td>
</tr>
<tr>
<td>R</td>
<td>Ripe</td>
</tr>
<tr>
<td>$R_{\text{CO}_2}$</td>
<td>Respiration rate ml. CO$_2$. kg$^{-1}$. hr$^{-1}$</td>
</tr>
<tr>
<td>$R_{\text{eq}}$</td>
<td>$R_{\text{CO}_2}$ at equilibrium</td>
</tr>
<tr>
<td>RH</td>
<td>Relative humidity</td>
</tr>
<tr>
<td>$R_i$</td>
<td>$R_{\text{CO}_2}$ increase</td>
</tr>
<tr>
<td>ROS</td>
<td>Radical oxygen scavenging</td>
</tr>
<tr>
<td>$R_p$</td>
<td>$R_{\text{CO}_2}$ peak</td>
</tr>
<tr>
<td>rpm</td>
<td>Revolutions per minute</td>
</tr>
<tr>
<td>RQ</td>
<td>Respiratory quotient</td>
</tr>
<tr>
<td>RR</td>
<td>Respiration rate (consumption/production) m$^3$. kg$^{-1}$. hr$^{-1}$</td>
</tr>
<tr>
<td>RTE</td>
<td>Ready-to-eat</td>
</tr>
<tr>
<td>S/A</td>
<td>Sugar acid ratio</td>
</tr>
<tr>
<td>SBSE</td>
<td>Stir bar sorptive extraction</td>
</tr>
<tr>
<td>SD</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>SHA</td>
<td>Static headspace analysis</td>
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<tr>
<td>SL</td>
<td>Shelf-life</td>
</tr>
<tr>
<td>$S_{\text{max}}$</td>
<td>Maximum probe firmness, N</td>
</tr>
<tr>
<td>$S_{\text{min}}$</td>
<td>Minimum probe firmness, N</td>
</tr>
<tr>
<td>SNIF</td>
<td>Surface nasal impact frequency</td>
</tr>
<tr>
<td>Sp</td>
<td>Spring</td>
</tr>
<tr>
<td>SPME</td>
<td>Solid-phase micro-extraction</td>
</tr>
<tr>
<td>Sum</td>
<td>Summer</td>
</tr>
<tr>
<td>T</td>
<td>temperature</td>
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<tr>
<td>t</td>
<td>time</td>
</tr>
<tr>
<td>TA</td>
<td>Titratable acidity, citric acid equivalents</td>
</tr>
<tr>
<td>TAA</td>
<td>Total antioxidant activity</td>
</tr>
<tr>
<td>TBBCs</td>
<td>Total bacterial counts</td>
</tr>
<tr>
<td>TC</td>
<td>Total carotenoids</td>
</tr>
<tr>
<td>TEAC</td>
<td>Trolox equivalent antioxidant capacity</td>
</tr>
<tr>
<td>TP</td>
<td>Total phenolics</td>
</tr>
<tr>
<td>TRAP</td>
<td>Total radical-trapping antioxidant power</td>
</tr>
<tr>
<td>TSA</td>
<td>Tryptone soya agar</td>
</tr>
<tr>
<td>TSB</td>
<td>Tryptone soya broth</td>
</tr>
<tr>
<td>UR</td>
<td>Under-ripe</td>
</tr>
<tr>
<td>VAC</td>
<td>Volatile aromatic compounds</td>
</tr>
<tr>
<td>$V_f$</td>
<td>Free volume</td>
</tr>
</tbody>
</table>

xlviii
Important definitions

The following definitions are applicable throughout this thesis:

- **Fresh fruit**: fresh produce that is likely to be sold to consumers in an unprocessed or intact form.

- **Fresh-cut fruit**: fruits that have been trimmed and/or peeled and/or cut into 100% usable product that is bagged or pre-packaged and stored at refrigeration temperatures.

- **Food Quality**: the totality of features and characteristics of a particular product that bear on its ability to satisfy stated or implied needs.

- **Deterioration**: a series of cumulative, continuous deteriorative changes occurring in a food system over time which may affect the products wholesomeness, result in a reduction of its quality, and/or alter its serviceability and market appeal.

- **Food Safety**: assurance that food will not cause harm to the consumer when it is prepared and/or consumed according to its intended use.

- **Microorganism**: includes bacteria and fungi (yeasts and moulds).

- **Pathogen**: microorganism capable of causing disease or injury in humans, animals or plants.

- **Phytochemical**: refers to a wide variety of compounds, typically plant based, which exhibit various beneficial properties in humans.
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Firstly, my extended and most sincere gratitude to my supervisor, Professor David O’Beirne, for the invaluable opportunities and allowing me to undertake this Ph.D. Your constructive support and guidance throughout the duration of my studies I value deeply. I learned so much. Thank you for everything you have done for me over the past five years. Enjoy your deserving retirement!

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Special thanks must go the Foodies (you know who you are)! Let us never forget where it all started and how it all began…

To the amazing Finnegan and Rourke clans; my wonderful parents Kathleen and Michael, for providing constant love and support and continuously encouraging me to attain the greatest gift of all, education. I will never know stronger persons.

To my sisters, Kellie (& bump) and Áinne… What can I say only your over qualified chef ‘may have’ finally finished school 😊

To Seamus and Sharon (& Floss), thank you for putting up with my antics, for allowing me to slowly take over your house and reside at your kitchen table for the last 4 years. It’s all ahead of you Sharon 😊 I hope you enjoy the read! To SNÓrla, for all the well needed distractions and for making me laugh when I needed to most.

And finally, my biggest thank you of all to David Rourke; for just being you. I wouldn’t be who I am today without you! Here’s to the next chapter(s) xxx
“Let the future tell the truth, and evaluate each one according to his work and accomplishments.

The future, for which I have really worked, is mine”

Nikola Tesla

1856-1943
Chapter 1

Review of Literature
Introduction

The minimal processing of fruits, more commonly referred to as “fresh-cut” fruits, is a state-of-the-art technology by which a variety of temperate, tropical and subtropical fruits can be made available in ready-to-eat form. In recent years, the fresh-cut market has grown exponentially worldwide due to consumer demands for healthier, nutritious and convenient products (Euromonitor, 2012; Rabobank, 2009; Rößle, 2009).

Dietary guidelines have led to a worldwide increase in consumption of fresh fruits as key sources of vitamins, minerals, antioxidants and dietary fibre. The impetus behind this growth has been the increase in consumer awareness of health issues such as cardiovascular diseases, diabetes, cancer and obesity, and a demand for preservative-free fresh products with maximum convenience, requiring minimum preparation. As a result, fresh-cut fruit products are therefore considered a valued addition to the marketplace (Ragaert et al., 2004; Willcox et al., 2004; Varoquaux and Mazollier, 2002).

Consumers expect fresh-cut fruit to be without defects, have good sensory appeal and nutritional quality and have exceptional shelf-life, and be microbiologically safe (Watada and Qi, 1999). However, while EU markets (UK, Germany, Spain and Italy) have seen significant growth over the last decade (Appendix B.2), the Irish market has yet to reach the same level of success (Euromonitor, 2012). Rapid introduction of this technology has led to significant knowledge gaps leading to poor, unfavourable, inconsistent end-product quality. These gaps in particular relate to selection of suitable raw materials, optimum processing and packaging techniques and storage conditions.
1.1. Fresh-cut fruit

The USDA & FDA define fresh minimally-processed of fresh-cut fruit products as fruits and vegetables that have been freshly cut, washed, packaged and maintained with refrigeration (Beaulieu and Gorny., 2004). The International fresh-cut produce association defines a fresh-cut product as fruits or vegetables that have been trimmed and/or peeled and/or cut into 100% usable product that is bagged or pre-packaged to offer consumers high nutrition, convenience and flavour while still maintaining freshness (Fresh Cut Fruit Europe, 2006).

Fresh-cut fruit commodities, have a relatively shorter shelf life than their whole or intact counterparts as removal of the epidermis and subsequent slicing increases respiration rate, leaving the fresh-cut flesh less resistant to oxidative and enzymatic browning and allowing entry of bacteria (Wiley, 1994). These fruits become highly perishable, with a shelf-life as short as 1-3 days at chill temperatures (Ahvenainen, 1996). Ideally, the shelf-life of fresh-cut fruit should be at least 4-7 days under correct storage conditions, however, in today’s market place, consumers in the catering industry seek some products with sustained shelf-life of up to 21 days, depending on the product (Wiley, 1994).

While conventional food processing methods may extend the shelf-life (SL) of intact fruit and vegetables, fresh-cut processing renders fruits (more so than vegetables) highly perishable, requiring refrigerated storage to ensure adequate SL. Among the limitations of SL of fresh-cut fruits are: discolouration (browning, whitening, and translucency), firmness changes (increased softening, moisture loss and cellular damage), and development of off-flavour, odours and microbial spoilage.
1.2. **Fresh-cut fruit processing**

Fresh-cut processing (Figure 1.1) is the term used to describe non-thermal technologies used to process food in a manner which retains much of the fresh-like characteristic of the processed commodity (Manvell, 1997). It serves two purposes; (1) to retain freshness and (2) to ensure an adequate shelf-life sufficient to make distribution feasible within the region of consumption (Ahvenainen, 2000).

1.2.1. **Raw materials**

A critical factor in producing a high quality end product is the initial quality of the raw material. Raw materials of optimal quality are not always available due to season, distribution limitations and other reasons. The level of maturity and ripeness are important factors to be considered. A major problem for processors is that the optimal ripeness for harvesting is not always the optimum ripeness for processing (Beaulieu and Gorny 2004).

1.2.2. **Quality control**

A detailed product specification for problematic fruits of interest (previously identified in Appendix B.3) is outlined in Appendix D. Initial inspection of produce will eliminate any fruit which are not fit for use. In some cases, processors allow for some tolerance i.e.: 10% on bruises or scars per of particular fruits. Fruit normally has to be free from all visible contamination by dust and spray residue. All batches must be of uniform colour with no unusual discolouration i.e.: Granny Smith apples must be uniformly green with no pale or patchy coloured fruit. For some fruits e.g. strawberries the calyx and stalks may be permitted however; for other fruits (such as mangoes) the stalk must not be present. Fruit size is also a factor, with whole strawberries, for example, of 15-25mm in diameter being acceptable for processing.
Figure 1.1 Minimal Processing – Diagrammatic Representation of a Typical Industrial Fresh-cut Fruit Unit Operation.
1.2.3. Pre-cooling and preliminary washing

When fruit arrives at the processing site, it is transferred into holding tanks with overhead sprayers to wash and clean away any residual field dust or contamination during transport. Washing can be effectively carried out with untreated water at 5°C (Ahvenainen, 2000). However, the water nowadays may contain a mild sanitiser such as chlorine. Once the cooled fruit enters the cold chain it should not be allowed heat up again. After pre-cooling/ washing, the fruit is passed through a drying tunnel that removes excess water.

1.2.4. Peeling and/or deseeding

Peeling and/or deseeding is dependent on the nature of the raw material. Generally, hand processing is preferred for fresh-cut fruits because of the diversity of fruit shape, size and their sensitivity to damage. However, in large industrial scale practices there are several other peeling methods such as mechanical, chemical and high pressure steam peelers. Mechanical peeling is commonly used for more robust fruits such as apples and oranges, accomplished by subjecting the fruit to a device operating on the principle of a lathe. The fruit is mounted between spikes with one or more fixed rotating blades being brought to the periphery of the fruit in order to initiate manual peeling (FAO, 2010). During high pressure or flush steam peeling, the surface of the fruit, for example pineapple, is generally heated by high pressure stem (1.5MPa) in a rotating pressure vessel. The skin is subsequently removed by release of this pressure causing steam to form under the peel and surface of the fruit (Saravacos et al., 2002; Fellows, 2000; Brâna et al., 1997).

However, removal of the outer epidermal layer of most fruits causes damage to underlying cells which release intracellular enzymes (oxidases, peroxidises and proteases etc), which can affect the flavour, colour and texture of the fruit (Watada, 1996). Cellular sap released in addition to the increased surface area, can also give support to microbial growth. Peeling increases respiration rate and C2H4 induced biosynthesis which for some fruits can accelerate senescence (Abeles, 1992) so is avoided where possible. Furthermore, many authors have reported the development of strange tastes due to the aggressive peeling methods used (Ben-Shalom et al.,
Therefore, in view of these circumstances, it is quite interesting to consider enzymatic peeling as a novel method. During this technique, enzymatic preparations of polygalacturonase (EC 3.2.1.15), pectin lyase (EC 4.2.2.10) and cellulase (EC 3.2.1.4) which have degradative activities on the structural polysaccharides in the cell wall are employed (Ros et al., 1996). The selection and combination of these enzyme preparations are heterogeneous mixtures of pectinases, hemicellulases (EC 3.2.1.8) whose activity is the degradation of the cell wall is particularly influenced by temperature and pH (Prakash et al., 2001; Pagan et al., 2005; Pretel et al., 2008).

1.2.5. Size reduction

Fresh-cut processing may involve slicing, shredding or dicing of fruit in order to render them RTE. Prepared fruits are more susceptible to spoilage than their whole counterparts. Cutting of produce destroys internal compartmentation (Artés et al., 2007). Exposing more surface area induces a higher dehydration rate and consequently a greater weight loss. Varoquaux (1991) showed that kiwifruit slices lost 50% of their internal firmness in less than 2 days when stored at 2°C. It was suggested that this integrity loss was due to the enzymatic hydrolysis of cell wall components released due to processing. Furthermore, the surfaces of cut produce can become sites of microbial growth. Therefore peeling and/ or size reduction should be performed with blades that are as sharp as possible, thus reducing the extent of damage to cells, maintaining the cellular integrity and avoiding loss of internal fluids. A study by Bolin & Huxsoll (1991b) showed that slicing with a sharp blade was much more superior to slicing with a blunt blade and either chopping or slicing with a blunt blade as the shelf-life of lettuce was reduced, in some cases by 50%. Barry-Ryan and O’Beirne, 1998, concluded that a sharp blade compared to a blunt blade reduced microbial levels and off-odour development, and prolonged SL of fresh-cut carrots. Portela and Cantwell, 2001) determined that cutting melon pieces with a sharp rather than a blunt borer resulted in a longer shelf-life at 5°C with notable improvements in colour quality (translucency).

Other novel techniques of minimal processing involve the use of high-pressure water to cut through the fruit, and immersion therapy, whereby the intact
fruit is submerged in water so that turgor pressure is controlled (Allende et al., 2006; Ahvenainen, 1996).

1.2.6. Washing and/or post-cutting dipping treatments

Washing after slicing is an essential step for the removal of cellular sap and tissue debris from the cut surface. Hypochlorite, citric and ascorbic acid are commonly used to reduce microbial contamination and enzymatic browning of some produce. However, there is a strong desire by consumers for products with ‘clean labels’ in the marketplace. This is generally accepted in the EU as being the removal of chemical-sounding ingredients to create a simpler ingredient list that also includes natural-origin-sounding ingredients contributing to a healthier sounding product profile (Robin, 2010). Bearing that in mind, researchers are coming up with novel ways of treating products to accommodate this new market trend with essential oils from lemongrass, oregano and vanillin incorporated into edible coatings (from apple puree-alginate) (Rojas-Grau et al., 2007), animal products (e.g. lysozyme from eggs, milk) (Benkerroum, 2008; Cegielska-Radziejewska et al., 2008) and whey permeate (by-product from cheese industry) all with the potential as to act as microbial and sanitising agents (Ahmed et al., 2010). Furthermore, the recommended quantity of water to be used is 5-10L/kg of product before peeling/cutting and 3L/kg of product after (Ahvenainen, 2000). In addition, washing in flowing or bubbling water (agitated using a stream of air) is preferred over dipping. The turbulence permits the elimination of most foreign matter with much less bruising when compared to mechanical agitation (Dowling, 1991).

After washing/dipping, the excess moisture must be completely removed to reduce microbial spoilage. Drying methods such as draining and spinning are proposed, but care must be taken to avoid unnecessary damage to fruit tissue (Soliva-Fortuny et al, 2003).

1.2.7. Packaging and refrigerated storage

Generally, fresh-cut fruits are packaged in sealed packs/ containers within which modified atmospheres develop. Packs format diversification in recent times has led
to an increased demand for improved packaging technologies (see Section 1.6). In addition, these packs are maintained in refrigeration units at 0-4°C storage. There are two different classifications of refrigeration units used to display fresh-cut fruit products in supermarkets; (1) horizontal and (2) vertical. Horizontal units allow for the entire package to maintain a consistent temperature and therefore will not produce a great amount of condensation. Vertical units allow the outside of the package to be in direct contact with air in the supermarket which creates a perfect environment for the generation of condensation. However, in this situation, the most outside package(s) will experience the greatest condensation. Therefore, temperatures are not always optimum, with fluctuations between stores common place (Nunes et al., 2009).

1.3. Components of fresh-cut quality

Quality is hard to define and normally exists as a combination of characteristics, often classified as external, internal and latent. External quality attributes refer to visual appearance and firmness. Internal characteristics are determined once a product is cut and/or eaten, and include aroma, taste and texture (mouth-feel). Latent characteristics are usually not determined visually (except where microbial spoilage occurs) and include wholesomeness and nutritional value.

1.3.1. Appearance

The appearance of fresh-cut fruit is a fundamental quality attribute for consumer acceptance and relates to size, shape, colour and glossiness (Kader, 2002). It also refers to cleanliness and the absence of defects which are directly related to spoilage. Fresh fruit defects include evidence of bruising/ crushing of pieces due to improper handling or mechanical damage (Martin-Bellosos et al., 2007), shrivelling due to water loss, mushiness, sogginess or tissue softening, sliminess and water soaking due to ageing (Montero-Calderón et al., 2009) or colour changes due to enzymatic browning or other physiological disorders (Montero-Calderon et al., 2008). Microbial spoilage can also induce changes in visual appeal as a result of mould growth and package swelling due to the release of gases by bacteria (Kader, 1989).
Acidulants and reducing agents such as citric and ascorbic acid respectively, are commonly used in the food industry to prevent polyphenoloxidase (PPO)-mediated cut-surface discoloration of fresh-cut apples. Ascorbic acid works by converting quinones (formed by PPO from phenolics) back to phenolic compounds. Unfortunately, once all the ascorbic acid is exhausted, PPO browning will proceed uninhibited. Usually used in combination with citric acid, it also reduces surface pH of commodities, further slowing browning.

1.3.2. Firmness

Firmness properties relating to texture play an important role in the quality of fresh-cut fruits (Cantwell and Portela, 1997; Abbey et al., 1988). A major problem for processors is the susceptibility of fresh-cut fruits to firmness loss during harvesting, handling and storage (DeEll et al., 1999; Soliva-Fortuny et al., 2003; Barrett et al., 2010). In fresh-cut fruit, these changes appear due to increased cellular decompartmentalisation as a consequence of processing (Sams, 1999). Softening in this instance is frequently attributed to enzymatic degradation of cell wall components (Vicente et al., 2007; Varoquaux et al., 1990) and by decreased turgor due to water loss. Calcium (Rico et al., 2007), pectin (Van Buren, 1979) and cellulose (McFeeters et al., 1984) are found in the intercellular region of fruits and are highly influenced by polygalactauronase (PG) and pectin methyl esterase (PE) activity (Prasanna et al., 2007).

However, fresh-cut fruit firmness can be maintained by application of calcium compounds such as calcium chloride (Ponting et al., 1971; 1972) which is attributed to the stabilisation of membrane systems and the formation of Ca-pectates, which increase rigidity of the middle portion and cell wall of the fruit (Grant et al., 1973; Jackman and Stanley, 1995b) thus inhibiting the degradation of the middle-lamella (Buescher and Hobson, 1982) and improving cell strength (Miganini et al., 1995). When combined with mild heat treatments allows the formation of COO- groups from the pectin content of fruits which make Ca2+ ions which form salt-bridge cross link making the cell wall less acceptable to the enzymes that cause softening (Kim et al., 1993; 1994).
1.3.3. Aroma and Taste

Flavour quality is extremely complex and involves perception of the tastes and aromas which combine to deliver overall flavour. Flavour attributes arise from many sources including sugars (sweetness), organic acids (acidity), bitter compounds and astringency of phenolic compounds and tannins (bitterness). Aroma (and off-odour) attributes on the other-hand are the result of complex mixtures of a large number of volatile aromatic compounds (VACs), whose composition is specific to species and often to variety (El Hadi et al., 2013).

Volatile can be classified as primary or secondary compounds, indicating whether they were present in intact fruit tissue or produced as a result of tissue disruption (El Hadi et al., 2013). They may emanate from either intact or disrupted fruit tissues and influence the aroma profiles and aroma perception. These compounds are a volatile mix of esters, alcohols and aldehydes, terpenes among others which define and separate each fruit (Sanz et al., 1997). These aroma compounds are especially important for fresh-cut fruit products, in particular mixed fruit packs where products, packaged together, gather and concentrate aroma volatiles which are released upon opening (Lamikanra and Richards, 2002). Fruits such as pineapple, melon, banana and kiwifruit owe their aromas to the presence of esters.

There are several pathways involved in VAC biosynthesis. Volatiles important for aroma (and flavour) are typically biosynthesised via membrane lipids, amino acids and carbohydrate pathways. Therefore, an important step in these pathways is the availability of primary precursor substrates, including fatty acids, amino acids and glucosides, all of which are highly regulated during fruit development (Song et al., 1997; 2008).

Fatty acids are primary precursors of aroma volatiles in most fruit (Sanz et al., 1997). Fatty acid-derived straight chain alcohols, aldehydes, ketones, acids and esters, ranging from C_1 to C_{20}, are important character-impact aroma compounds that are responsible for fresh fruit flavours. They are formed via three main processes: α-oxidation, β-oxidation and the LOx pathway (Schwab et al., 2002).
\textit{\textbf{α- and β-oxidation}}

The metabolism of polyunsaturated fatty acids, commonly referred to as the lipid oxidation (LOx) pathway, contributes to the flavours of green fruits such as kiwifruit. Saturated and unsaturated volatile C6 and C9 aldehydes and alcohols are typically involved. These short-chain aldehydes and alcohols are produced by plants in response to wounding and play an important role in the plants defence strategies and pest resistance (Matsui, 2006; Stumpe, 2006). At least four enzymes are involved in the biosynthetic pathway leading to their formation: LOx, hydroperoxide lyase (HPL), 3(Z), 2(E)-enal isomerise and alcohol dehydrogenase (ADH). When fruit are cut and/or macerated/homogenised, linoleic and linolenic acid are oxidised to various C6 and C9 aldehydes (Lea, 1995) contributing to green leafy aromas.

Many of the aliphatic esters, alcohols, acids, and carbonyls found in fruits are derived from the oxidative degradation of linoleic and linolenic acids (Reineccius, 2006). In addition, some of the volatile compounds derived from enzyme-catalyzed oxidative breakdown of unsaturated fatty acids may also be produced by autoxidation. Autoxidation of linoleic acid produces 9,13-hydroperoxides, whereas linolenic acid produces 12,16-hydroperoxides (Berger et al., 2007). Hexanal and 2,4-decadienal are the primary oxidation products of linoleic acid, while autoxidation of linolenic acid produces 2,4-heptadienal as the major product (Figure 1.2). Further autoxidation of these aldehydes leads to the formation of other volatile products (Chan, 1987).

Sanz et al., (1997) reported that β-oxidation of fatty acids is the primary biosynthetic process providing alcohols and acyl coenzyme A (CoAs) for ester formation. (β-oxidation results in successive removal of C2 units (acetyl CoA) from the parent fatty acid. Fatty acid acyl-CoA derivatives are then converted to shorter chain acyl CoAs by losing two carbons in every round of the β-oxidation cycle, requiring flavinadenine dinucleotide (FAD), nicotinamide adenine dinucleotide (NAD), and free CoA. Acyl CoAs are reduced by acyl CoA reductase to aldehyde that in turn is reduced by ADH to alcohol for use by AAT to produce esters (Bartley et al., 1985).
Amino acid pathways

Amino acids, such as alanine, valine, leucine, isoleucine, phenylalanine and aspartic acid, are also involved in aroma biosynthesis in fruit as direct precursors. Their metabolism is responsible for the production of a broad number of compounds, including alcohols, carbonyls, acids and esters (El Hadi et al., 2003; Baldwin et al., 2002). Amino acids can undergo an initial deamination or transamination leading to the formation of the corresponding α-keto acid. Subsequent decarboxylation followed by reductions, oxidations and/or esterifications give rise to aldehydes, acids, alcohols and esters (Reineccius, 2006; Tavaria et al., 2002; Beck et al., 2002). These amino acids can also be the precursors of acyl-CoAs, which are used in alcohol esterification reactions catalyzed by AATs. For example, isoleucine could give rise to 3-methylbutanol and 2-methylbutyryl-CoA, both used in an esterification reaction to yield the ester 3-methylbutyl 2-methylbutanoate while it has been suggested that alanine serves as a precursor for volatile ethyl esters, which can be produced by AAT (Perez et al., 2002; Beekwilder et al., 2004).
**Terpenoid pathway**

The terpenoids compose the largest class of plant secondary metabolites with many volatile representatives being present in a variety of fruits. Terpenoids are derived from the universal C$_5$ precursor isopentenyl diphosphate (IPP) and its allylic isomer dimethylallyl diphosphate (DMAPP), which in higher plants are generated from two independent pathways located in separate intracellular compartments. In cytosol, IPP is derived from the long-known mevalonic acid (MVA) pathway that starts with the condensation of acetyl-CoA (Newman and Chappell, 1999). In plastids, IPP is formed from a MVA-independent pathway (or MEP pathway) with pyruvate and glyceraldehydes 3-phosphate as direct precursors and methylerythritol phosphate (MEP) as the key intermediate (Lichtenthaler, 1999). However intermediate cross-links between these two IPP biosynthetic pathways is prevalent, particularly in the direction from plastids to cytosol (Figure 1.3) (Dudareva et al., 2005; Laule et al., 2003). Consequently, monoterpenes (C$_{10}$) and sesquiterpenes (C$_{15}$) have a high vapour pressure allowing their release into the atmosphere.

**Figure 1.3** The biosynthesis pathway of isoprenoids in plant cell.

Taken from (El Hadi et al., 2013). **Key of abbreviations:** DMAPP, dimethylallyl diphosphate; DXP, 1-deoxy-D-xylulose-5-phosphate; DXS, DXP synthase; DXR, DXP reductoisomerase; FPP, farnesyl diphosphate; G3P, glyceraldehyde 3-phosphate; GPP, geranyl diphosphate; GGPP, geranyl geranyl diphosphate; HMGR, HMG-CoA reductase; IPP, isopentenyl diphosphate; MEP, methylerythritol phosphate; MVA, mevalonic acid.

Moreover, it is important to consider not just desirable flavour compounds but also undesirable off-flavours/odours which may have developed during storage as a result of growth of spoilage microorganisms or inadequate packaging which leads to fermentation (Kader and Mitcham, 1999). However, usually by the time microbial
spoilage occurs, firmness and appearance are also likely to be degraded (Huxsoll et al., 1989).

1.3.4. Nutritional Quality

Fresh fruits contain small to significant concentrations of several important nutrients such as carbohydrates, vitamins, minerals and phytochemicals (Table 1.1). A vast amount of data has been accumulated on the compositional characteristics of different fruits, with compositions varying not only according to botanical variety, (Chen, 1992; Konja and Lovric, 1993) cultivation practices and climate (Nagy et al., 1992; Somogyi et al., 1996) but also due to changes in maturity at harvest (Villanueva et al., 2004), and the condition of ripeness, processing and storage (Gil et al., 1996; 2001).

Fruits are important sources of transitional metals that have a role in the synthesis and structural stabilisation of proteins and nucleic acids (Halliwell and Gutteridge, 2007). With regards vitamins, most fruits are low in B-vitamins, but citrus fruits, including oranges and kiwifruit, are excellent sources of vitamin C (Belitz et al., 2004; Ansorena, 1999).

Table 1.1 Fruit Content of Vitamins, Total Antioxidant Capacity (TAC) and Fibre adapted from Crujeiras et al., 2010: Nutritional value and phytochemical content of fruits, vegetables and legumes, In. Bioactive Foods in Promoting Health: Fruits and Vegetables.

<table>
<thead>
<tr>
<th>Fruit</th>
<th>Vit C mg/100g</th>
<th>Vit E mg/100g</th>
<th>Vit A µEq retinol/100g</th>
<th>TAC mmol/kg</th>
<th>Fibre g/100g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple</td>
<td>12.4</td>
<td>0.40</td>
<td>4.0</td>
<td>3.23</td>
<td>2.3</td>
</tr>
<tr>
<td>Grape (red)</td>
<td>4.0</td>
<td>0.70</td>
<td>3.0</td>
<td>11.09</td>
<td>0.4</td>
</tr>
<tr>
<td>Grape (green)</td>
<td>4.0</td>
<td>0.70</td>
<td>3.0</td>
<td>3.25</td>
<td>0.9</td>
</tr>
<tr>
<td>Melon</td>
<td>25.0</td>
<td>0.1</td>
<td>784</td>
<td>5.73</td>
<td>0.7</td>
</tr>
<tr>
<td>Orange</td>
<td>50.6</td>
<td>0.21</td>
<td>49.0</td>
<td>20.50</td>
<td>2.3</td>
</tr>
<tr>
<td>Pineapple</td>
<td>20.0</td>
<td>0.1</td>
<td>3.0</td>
<td>15.73</td>
<td>1.2</td>
</tr>
<tr>
<td>Strawberry</td>
<td>60.0</td>
<td>0.2</td>
<td>1.0</td>
<td>22.74</td>
<td>2.2</td>
</tr>
</tbody>
</table>

* Source: Belitz et al., 2004; Ansorena, 1999.
* Source: Mataix, 2003
* Source: Pellegrini et al., 2003: ferric reducing-antioxidant power (FRAP; mmol Fe³⁺/kg).
**Phytochemicals**

The cooperative integration of various antioxidant molecules and minerals is essential in retarding the rate and extent of quality loss and deterioration (Figure 1.4). Some of these compounds also influence the overall organoleptic attributes of fruits i.e. flavonoids and phenolic acids. Fruits are able to supply different non-nutritional components such as polyphenols and chlorophylls which may impart health benefits and positive biological functioning (Pellegrini et al., 2003). Organic acids, in association with sugars, play a major role in taste, while esters of aliphatic alcohols and short chain fatty acids are associated with aroma. In addition to contributing to flavour, pigments such as chlorophyll, carotenoids and anthocyanins which are responsible for the characteristic colour of fruits such as kiwifruit, cantaloupe melon and strawberry respectively. Many vitamins (C and E) also serve multiple functional properties, by acting as antioxidants, preventing undesirable colour changes and retarding rancidity in plant products. Pro-vitamin A (β-carotene) and riboflavin (vitamin B12) contribute to the colour of plant pigments such as pineapple, cantaloupe melon and strawberry (Table 1.2).

**Table 1.2** Fruit pigments, related colour and polyphenols

<table>
<thead>
<tr>
<th>Fruit</th>
<th>Colour</th>
<th>Pigments</th>
<th>Polyphenols</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kiwifruit</td>
<td>Green</td>
<td>Chlorophyll, Lutein,</td>
<td>Vitamin C*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Zeaxanthin</td>
<td></td>
</tr>
<tr>
<td>Cantaloupe</td>
<td>Deep Orange</td>
<td>α-carotene, β-carotene</td>
<td>Quercetin, Chlorogenic acid, Vitamin C, Glutathione, Rutin Ferulic acid</td>
</tr>
<tr>
<td>Orange</td>
<td>Orange</td>
<td>β-cryptoxanthin, Zeaxanthin, Lutein</td>
<td>Hesperidin, Vitamin C, Limonene, β-sitosterol, Glutathione</td>
</tr>
<tr>
<td>Pineapple</td>
<td>Yellow</td>
<td>β-carotene Flavonoids</td>
<td>Quercetin, Chlorogenic acid</td>
</tr>
<tr>
<td>Strawberry</td>
<td>Red</td>
<td>Anthocyanins</td>
<td>Quercetin, Chlorogenic acid, Phenolic acids, Gallic acid</td>
</tr>
<tr>
<td>Grape</td>
<td>Blue/Black</td>
<td>Anthocyanins</td>
<td>Catechins, Myricetin, Vitamin C, Resveratrol</td>
</tr>
<tr>
<td></td>
<td>Red/Purple</td>
<td>Proanthocyanidins</td>
<td></td>
</tr>
</tbody>
</table>

(adapted from Blasa et al., 2010)

*organic acid

**Polyphenols**

The term ‘phenolics’ encompasses approximately 8,000 naturally occurring compounds referred to as polyphenols and simple phenols, all of which possess a
phenol as their common structure. They contribute to organoleptic qualities of fruits and defence against pathogen attack (Blasa et al., 2010). Approximately one-third of plant phenolics are phenolics acids and the rest are mostly flavonoids (Kris-Etherton et al., 2002). Phenolic acids are divided into two sub-groups which are the derivatives of hydroxybenzoic and hydroxycinnamic acids. The most common phenolic acids found in fruits are caffeic, p-coumaric, vanillic, ferullic and protocatechuic (Erlund, 2004; Moyer et al., 2002) and are listed in Table 1.2. They are not found in free forms in plants because the carboxyl groups are very reactive and easily transform into esters or amides when combined with aliphatic alcohols and phenols or amino compounds. The majority are linked to cellulose, proteins and lignin or to small organic molecules (e.g. glucose) or large polyphenols known as flavonoids through ester, ether or acetyl bonds (Rababah et al., 2005).

**Chlorophylls**

Chlorophyll is a compound known as a chelate that consists of a central metal ion (Magnesium; Mg$^{2+}$) bonded to a large organic molecule, composed of carbon, hydrogen, and varying degrees of O$_2$ and nitrogen. The large organic molecule is referred to as porphyrin and contains four nitrogen atoms bonded to the Mg$^{2+}$ ion in a square planar arrangement (Figure 1.5). Although not considered an antioxidant, chlorophylls are widely distributed in the botanical world (Ferruzzi et al., 2002; Ferruzzi and Schwartz, 2001). Chlorophyll exists as both $a$ and $b$ forms and foods that are high in chlorophyll are usually high in $\beta$-carotene (Total Carotenoids).

![Chemical structure of chlorophyll with the porphyrin ring shown in red with interchangeable $R$ groups for chlorophyll $a$ and $b$ respectively.](http://www.webexhibits.org/causesofcolor/7A.html)
Figure 1.4 Different categories of diet phytochemicals with bioactive (antioxidant) properties. (Adapted from Blasa et al., 2010)

Chlorophyll \( a \) and \( b \) are identical in composition apart from one side-chain, composed of a \(-\text{CH}_3\) in chlorophyll \( a \), while in chlorophyll \( b \) it is \(-\text{CHO}\). Furthermore, the high antioxidant capacity of chlorophyll \( a \) over chlorophyll \( b \) may be due to its high abundance found in plants (ratio 3:1) thus it may play a role in protecting against lipid oxidation (Lanfer-Marquez et al., 2005; Ferruzzi et al., 2002).

Figure 1.6 Spectrometrically measured signals of pigment mixtures (ATB, 2013)
**Carotenoids**

Most orange, yellow and red fruit such as citrus, peach, cantaloupe melon and tomatoes are known to contain high concentrations of carotenoids which accumulate during fruit ripening (Khachik *et al*., 1991). The major dietary carotenoids are α-carotene, β-carotene, lycopene and the xanthophylls, β-cryptoxanthin, lutein and zeaxanthin (Potter and Hotchkiss, 1996; Blasa *et al*., 2010). Dietary carotenoids contribute to both the appearance and appeal of fruit as well as provide additional nutritional value in the form of antioxidants (McGhie and Ainge, 2002). Carotene, takes many forms with β-carotene containing the highest provitamin A activity of all carotenoids. Xanthophylls are yellow carotenoids pigments involved in photosynthesis. Figure 1.6 shows the typical chlorophyll and carotenoid profiles observed spectrometrically.

1.3.5. **Microbial stability**

Fresh-cut fruits, once considered a relatively safe commodity, are attracting increasing microbiological concern (Brackett, 1999; Westrell *et al*., 2009; Hong *et al*., 2014).

In 2007, in the European Union, Salmonella was found in around 0.3% of produce-related samples tested. Large investigations on prevalence of pathogenic bacteria in fruits and vegetable were conducted in the UK, Ireland, Germany and the Netherlands in that year (Westrell *et al*., 2009). The proportion of produce samples that yielded Salmonella in these studies ranged from 0.1% to 2.3%, with pre-cut products having some of the highest proportions contaminated. *Escherichia coli* 0157:H7 has been isolated from fresh-cut apple tissue (Janisiewicz, *et al*., 1999), while *Listeria monocytogenes* has been cultured on a variety of fresh-cut vegetables and fresh-cut cantaloupe melon (Hong *et al*., 2014; Farber *et al*., 1998; Francis and O’Beirne, 1998; Babic *et al*., 1997;).

Fresh-cut fruit products are not pasteurised and may be consumed raw. The application of minimal processing techniques and the subsequent storage have presented indigenous and pathogenic microorganisms with novel ecosystems in which to grow. Some recent foodborne outbreaks have outlined the seriousness of
these risks resulting in serious illness and high mortalities, e.g. *norovirus* outbreak in frozen raspberries; Scandanavia, 2006; *Escherichia coli* 0157:H7 outbreak associated with fresh spinach; US, 2007; *Salmonella* outbreak in tomatoes, US, 2008 and the *Listeria monocytogenes* outbreak of 2012 in Colorado, USA that resulted in a 20% mortality rate of infected persons having consumed cantaloupe melons (Center for Disease Control, 2012). A report by the EU scientific committee on food (2002) stated that the prevalence of foodborne pathogens of fruit and vegetable origin and their involvement in outbreaks are not well documented from a European perspective (Abadias et al., 2008).

A diverse community of epiphytic microorganisms that present a further competitive barrier to the spoilage organism typically colonize the outermost fruit surface. External damage such as bruising, cracks, and punctures creates sites for establishment and outgrowth of the spoilage microbes. Lesion development can be relatively rapid, occurring within days or weeks. This presents the risk that rapidly reproducing spoilage microorganisms will arrive within open wound sites at the packing facility, and thereby, through shedding from the asymptomatic wound, present the potential for cross contamination within the facility during handling, culling, washing, sorting, and packing before storage.

The laboratory of Food Microbiology and Food Preservation (IFMFP), Ghent University, Belgium, has proposed specific microbiological guidelines for spoilage causing microorganisms (*Table 1.3*). This will be further discussed in section (1.6).

**Table 1.3 Microbiological guidelines for Fresh-cut Fruit (CFU/g)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Target</th>
<th>Tolerance</th>
<th>Best-Before-Date</th>
<th>Total aerobic</th>
</tr>
</thead>
<tbody>
<tr>
<td>psychrotrophic count</td>
<td>$10^5$</td>
<td>$10^6$</td>
<td>$10^7$</td>
<td></td>
</tr>
<tr>
<td>Lactic acid bacteria</td>
<td>$10^3$</td>
<td>$10^4$</td>
<td>$10^7$</td>
<td></td>
</tr>
<tr>
<td>Yeasts</td>
<td>$10^3$</td>
<td>$10^4$</td>
<td>$10^5$</td>
<td></td>
</tr>
<tr>
<td>Moulds</td>
<td>$10^2$</td>
<td>$10^3$</td>
<td>$10^4$</td>
<td></td>
</tr>
</tbody>
</table>

*a* Incubated for 5 days at 22°C  
*b* When the number of lactic acid bacteria on the best before date is greater than $10^7/$g the food product can only be rejected on condition that there were unacceptable sensorial deviations  
*c* Target is the guideline for the production day, in best conditions produced.  
*d* Tolerance is the maximum guideline for production day.  
*e* Best-before-date is the end of the shelf-life; above these guidelines notable spoilage will occur.
For pathogens, the Scientific Committee on Veterinary Measures (SCVM) relating to public health issued an opinion on *Listeria monocytogenes*. That opinion recommended that it be an objective to keep the concentration of the pathogen in foods below 100 CFU/g. For *Salmonella*, absence in 25g of products placed on the market during their shelf-life is acceptable, while for *Escherichia coli*, 100-1000 CFU/g during the manufacturing process is tolerable (FSAI, 2014).

1.4. Physiological, biochemical and microbial effects of fresh-cut processing

Deterioration of food can be defined as a process of changing to an inferior state. In terms of fresh-cut fruit, there are many obvious deterioration patterns, which differ from fruit to fruit with many common characteristics such as appearance, firmness and flavour (section 1.3) susceptible to change. Deterioration exists in the form of many complex processes that occur simultaneously as a result of mechanical damage, biochemical changes, physiological ageing and microbial spoilage.

Fresh-cut processing heightens the perishability of fruits with the mixing of previously sequestered enzymes and substrates resulting in the deterioration of organoleptic properties such as loss of characteristic appearance and firmness (excessive flesh softening), and compositional changes leading to flavour loss and discolouration (Lamikanra, 2002).

1.4.1. Enzymatic browning

Enzymatic browning (EB) is probably the most common defect of appearance in fresh-cut fruits. EB mostly occurs during processing and subsequent storage. According to the Food and Agriculture Organization for the United Nations (FAO), it is estimated that over 50% of losses in fruit occur as a result of EB (Dauthy, 1995). EB is predominantly caused by physical stresses such as cutting or wounding and is initiated when fruit tissue or cell contents are exposed to oxygen, and oxidative enzymes such as polyphenols oxidase (PPO), phenylalanine ammonia lyase (PAL) are released. PPO is a group of copper protein complex enzymes that catalyse the
oxidation of phenolics. They are widely found in fruits (and vegetables) and are the most important enzymes associated with discoloration of fresh-cut products. PPO activity was detected in all parts of affected fruits, including the peel, the flesh and the cortex (Alzamora et al., 2000). Since EB is basically due to oxidation of phenolic compounds catalysed by the presence of PPO generating colourless quinones that are later polymerised into melanins which result in brown discoloration, the concentration of phenolics compounds and antioxidants respectively, in the tissue are of high importance (Martín-Bellosa et al., 2006; Castañer et al., 1996). The depth of browning depends on the structure of the polyphenolic substrates (Toivonen and Delaquis, 2006). Different fruit types differ in the degree of browning (Yano and Saijo, 1987) with apples and pineapples being most affected (Figure 1.7). Furthermore, the extent of symptoms varies with cultivar, fruit size, temperature and nutritional composition (Weerahewa and Adikaram, 2005).

![Figure 1.7](https://geneticmaize.wordpress.com/2012/07/18/okanagan-specialty-fruits/)

**Figure 1.7** (A) Fresh-cut golden delicious apples and (B) evidence of enzymatic browning after short period of time. Taken from:

(Figure 1.8 illustrates the location of phenolic compounds and enzymes within a typical plant cell. The formation of highly reactive quinones enables them to react with amino and sulfhydryl groups of proteins and enzymes as well as with other substances such as chlorogenic acid derivatives and flavonoids (Basta et al., 2010). Many fruits such as apple, peach and pear have high levels of preformed phenolic compounds where, following cutting, very rapid surface browning takes place (Artés et al., 1999). In tissue with low initial levels of preformed phenolics, browning results from the induced synthesis and subsequent accumulation of substrates (Castañer et al., 1999). In the biosynthesis of phenolics compounds, PAL appears to play a fundamental role, whose activity is enhanced by the presence of ethylene (C$_2$H$_4$).

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Peroxidises (POx) also contribute directly or indirectly to browning (Lamikanra, 2002; Martin-Belloso et al., 2006). Its main function is to control the level of peroxides generated in oxygenation reactions to avoid excessive formation of free radicals (Alzamora et al., 2000).

**Figure 1.8:** The localisation of phenolic compounds and phenolic oxidising enzymes in a typical plant cell. POD: phenol peroxidase; PPO: polyphenol oxidase. (taken from Toivonen et al., 2008).

### 1.4.2. Whitening and translucency

Whitening is a defect frequently associated with oranges, while translucency is associated with some melon varieties (Portela and Cantwell, 1998; Portela et al., 2001). White blush, which is more commonly associated with fresh-cut carrots, can be caused by exposure of outer superficial cells to dry conditions as a result of minimal processing which results in dehydration. Wound response causes post-processing accumulation of lignified material which intensifies the incidence and severity of white blush (Toivonen et al., 2008; Rico et al., 2007; Bolin et al., 1991a). The degree of formation of this lignin-type material is directly related to the severity of processing (Watada, 1986). In fresh-cut lemons, increases in luminosity were observed at smallest cut sizes, and could be attributed to tissue dehydration (Ártés-Hernández et al., 2007).
In the presence of O$_2$, LOx catalyses the oxidation of polyunsaturated fatty acids, converting them to a variety of carbonyl compounds and oxygenated derivatives with free radical by-products (Verhagen et al., 1978). Furthermore, LOx activity catalyses the co-oxidation of pigments and has a bleaching effect on carotenoids (Weber et al., 1974), and chlorophyll (Imamura and Shimizu, 1974; Holden, 1974; Klein et al., 1984) which is deleterious to post-cutting quality. However the extent of discolouration differs from product to product and is influenced by factors such as final cut size, cut blade sharpness, mechanical aspects of the size reduction (manual versus machine operated), and physical and mechanical properties of the whole product (Abe et al., 1993).

Loss of natural berry colour was reported to be affected by ascorbic acid (AA) content. Skalsky and Sistrunk, (1973), suggested that anthocyanins may be destroyed either through direct oxidation by quinones formed from catechin by PPO action, or through copolymerization of anythocyanins to tannins (Jackman et al., 1987).

Another factor affecting the appearance aspect of fresh-cut fruit products is the change in homogeneity of the tissue that results in the development of translucent flesh. This physiological disorder is commonly referred to as translucency and is characterised by dark and glassy flesh, and seems to be of particular importance in melons (Aguayo et al., 2003, Saftner et al., 2005), pineapple (Chen and Paull, 2001, Montero-Calderon et al., 2008) and kiwifruit (Agar et al., 1999). Translucency of water-soaked areas is also a frequent disorder of tomatoes stored under MAP (Gil et al., 2002), while development of translucent flesh has been found to be the principal visual deterioration symptom in fresh-cut ‘Piel de Sapo MAP melon (Bai et al., 2001).

1.4.3. Excessive tissue softening

The range of textural traits that are encountered in fresh and fresh-cut fruits is vast, and to a large extent can be explained in terms of changes in specific cellular components. Cell turgidity, determined by osmotic forces, plays an important role in fruit firmness (Dauthy, 1995). This osmotic pressure with cell vacuoles and
protoplasts pushes the protoplasts against the cell walls and causes them to stretch slightly, owing to their varying degrees of elasticity. In the protoplasm, water functions as a solvent in which gases, minerals and other solutes enter and move through the plant. As it moves it acts as a reagent in many important physiological processes.

In fresh-cut fruit, mechanical damage due to processing greatly accelerates the rate of water-loss, resulting in a loss of turbidity and permselectivity. Without turbidity and permselectivity, the state of osmotic pressure in the cell vacuoles and protoplast cannot exist and water and dissolved substances are free to diffuse in and out of cells, leaving the remaining tissue highly susceptible to dehydration and softening as a result of increased transpiration. Wilting, meallness, shrivelling, loss of firmness, and other textural changes depending on the commodity are induced. It is a major cause of reduced quality in perishable products. Extensive water loss can lead to cell decompartmentation, leakage, collapse and eventual death (Littman, 1972).

Mattoo et al., (1983) and Hyodo et al., (1985) concluded that the wounding increased the activities of enzymes such as PG, β-galactosidases, LOx, phospholipase-δ and ACC synthase/ oxidase that attack cell walls and membranes. Pectins are important components of the cell wall and middle lamella in higher plants giving structure and rigidity to plant tissues. The main types of pectic enzymes responsible for pectin degradation in fruits are depolymerises; (PG) and pectic lyase (PL) and PE (Alzamora et al., 2000). PG hydrolyses glycosidic linkages of pectin acids and polygalacturonates within the pectin molecule resulting in softening of fruit tissues.

LOx activity is also directly related to plant tissue softening. Inhibition of this activity has been shown to delay ripening and softening in peaches and kiwifruit and it has been correlated with plant tissue development and pathogen resistance (Lamikanra, 2002). The free radicals by-products generated through LOx activity can cause cell membrane leakage and the release of stored hydrolytic enzymes and organic acids from the vacuole, thus accentuating cellular decompartmentalisation and damage resulting in excessive tissue softening. These free radicals are also
capable of attacking protein moiety of the cell membrane contributing to further membrane disintegration (Basta et al., 2010).

1.4.4. Phytochemical changes

The concentrations of micronutrients and phytochemical compounds found in plant foods at harvest are known to change due to processing. Table 1.4 shows the effect of some major fresh-cut unit operations on key nutrients. Vitamins, carotenoids and some subclasses of polyphenols are more concentrated in the peel or rind of fruits than in the pulp. Thus, preliminary processing operations such as washing, peeling, trimming, de-hulling or de-stemming can discard appreciable amounts of nutrients leading to a reduction in the levels of these substances in samples analysed (IUFOST, 2000-2010). Subsequent cutting and slicing etc., increases flesh exposure to O₂ and releasing enzymes that catalyse the degradation of these compounds (Kader, 2002). In a study by Gil et al (2006), the quality changes and nutrient retention in fresh-cut versus whole intact pineapples, mangoes, cantaloupe melon, watermelon, strawberries and kiwifruits fruits during 9 day storage at 5°C were evaluated and compared. Vitamin C losses after 6 days at 5 °C were ≤5% for mango, strawberry and watermelon pieces, 10% in pineapple pieces, 12% in kiwifruit slices and 2% in cantaloupe cubes. No losses in carotenoids in kiwifruit slices and watermelons cubes were observed, but losses in pineapple were the highest at 25% followed by 10-15% in cantaloupe, mango, and strawberry pieces after 6 days storage.
Table 1.4 Effects of fresh-cut processing on levels of phytochemicals and organic acids

<table>
<thead>
<tr>
<th>Unit Operation</th>
<th>Carotenoids</th>
<th>Antocyanins</th>
<th>Polyphenols</th>
<th>Ascorbic Acid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peeling</td>
<td>Promotes leaching</td>
<td>Promotes leaching</td>
<td>EB promotion</td>
<td>Exposure to oxidative and hydrolytic degradative enzymes</td>
</tr>
<tr>
<td></td>
<td>&amp; synthesis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size Reduction</td>
<td>Promotes leaching &amp;</td>
<td>Promotes leaching</td>
<td>EB promotion</td>
<td>Promotes leaching</td>
</tr>
<tr>
<td></td>
<td>Provitamin A activity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blanching</td>
<td>POx inactivation</td>
<td>Promotes leaching</td>
<td>EB retardation</td>
<td>Heat destruction</td>
</tr>
<tr>
<td>Acidification</td>
<td>Xanthophyll transformation</td>
<td>Changes in pigment Hue and Chroma</td>
<td>PPO inhibition</td>
<td>Concentration dependent as may undergo decomposition with CO₂ production</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antibrowning agents</td>
<td>O₂ protection</td>
<td>Leaching of soluble pigments</td>
<td>O₂ protection</td>
<td>loss of activity in alkaline environments</td>
</tr>
<tr>
<td>Antimicrobials</td>
<td>Leaching of soluble pigments</td>
<td></td>
<td>EB reduction by sorbates and benzoates</td>
<td></td>
</tr>
<tr>
<td>MAP</td>
<td>loss of chlorophyll</td>
<td>Destabilisation with</td>
<td>Retention and/or</td>
<td>Transformation to DAA</td>
</tr>
<tr>
<td></td>
<td>Provitamin A activity</td>
<td>elevated CO₂</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(adapted from Alzamora et al., 2000; Basta et al., 2010).

**Key:** EB (enzymatic browning), PP (polyphenols), DAA (dehydroascorbic acid), PPO (polyphenol oxidase), POx (peroxidase), O₂ (oxygen) & CO₂ (carbon dioxide).

1.4.5. Changes in flavour and aroma

Aroma compounds are often only released upon cell disruption when previously compartmentalized enzymes and substrates interact (Buttery, 1993). Some aroma compounds are bound to sugars as glycosides or glucosinolates. Glycosides of aroma compounds in fruit are mainly O-β-D-glucosides and O-diglycosides, but triglycosides have also been identified (Sarry and Gunata, 2004). In intact fruits, myrosinase and glucosonolates are sequestered within distant subcellular compartments and/or in distant cells. The glucosinolate and corresponding metabolising enzymes only come in contact following cell disruption (Halkier and Gershenzon, 2006). The proportion of glycosidically bound volatiles is usually greater than that of free volatiles, making them an important potential source of flavour compounds. The odorous aglycones may be released from the sugar moiety during maturation, processing and storage, or by the action of enzymes, acids or heat (Reineccius, 2006).
Tissue disruption leads to the degradation of endogenous lipids to fatty acids, then oxidation to yield a hydroperoxide followed by selective cleavage to for certain volatile aromatic compounds (Galliard et al., 1977). Roma-Parada et al., (1991) found that 15% CO₂ damaged membrane integrity and accelerated loss of phospholipids (Duan et al., 2013) and polyunsaturated fatty acids from mitochondrial membranes and increased leakage of amino acids. In CL fruits such as kiwifruit and cantaloupe melon, membrane deterioration is accelerated and membrane permeability is increased by cutting possibly, attributed to C₂H₄ emanating from sites of injury and lipid degradation, especially for lipid peroxidation of unsaturated fatty acids.

1.4.6. Microbial response to processing

Microbiological spoilage defects of fresh-cut fruits include visible microbial growth, off-aroma and off-flavour formation, soft-rot/water soaking and sliminess. O’Connor-Shaw et al. (1994) observed mould growth at 14 days on cut pineapples held at 4°C and at 4 days when held at 20°C. White mould colony formation was observed at 11 days on cut cantaloupe held at 4°C and at 7 days on cut honeydew held at 8.5°C. Visual evidence of bacterial spoilage of cut cantaloupes results from the presence of bacterial colonies, slime, juice turbidity, and off-odour (Sapers, et al., 2005).

Bacterial soft rot, which is characterised by water soaking and the formation of a slimy surface on plant tissues, has been identified as the leading cause of storage disorders in many types of whole produce (Lund, 1979), and is frequently observed in fresh-cut fruits (Ukuku & Fett, 2002; O’Connor-Shaw et al., 1994). Many microbes use pectinolytic enzymes to overcome plant defence mechanisms and access plant nutrients. The pectinolytic enzymes, such as PE and PG can degrade pectins in the middle lamella of the cell, thereby resulting in liquification of the plant tissue leading to conditions such as soft rots. Other enzymes such as hemicellulase, cellulases, and proteases are also involved in the spoilage process but are usually secondary to pectinases (Liao, 1997).
Water soaking has also been commonly associated with spoilage of cut cantaloupe, honeydew, and watermelon (Ukuku & Fett, 2002), especially under abuse storage temperatures (>4°C). Studies show that spoilage microorganisms such as *Gluconobacter* and *Acetobacter* can cause discoloration of whole produce, and fungal spoilage has discoloured cut apples treated with antioxidants and packed in MA.

### 1.5. Factors affecting fresh-cut fruit quality

Growing conditions, cultural practices, cultivar, maturity, harvesting and handling methods, inspection standards and the duration and conditions of subsequent storage all affect the quality of fruits used for fresh-cut production (Shewfelt, 1987). Cultural factors include growing location, soil condition (nutrient and moisture levels), and climate. These, in turn, determine what crops are grown and when (seasonality).

#### 1.5.1. Cultivar and growing conditions

Without a reliable, consistent cultivar, there will be no quality commodity to process and package. Table B.1 in Appendix B.1 outlines the main varieties of intact fruit raw materials and their corresponding geographical origins available to Irish processors. While uniform size, high yields, harvest ability (mechanical or manual), uniform ripening and reduced wastage are all desirable traits for both whole and fresh-cut produce, there are particular traits especially required for fresh-cut. Cultivar differences exist (Lamikanra et al., 2003; Aguayo et al., 2004), in particular for respiration (Kader, 2002; Gorny, 1998, 2000) that may influence packaging and in-pack atmosphere modification, susceptibility to mechanical damage, browning potential, texture and flavour. The processor must work with what is available during a given season, which slows production, and results in adjustments to processing procedures, packaging requirements and SL expectations. Therefore, choosing a cultivar that performs optimally in a particular season is the first step in the production of high quality fresh-cut products.
Lack of nutrients in the soil can seriously affect the quality of fresh produce at harvest. Phosphorus, potassium and, in particular, nitrogen fertilisation levels can influence a range of quality parameters such as poor visual red colour development when levels are high (Chatzitheodorou, et al., 2004; Crisosto et al., 1997). Bett-Garber et al., (2003) studied the influence of soil type (sandy loam and heavy clay) and storage conditions on the sensory quality of fresh-cut cantaloupe melons. Melons grown in sandy loam were lower in sweet aromas and sweet taste, and higher in exudate with a fermented flavour.

1.5.2. Maturity and ripeness stage

Fruits undergo a number of physiological changes during maturation and ripening (Figure 1.9).

![Physiological age line for fruits](source: O’Beirne, 2009).

Fruit factors along with environmental factors contribute to this age line. Fruit factors include type of fruit, species and cultivar, physiological age and seasonality. Environmental factors may include temperature, O\textsubscript{2} levels, CO\textsubscript{2} levels, ethylene (C\textsubscript{2}H\textsubscript{4}) levels, orchard chemicals, climate, light and moisture (O’Beirne, 2009; Sams, 1999). Maturity is the stage at which a commodity has reached a sufficient stage of development that after harvesting and postharvest handling (including ripening, where appropriate) its quality will be at the least minimum acceptable. Physiological maturity refers to the development of an organ to the stage where it has the capacity to ripen.

There are many methods to determine the maturity of a fruit and can be grouped into physical, chemical, physiological, computational and electronic (Soliva-Fortuny et al., 2004; Ozanich, 1999). Physical determinants include external
colour, internal colour and structure (Portela and Cantwell, 2001), shape of fruit and specific gravity (Kader, 2002), surface morphology and structure (Beaulieu et al., 2004), firmness (Gorny et al., 1998; Soliva-Fortuny et al., 2004). Chemical methods include compositional changes such as starch, sugar acid and juice content, astringency and volatile release (Beaulieu and Lea, 2003). While most fruits, such as pineapples, are better suited to minimal processing when in less mature physiological stages, some produce such as bell peppers and melons may be most suitable at more advanced stages of maturity (Lamikanra, 2002; Saftner et al., 2006).

1.5.3. Respiration rate

Respiration has been defined as a metabolic process which provides energy for plant biochemical processes and is an essential element of normal post-harvest metabolism and an important determinant of storage life (Cliffe-Byrnes and O’Beirne, 2005). The process itself takes place in two phases (Figure 1.10). Phase I is known as glycolysis and is common to both types. Reactions in phase II are either aerobic or anaerobic.

![Figure 1.10 The process of respiration (Cellular Respiration, 2013).](image)

When the amount of available O₂ falls to 2% or less, the process itself may be inhibited leading to anaerobic respiration or fermentation. In fermentation, sugars are broken down into alcohol with ethyl alcohol (ethanol) being the predominant end-product. This phase causes off-flavours/ -odours to develop in fruits, as well as promoting premature ageing and rapid deterioration.
Respiration rate is affected by cultivar, ripening, ageing, wounding (processing) and storage (temperature and time). The physical damage caused by minimal processing increases respiration rate and ethylene production (Finnegan et al., 2013). As a result, plant tissues with high respiratory rates and/or low energy reserves have a shorter postharvest life (Eskin, 1990) as illustrated in Figure 1.11. Higher respiration rates also result in more rapid losses of sugars, organic acids and other substances which contribute to the flavour of the final product (Kader, 2002).

Figure 1.11 Postharvest Life of Fruit Commodities as a function of Respiration.

Different fruits exhibit different respiration rates which are highly affected by processing and temperature (Table 1.5). A two-three fold increase in biological activity has been reported for every $10^\circ\text{C}$ increase in temperature (Burzo, 1980; Zagory and Kader, 1988).

Table 1.5 Respiration rates (mg CO$_2$ kg$^{-1}$ h$^{-1}$) for various fresh-cut fruits in air at various storage temperatures adapted from Gorny, (1998).

<table>
<thead>
<tr>
<th>Commodity</th>
<th>FC</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0 to 2.5</td>
</tr>
<tr>
<td>(1) Apple ‘Granny Smith’ Sliced</td>
<td>3.7</td>
<td>-</td>
</tr>
<tr>
<td>(2) Kiwifruit Sliced</td>
<td>2.0 – 6.0</td>
<td>-</td>
</tr>
<tr>
<td>(3) Cantaloupe Cubed</td>
<td>4.0 – 10.0</td>
<td>5.9 – 31.2</td>
</tr>
<tr>
<td>(4) Honeydew Cubed</td>
<td>3.6 – 10.2</td>
<td>-</td>
</tr>
<tr>
<td>(5) Orange Peeled, Sliced</td>
<td>-</td>
<td>3.3 – 5.7</td>
</tr>
<tr>
<td>(6) Pineapple</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(7) Nectarine Cubed</td>
<td>4.0 – 5.0</td>
<td>-</td>
</tr>
<tr>
<td>(8) Golden Cubed</td>
<td>11.0 – 14.0</td>
<td>2.0 – 5.9</td>
</tr>
<tr>
<td>(9) Strawberry Cubed</td>
<td>-</td>
<td>11.1</td>
</tr>
<tr>
<td>(10) ‘Cosmos’ Whole</td>
<td>1 – 2</td>
<td>3 – 4</td>
</tr>
</tbody>
</table>

Stems removed as respiration ~15x higher than berry respiration (adapted from UC Davis Product Fact Sheets, 2010).
1.5.4. Ethylene

Ethylene (C$_2$H$_4$) plays an active part in tissue differentiation, fruit ripening and degreening, anthocyanins synthesis, production of volatile compounds (aroma), senescence and the response of plants to both biotic and abiotic stresses (Grichko and Glick, 2001; Kanellis et al., 2002). C$_2$H$_4$ production can be stimulated by many factors such as ripening, senescence, wounding, fungal infection, water stress and elevated temperatures (Kader, 2002). In addition, certain fruits such as pineapple and bananas can be harvested mature but un-ripe and de-greened or ripened at a later stage by exposure to predetermined concentrations of exogenous ethylene (Ethephon) (Dhall and Singh, 2013). Perishable commodities vary in their sensitivity to ethylene. For some plant responses, levels as low as 4 ppb (Mattoo and Suttle, 1991) can have an effect while most other responses are typically seen between 0.1 to 10 ppm (Wheeler et al., 1996). Common effects of C$_2$H$_4$-induced injury on fruit include; softening and development of off-odours in watermelon, increased ripening and softening of mature green tomatoes and shattering of raspberries and blackberries (Saltveit, 1999). The degree of damage depends upon the concentration of C$_2$H$_4$, length of exposure time and product temperature.

1.5.5. Processing

Harvested fruits are subjected to many forms of handling making them susceptible to mechanical injuries such as bruises and wounding. Bruises can be both noticeable and non-noticeable, both of which can affect respiration and quality. Injured fruits respire and transpire more rapidly and the extent of the increment is directly proportional to the severity of the bruising (Kader, 1987).

The physiology of fresh-cut fruit is essentially the physiology of wounded tissue. This type of processing, involving peeling, slicing, chopping, or shredding, differs from traditional processing in that the tissue remains viable during subsequent handling. Thus, the behaviour of the tissue is generally typical of that observed in plant tissues that have been wounded or exposed to stress conditions (Brecht, 1995). This includes increased respiration and C$_2$H$_4$ production, and, in some cases, induction of wound-healing processes. Other consequences of wounding are chemical or physical in nature, such as browning reactions, LOx and enhanced water
loss. It is well recognised that the wounding of plant tissue increases the respiration rate and may induce chemical changes and meristematic activity in the region of the wound. Much information has been gathered concerning tissue responses from cut vegetative tubers and tuberous roots (Laties, 1964, 1968; Saltveit, 1997; Surjadinata and Cisneros-Zevallos, 2003).

The response of fruit tissues to wounding is variable, and is highly influenced by fruit type, cultivar and maturity (Ahvenainen, 2000; Aguayo et al., 2004; Gorny, 1998; Kader, 2002) as well as size (Beaulieu et al., 2004), morphology (Nguyen-the and Carlin, 1994) and the permeance of the fruit to different atmospheres (Kader, 1989).

Wounded or stressed plant tissue produce signals that induce a wide range of genetic responses intended to help repair the plant (Hillwig et al., 2008; Dangl and Jones, 2001). Oligogalaturonides, which come from the cell wall (Ferrari et al., 2013), jasmonic acid and methyl jasmonate (Howe, 2004) from cell membranes (plastids, linolenic acid) via LOx; salicylic acid and methyl salicylate from benzoic acid (Mur et al., 1997) and ascorbic acid (Hillwig et al., 2008, Wasternack et al., 2006), regulate signalling pathways that induce wound-response genes. These signals may also give rise to pathogenesis-related proteins and proteinase inhibitors (Fallico et al., 1996). \( \text{C}_2\text{H}_4 \) has been shown to signal wound responses (O’Donnell et al., 1996).

Therefore, the minimal processes such as cutting and shredding must be performed with blades that are as sharp as possible, reducing the extent of damage to cells. A study by Bolin & Huxsoll (1991b), showed that slicing with a sharp blade was much more superior to slicing with a blunt blade and either chopping or slicing with a blunt blade as the shelf-life of lettuce was reduced, in some cases by 50%. Portela and Cantwell, (2001) concluded that cutting melon pieces with a sharp rather than a blunt borer resulted in a longer shelf-life at 5ºC with notable improvements in colour quality (translucency).

Interestingly, new product development has produced fresh-cut fruits in a wide variety of shapes and sizes (Figure 1.12). This also impacts on the degree of damaged incurred by the fruit, with some shapes and sizes causing more damage to
the tissue than others. Finnegan et al., (2013) studied the effects of cutting size on fresh-cut pineapple cv MD2 and concluded that smaller cut sizes caused a greater increase in the wound-response of the fruit, demonstrated by a higher increment in respiration rate initially after processing at 4°C. Rivera-Lopez et al., (2005) compared fresh-cut cubes to fresh-cut slices of papaya at 5°C and 10°C. They concluded that slices presented a slight advantage over cubes when comparing chemical and physical attributes such as soluble solids and weight-loss respectively, with better quality observed at lower temperatures. Aguayo et al., (2004) demonstrated that firmness was greatly affected by shape as well as water evaporation, with cylinders of melon showing higher translucency scores over slices. Artés-Hernandez et al., (2006) found that four cut types of lemons stored at 0, 2, 5 and 10°C remained marketable for up to 7 days, but that wedges, slices and ½ slices stored at 0, 2 and 5°C preserved their sensory attributes for up to 10 days. Ethanol was found to increase up to three-fold in ½ and ¼ slices after 10 days at 10°C.

![Figure 1.12 Examples of novel fresh-cut fruit products.](image)

1.5.6. Environmental factors

Since fresh-cut fruits are more perishable than whole, intact products, they should be held at lower temperatures than that recommended for intact commodities. The
optimum temperature for most fresh-cut fruits is generally 0°C. However, many are prepared, shipped and stored at temperatures of 5°C, sometimes even 10°C (Watada et al., 1996).

Chilling injury (CI) is a physiological disorder that is occasionally reported on fresh sub-tropical and in particular tropical fruits such as pineapple, cantaloupe, honeydew, nectarine and mango. If these intact fruits are stored at temperatures less than 12°C, increased pathological decay and subsequent physiological breakdown occurs (Montero-Calderón et al., 2008; Beaulieu et al., 2002; Portela et al., 1997). CI is most often characterised by areas of the peel or rind that collapse and darken to form sunken pits (Ritenour et al., 2003). Less severe symptoms may appear as circular or arched areas of discolouration or scalding. Symptoms are typically more pronounced after fruit are warmed to room temperatures (>15°C) following exposure to chilling temperatures (Saltveit and Morris, 1990). However, a significant number of fresh-cut fruits are not as susceptible to CI as the corresponding intact fruit as processing involves removal of outer rind and peel.

Fresh-cut fruit are very sensitive to humidity levels as they have large surface areas, in many cases without any skin or peel, and as a result they lose a substantial amount of weight (water loss), through transpiration, particularly at elevated temperatures (Watada et al., 1996). At an RH below 90%, excess moisture loss can lead to loss of weight with subsequent textural change defects.

1.5.7. Microbial spoilage

Fresh-cut fruit present ideal conditions for the survival and growth of many types of spoilage microorganisms. Minimal processing of fruits removes the natural protection of the fruit epidermis and destroys the internal compartmentalisation that separates enzymes from substrates. Their internal tissues are nutrient rich and their principal storage polymer is starch. Spoilage microorganisms exploit the host using extracellular lytic enzymes that degrade these polymers to release water and the plant’s other intracellular constituents for use as nutrients for their growth. Consequently, plant tissues suffer physical damage that makes them more susceptible
to further contamination and heightens their perishability when compared to their intact counterpart resulting in the average SL being decreased substantially. Brackett, (1994) concluded that microbial decay and off-flavour/odour can be a major source of spoilage of fresh-cut produce and, as such, a limiting factor for SL (O’Connor-Shaw et al., 1996). Microbial spoilage including off-flavour development (e.g., fermented aroma with cut lettuce, sour taste with cantaloupe), slimy surface (e.g. fresh-cut melon), wetness and soft rot (e.g., fresh-cut kiwifruit), discoloration (e.g., apple wedges), and visual microbial growth/colonies (such as apple wedges, cantaloupe chunks, and cored pineapple) has been used as a main objective criterion to determine the SL of fresh-cut products. It can result in a 30% to 50% shrinkage of fresh-cut fruits (Barth, 2009). Figure 1.13 illustrates an overview of the dominating mechanisms of spoilage and influential parameters of spoilage associated with fresh-cut fruits.

![Figure 1.13 Schematic overview of the dominating mechanisms of fruit spoilage.](image)

Figure 1.13 Schematic overview of the dominating mechanisms of fruit spoilage.
The predominant microorganisms responsible for the spoilage of fresh-cut produce include: mesophilic and psychrophilic bacteria (TBCs), lactic acid bacteria (LAB), faecal coliforms, and yeasts & moulds (Nguyen-the and Carlin, 1994). For most fresh-cut fruits such as apples, pineapples, strawberries, grapes, and a few fresh-cut vegetables, such as tomatoes, there is sufficient acidity to limit spoilage primarily to fungi (Splitsstoesser, 1987) and aciduric bacteria (LAB, *Acetobacter*, *Gluconobacter*) (Tournas *et al.*, 2001), while mesophilic bacteria were consistently predominant on fresh-cut honeydew and cantaloupe melon pieces, even at the end of the shelf life (O’Connor-Shaw *et al.*, 1994; Ukuku & Fett 2002) due to the relatively neutral pH of these fruits. Yeasts can grow well in a pH range of 3–10 while moulds can grow from pH 2 to 11, but favour acidic pH. Yeasts of the genera *Saccharomyces*, *Candida*, and *Hansenula* species have been associated with fermentation of fruits. Furthermore, yeasts have a slightly higher growth rate than moulds, are capable of fermenting sugars into alcohols, and are responsible for off-flavours and off-odours. Moulds on the other hand cover surfaces as fluffy, cotton-like mycelia and usually produce masses of asexual, or sometimes sexual, spores (Barth, 2009).

*Listeria (L) monocytogenes* is ubiquitous in soils, plant matter and water. In addition, animals, including humans, can serve as effective vectors in the spread of *listeriosis*, carrying the pathogen in their intestinal tract. As a result, *L. monocytogenes* has been isolated from minimally processed fruits and vegetables at numbers <100 cfu/g⁻¹. Survival and growth of *L. monocytogenes* on produce is affected by product type, physiological age, cut type, level of contamination and by the native or epiphytic microflora, in addition to temperate and atmosphere (Francis and O’Beirne, 2008a, b). The primary areas for control of this pathogen are efficient implementation of hazard analysis critical control point (HACCP) procedures, involving correct monitoring of critical control points (CCPs), proper cleaning and sanitation of work surfaces, personnel hygiene and good, clean air flow within production environments. *L. monocytogenes* is an important human pathogen associated with fresh-cut produce because the pathogen is widespread in the natural environment. The pathogen is psychrotrophic from nature (minimal temperature for growth is between 0 and 4°C), the minimal pH is 4.5 to 5 and it is not influenced by MAs (Francis and O’Beirne, 1997; Carlin *et al.*, 1996; Zagory, 1999; Rocha *et al.*, 1995).
1.6. Modified atmosphere packaging

Modified atmosphere packaging (MAP) involves a multidisciplinary approach including, produce physiology, processing technology and polymer engineering, to maintain product freshness. It normally complements refrigeration as an additional hurdle to aid in food preservation. For fresh-cut fruits, reduced oxygen (O\textsubscript{2}) and increased carbon dioxide (CO\textsubscript{2}) atmospheres have been shown to significantly extend quality and shelf-life. However, the concentrations of these gases are generally commodity dependent and differ considerable (Figure 1.14).

![Figure 1.14](image)

**Figure 1.14** Illustrates the optimum or equilibrium atmospheres for a variety of fresh-cut temperate, sub-tropical and tropical fruits. (Data was taken from Gorny, 2001 to manipulate a graphical representation of MA recommendations).

1.6.1. MAP generation

Modified atmospheres can be generated passively or actively (Figure 1.15). Passive modification (PMA) relies on the respiration rate of the product and the gas transfer across the packaging film used. Thus, depending on the permeability of the film used, varying degrees of atmosphere modifications can be achieved for a particular fresh-cut product.
Figure 1.15 Simulated examples of changes in \( \text{O}_2 \) and \( \text{CO}_2 \) concentrations during passive modification versus active modification of packaged produce.

In contrast, active MAP involves flushing packages with specified gas mixtures (depending on the commodity types) (Zagory and Kader, 1988). It has been said that this technology has considerable potential however, it is considered relatively expensive (Rooney, 1995), and therefore its use in fresh-cut fruit products is limited and rarely observed.

The main differences between the two systems are outlined in Table 1.6. One of the main disadvantages to PMA packaging is the length of time necessary to achieve dynamic steady state or optimal gas composition while the major concerns of active MA is the cost.

A useful MA is one in which reduces respiration rate to the lowest viable level, thus prolonging SL for extended periods of time without generating an in-pack environment favourable to anaerobic fermentation. This concept enabled the development and establishment of ‘optimum’ MAs. These optimum MAs not only change from product to product but also with cultivar, origin and season (Kader and Morris, 1977). Table 1.7 presents a list of recommended atmospheres for a range of fresh-cut fruits.
### Table 1.6 Types of modified atmosphere packaging for fresh-cut produce

<table>
<thead>
<tr>
<th></th>
<th>Passive</th>
<th>Active</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
<td>Modification of the in-pack gas composition due to gradual interchanges between the product respiration rate and the gas exchange rate through the package.</td>
<td>Modification of the in-pack gas composition by replacing the [air] at the initial moment of sealing with a specific gas mixture either by drawing a vacuum or filling a gas mix.</td>
</tr>
<tr>
<td><strong>Equilibrium time</strong></td>
<td>1-2 days to 10-12 days</td>
<td>1-2 h</td>
</tr>
<tr>
<td><strong>Suitable products</strong></td>
<td>Mushrooms, carrots, strawberry, spinach</td>
<td>Cut apples, dry fruits</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>No extra cost involved if the package is properly designed and maintained at optimum storage conditions.</td>
<td>Extra investment is required for special machinery, i.e. gas mixer, gases, packaging machine etc.</td>
</tr>
<tr>
<td><strong>Labelling Requirements</strong></td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Taken from Mahajan et al., (2007)

However despite the known benefits observed for fresh-cut fruit in many studies (Ahvenainen, 1996; Rico *et al*., 2007; Rojas-Grau *et al*., 2009; Sandhya, 2010), a comprehensive study of many Irish multiples by Finnegan, 2008-2010, (Appendix B) revealed that most fresh-cut fruit processors do not aim at optimising gas compositions inside packages. As a result, the reported benefits of optimal MA observed in literature fail to materialise in the commercial supply chain and the efforts to achieve optimal MA conditions contribute little to economic gain to the processor and consumer alike. The discrepancy between potential benefits reported in literature and the apparent lack of adoption of this knowledge by industry may be due to several reasons, such as: 1) deficient knowledge transfer, 2) cost reduction measures given the perishability of the products, 3) an attempt to accommodate the diverse array of fruits contained within these packs by allowing the fruits to passively modify the packages themselves and/or 4) simply a safety parameter employed i.e. that in the event of temperature abuse during distribution O₂ levels would not fall to anaerobic levels thus inducing fermentation.
Table 1.7 Recommended MA concentrations for different Fresh-cut Fruits.

<table>
<thead>
<tr>
<th>Fruit</th>
<th>Optimum Recommended Atmospheres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple</td>
<td>&lt;1%O$_2$ \textsuperscript{a} or &lt;1%O$_2$ + 4-10 % CO$_2$ \textsuperscript{b}</td>
</tr>
<tr>
<td>Cantaloupe melon</td>
<td>4 k%O$_2$ + 10 % CO$_2$ \textsuperscript{a} or 3-5 % O$_2$ + 6-15 % CO$_2$ \textsuperscript{b}</td>
</tr>
<tr>
<td>Honeydew melon</td>
<td>2 % O$_2$ + 10 % CO$_2$ \textsuperscript{a,b}</td>
</tr>
<tr>
<td>Grape *</td>
<td>3-5 % O$_2$ + 1-3 % CO$_2$ \textsuperscript{c}</td>
</tr>
<tr>
<td>Kiwifruit</td>
<td>2 % O$_2$ + 5 % CO$_2$ \textsuperscript{a} or 2-4 % O$_2$ + 5-10 % CO$_2$ \textsuperscript{b}</td>
</tr>
<tr>
<td>Orange</td>
<td>AIR \textsuperscript{a} or 14-21 % O$_2$ + 7-10 % CO$_2$ \textsuperscript{b}</td>
</tr>
<tr>
<td>Pineapple</td>
<td>3-5 % O$_2$ + 5-8 % CO$_2$ \textsuperscript{b}</td>
</tr>
<tr>
<td>Strawberry</td>
<td>1-2 % O$_2$ + 10 % CO$_2$ \textsuperscript{a} or 1-2 % O$_2$ + 5-10 % CO$_2$ \textsuperscript{b}</td>
</tr>
</tbody>
</table>

\textsuperscript{*} whole (intact); Sources: \textsuperscript{a} Hui \textit{et al.}, 2006; \textsuperscript{b} Gorny, 2001; \textsuperscript{c} Scharnow, 2013.

1.6.2. MAP Design

A useful modified atmosphere can be created and maintained within the package if the product’s respiration rate matches the gas permeability of the film at refrigerated storage temperatures (Mahajan \textit{et al.}, 2007; Hertog and Banks, 2003; 2004; Fonseca \textit{et al.}, 2002). Gas flow is generated through the packaging material (diffusion) and, the ratio between permeability to CO$_2$ and O$_2$ due to film permeability (permeation) is referred to as selectivity ($\beta$) (Figure 1.16).

\[ RQ = \frac{\text{mL of CO}_2 (kg.h)}{\text{mL of O}_2 (kg.h)} \]

\[ \beta = \frac{\text{CO}_2 \text{ permeability}}{\text{O}_2 \text{ permeability}} \]

\[ 0.7 < RQ < 1.3 \quad 4 < \beta < 9 \]

Figure 1.16 Basic principles of MAP; key: increasing CO$_2$ production and decreasing O$_2$ consumption; and exchange between product and package.
Table 1.8 lists important design variables that need to be considered. These variables can be sub-divided into commodity related factors such as product weight, recommended gas atmosphere composition, respiration rate, package system factors such as package geometry, permeability of the polymeric film and environmental factors such as temperature, relative humidity and external gas composition (Mahajan et al., 2009; 2007; 2006; Varoquaux and Wiley, 1994; Kader, 1989).

Table 1.8 Variables used in MAP Design.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Produce</td>
<td>M</td>
<td>kg</td>
</tr>
<tr>
<td>Desired gas composition</td>
<td>yO&lt;sub&gt;2&lt;/sub&gt;-yCO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>%</td>
</tr>
<tr>
<td>Respiration rate</td>
<td>R&lt;sub&gt;O2&lt;/sub&gt;, R&lt;sub&gt;CO2&lt;/sub&gt;</td>
<td>ml kg&lt;sup&gt;-1&lt;/sup&gt; h&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Film-Package</td>
<td>A</td>
<td>m&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Area available for gas exchange</td>
<td>β</td>
<td>-</td>
</tr>
<tr>
<td>Selectivity</td>
<td>X</td>
<td>m</td>
</tr>
<tr>
<td>Thickness</td>
<td>V</td>
<td>m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Volume</td>
<td>N</td>
<td>-</td>
</tr>
<tr>
<td>Number of holes or perforation</td>
<td>D</td>
<td>m</td>
</tr>
<tr>
<td>Diameter of hole/perforation</td>
<td>L</td>
<td>m</td>
</tr>
<tr>
<td>Length of perforation</td>
<td>PO&lt;sub&gt;2&lt;/sub&gt;, PCO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>ml (STP) m&lt;sup&gt;-1&lt;/sup&gt; h&lt;sup&gt;-1&lt;/sup&gt; atm&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Environmental</td>
<td>T</td>
<td>°C</td>
</tr>
<tr>
<td>Temperature</td>
<td>yO&lt;sub&gt;2&lt;/sub&gt;out, yCO&lt;sub&gt;2&lt;/sub&gt;out</td>
<td>%</td>
</tr>
<tr>
<td>External gas composition</td>
<td>RH</td>
<td>%</td>
</tr>
<tr>
<td>Relative humidity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Adapted from Mahajan et al., 2007; 2009)

1.6.3. Design Methodology

A mathematical model for respiration rate of fresh-cut fruit is usually a function of O<sub>2</sub>, CO<sub>2</sub> and temperature and is the first and most important factor (besides temperature) to be considered. Respiration rates are usually expressed as weight or volume of gas produced or consumed per kg fresh weight of product per hour. Reducing the rate of respiration can delay the ageing and subsequent quality loss of the product. Different fruits and different parts of a fruit have different respiration rates. Whole fruits differ in their respiration and C<sub>2</sub>H<sub>4</sub> production rates when
compared to their fresh-cut counterparts. Postharvest researchers have developed many methods for the quantitative measurement of RQ. These include methods based on the production of energy (heat), consumption of O\(_2\), loss of substrate, and production of CO\(_2\) (Forney, 2009; Yahia, 2009).

**Respiration rate**

A respirometer is an apparatus designed to measure oxygen consumption and/or carbon dioxide production. The usual methods of measuring respiration are:

- the permeable system,
- the closed or static system &
- the flow-through or dynamic system.

**Figure 5.3** (chapter 5) illustrates a respiring product stored within a rigid container and housed within a pillow-pouch package comprised of a plastic polymeric film. This is the simplest concept and known as the permeable system which allows a package of known permeability and dimensions, filled with a product of known weight, to serve as the single regulator of gas exchange (Beaudry et al., 1992; Joles et al., 1994; Lee, et al., 1996; Smyth et al., 1998; Beaudry, 1993). The steady state O\(_2\) and CO\(_2\) concentrations are determined and a mass balance is performed in order to estimate the respiration rates. Assuming that there is no gas stratification inside the package and that the total partial pressure remains constant, the differential equations of mass balance for O\(_2\) and CO\(_2\) in a MAP containing a respiring product can be calculated as follows:

\[
V_f \times \frac{d(Y_{O_2})}{dt} = \frac{P_{O_2}}{e} \times A \times (Y_{O_2}^e - Y_{O_2}) - R_{O_2} \times M
\]

or

\[
R_{O_2} = \frac{P_{O_2}}{100 \times L \times M} \times A \times (Y_{O_2}^e - Y_{O_2}) \quad (1.1)
\]

\[
V_f \times \frac{d(Y_{CO_2})}{dt} = \frac{P_{CO_2}}{e} \times A \times (Y_{CO_2}^e - Y_{CO_2}) - R_{CO_2} \times M
\]

or

\[
R_{CO_2} = \frac{P_{CO_2}}{100 \times L \times M} \times (Y_{CO_2} - Y_{CO_2}^e) \quad (1.2)
\]
Where; \( R \) = respiration (consumption/production) rate, \( m^3 \text{ kg}^{-1} \text{s}^{-1} \); \( P \) = permeability coefficient; \( A \) = surface area \( m^2 \); \( L \) = thickness, \( m \); \( M \) = mass, \( kg \); \( \epsilon \) = external and \( Y \) = volumetric concentration, \( \% \text{ v/v} \). \( V_f \) = free volume within a pack. The subscripts \( \text{O}_2 \) and \( \text{CO}_2 \) refer to the oxygen and carbon dioxide, respectively.

In a closed or static system, a gas-tight container of known volume is filled with product and the container, containing ambient air, is closed (Song, et al., 1992; Gong and Corey, 1994; Jacxsens et al., 1999). Changes in the concentrations of \( \text{O}_2 \) and \( \text{CO}_2 \) over a certain period of time are measured and used to estimate respiration rates (Equations: 1.3 and 1.4).

\[
R_{\text{O}_2} = \left( Y^{\text{fi}}_{\text{O}_2} - Y^{\text{ff}}_{\text{O}_2} \right) \times \frac{V}{100 \times M \times (t_f - t_i)} \tag{1.3}
\]

\[
R_{\text{CO}_2} = \left( Y^{\text{fi}}_{\text{CO}_2} - Y^{\text{ff}}_{\text{CO}_2} \right) \times \frac{V}{100 \times M \times (t_f - t_i)} \tag{1.4}
\]

Where; \( R \) = respiration (consumption/production) rate, \( m^3 \text{ kg}^{-1} \text{s}^{-1} \); \( M \) = mass, \( kg \); and \( Y \) = volumetric concentration, \( \% \text{ v/v} \); \( V \) = free volume, \( m^3 \); \( t \) = time, \( s \); \( i \) = initial; and \( f \) = final.

In the flow through or dynamic system, a known weight of product is enclosed in an impermeable container ventilated with a gas mixture flowing at a constant rate (Riad et al., 2002; Smyth et al., 1998; McLaughlin and O’Beirne, 1999; Finnegan et al., 2013). The concentration of \( \text{CO}_2 \) leaving the container increases until as much \( \text{CO}_2 \) leaves the container (concentration x flow) as is produced by the tissue. At that time the system is in equilibrium and usually occurs in the same time it takes for 5-times the volume to flow through the container. In general, gas exchange takes place until dynamic steady-state equilibrium is reached. Equations 1.3 and 1.4 are first-order linear differential equations, which are useful for describing the unsteady-state behaviour of MAP systems during passive modification. The respiration rate (either oxygen uptake or carbon dioxide production) is readily calculated (Chapter 5.2.3) from the overall differences in gas concentrations between the inlet and the outlet.

To use these equations in package design, it is necessary to track all design variables that affect this approach. The success of this MAP technique depends on the ability to predict \( P \) and \( R \) which are respectively the gas transport across the package and the respiration rate of the product. As these two parameters are highly
dependent on environmental factors, such as temperature, O$_2$, CO$_2$, and RH, in effect, proper MAP design must consider all of these factors.

However, limitations exist for all three systems and is summarised in **Table 1.9**. The permeable system is the least accurate method because the determination of many variables i.e. package dimensions, surface area and thickness and permeability of gas exchange material, are involved. In a static system it is extremely difficult to accurately measure the gas volume as the apparatus is very susceptible to leaks. A closed system also doesn’t allow respiration rates to be measured for any combination or mixes of gases. In a dynamic system, flow rates have to be carefully chosen and monitored in order to accurately measure the differences in gas concentrations between the inlet and the outlet.

**Table 1.9** Main advantages and limitations of the three methods of respiration rate measurement.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Permeable</th>
<th>Static (closed)</th>
<th>Flow-through (dynamic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-destructive</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Time and labour intensive</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Complexity of apparatus</td>
<td>Complex</td>
<td>Simple</td>
<td>Complex</td>
</tr>
<tr>
<td>Ability to test diff gas atm</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Constant test concentration</td>
<td>Y$^1$</td>
<td>N</td>
<td>Y$^1$</td>
</tr>
<tr>
<td>Suitable for low respiring products</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Suitable for high respiring products</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>Accuracy is dependent on:</td>
<td>$P$, $L$ &amp; $A$</td>
<td>$V$</td>
<td>$F$</td>
</tr>
</tbody>
</table>

$^1$ Steady state conditions adapted from Fonseca et al., 2002.

**Commercial packaging materials**

Most minimally processed products are either packaged in flexible film pouches which are heat sealed, or in over wrapped trays (made of clear polyvinyl chloride (PVC), polypropylene (PP), polyethylene terephthalate (PET) or polylactic acid (PLA). The materials used for fresh-cut fruit packaging are mainly microperforated oriented polypropylene (OPP) and high or low density polyethylene (HDPE, LDPE). In medium and high respiring commodities such as fresh-cut fruits, use of commonly available films such as LDPE and PP is not ideal due to their low gas transmission
rates, which may lead to induction of anaerobic respiration (Cliffe-Byrnes and O’Beirne, 2005). Orienting polypropylene improves its water vapour barrier, dimensional stability and stiffness. Micro-perforating OPP film results in an average protective effect against oxygen and carbon dioxide transmission. Two of these films used are PA90 & PA210, and have an anti-mist coating (Amcor Flexibles Gloucester, U.K). Both films had micro-perforations jagged along the length of the film, with the PA210 having more perforations and being slightly more gas permeable than the PA90 film.

NatureWorks LLC, Nebraska, USA successfully launched a novel low cost PLA packaging system to compete with conventional petroleum-based polymers. PLA’s inherent barrier properties are similar to those of uncoated PET and PLA’s mechanical properties resemble those of polystyrene (Table 1.10).

<table>
<thead>
<tr>
<th></th>
<th>Polymer</th>
<th>H₂O transmission rate</th>
<th>OTR g.mil.100 in².day⁻¹</th>
<th>CTR g.mil.100 in².day⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLA</td>
<td>18-22</td>
<td>38-42</td>
<td>170-200</td>
<td></td>
</tr>
<tr>
<td>PET</td>
<td>1</td>
<td>3.0-6.1</td>
<td>15-25</td>
<td></td>
</tr>
<tr>
<td>HDPE</td>
<td>0.3-0.4</td>
<td>130-185</td>
<td>400-700</td>
<td></td>
</tr>
</tbody>
</table>

Taken from Sand, (2011)

However, the optimal permeability is dependent on the size of the package compared to the amount of produce and the respiration rate – and thereby all the factors that influence respiration rate (Kaur et al., 2011; Lee et al., 1991; Mahajan et al., 2007).

**Gas permeability**

Packages with high gas permeability are required for high respiring produce, while low permeability packages are required for low respiring products. The required permeability can be achieved by (1) selection of polymeric films with suitable gas permeabilities, (2) by use of macro-perforated films and (3) by use of micro-perforated films.
Few non-perforated polymeric films are suitable for fresh-cut fruit packaging as their CO₂ permeability is generally 3 to 6 times higher than that of their O₂ permeability. These films are most suitable for less CO₂ tolerant commodities such as apples, bananas, grapes and mangoes. Perorated films have much higher gas permeability however; the ratio of CO₂ to O₂ permeability is much lower. Such films are accommodating of commodities tolerant to low levels of O₂ such as fresh-cut fruit products.

Perforation-mediated modified atmosphere packaging (PM-MAP) has shown excellent benefits for conventional MAP in packaging of fresh-cut fruit (Rennie and Tavolaris, 2009; Pandey and Goswani, 2012; Xanthopoulos et al., 2012). In this technique, instead of using common polymeric films, a package, container or high-barrier film is used in which the regulation of gases is achieved by single or multiple perforations in an otherwise impermeable hermetically sealed package. Use of PM-MAP has many potential advantages over macro-perforated or polymeric films. It is a flexible system due to its ability to change the gas transfer coefficient of the package by changing the size and number of the perforations, which implies that products with a wide range of respiration rates can be packed in this system (Mahajan et al., 2006). MAP using perforations can be adapted easily to any impermeable container, including large bulk packages. Polymeric films are not strong enough for packs much larger than those used for retail, but perforations can be applied to retail packages as well as shipping boxes because rigid materials can be used (Riad et al., 2002). Rigid packages also can prevent mechanical damage of the product (Kader, 1989). Commodities requiring high CO₂ concentrations and relatively low O₂ concentrations can be packed with this system (Fonseca et al., 1997).

In gas permeable films, different types of gas molecules diffuse at different rates through a film; in general CO₂ permeates faster than O₂. The higher permeability of films to CO₂ is in part due to the greater solubility of CO₂ in the film structure. In industry, permeability is referred to as gas transmission rate of a film of given thickness. Selecting a packaging film with correct permeability is essential to accommodate respiratory gas exchange and ensure that a useful MA is established. Therefore, gas permeability is the most fundamental properties of packaging materials involved in MAP design. Mass transfer through a polymeric film, also
referred to as permeation, is associated with a partial pressure difference of gases and/or vapour between two sides of a package. Therefore, it is recognised that permeation is a dual composite phenomenon involving diffusion and sorption which occur simultaneously (Torreiri et al., 2009).

The permeability coefficients of many films obtainable from manufacturers are usually measured at ambient temperatures, i.e. 20-25°C. The data on film permeability must be then converted to the storage temperature used for the produce. In this context, an Arrhenius model is used as follows:

\[ P_{O_2} = P^*_{O_2} \exp\left\{ \frac{-E_{O_2}}{R \times T} \right\} \]

and

\[ P_{CO_2} = P^*_{CO_2} \exp\left\{ \frac{-E_{CO_2}}{R \times T} \right\} \]

Where;

- \( P_{O_2} \) = permeability for \( O_2 \), mL.mil.m\(^{-2}\).day\(^{-1}\).atm\(^{-1}\).
- \( P^*_{O_2} \) = permeability pre-exponential factor for \( O_2 \), mL.mil.m\(^{-2}\).day\(^{-1}\).atm\(^{-1}\).
- \( E_{O_2} \) = activation energy of permeability for \( O_2 \), kJ.mol\(^{-1}\).
- \( R \) = Gas constant (0.008314 kJ.mol\(^{-1}\).K\(^{-1}\)).
- \( T \) = Storage temperature (°C).

The effective change in package atmosphere due to temperature change is governed by the difference in activation energies of both respiration and permeation. Therefore, in order to effectively design a MAP for fresh-cut fruits it is important to compare the activation energies of both the respiring product(s) to the activation energy of the permeation process. When the difference in activation energy is small, fluctuations in temperature do not cause significant changes to the permeability of packages and thus the package atmosphere. MA packaging systems have activation energies between 20-40kJ.mol\(^{-1}\), while for perforated films the activation energy is less than 5 kJ.mol\(^{-1}\) (Cameron et al., 1995). Packages that use perforations are particularly vulnerable to increased temperature because gas diffusion through macro-/ micro-perforated holes increases with increasing temperature while activation energies for a product can be high. The activation energy values for common fruits range from 29.0 to 92.9 kJ.mol\(^{-1}\), while for fresh-cut fruit, values can range from 67 to 220 kJ.mol\(^{-1}\) (Jacxsens et al., 2000; Lee et al., 1991; Charles et al., 2005) and higher for mixed fruit packs.
Christie et al., (1995) demonstrated the time-temperature permeability effects of polymeric permeable films. In practice, films are taken from room temperature (~20°C and 60% RH), packed with produce, and stored at relevant cold temperature with 90-5% RH. Significant time-temperature dependent changes in permeability were observed with these polymers subjected to the above storage patterns. Therefore, conditioning of packaging films to the appropriate packaging, distribution and storage conditions prior to use should be performed to allow films to adapt to the appropriate conditions and thus maintain their effectiveness is achieving EMA. As a result, the first aspect to be evaluated in terms of film selection is film permeability at testing conditions. Mahajan et al., (2006) claimed that a polymeric film with selectivity (β) within the set interval for β_{min} and β_{max} is one best defined for a particular product.

Perforations for fresh-cut fruit packaging

The use of perforations and the development of PM-MAP technology has recently been reported (Fonseca et al., 2002; Rennie and Tavolaris, 2009; Pandey and Goswani, 2012; Xanthopoulos et al., 2012). Films of enhanced permeability are required for the packaging of perishable fresh and fresh-cut products with high respiration rates. A wider range of selectivity β values, especially those below 3, are necessary to better match the respiratory behaviour of man products (Mahajan et al., 2006). The use of perforated systems or micro-porous films presents possible solutions to meet these requirements. The presence of perforations on a film allows the regulation of gas exchange by diffusion as well as convection (Mannapperuma et al., 1991). The perforations provide an alternative route for gas transport, which may be treated as macroscopic diffusion in a cylindrical path filled with air (Mahajan et al., 2007). This is due to the perforation size which have diameters in the order of 10^{-4} m or greater, whereas the mean free path of gas molecules at atmospheric pressure is considerably less (1 or 2 x 10^{-7} m (Fishman et al., 1996).

While several techniques have been employed by the fresh-cut produce industry to accommodate atmospheric changes in fresh-cut packages, none have been as successful as the introduction of perforations into polymeric films. Macro- and microscopic perforation is a technique whereby holes are made on the film (usually after printing) and during the film converting process. This technique maximises the
‘flexibility’ and usability of particular films in order to provide the right type of atmospheric conditions at the late processing stage based on the type of commodity or commodities to be packaged.

The consistency of micro-perforations is very important for fresh and fresh-cut fruit applications (Chow, 2003). Table 1.11 shows an example of an application where there is a limited packaging surface area for gas exchange such as in plastic containers with a lid made from flexible film, i.e. clamshell. Examples of two fresh fruit are shown: Melon, having a requirement for higher OTR vs. citrus (orange) requiring a significantly lower OTR. Because of the limited lid surface area, the highly permeable polyethylene film would only give an OTR value of 254 which is too small for the required OTR value. However, with the perforation of either four or two holes, respectively, for the two containers, the OTR value is nearly achieved. Because of the limited number of perforations that are required, the accuracy of perforation becomes of utmost importance for retaining the freshness of the fruit while avoiding anaerobic condition.

Table 1.11 Micro-perforation requirements for a typical fresh-cut fruit container.

<table>
<thead>
<tr>
<th>Fresh Fruit Lid Perforation</th>
<th>6 oz. Melon</th>
<th>6 oz. Citrus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Container ID (in)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Lid Area (in²)</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>OTR Required</td>
<td>1600</td>
<td>320</td>
</tr>
<tr>
<td>OTR for 1 mil permeable PE</td>
<td>254</td>
<td>254</td>
</tr>
<tr>
<td>OTR on lid without perf</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td># of perf on lid (4 mil hole)</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>OTR on lid with perf</td>
<td>958</td>
<td>314</td>
</tr>
</tbody>
</table>

Since the β value of many polymeric films is much larger than that of the RQ of a given product, there will be more CO₂ leaving the package than O₂ entering. Because N₂ cannot fill this free volume created by CO₂ exiting, the package free volume tends to shrink during storage (Mahajan et al., 2006). With perforated films, most mass
transfer occurs through the perforations thus eliminating volume shrinkage and subsequent pack collapse. The gases are therefore diffusing through into air and, as a result, have similar diffusion coefficients. The effective permeability to O₂ is very close to that of CO₂, therefore, in such films, the permeability ratio for these gases is approximately equal to one (Emond et al., 1993; Cliffe-Byrnes, 2000).

The total flow through polymeric film having \(N_H\) number of holes is defined as Equation 1.7:

\[
\text{Total Permeation} = \left\{ \text{permeation through film} \right\} + \left\{ \text{permeation through one hole} \times N_H \right\}
\]

If the distance between perforations is much greater than their radius, the diffusive path length becomes the length of the cylindrical pore plus the radius of the hole. Diffusive flux in this instance obeys Fick’s Law as follows:

\[
P_{O_2} = \left[ P_{film\,O_2} + \frac{\pi R_H^2 \times D_{O_2}}{e + R_H} \times N_H \right] \tag{1.8}
\]

\[
P_{CO_2} = \left[ P_{film\,CO_2} + \frac{\pi R_H^2 \times D_{CO_2}}{e + R_H} \times N_H \right] \tag{1.9}
\]

Where:
- \(P_{O_2}\) and \(P_{CO_2}\) = Permeability for O₂ and CO₂ respectively, \(\text{mL.mil.m}^{-2}.\text{day}^{-1}.\text{atm}^{-1}\) with perforations
- \(P_{film\,O_2}\) and \(P_{film\,CO_2}\) = Permeability for O₂ and CO₂ of the film respectively, \(\text{mL.mil.m}^{-2}.\text{day}^{-1}.\text{atm}^{-1}\)
- \(\pi\) = pi
- \(R_H\) = the radius of the holes, m
- \(D_{O_2}\) and \(D_{CO_2}\) = Diffusity of O₂ and CO₂, respectively, in air, \(\text{m}^2.\text{sec}^{-1}\)
- \(e\) = thickness of the film, m

The number of perforations, cross sectional area of each perforation and the length of the diffusion channel affect the rate and degree to which the EMA can be attained, and thus can be used as control variables to obtain a desired package atmosphere.
**Needle perforations**

Perforation can be made with needles (Figure 1.17). of 0.3-1 mm. Calculations show that a single cylinder hole of this diameter will allow far too large quantities of oxygen to pass through the hole (Mahajan et al., 2006), but needles do not make cylindrical holes in a packaging film. Packaging film is tough, so depending on the film material, the shape of the needle and the piercing technique, the hole is as follows:

![Figure 1.17 Needle perforations on polymeric films: (a) Piercing with flap (b) Non-perforated appendix (c) Piercing with crater. (Taken from Danish Technological Institute of Packaging and Transport, 2008).](image)

It is important to be absolutely sure that the film is pierced in order to establish a useful EMA. If the packaging film is elastic and tough, an “appendix” may appear increasing the permeability of the film, because the area is increased and the film becomes thinner, however the film may be still far too airtight. If the film is pierced, very different types of holes will appear depending on the type of needle and material as seen in Figure 1.17. Common to these holes is that the film has withdrawn, making the hole considerably smaller than expected. At the same time a “valve” has been made which may partly close when the pressure goes against the perforating direction of the needle (Brandenburg, 2012).

**Perforation with electrostatic energy**

Plastic film can also be perforated by electrical discharge, i.e. a spark. The size of the hole can vary by reducing or increasing the electric charge. This technique is slow and only works well for thin polymer materials (Chow, 2003).
**Laser perforation**

For industrial lasers, such as CO\textsubscript{2} lasers, the intensity of the light is readily absorbed by the polymeric film. The film is heated, melted and instantaneously vaporized, leaving a very small well defined hole on the film. As the laser pulses, holes can be made to obtain the desirable number per unit length as the web advances (Chow, 2003). Depending on the intensity of the laser, different sized holes can be obtained.

1.7. Effects of MAP on the physiological, biochemical and microbiological quality and safety of fresh-cut fruit

Postharvest physiology, including respiration rate, transpiration, senescence and extrinsic stress responses, as well as produce biochemistry such as C\textsubscript{2}H\textsubscript{4} synthesis, EB, chlorophyll degradation, metabolism of aroma volatiles and nutrient depletion, directly determine the quality and shelf-life of fresh-cut fruit produce stored under MAP. In general, low O\textsubscript{2} combined with elevated CO\textsubscript{2} reduce respiration rates and prolong shelf-life. Brown discoloration can occur when O\textsubscript{2} and CO\textsubscript{2} levels are suboptimal for a particular EB prone commodity.

In the absence of O\textsubscript{2}, anaerobic respiration occurs and generates off-flavours, off-odours and metabolic tissue damage. It can occur when the partial pressure of O\textsubscript{2} falls below 10% (Lamikanra, 2002). For some fresh-cut products, the O\textsubscript{2} levels can be allowed drop to levels near or at the respiratory quotient breakpoint (RQB) without resulting in injury (Izumi et al., 1997; O’Hare et al., 1995; Varoquaux et al., 1996). These low O\textsubscript{2} levels (0.25-1%) were beneficial in retaining quality of fresh-cut produce. Gil et al., (1998) used low O\textsubscript{2} atmospheres (0kPa and 0.25kPa) and air with Fuji apple slices. They concluded that a reduction of O\textsubscript{2} within packs delayed oxidative reactions such as the browning that occurs at cut surfaces. Marrero and Kader (2006) studied the effects of MAP on fresh-cut pineapple stored at different temperatures and found that the use of 8% O\textsubscript{2}; 10% CO\textsubscript{2} was successful at retaining fresh-like colour than fresh-cut pineapple stored in air.

In general, CO\textsubscript{2} levels greater than 20% (and depending on O\textsubscript{2} concentration and commodity type), can result in vast accumulation of ethanol and acetaldehyde (Kader, 1986) and stimulate respiration rate (Varoquaux and Wiley, 1994). Elevated
CO₂ levels can inhibit mitochondrial activity, thereby diverting pyruvate to acetaldehyde and ethanol formation even when ample \( O_2 \) is present (Laties, 1978). Although it is well recognised that high CO₂ increases the permeability of a plant to water, many of these influences mediated through effects of gas cytoplasmic pH, suppression or induction of protein synthesis, activation or inactivation of pre-existing enzymes or an antagonism to \( C_2H_4 \) action (Mathooko, 1996) are multifaceted, highly complex and not fully elucidated.

Oms-Oliu et al., 2007 investigated MAP on fresh cut melon and concluded that a 70 kPa \( O_2 \) atmosphere prevented anaerobic fermentation however under an atmosphere of 2.5 kPa \( O_2 \) and 7 kPa CO₂ fermentative pathways were triggered. Additionally high \( O_2 \) levels preserved the colour and firmness of fresh-cut melon better than low levels.

Moreover, MAP can influence the textural quality (firmness) and softening of fresh-cut fruit. The rates of softening and firmness are reported to differ among fruit type and packaging. Chonhenchob et al., 2007 demonstrated that the firmness of fresh-cut pineapples, mangoes and cantaloupe melons stored under MAP decreased during storage at 4°C however the slowest changes were observed in PET containers. MAs do not directly affect water-loss. Since most packaging films used for MAP exhibit low permeability to water vapour, water is accumulated within packs, producing a rise in RH. Therefore, the moisture content of the atmosphere within packs are usually quite high as there is moisture being produced from plant transpiration and this combined with reduced air circulation produces humidity conditions that approach saturation. Thus, the dew-point may be reached with slight temperature fluctuations resulting in condensation on the packaging film as well as the product. Packaging of produce in films therefore can reduce water-loss by providing high RH. Water-loss can lead to the development of off-colours resulting in limited SL of many perishable commodities. Srilaong et al., (2002) demonstrated that water-loss in rambutan fruit cv Rong-Rien has the effect of inducing browning during MAP storage. They found that MAP changes within packs reduced the respiration rate of the fruits so that water-loss decreased in contrast to ventilated and unpackaged packs (control). They concluded that RH inside packages was an important factor in suppressing water-loss and that the MA gas concentrations may have a secondary effect at reducing transpiration. Furthermore, they showed that
MAP reduced ion leakage susceptibility (which is directly related to stress and the development of senescence) therefore delaying the onset of senescence in rambutan fruit thus prolonging SL.

As mentioned previously, MAP is one of the most important extrinsic factors that affect microbial spoilage of fresh-cut produce. The reduction of \( \text{O}_2 \) coupled with an increase in \( \text{CO}_2 \) can have different effects on fruits depending on the native microbial (and/or pathogenic) populations present. Microorganisms such as mesophilic bacteria, LAB, coliforms, yeasts and moulds have been found to be actively growing inside packaged fresh-cut fruit. In addition, while MAP might inhibit the growth rate of many microorganisms, it could permit the growth of other microflora and allow pathogens to thrive under certain conditions. In recent years, several new modified atmosphere packaging treatments have emerged aimed at preventing microbial growth by actively introducing antimicrobial agents into the packages (Han, 2003; Farber et al., 2003).

Several studies have also revealed that high \( \text{O}_2 \) concentrations have been effective in reducing microbial growth, preventing anaerobic fermentation, and also inhibiting enzymatic discoloration (Day, 2000; 2008; Jacxsens et al., 2001; 2010; Allende et al., 2006).

The effectiveness of \( \text{CO}_2 \) is highly dependent upon many factors including the concentration of \( \text{CO}_2 \), the type of product being packaged, the storage temperature and fundamentally, the age and load of the native bacterial populations, i.e. the growth phase of any organisms, present on a given product. The atmospheric conditions used in traditional MAP are usually not high enough in \( \text{CO}_2 \) (>20%) to prevent microbial proliferation and the actual inhibitory effects of traditional MAP \( \text{CO}_2 \) concentrations have been postulated. Therefore, the greatest safety concern with MAP foods is that the technology might inhibit spoilage bacterial or fungal microflora while allowing pathogenic microorganisms to thrive (Francis and O’Beirne, 1997).
1.8. Quality evaluation

In evaluating the extent of quality deterioration in fresh-cut produce, both objective and subjective approaches are often combined.

1.8.1. Colour

Colour is a key component of fresh-cut quality (Sams, 1999). Typically, fruits which are red and yellow in colour are associated with ripeness whereas, green colours in fruits are deemed in most cases unripe. Browning, translucency and whitening are all associated with spoilage or deterioration of fresh-cut fruits. Instruments, such as colorimeters, provide a specific colour value based on the amount of light reflected from the surface of the product or the amount of light being transmitted through a product. Colour charts give illustrated details by periodic reference to colour standards or true size colour replicas of a product. The light reflected from the object passes through a red, green and blue glass filter to stimulate the standard observer function for a particular illuminant. A photo detector beyond each glass filter detects the amount of light passing through and the resulting signals are displayed as X, Y and Z values on screen as can be seen in Figure 1.18 (Hunterlab, 2001; Ohno, 2000).

![Figure 1.18](image.png)

**Figure 1.18** Hunter L*, a* and b* values as displayed using a colorimeter.

Taken from Ohno, (2000).
Chapter 1

The CIE \(L^*, a^* \& b^*\) values are one of the recommended colour parameters used to perceive the colour of samples (Figure 1.18). \(L^*\) is the light and dark axis where \(L^* = 0\) represents black and \(L^* = 100\) represents white (high reflection). \(a^*\) is the red and green axis, where positive \(a^*\) values indicate a red colour and a negative \(a^*\) value indicates a green colour, \(b^*\) is the yellow to blue axis where positive \(b^*\) values indicate yellow colour and negative \(b^*\) value indicates a blue colour. These \(L^*, a^* \& b^*\) values can be used to calculate other parameters such as browning and whitening indices. Decreasing \(L^*\) and an increasing \(a^* \& b^*\) values denote browning (BI) in fruits while the opposite, increasing \(L^*\) and decreasing \(a^* \& b^*\) values indicate whitening (WI) of certain fruits. Another parameter Delta E (\(\Delta E\)), uses these \(L^*, a^* \& b^*\) values to assess quality changes during a period of storage. All these parameters are used in determining the quality of fresh-cut fruit.

1.8.2. Texture

Textural characteristics such as crispness and juiciness are of great importance in the enjoyment of fruit. Minor defects such as bruising or mechanical damage due to slicing can deter from the expected textural characteristic of a product resulting in consumer rejection. As a result, instrumental analysis of fruit texture has become one of the essential steps of fruit quality assessment both pre- and postharvest (Harker et al., 2002). Different cultivars vary widely in their rate of textural deterioration and there is not always a relationship between the rate of softening in whole fruit and in its fresh-cut counterparts (Gorney et al., 2000; Aguayo et al., 2004). Firmness is a common parameter assessed by means of empirical mechanical tests used to measure and maintain consumer’s perceptions of texture throughout storage and processing (Alvarez et al., 1997). Puncture or plunger tests (using a pentrometer) are normally used to measure the firmness of fruits to estimate harvest maturity. A thin slice of skin is normally removed from the area to be tested and measurements are made using a rounded-tip probe of specific geometry and of maximum force required to insert the probe into the flesh (Abbott et al., 1992; Bourne, 1974; Haller, 1941; Magness and Taylor, 1925;).

Tissue softening affects fresh-cut fruit firmness which is a very serious problem limiting the quality and shelf-life of products. Optimum harvesting time,
dipping treatments and storage conditions can maintain or improve fresh-cut fruit firmness (Portela et al., 1997; Ponting et al., 1971; Beaulieu, 2011).

Textural change is the major event in fruit softening and is the integral part of ripening. Depending upon their inherent composition, particularly cell wall composition, different fruits soften at different rates and to varying degrees (Tucker and Grierson, 1987). Fruit pulp or the mesocarp is the edible part of the fruit, and is composed of thin-walled storage parenchymatous cells. These cells are characterized by a prominent cell wall consisting of complex network of polysaccharides and proteins, which gives mechanical strength to tissues. The primary cell wall contains 35% pectin, 25% cellulose, 20% hemicelluloses and 10% structural, hydroxyproline rich protein (Brownleader et al, 1999). Fruit texture is influenced by various factors like structural integrity of the primary cell wall and the middle lamella, accumulation of storage polysaccharides, and the turgor pressure generated within cells by osmosis (Jackman and Stanley, 1995). Fruits such as mango, papaya and banana undergo drastic and extensive textural softening from ‘stone hard’ stage to a ‘soft pulpy’ stage associated with a change in turgor pressure, whereas apple and citrus fruits do not exhibit such a drastic softening as enzymatic hydrolysis of starch results in pronounced loosening of cell structure (Prasanna et al., 2007; Tucker and Grierson, 1987).

1.8.3. Analysis of taste and aroma compounds

Sugars are the major soluble solids components in fruit juice. The percent soluble solids concentration (%SS) can be determined in a small sample of fruit juice using an instrument called a refractometer. Determining %SS is an important factor in determining the maturity of fruit which itself determines the overall flavour quality of a fresh-cut product. Watada and Qi, (1999) reported that the quality of young honeydew melon cubes with 8.8% soluble solids was lower than that of mature fruits with 13% SS after a storage period of a few days, and then honeydew melon cubes with 8.8% SS deteriorated more rapidly than those with 13% SS.

As the total acid content or titratable acidity (TA) of fruit changes with maturity, determining the total acid concentration of fruits before harvesting is also
important. The acids in fruit have a significant bearing on pH and play a significant role in taste, colour and microbial stability of the fruit, and in turn affect the overall quality and shelf-life of fresh-cut fruit products. TA can be determined by titrating a known volume of the fruit juice with 0.1N sodium hydroxide (NaOH) to an end point of pH 8.2 and calculating % acidity as the primary acid present. The predominant organic acids used for TA calculations of some fruit commodities are malic (stone fruits, apples and kiwis), citric (citrus fruits) and tartaric (grapes) acids.

TA maturity standards required for both domestic and international commerce. Examples of the TA requirements for some fresh fruit commodities are listed in Table 1.12.

### Table 1.12: Specific maturity standards required for some fresh fruit commodities.

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Sample Temperature Range</th>
<th>TA Range/ 100ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cranberry</td>
<td>0 – 35ºC</td>
<td>1.6 - 3.6 g of citric acid</td>
</tr>
<tr>
<td>Table Grape</td>
<td>0 – 35ºC</td>
<td>0.4 – 0.9 g of tartaric acid</td>
</tr>
<tr>
<td>Orange</td>
<td>0 – 35ºC</td>
<td>0.8 – 1.4g of citric acid</td>
</tr>
<tr>
<td>Apple / Pear</td>
<td>0 – 35ºC</td>
<td>0.36 – 0.80g of malic acid</td>
</tr>
<tr>
<td>Pineapple</td>
<td>0 – 35ºC</td>
<td>0.70 – 1.60g of citric acid</td>
</tr>
<tr>
<td>Strawberry</td>
<td>0 – 35ºC</td>
<td>0.60 – 1.10g of citric acid</td>
</tr>
<tr>
<td>Mango</td>
<td>0 – 35ºC</td>
<td>0.34 – 0.84g of citric acid</td>
</tr>
</tbody>
</table>

Adapted from Mitcham et al., (1996)

The ratio of sugar to acid affects the taste and acceptability of fruit. These measurements assist in determining when a fruit is ready for harvesting and subsequent processing. In the production of fresh-cut fruits, it is essential to use mature fruit with acceptable eating quality for processing; over-mature fruit will deteriorate more quickly (Watada and Qi, 1999).

**Volatile aroma analysis**

Volatile aromatic compounds (VAC) play a major contribution in imparting flavour to fruits and their existence within a fruit system is highly complex. Many factors
affect their production during ripening, harvest, postharvest and storage, are reliant on many factors (section 1.5). It is important to know the typical VAC pattern of a fresh product and how it is affected by processing and subsequent storage (Kataoka et al., 2000). Volatiles can be extracted by many different means but static headspace analysis (SHA) coupled with solid-phase microextraction (SPME) and followed by gas chromatography - mass spectrometry (GC-MS) analysis is widely used for fruits.

Snow and Slack, (2002) defined headspace analysis as a “vapour-phase extraction, involving the partitioning of analytes between a non-volatile solid-phase and the vapour phase above the solid sample with this mixture transferred to a GC or similar device for analysis”. Static headspace analysis (SHA) is the same concept and involves letting the vapour above the sample come into equilibrium before extracting it for analysis. SHA has been used for decades for flavour analysis and today remains the most validated amongst headspace analysis techniques (El Hadi et al., 2013).

Solid-phase microextraction (SPME) is a relatively new sample preparation technique using a fused-silica fibre that is coated with an appropriate stationary phase (Harris, 2007). Analytes in the sample are directly extracted to the fibre coating (Figure 1.19). Royer et al., (2001) successfully developed an automated HS-GC method for the determination of dithiocarbamates (pesticides) in plant matrices. Shang et al., (2002) used HS-SPME to determine the aroma components of fresh, frozen and withered Michaelia alba flowers and were able to determine the differences in the compounds present in each one.

In SHA-SPME the sample is placed in a vial which is hermetically sealed using a septum screw cap. The SPME needle pierces the septum and the fibre extends through the needle and is exposed to the vapour phase above the solid sample. The target analytes partition from the sample matrix into the stationary phase. Agitation of the sample is often carried out to increase the rate of equilibrium. After a suitable extraction time, the fibre is withdrawn into the needle, the needle removed from the septum and inserted directly into the injection port of the GC. Desorption of analytes from the fibre coating is performed by heating the fibre in the injection port. Once in the ‘inject’ position, the fibre desorbs the analytes and delivers them to the column for separation.
A more recent development in sorbent chemistry employs the use of a magnetic stir bar coated with polydimethylsiloxane (PDMS) (Figure 1.20). Termed stir bar sorptive extraction (SBSE), this method uses the same practical theory as SPME but with the stir bar being placed in the headspace of the sample. The stir bar has a PDMS phase with a volume of 25-125µl, compared to the significantly smaller 0.6µl of a 100µm SPME fibre. Bicci et al., (2002) used headspace-stir bar sorptive extraction (HS-SBSE) to analyse the flavour components of various coffees. This larger surface area allows increased sensitivity. Stir bars are desorbed in the injection port of the GC in a rapid, high temperature step under inert gas flow which ensures the highest sensitivity and eliminates the need for solvent use and disposal (Baltussen et al., 1999).

In any analytical process it is important to consider the limitations of the methods used. In the case of GC analysis, the weaknesses in sampling or extraction method, the GC separation method and detection methods must be considered. In principle, the method of choice largely depends on the compounds of interest. There are many advantages to SHA. It is fast and simple; reproducible and non-destructive. It also
eliminates the need for solvent and non-volatile contaminants such as sugars and organic acids and salts that can partition to the fibre during extraction. Therefore, because the fibre is never in direct contact with the sample it has a longer life span. It also has a shorter equilibration time, but lacks the sensitivity of submersion and, as a general rule, is only used to identify main components (Alves et al., 2005). SHA-SPME also exhibits low background noise and is suitable for the extraction of more-volatile analytes however, is unsuitable for less-volatile or thermally labile compounds.

In general, volatile compounds need a thick polymer coating which requires a longer time to achieve extraction equilibrium. Mixed coating fibres containing divinylbenzene (DVB), copolymers such as carboxen (CAR) which is a porous activated carobon support) and a non-polar polydimethylsiloxane (PDMS) increase retention capacity due to the mutually potentiating effect of adsorption and disruption to the stationary phase, and can be used effectively for the extraction of volatile low-molecular mass and polar analytes.

In addition, if the previous GC-MS system is additionally equipped with a sniff port (GC-O) it is possible for a human to detect the compounds in the volatile compounds mixture that actually have an odor and therefore may be important in the sensory flavor of the sample. GC-O methods are classified as detection frequency, dilution to threshold, or direct intensity. Croissant et al., (2009) has reviewed common methods for GC-O include aroma extract dilution analysis (AEDA), post-peak sniffing, combined hedonic aroma response measurements (CHARM), Osme, and nasal impact frequency/surface nasal impact frequency (NIF/SNIF). These studies often are followed by reconstitution studies of key compounds detected using sensory analysis (Poehlmann, and Schieberle, 2013; Careri et al., 2002). Furthermore, it is sometimes possible to use an “electronic nose” to assess the composition of the volatiles compounds of a sample (Maul et al., 2000; Berna et al., 2005) and determine whether those compounds match predetermined groupings to identify products that may meet certain criteria. An electronic nose is composed of a number of sensors that interact with the volatiles that result in a change in their properties that is recorded and afterwards analysed (Dynerski et al., 2011). Electronic noses do not attempt to identify individual compounds and thus are more of an additional tool to GC techniques and sensory analysis.
In a mixture of odorants we now need to assess which odorants are more important. This will depend on the threshold of an odorant and its concentration. A compound may have a high concentration but if its threshold is large (i.e. a high concentration of this compound is needed to smell it) it will not contribute significantly to the aroma. Conversely, a compound with a low threshold and large concentration will probably dominate the aroma (Chambers and Koppel, 2013). The odour activity value (OAV) is equal to the concentration of a component of the aroma divided by its detection threshold level. The more powerful odorants are very difficult to measure as they occur in very low concentrations. The more powerful odorants are very difficult to measure as they occur in very low concentrations (Parker et al., 2012).

1.8.4. Total antioxidant activity
Trolox equivalent antioxidant capacity (TEAC) and total radical-trapping antioxidant power (TRAP) are widely used for determining total antioxidant activity (TAA). Because different antioxidant compounds may act in vivo through different mechanisms, no single method can fully evaluate the TAA of foods. The TEAC assay utilises 2,2′-azinobis(3-ethylbenzothiazoline-6 sulfonic acid) radical cation (ABTS), which is oxidised by peroxyl radicals to the stable radical cation (ABTS+), absorbing light at 734nm. From a methodological point of view, the DPPH assay is recommended as easy an accurate with regard measuring the antioxidant activity of fruit. It is based on the measurement of the scavenging ability of the antioxidants towards DPPH which is reduced to the corresponding hydrazine when it reacts with hydrogen donors. It is evaluated on the basis that the DPPH signal intensity is inversely related to the test antioxidant concentration. In the presence of antioxidants, radical formation is inhibited, and the exponential absorbance decay is monitored spectrophotometrically against the presence of a control sample, Trolox, at a fixed point in time. The antioxidant capacity is expressed as Trolox equivalents.

The antioxidant capacity of several substances occurring in plants has been documented in human intervention studies, although most of the work has been directed toward the effects of vitamins C and E and β-carotene (Blasta et al., 2010). Berries and some varieties of apples have a relatively high TAA, which is likely to be associated with the high content of flavonoids such as anthocyanins. Oranges and grapes exhibited intermediate TAA, probably associated with higher concentrations
of phenolic compounds and vitamin C, while melons had lowest TAA values. However, TAA assays such as DPPH are performed at non-physiological pH values thus making it difficult to transfer the results from this assay to the physiological environment \textit{in vivo}; they only serve to give an idea of the protective efficacy of secondary plant products (Schleiser \textit{et al.}, 2002).

### 1.8.5. Sensory Evaluation

Studies which investigate the importance of sensory parameters on consumer acceptability conclude that flavour is the most important component, followed by texture and then appearance (Fillion and Kilcast, 2000; 2001). Sensory analysis applies principles of experimental design and statistical analysis to the use of human organoleptic senses for the purpose of evaluating consumer products and is often correlated with instrumental analysis (Le Calvé, 2000).

Descriptive tests are used to discriminate between different of products. Panellists are required to detect and describe the perceived qualitative and quantitative sensory attributes of a sample. Qualitative aspects define a product in terms of appearance, aroma, texture and flavour. Quantitative ranking scales allow panellists to rate the product using a set hedonic scale. Chapter 2 describes the various sensory attributes used to determine the quality of a given commodity. Numerical rating scales and their descriptive equivalents are described in Section 2.2.

### 1.8.6. Microbial enumeration

Monitoring microflora changes and determining the type and load of microorganisms present within MA packaged fresh-cut fruits is an important aspect of quality assessment in these products (section 1.5.4; section 3.2).

### 1.9. Principal component analysis

Traditionally, product quality changes have been assessed in terms of single attributes such as colour and/or textural defects, sugar and acidity changes and the
development of undesirable off-odours through sensory evaluation during storage. However, relating these subjective and objective measurements, as affected by both intrinsic and extrinsic factors, to see what pattern exists has rarely been observed for fresh-cut fruit. Furthermore, continuous measurement over an appropriate time scale (e.g. 7 Day storage) generates large data matrices which can be sometimes hard to summarise.

In this instance, principal component analysis (PCA) can be used. PCA is a method of multivariate analysis broadly used with datasets of multiple dimensions. PCA aims to reveal patterns in the data, especially among samples that could not be found by analysing each variable independently. One way of detecting such patterns is to plot the quality attributes in multidimensional space, the dimensions of which are the new derived variables for each sample. PCA allows the reduction of the number of defined variables in a multidimensional dataset, although it retains much of the variation within a dataset. It produces linear combinations of the original variables to generate axes or principal components (PCs). The order of the PCs denotes their importance to that particular dataset, while the loadings indicate how much each variable is involved in each axis positively or negatively. For datasets with many variables, the variance of some axes may be great, whereas others may be small, such that they can be ignored (Swan and Sandilands, 1995). The ordination approach permits the construction of a multidimensional space whereby each vector represents a quality attribute in the study. This multidimensional space is reduced to two (or sometimes three) dimensions for graphical interpretation and communication thus allowing the examination of relationships among samples. Ordination in this manner is often referred to as scaling or factor analysis (reduced space), and the attributes are ordered along each axis with the distance between each one representing their biological dissimilarity (Holland, 2008).

**Figure 1.21** illustrates a basic understanding and interpretation of a PCA ellipsoid. PC1 describes the highest amount of variance while PC2 describes the second highest, and so on. *PC1 has a dashed line passing through the greatest dimension of the ellipsoid (perpendicular to the x-axis) and is the major axis of the ellipsoid. PC2 has a similar line passing through the ellipsoid (parallel to the x-axis; and it demonstrates the second highest variance.* Generally the first three PCs
represent the highest variance present in the datasets, giving the best visualisation of the differentiation of the different clusters.

In addition, because all units of measurement in quality evaluation testing are different, the data is frequently centred and standardised to unit variance to have equal weight in analysis with the impending illustration referred to as a correlation matrix. After centring the data, loadings are plotted on the ellipsoid with respect to their means (dashed lines). Each of the loadings represents the axis of the original space.

The can be used to estimate which of the original variables (attributes) contribute strongly to deterioration. Ideally, each loading should load strongly on one component (axis) with the loadings close to a positive or negative one (strong correlation) or zero (no correlation). In terms of interpretation, a negative loading for an attribute on axis I, for example, means that along axis I, all negative loadings correlate positively with other variables in the same axis plane and negatively with other variables loaded positively.

![Figure 1.21 Principal Component Analysis – Axis (PC) Interpretation.](image_url)
1.10. Conclusion

The literature review highlighted that the effects of variations in intrinsic and extrinsic factors on quality of fresh-cut fruits are still poorly understood. It also illustrated inferior quality of commercial products and the need to optimise packaging. The experimental work which follows addresses the effects of both intrinsic and extrinsic factors, namely raw material suitability, processing and packaging, on fresh-cut fruit quality and assesses product-package compatibility with a view to technology optimisation.
Chapter 2

Characterising deterioration patterns in fresh-cut fruits using Principal Component Analysis:

*Effects of Intrinsic and Extrinsic Factors*


**Paper II:** Finnegan, E. and O’Beirne, D. (2014b) “Characterising Deterioration Patterns in Fresh-cut Fruits using Principal Component Analysis II: Effects of Physiological Age, Seasonality, Processing and Packaging.” Submitted to *Postharvest Biology and Technology* (with revisions), August 2014.
This chapter (2) demonstrates the applied use of principal component analysis (PCA) in characterising the processes of deterioration in a variety of fresh-cut fruit as affected by common intrinsic and extrinsic factor variables. For ease of interpretation, it is presented in two parts.

Part I is entitled “Characterising deterioration patterns in fresh-cut fruits using principal component analysis”. It demonstrates the practical application of PCA in characterising and tracking the deterioration patterns of fresh-cut pineapple, strawberry, kiwifruit and cantaloupe melon during storage. Effects of geographical origin and cultivar were studied to demonstrate efficacy of the application.

Part II is entitled “Characterising deterioration patterns in fresh-cut fruits using principal component analysis: Effects of ripeness stage, seasonality, processing and packaging”. It demonstrates the applied use of PCA in characterising and tracking deterioration patterns in a variety of fresh-cut fruits as affected by the aforementioned intrinsic and extrinsic factor variables. Supplementary in-pack gas atmosphere data for effects of packaging and storage temperature, used in PCA analysis, is presented in Appendix C.1-4.
Chapter 2.1

“Characterising deterioration patterns in fresh-cut fruits using Principal Component Analysis: I”
2.1. Abstract
Principal component analysis (PCA) was used to track quality deterioration patterns in fresh-cut pineapple, strawberry, kiwifruit and cantaloupe melon during storage. Twenty-seven physiological, biochemical, microbial and sensory attributes, reported as indices of quality, were used to successfully characterise and track deteriorative changes. Freshness for all fruits was characterised by PCA as excellent visual appearance, aroma and firmness. Deterioration was characterised, for the most part, by increased tissue breakdown (exudate and cell permeability levels), firmness loss, increased off-odour development, colour loss (browning and translucency) and high microbial counts. Effects of cultivar and geographic origin were apparent in some fruits. PCA has the potential to track the effects of intrinsic and extrinsic factors of deterioration and could form the basis of future strategies to optimise quality.

Author’s remark:
“Good” and “Poor” quality attributes as interpreted by the author differed from fruit to fruit. However, an over-lapping pattern of the following attributes was noted in all cases:

Good quality attributes for the most part were attributed to:

- Overall acceptability
- Appearance
- Colour (both instrumental and sensory)
- Aroma
- Firmness (both instrumental and sensory)

While poor quality attributes were attributed to:

- Loss of firmness reported as increased drip-loss, weight-loss, exudate and cell permeability.
- High microbial counts
- Off-odour development
- In-pack CO₂ accumulation

Keywords: Minimal processing, Quality, Characterisation, Acceptability, Modified Atmosphere Packaging, Geographic origin.
2.2. Introduction

Ensuring quality retention in fresh-cut fruits continues to be a challenge. While storage-life and quality are strongly affected by raw materials, severity of processing and storage conditions (Artes et al., 2006), the precise mechanisms and dynamics of deterioration are incompletely understood. Greater understanding may enable optimised or alternative strategies to be identified and applied. Changes in product appearance and firmness are often first observed, followed by development of off-odours and off-flavours and microbial proliferation. Of particular importance are discolouration (browning, whitening and translucency), loss of firmness (membrane degradation, tissue softening and ion leakage) and decreases in nutritional value (Klein, 1987) coupled with development of off-odours, off-flavours and microbial growth (Brecht, 1995; Varoquaux and Wiley, 2004 and Ruiz-Cruz et al., 2010). However these physical, physiological, biochemical and microbial changes occur at different rates and to different extents and are greatly influenced by intrinsic and extrinsic factors, causing significant quality losses between harvest, processing, storage and consumption (Rolle and Chism, 1987; Watada and Qi, 1999; Emonger, 2009; Mahdavian et al., 2007; Mba et al., 2007; Safizadeh et al., 2007; Kazeim et al., 2011 and Shirzadeh and Kazemi, 2011).

Significant effects of production locality and/or cultural practices have been noted in many fruits (Blanpied et al., 1987; Rowell, 1988) attributable to the fact that worldwide fruit production has expanded greatly in terms of traditional and new locations of diverse climatic conditions, cultural practices and harvesting techniques. Therefore there is a need for a dynamic overview of the complex continuous quality tests of traditional evaluation systems, where datasets can be simplified to graphical representations for quality interpretation. Such systems are emerging (Chen et al., 2013; Dong et al., 2013; El Kar et al., 2013; Wilson et al., 2013; Hurtado et al., 2012; Infante et al., 2011 and Rocha et al., 2010) from a biological, sensorial, physiological and microbiological point of view.

In postharvest science, principal component analysis (PCA) is an emerging method for routine data analysis (Kienzle et al., 2011; Reichel et al., 2010). It is regarded as an unsupervised method of multivariate analysis, meaning that the model is not guided in a predetermined direction. Furthermore, PCA is viewed as an
iterative measure of ‘real world’ observation through which a dataset is resolved into a matrix in the form of principal components (PCs) that can be handled by classical statistic methods, visualised and interpreted to extract the particular information required (Wang et al., 2012).

By applying PCA to a range of sensory, physical and chemical data, clearer patterns may emerge that cannot be seen with individual measurements over large data-sets. One way of detecting such patterns is to plot the quality attributes in multidimensional space, the dimensions of which are the new derived variables. In this case, the attributes are ordered along each retained principal component (PC) with the distance between each one representing their biological dissimilarity (Holland, 2008).

Typically, only the first two PCs accounts for meaningful variance, hence only PCI and PCII are commonly retained and interpreted in simple structure biplots. Furthermore, because all units of measurement in quality evaluation are different, the data is frequently centred and standardised to unit variance to have equal weight in analysis, with the resulting illustration referred to as a correlation matrix. The loadings produced will show a similar pattern, although their absolute differences will differ, with variables plotted along PCI and PCII displaying different constructs sharing the same conceptual meanings respectively, i.e. good quality and poor quality. In terms of interpretation, a negative loading for an attribute on PCI, for example, means that along PCI, all negative loadings correlate positively with other variables in the same axis plane and negatively with other variables loaded positively.

However, although it is widely used and accepted in postharvest food science and industry, PCA is relatively unpractised when it comes to quality evaluation and factor analysis. The dynamic output from such a system are often visualised as intricate patterns that can neither in detail be predicted nor exactly interpreted by users. The aim of the present study was to evaluate the effectiveness of PCA in characterising and tracking quality changes in a number of fresh-cut fruits. Deterioration patterns due to cultivar and geographic origin differences were also determined with a view of optimising intrinsic factors affecting fresh-cut fruit quality.
2.3. Materials and methods

2.3.1. Plant materials

Whole fruits were collected from a local wholesaler (Richardson’s Fruit and Vegetables, Limerick, Ireland) the day before each trial and stored at 4°C (for a maximum of 15h for chilling sensitive commodities) until processed. Intrinsic factors (geographical variation of fruit origin and cultivar) of intact fruits studied are shown in Table 2.1 but prior postharvest storage conditions were unavailable.

Table 2.1: Fruit types, cultivars/ variety, countries of origin and class used.

<table>
<thead>
<tr>
<th>Fruit</th>
<th>Cultivar/ Variety</th>
<th>Country of Origin</th>
<th>Class</th>
<th>Season</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pineapple</td>
<td>Del Monte Gold Extra Sweet <em>Ananas comosus</em> L. Merr MD2</td>
<td>Costa Rica, Brazil</td>
<td>Extra</td>
<td>Autumn</td>
</tr>
<tr>
<td>Strawberry</td>
<td><em>Fragaria spp.</em> Elsanta Festival Orly, Camarosa, Orly, Camarosa</td>
<td>Ireland, Egypt, Ethiopia, Spain, Morocco</td>
<td>I, I, I, I</td>
<td>Summer</td>
</tr>
<tr>
<td>Kiwi</td>
<td><em>Actinidia delicosa</em> cv Hayward, Hayward, Hayward</td>
<td>New Zealand, Italy, Brazil</td>
<td>I, I</td>
<td>Autumn</td>
</tr>
<tr>
<td>Melon</td>
<td><em>Cucumis melo</em> L. var reticulatus, <em>Cucumis melo</em> L. var reticulatus, <em>Cucumis melo</em> L. var cantalupensis</td>
<td>Costa Rica, Brazil, Italy</td>
<td>I, I</td>
<td>Winter</td>
</tr>
</tbody>
</table>

2.3.2. Fresh-cut processing and packaging

Fresh-cut fruits were processed at room temperature (~22°C). Peels, husks, stems and hulls were manually removed using a stainless steel knife and the fruits were cut to size as required. All fruits were cut into 25mm (pineapple and melon) and ¼ (kiwifruit) sizes while strawberries were de-hulled and halved (Figure 2.2). All samples (150g) were placed in rigid polylactic acid (PLA) trays within pillow packs (412.9cm²) and sealed using an impulse bench-top heat sealer (Relco, U.K. Ltd.,
A high barrier laminate flexible film (PET12/PE55) with $O_2$ and $CO_2$ permeabilities of 62,814 and 212,776 ml. microns/m$^2$.day.atm. was used to make the pillow packs (Amcor Flexibles, Gloucester, UK). This resulted in product modification of the atmosphere within packs.

2.3.3. Quality testing

In-pack gas atmosphere composition

The percent concentration of atmospheric gases within packs was measured at room temperature (~20°C) using a gas-space analyser (Systech Instruments, U.K) fitted with a 50mL air tight syringe. The mean values of duplicate $O_2$ and $CO_2$ concentrations were recorded and the experiment repeated twice.

Moisture loss (%)

Percent weight loss was calculated using the method from Moneruzzaman et al., (2008) and expressed as gram loss per fresh-cut weight using the following equation (1.10):

$$\frac{\text{Initial Weight of Pack} - \text{Weight on Day of Analysis (g)}}{\text{Initial Weight of Pack (g)}} \times \frac{100}{1}$$

Drip-loss, exudate and cell permeability

The volume of free liquid released during storage (drip-loss) was recorded as mL/150g fresh weight. Exudate levels were quantified using the method by Carlin et al., (1990) with slight modifications, and recorded as grams per 100g fresh weight. Cell permeability was determined by monitoring leakage of UV-absorbing solutes as reported by Picchioni et al., (1994) with slight modifications. The absorbance of the clarified solution was measured at 260nm against distilled water (UV/Vis spectrophotometer, Varian Cary 100, Agilent Technologies LTD, Dublin, Ireland).
**Percent soluble solids**

Percent soluble solids was measured in clear fruit juice from homogenised fruit pieces using an Atago Digital Pocket Refractometer (Atago Co., LTD., Tokyo, Japan).

**Tissue pH and titratable acidity**

Tissue pH was recorded from homogenised fruit pulp. Clear juice (10mL) was mixed with 10mL of distilled and deionised water was measured using a Jenway 3510 pH meter. Titratable acidity was calculated as citric acid by titrating juice samples to pH 8.2 using 0.1N NaOH.

**Colour**

Surface colour of fresh-cut fruits was determined using a Minolta chromameter 5081, fitted with an 11-mm aperture and a D65 illuminant (Konics Minolta, Sensing Inc., Osaka). Three measurements were taken at random locations on each of the fruit samples, and this was replicated three times. CIE L*, a* and b* values were determined and presented herein. Using standard CIE L*, a* and b* values, indices of colour quality were measured. Browning index was calculated as BI = (100(x – 0.31)) / 0.17, where x = [(a-1.75*L) / [(5.645*L) + a - (3.012*b)]. Whitening Index was calculated as WI = 100 - [(100 - L*)2 + (a*)2 + (b*)2] ½. Delta E was calculated as ∆E = [(L_f – L_i)² + (a_f–a_i)² + (b_f–b_i)²]½. Where, f = final & i = initial. Chroma was calculated as C* = √a² + b², and Hue angle was calculated as H° = tan⁻¹ (b*) / (a*) where, if H<0° then h = h+360; if H>0° then h = h-360, r = 180/π.

**Texture**

Firmness was determined using a TA.XT Plus Texture Analyser (Stable Micro Systems, Surrey, UK) fitted with a 6mm flat tipped cylindrical probe. The force required to penetrate (F) a piece of fruit was recorded as both the maximum and mean force in Newtons (N). The fresh-cut pieces were of uniform shape and size to allow for repeated accuracy of results. Using the Kramer Shear Cell and Extended Craft Knife (pineapple only) attachments, the maximum force, area and mean force
required to shear (S) through 150g of fruit samples, in duplicate, was recorded in Newtons (N) as an index of product firmness.

2.3.4. Microbial enumeration

The different media used were prepared, plated and stored according to manufacturer’s instructions (Oxoid Ltd, Basingstokes, UK). On each sampling day, 10g of fruit was aseptically removed from each pack and homogenised with 90mL of 0.1% peptone water at high speed for 120s. Serial dilutions ($10^{-1}$ to $10^{4}$) were prepared by mixing 1mL of the homogenate liquid with 9mL of 0.1% peptone water. Total viable counts (mesophiles and psychrophiles) and yeasts and moulds were prepared in the following way: aliquots (100µl) of each serial dilution were applied on to the surface of appropriate media and were surface spread in duplicate using an inoculation spreader. For lactic acid bacteria (LAB), media pour plates were prepared whereby 100µl of sample was added to the media followed by a molten overlay of media (50°C). Total viable count plates for mesophiles and psychrophiles were incubated at 35°C and 4°C for 48h and 7 Days respectively, LAB plates for 48h at 35°C and yeast and mould plates for 5 Days at 20°C. Following incubation, colony-forming-units (CFU) were counted on plates that contained between 20-200 CFU. Results were expressed as colony-forming-units per gram (CFU/g) of sample.

2.3.5. Sensory evaluation

Descriptive tests were used to evaluate the sensory quality attributes of fruit packs. The quality attributes examined were overall visual appearance, colour, aroma, off-odour, texture, and overall acceptability. Evaluation was performed by an untrained sensory panel which consisted of 12 judges (8 female and 4 male), all members of the Life Science Department, University of Limerick. Before the start of each sampling day, panel members were familiarised with the product and scoring procedure. Panellists were then randomly grouped into pairs and given 1 sample pack (as is) to evaluate against that of a fresh-cut sample (control) in terms of the aforementioned attributes. External colour was assessed using descriptors developed by Kader and Cantwell, (2010). For visual appearance and overall acceptability,
fresh-cut fruits were evaluated under fluorescent lighting using a 9-point rating scale, where a score of 9 indicated the sample was excellent, 7 represented very good, 5 acceptable/ fair, 3 poor and 1 extremely poor. Evaluation of aroma was performed using quantitative descriptive sensory analysis techniques (Kader and Cantwell, 2010), where; 9 = excellent, normal characteristic aroma, 7 = very good, normal to slightly off, 5 = limit of marketability, 3 = fair, limit of usability, strong off-odours, slightly anaerobic, becoming offensive and 1 = poor, inedible, very strong off-odours, very fermented. In Table 2.2, panellists were asked to remark on the typical aroma noted for each of the samples with a list of the common aroma characteristics described by panellists listed. For texture evaluation panellists were asked to rank firmness (touch) by marking a 100mm line with unanchored terms where a score of 1mm = extremely soft while a score of 100mm = extremely firm. Quantitative results were obtained by measuring the distance from zero to the mark.

2.3.6. Statistical Analysis

Multi-factorial experiments were conducted in duplicate and repeated twice. Data for quality deterioration parameters were processed by analysis of variance (ANOVA, repeated-measures, SPSS 19, IBM, Chicago) with all factors in each experiment reported as fixed effects (p<0.05). Microbial populations and sensory parameters were individually analysed by two-way analyses of variance (paired t-test). For sensory parameters, panellists were reported as random effects and treatments as fixed effects (p<0.05). Tukey’s pairwise comparison test was used for differences between individual treatments (p<0.05).

For each experiment, PCA was performed on all quality and sensory variables (Canoco 4.5; Waigeningen, UR, NL). The analysis was performed on the response of 27 variables to six to ten sample treatments, each the mean of four replicates. All variables were mean centred and standardised (scaled) to unit variance prior to analysis i.e. correlation matrix. For each component of the PCA, a score for each sample was calculated as a linear combination for each physiochemical, sensory and microbial parameter measurements. The contribution of each parameter to the PCA score was deduced from the parameters loading for the factor. As PCA is performed
on a matrix of Pearson Correlation Coefficients, the data should therefore satisfy the assumptions for this statistic. However, it is often desirable to assess this reliability by computing coefficient alpha as an index of internal consistency and reliability. For that reason, Pearson’s correlation ($\rho$) was performed using SPSS 20, (IBM, Chicago, IL., USA) to better understand the association between monotonic quality (ratio) and sensory (ordinal) variables within a dataset and test the reliability of the technique. Where appropriate; ($\rho$) ranged from inverse (-1) to positive (+1) with small ($0.1 \leq |\rho| < 0.3$), medium ($0.3 \leq |\rho| < 0.5$) and large/strong ($|\rho| \geq 0.5$) effects noted.
Table 2.2 Intrinsic characteristics of intact fruit used

<table>
<thead>
<tr>
<th>Type/ Source</th>
<th>Origin</th>
<th>Cultivar</th>
<th>Physiological age</th>
<th>Aroma¹</th>
<th>Firmness, N</th>
<th>Soluble solids, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pineapple ¹</td>
<td>Costa Rica</td>
<td>Del Monte Gold</td>
<td>25 to 50</td>
<td>(8) Sweet, Pineapple</td>
<td>7.6</td>
<td>12.7</td>
</tr>
<tr>
<td></td>
<td>Brazil</td>
<td>Extra Sweet</td>
<td>25 to 50</td>
<td>(7) Sweet, Pineapple, Tart</td>
<td>7.3</td>
<td>12.3</td>
</tr>
<tr>
<td>Strawberry ²</td>
<td>Spain</td>
<td>Camarossa</td>
<td>5</td>
<td>(8) Strawberry, Sweet, Fresh</td>
<td>11.1</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>Morocco</td>
<td>Camarossa</td>
<td>4 to 5</td>
<td>(8) Strawberry, Sweet</td>
<td>9.6</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>Egypt</td>
<td>Festival</td>
<td>5</td>
<td>(9) Strawberry, Fresh</td>
<td>7.0</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>Ethiopia</td>
<td>Orly*</td>
<td>6</td>
<td>(6) Strong, Strawberry, Musty</td>
<td>4.4</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td>Ireland</td>
<td>El Santa</td>
<td>5</td>
<td>(8) Sweet, Strawberry, Fresh</td>
<td>2.4</td>
<td>8.3</td>
</tr>
<tr>
<td>Kiwifruit ²</td>
<td>Italy</td>
<td>Hayward</td>
<td>3</td>
<td>(9) Grassy, Green, Sweet, Fresh</td>
<td>1.5</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>New Zealand</td>
<td>Hayward</td>
<td>3</td>
<td>(9) Green, Grass, Fresh</td>
<td>2.8</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>Brazil</td>
<td>Hayward</td>
<td>3</td>
<td>(8) Green, Grass, Fresh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cantaloupe Melon ³</td>
<td>Costa Rica</td>
<td>N/A</td>
<td>5</td>
<td>(9) Pungent, Green, Musky</td>
<td>8.2</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>Brazil</td>
<td>N/A</td>
<td>5</td>
<td>(8) Pungent, Musky, Sweet</td>
<td>6.5</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td>Italy</td>
<td>N/A</td>
<td>5</td>
<td>(8) Melon, Sweet, Musky</td>
<td>7.3</td>
<td>6.5</td>
</tr>
</tbody>
</table>

¹External shell colour percentage was recorded against a Dole pineapple colour chart
²External shell colour was recorded against UC Davis colour charts. (Kader, and Cantwell, 2010)
³Numbers in brackets depict ripeness class and aroma scores
* Signs of mould in some fresh packs
2.4. Results

2.4.1. Processes of deterioration

Principal component analysis was carried out on the correlation matrix produced from twenty-seven quality attributes, previously identified as contributing to the quality deterioration of fresh-cut fruits. The factor loadings for the different quality ratings were plotted based on the first two principal components (PCs) with attributes and samples illustrated as vector angles and symbols respectively. PCI accounted for the greatest amount of the total variance (inertia) meaning that (under typical test conditions) PCI was correlated with many of the observed variables loaded on that component. PCII was uncorrelated with PCI and accounted for the largest amount of total variance in the dataset not accounted for by PCI. The proportion of variance accounted for was deduced using the cumulative percent of variance criterion for determining the number of PCs to retain. For the current analysis the cumulative percent of variance must have accounted for at least 90% of inertia in order to be retained and subsequently interpreted. Following this, the orthogonal biplot was reviewed for interpretability. The proportions of variance produced for biplots of each fruit type are presented in Table 2.3.

Table 2.3 Proportion of cumulative percentage variance and inertia for biplots construed for each fruit type and treatment

<table>
<thead>
<tr>
<th>Effects measured</th>
<th>Fresh-cut Fruit</th>
<th>PCI (%)</th>
<th>PC II (%)</th>
<th>PC III (%)</th>
<th>PC IV (%)</th>
<th>Inertia (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographical Variation of Fruit Origin and Cultivar</td>
<td>Pineapple</td>
<td>55.8</td>
<td>30.2</td>
<td>10.2</td>
<td>2.4</td>
<td>98.6</td>
</tr>
<tr>
<td></td>
<td>Strawberry</td>
<td>50.5</td>
<td>35.4</td>
<td>6.7</td>
<td>3.5</td>
<td>96.1</td>
</tr>
<tr>
<td></td>
<td>Kiwifruit</td>
<td>49.0</td>
<td>33.9</td>
<td>11.6</td>
<td>3.5</td>
<td>98.0</td>
</tr>
<tr>
<td></td>
<td>Cantaloupe Melon</td>
<td>65.8</td>
<td>24.3</td>
<td>8.5</td>
<td>0.9</td>
<td>99.5</td>
</tr>
</tbody>
</table>

* data disregarded for subsequent interpretation

1 Inertia is a measure of variation or ‘spread’ within a correlation matrix i.e. the total variance of the dataset (Husson et al., 2008).
In order to assess whether categories of variables were different from, or positively/ negatively associated with each other, confidence ellipses were drawn around them (Figure 2.1 a-d). These ellipses enclosed a group of related variables and/ or identified groups of related variables across each matrix.

A consistent trend was observed for all fruits studied in that the rotated factor pattern demonstrated a simple orthogonal structure with variable loadings on PCI and PCII measuring different constructs respectively. Furthermore, variables loading on PCI and PCII respectively share the same conceptual meaning, e.g. PCI refers to good quality attributes while PCII refers to poor quality attributes, with the exception of cantaloupe melon. Observations close to each other in the space of a PC are said to have similar characteristics. Similarly, variables whose unit vectors are close to each other are said to be positively correlated, meaning that their influence on the positioning of samples is similar. Variables distant from each other across an axis plane are defined as being negatively correlated. Poor quality attributes positively associated with increased deterioration were identified as increased microbial counts, increased cell permeability and exudate levels, increased off-odour development, CO₂ accumulation and discoloration. Good quality attributes were reported as good appearance, aroma, firmness and overall acceptability and in most cases were inversely correlated with the poor quality attributes previously noted. Coefficient alpha values (ρ) reported indicate the reliability of PCA interpretation using the biplot alone.

Irrespective of treatment, all samples moved in a similar pattern during storage indicating diminished quality and increased deterioration (see also Finnegan and O’Beirne, 2014b). As anticipated and as illustrated by small vector angles within the same component plane, scores for acceptability of appearance, aroma and firmness were highly correlated with overall acceptability for all fruits. For fresh-cut pineapple, poor quality attributes such as increased drip-loss, weight-loss and exudate were positively loaded on PCII, while good quality attributes such as fresh appearance (ρ=0.869), firmness (ρ=0.380), and aroma (ρ=0.780) were highly correlated with overall acceptability and negatively loaded. Tissue breakdown, reported as increased exudate and cell permeability levels, were shown to be negatively correlated (ρ=-0.612) with instrumental firmness measurements suggesting a direct relationship with deterioration.
For fresh-cut strawberry, poor quality attributes such as increased cell permeability, microbial counts (especially yeasts and moulds and lactic acid bacteria) and off-odour were positively loaded on PCI, while good quality attributes such as visual appearance ($\rho=0.869$), aroma ($\rho=0.780$) strongly correlated with overall acceptability, and negatively loaded. Firmness loss (both instrumental and sensory) was negatively loaded in PC I and II respectively, with sensory firmness negatively correlated with overall acceptability.

For fresh-cut kiwifruit, discoloration (loss of greenness observed as loss in luminosity ($L^*$) and greenness ($a^*$) with increased yellowness ($b^*$)) and loss of firmness were highly indicative of increased deterioration. There were strong correlations between appearance ($\rho=0.800$), firmness ($\rho=0.901$) and overall acceptability. Moreover, increased cell permeability levels were positively correlated with instrumental firmness levels ($\rho=-0.800$), again suggesting a relationship.

Interestingly, unlike other fruits, quality changes in fresh-cut cantaloupe melon occurred along PCII, moving from positive position to negative during storage. The positioning of loadings so closely together would suggest minimal quality change during storage. The positioning of sample scores on the far left would also suggest that fruit pieces were less affected in terms of quality change than other fruits. An exception to loadings is the positioning of CIE $L^*$, $a^*$ and $b^*$ values and sensory firmness which appeared to be the greatest attributes affected; observed as loss of luminosity and orange hue and loss of firmness in favour of increased colour change (sensory colour) and increased instrumental firmness. Furthermore, aroma scores were highly correlated with acceptability ($\rho=0.736$). Furthermore, increased off-odour ($\rho=-0.865$) and microbial counts ($\rho=-0.800$) were highly associated with increased deterioration during storage. Sugar/acid ratio and percent soluble solids were inversely correlated ($\rho=-0.642$) indicating the importance of sweetness in melon quality compared to the other fruits studied.
Figure 2.1 Principal Component Analysis (PCA): Biplot of the loadings and scores of PC1 and PC2 after analysis of effects of geographical origin and cultivar on quality evaluation attributes for (a) Fresh-cut Pineapple (b) Fresh-cut Strawberry and (c) Fresh-cut Kiwifruit (d) Fresh-cut Cantaloupe Melon during 7 Day storage at 4°C.

**Key of abbreviations (attributes):** CO₂ (carbon dioxide), O₂ (oxygen), F (puncture probe firmness - 6mm), S (Shear firmness), max (maximum firmness, Newton), mean (mean firmness, Newton), LAB (lactic acid bacteria), Y&M (yeasts and moulds), L* (CIE L* Lightness-Darkness), a* (CIE a* green-red) and b* (CIE b* blue-yellow).

**Key to confidence ellipses:**

- Microbial traits
- Firmness traits
- O₂/CO₂
- aroma/off-odour
- sensory traits

Fresh samples evaluated initially on Day 0; ★ Day 1; ▲ Day 4 ▣ and Day 7 ✗

**Key of symbols (Samples):**

- **Pineapple:** ★ (Brazil) and ☼ (Costa Rica).
- **Strawberry:** ○ (Spain), ☼ (Ireland), ☼ (Morocco), ★ (Egypt) and ○ (Ethiopia).
- **Kiwifruit:** ○ (Brazil), ○ (Italy) and ★ (New Zealand).
- **Cantaloupe Melon:** ★ (Costa Rica), ☼ (Brazil) and ○ (Italy).
2.4.2. Effects of origin and cultivar

Depending on the source of the whole fruit used for fresh-cut fruit processing and/or the cultivar, sample loadings were separated out along the PCs according to their initial quality and patterns of deterioration. The data show the relationships between the geographic origin of the raw material, the cultivar (fresh-cut strawberry only), storage time and overall quality loss (Figure 2.1 a-d).

In the case of pineapple (Figure 2.1a), fresh-cut Del Monte Gold Extra Sweet from Costa Rica and Brazil were compared. Fresh-cut fruits from both sources displayed similar patterns of deterioration during storage, with Costa Rican grown fruits having slightly better quality throughout. Deterioration was slowest between Day 0 and Day 1, and more rapid thereafter, showing increasing cell permeability, in-pack CO₂ accumulation, off-odour development and microbial counts, slightly more so for Brazilian grown fruit.

In the case of strawberry (Figure 2.1b), the cultivar ‘El Santa’ (from Ireland), ‘Camarosa’ (from Spain and Morocco) ‘Festival’ (from Egypt) and ‘Orly’ (from Ethiopia) were compared. All samples quickly lost their initial fresh-cut quality characteristics and, by Day 4, were characterised as having very high in-pack CO₂ levels, high microbial counts, decreased acceptability and darkening red hue. Irish El Santa strawberries had the greatest rate and extent of deterioration as demonstrated by the positioning of the sample loadings across the axes planes. Compared to the other cultivars, Camarosa samples were located low in the axis plane indicating slightly poorer quality (p>0.05).

In the case of kiwifruit (Figure 2.1c), fruits of the cultivar ‘Hayward’ were compared from three sources and analysed over 2 months (August and October). Fresh-cut New Zealand fruits had best initial quality, and retained good appearance, aroma, firmness and acceptability for longer. Scores were located further down to the right of the good attribute plane, moving towards the poor attribute plane as storage progressed. Fresh-cut Italian and Brazilian fruits had initially poorer quality, and were positioned further to the left of the plane, characterised as having reduced appearance, firmness and overall acceptability. Fresh-cut New Zealand kiwifruit deteriorated later in storage, the greatest rate of deterioration from Day 4 to Day 7. By contrast, Brazilian kiwifruit had greatest quality loss early, from Day 1 to Day 4.
Cantaloupe melons were studied from three sources, *reticulantus* from Costa Rica and Brazil, and *cantaloupensis* from Italy (Figure 2.1d). Fresh-cut Costa Rican melons initially had best appearance, aroma and acceptability and retained these well until Day 4. Fresh-cut Brazilian fruits also displayed good initial quality, but lost this more rapidly. Fresh-cut Italian melons were positioned lower down towards the poorer end of the axis plane from the start, characterised as having reduced visual appeal and overall acceptability.

2.5. Discussion

2.5.1. Processes of deterioration

The PCA plots combined sensory and instrumental measurements of quality to provide “maps” of deterioration of fresh-cut fruits. The general pattern was loss of initial high sensory scores and the concurrent development of poor quality attributes during storage: off-odours, increased cell permeability and tissue breakdown, translucency, loss of firmness and high microbial growth. Flesh translucency is apparent when the cellular spaces are filled with liquid, giving tissues a more vitreous appearance (O’Connor-Shaw *et al.*, 1994; Chen and Paull, 2001; Montéro-Calderón *et al.*, 2008a, b). In the current PCA plots, this was recorded as increasing lightness and greenness/yellowness in fresh-cut pineapple and kiwifruit. Translucency was usually followed by development of off-odours (melon) and browning at cut edges (pineapple). In general, tissue breakdown and cell leakage, reported as increased drip-loss, cell permeability and exudate levels, correlated well with increased microbial growth and development of off-odours. Products of microbial spoilage and fermentation result in aroma and flavour defects of fresh-cut fruits, during MA storage (Carlin *et al.*, 1989; 1990). High CO$_2$ atmospheres, as observed in fresh-cut strawberry packs, can have contradictory effects on quality as they can damage product firmness but may also reduce bacterial and fungal growth, depending on the product in question (Carlin *et al.*, 1990; Babic *et al.*, 1993; Madrid and Cantwell, 1993; Barber *et al.*, 2000).
2.5.2. Effects of fruit type, cultivar and origin

The relative importance of these different processes of deterioration varied with fruit type, and the rates of quality change during storage varied with fruit type, cultivar and geographic origin. Deterioration in fresh-cut pineapple was primarily in appearance, firmness and aroma coupled with an increase in browning, flesh softening, drip-loss and translucency, and development of off-odours. This is in line with degradative processes known to occur during storage which can cause tissues to discolour and loose moisture (Ártés et al., 2007; Gil et al., 2006; Saltveit, 2000). When the same cultivar was compared from two geographic origins, the patterns and rates of deterioration were similar, though there was a consistent difference in quality throughout.

In fresh-cut strawberry, the plots showed that deterioration was related to loss of firmness/increased cell permeability, weight loss, mould growth and off-flavour development, and that quality loss was rapid in the early stages of storage, between Day 1 and Day 4. When strawberries from different sources were compared, most were similar in their pattern and rate of deterioration, but Irish grown *El Santa* deteriorated faster than the other samples. Wright and Kader (1997) reported that the visual quality of strawberries decreased during 7 Day storage, and regardless of packaging film and cultivar, decreased in firmness (Rosen and Kader, 1989), with shelf-life limited by discolouration, decay and/or visible microbial growth (Barth et al., 2009).

For fresh-cut kiwifruit, quality losses were associated with a severe loss in firmness (to a mushy consistency) and appearance (colour loss and translucency) coupled with a loss of aroma. In fleshy fruits which ripen during storage, the degradation of chlorophyll is more pronounced with concurrent decreases in total carotenoids (Lodge and Perera, 2011). Plots for fruits of the same cultivar but from different sources, showed that New Zealand fruit had better quality and slower deterioration than fruit grown in Brazil or Italy. The different extremes of quality change could be attributable to harvest seasons, in that kiwifruit from Italy could be stored for up to 1 year or freshly harvested, depending on when they were purchased within season, while kiwifruit from New Zealand could be stored for up to 6 months.
before purchased. This will be covered in more detail in paper II (Finnegan and O’Beirne, 2014b).

In the case of cantaloupe melon, the plots showed that increased microbial growth, translucency, sponginess and off-odour development were characteristic of diminished quality. Fresh-cut melon lost its initial vibrant colour in favour of a more translucent, water-soaked appearance, especially where fruit was submerged in its exudate. Although the fruit pieces quickly lost their acceptability to panellists, they actually increased in instrumental firmness during storage. This was picked up by the PCA plot. Moreover, translucency, which is commonly reported in melon varieties (Cantwell and Portela, 1998; Portela et al., 2001; Aguayo et al., 2003) was apparent in this study and recorded by PCA as decreasing lightness (L*) and orangeness (a*).

Fresh-cut melon (CH) produced from fruits grown in Italy were of lower quality than those from fruits grown in Costa Rica or Brazil. Yeast counts were high in fresh-cut cantaloupe melon packs (especially Italian fruit), and they developed noticeable off-odours which were successfully recorded by PCA. Babic et al., (1992) reported that large cell numbers of yeasts (>10^5 CFU g⁻¹) produce off-odours in fresh-cut produce. Beaulieu (2005) previously highlighted the difficulty in procuring cantaloupes of consistent quality, with changes in sugars, colour and volatile ester formation being the main reasons for raw material inconsistency during storage. These variations in quality may be partly attributed to storage conditions as previously discussed for kiwifruit, in addition to pre-harvest factors such as genotype, which will be discussed further in Chapter 2 part II (Finnegan and O’Beirne, 2014b).

Overall, there were significant effects of geographic origin of the fresh-cut kiwifruit and melons studied. Climate, cultural practices and postharvest systems have all been implicated as causes of product variability in fruits harvested from different production zones (Mowat and Kay, 2007; Mowat and Maguire, 2007; Leverington, 1970; Sideris and Krauss, 1933a,b; Miller et al., (1998); Bergqvist et al., (2001); Mazur et al., (2012); Ritenour, (2010). Furthermore, strawberry varieties studied were ever-bearing (Camarosa and Festival) and June-bearing (El Santa and Orly) with each having individual
production characteristics and intermittent seasonal effects. In addition, the production season of certain countries helps to explain cultivar effects as in Spain strawberry production starts in mid-Jan lasting until June while in Morocco starts late-Jan lasting until April. For cantaloupe melon and kiwifruit, differences in quality may be attributed to the difference in ripening behaviour of fruit from warmer climates (Marsh et al., 2004). Large changes in a number of chemical and physical parameters have been recorded not only in whole fruits (Marsh et al., 2004; O’Connor-Shaw et al., 1994) but also in the different tissue types within the fruit itself (Montero-Calderon, 2008; Wang et al., 1998; Hallett et al., 1992). Higher respiration rates were recorded in the field for fruit growing at higher temperatures (Walton and DeJong, 1990) which appear to rapidly metabolise a particular acid pool when fruit are first placed in storage (Crisosto et al., 1984; Crisosto and Crisosto, 2001) therefore helping to explain the different behaviour of fruits harvested from different environments. For kiwifruit, in adequate winter-chilling may be one of the main obstacles to productivity and quality which is of particular concern for Hayward which seems better suited to colder climates (Simonetto and Lamb, 2011).

2.6. Conclusion

In conclusion, it is clear that the PCA plots revealed similarities and differences in quality and patterns of deterioration resulting from cultivar or source of fruit. This related in the rate and extent of quality deterioration for each fruit studied with origin having more of an effect on kiwifruit quality than pineapple and melon. The largest effects observed were due to origin, which may have implications for raw material, process, and packaging optimisation. By comparing the effects of these intrinsic factors on rates and extent of deterioration, it is possible to extract estimates of effects on shelf life from the plots. This could allow for careful planning and implementation of optimised processing and packaging conditions given a particular situation, i.e. inconsistent source and/or cultivar variations.
Chapter 2.2

“Characterising deterioration patterns in fresh-cut fruits using Principal Component Analysis II: Effects of ripeness stage, seasonality, processing and packaging”
2.1. Abstract

Previous work demonstrated the benefits of principal component analysis (PCA) in tracking processes of deterioration in fresh-cut fruits, and illustrating differences due to growing region and cultivar (Chapter 2 part I). In this study, PCA showed significant effects of season, stage of ripeness (p<0.05), cut size, packaging materials, storage temperature and time (p<0.01) for a range of fresh-cut fruits. PCA plots were effective in characterising patterns of deterioration and in tracking differences in quality, in terms of the rates and extent of change. Some of the effects studied were large and may form the basis for optimising raw materials, processing and packaging of several fresh-cut fruits. Differences in shelf-life (SL) of up to three days could be attributed to seasonal variation. Reduced process severity increased SL by up to four days, while optimal packaging increased shelf life by about three days.

Keywords: Quality, Characterisation, Acceptability, Appearance, Firmness, Flavour
2.2. Introduction

Understanding the mechanisms that drive deterioration and their dynamics is important so that optimised or alternative strategies for optimised product quality can be identified. Our previous work demonstrated the benefits of PCA in tracking processes of deterioration in fresh-cut fruits, and in indicating differences due to growing region and cultivar (Finnegan and O’Beirne 2014a). In this study, PCA was applied to investigate the effects of other key variables: season, stage of ripeness, cut size, packaging materials, storage temperature and time.

Significant seasonal effects on quality have been reported (Montero-Calderón et al., 2008; Cao et al., 2010; Nielson and Leufvén, 2008; Mazur et al., 2012; Finnegan et al., 2013) and ripeness stage of fruits intended for fresh-cut processing, is also known to be a critical factor in determining quality (Beaulieu and Lea, 2005; Beaulieu and Gorny, 2004; Soliva-Fortuny et al., 2002; 2004).

Manual peeling and slicing resulted in some variability in the choice of cut piece size and shape used in commercial fresh-cut fruit processing. There are well known effects of blade type and sharpness on the quality of fresh produce (Bolin et al., 1977; Barry-Ryan and O’Beirne, 2000a, b). Greater size reduction generally implies increased process severity and can have major effects on deterioration (Argañosa et al., 2008; Artés-Hernández et al., 2007; Rivera-López et al., 2005 and Teixeira et al., 2001). The increased surface area potentially creates a greater area for stress response, and also a greater area for liquid and gas exchange. This could have implications for uptake of dipping solutions, for levels of exudate, and because gas exchange is more efficient, for different optimal in-pack atmospheres.

Modified atmosphere packaging is a key underpinning technology for fresh-cut produce. Intended modified atmospheres for fresh-cut vegetables are generally in the range 0.25-3% O₂, 3-10% CO₂, balance N₂. There is a limited literature describing which atmosphere is optimum for different types of fresh-cut fruits, but optimum ranges have been suggested (Gorny, 2003). It is likely that reduced O₂ and elevated CO₂ will improve shelf-life and quality in most fresh-cut fruits compared to storage in air (Chohenchob et al, 2007a; Martinez-Romero et al, 2003). Atmospheres that develop within MA packages are determined by respiration rate, product weight and volume, package permeability and area, storage temperature, and related factors.
(Mahajan et al., 2006). Ideally these result in optimum/intended atmospheres, but unintended atmospheres frequently develop due to poor compatibility of product respiration and gas permeability of the packaging and/or temperature abuse.

In this study, PCA was applied to determine effects of selected raw materials, processing and storage variables, and indicate opportunities for optimisation.

2.3. Materials and methods

2.3.1. Plant materials

Whole fruits were collected from a local wholesaler (Richardson’s Fruit and Vegetables, Limerick, Ireland) on the morning before each trial and stored at 4°C (for a maximum of 15h for chilling sensitive commodities) until processed. Descriptions of the fruits used are shown in Table 2.4.

<table>
<thead>
<tr>
<th>Fruit</th>
<th>Cultivar / Variety</th>
<th>Country of Origin</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pineapple</td>
<td>Del Monte Gold Extra Sweet <em>Ananas comosus</em> L. Merr MD2</td>
<td>Costa Rica</td>
<td>Extra</td>
</tr>
<tr>
<td>Strawberry</td>
<td><em>Fragaria spp.</em> Elsanta</td>
<td>Ireland</td>
<td>I</td>
</tr>
<tr>
<td>Kiwi</td>
<td><em>Actinidia delicosa</em> cv Hayward</td>
<td>New Zealand</td>
<td>I</td>
</tr>
<tr>
<td>Melon</td>
<td><em>Cucumis melo</em> L. var <em>reticulatus</em></td>
<td>Costa Rica</td>
<td>I</td>
</tr>
</tbody>
</table>

To evaluate seasonal variation, fresh-cut pineapples and strawberries were analysed over four seasons, Summer (May-June 2010), Autumn (September-October, 2010), Winter (November-December, 2010) and Spring (January-March, 2011). For experiments where the effects of ripeness stage were studied, under-ripe, ripe and over-ripe fruits were compared. In the present study, the ripeness stage of fresh-cut pineapple refers to the state of ripeness at processing, not at harvest. For over-ripe pineapple samples, fresh ripe fruits were purchased up to 5 days in advance and allowed to ‘over-ripen’ to a near senescent stage at an average room temperature of
22°C. For strawberry samples, under-ripe fruits were harvested immature, ripe fruits were harvested at best eating quality while over-ripe fruits were harvested ripe but allowed to ‘over-ripen’ to near senescent stage (as before). Strawberries were obtained from Kearns’ Fruit Farm, Enniscorthy, Wexford, Ireland. Intervening stages in this instance are not to be attributed to ripening but rather to senescence. All fruits were screened for defects (mould growth and softening) and pre-cooled at 4°C overnight before processing.

2.3.2. Fresh-cut processing and packaging

Fresh-cut fruits were prepared as described previously (Chapter 2.1). Common intrinsic effects are given in Table 2.5. For effects of packaging, these fruits were placed in pillow-pouch packs made using flexible films with a range of gas barrier properties. These were: a high barrier laminate (HB), oriented polypropylene (OPP) and micro-perforated OPP (PA90, PA210) from Amcor Flexibles, Gloucester, UK., and had oxygen/carbon dioxide transmission rates (mL/micron/m²/day.atm) of 62,814/212,776; 1,100/4,400; 1,050/5,200 and 6,259/30,800, respectively. A closed clamshell (CS) container was also used (Biopak, Worcestershire, UK.). This container had very high gas barrier properties (not available from supplier). Where effects of packaging type were studied, all laboratory packaged fresh-cut fruits were stored at 4°C and 8°C for a period of 7 Days. All other samples, unless otherwise stated, were stored at 4°C for 7 Days.

For effects of cut size, fruits were cut into various cut sizes (Figure 2.2). Fresh-cut pineapple and cantaloupe melon were sliced, de-cored/-seeded and cut into chunks of three different sizes (50, 25 and 10mm) using a hand-held stainless steel slicer. For fresh-cut kiwifruit, the whole fruit were carefully peeled before being cut in halves (longitudinal), quarters (transversal) and eights (longitudinal), where appropriate. For fresh-cut strawberries, the carpel was removed and the fruit de-hulled before being sliced into half pieces (longitudinal). For all other experiments fruits were processed into 25mm (melon and pineapple), ¼ (kiwifruit) or ½ (strawberry) cut piece sizes, where appropriate.
Figure 2.2 Cutting sizes/shapes used in sample preparation of fresh-cut (a) Pineapple – 10mm, 25mm & 50mm; (b) Cantaloupe melon- 10mm, 25mm & 50mm and (c) Honeydew melon – 10mm, 25mm & 50mm; (d) Kiwifruit- ⅛, ¼ & ½, and (e) strawberry – halves.

For different degrees of sharpness a stainless steel slicer (razor sharp, sharp and blunt knife) was used. The effect of pre-dipping pre-treatment using 1% ascorbic acid: citric acid on respiration rate of fresh-cut fruits (pineapple, cantaloupe melon and kiwifruit) was tested and compared with un-dipped samples. The dipping solution was prepared using chilled distilled water and fruits were submerged in the solution for 2 minutes with slight agitation and allowed to drain for 2 minutes.
Table 2.5 Intrinsic characteristics of intact fruit

<table>
<thead>
<tr>
<th>Type/ Source</th>
<th>Season</th>
<th>Physiological age</th>
<th>Aromaa</th>
<th>Firmness, Nb</th>
<th>Total soluble solids, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pineapple, Costa Rica</td>
<td>Summer</td>
<td>0 to 25</td>
<td>Under Ripe (0 to 1)</td>
<td>(7) Green, Acidic, Inedible</td>
<td>7.2</td>
</tr>
<tr>
<td>Del Monte Gold Extra Sweet cv MD2</td>
<td>Autumn</td>
<td>0 to 25</td>
<td>Under Ripe (0 to 1)</td>
<td>(6) Fresh, Acidic, Sharp</td>
<td>8.4</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td>1 to 2</td>
<td>Under Ripe (1 to 3)</td>
<td>(5) Green, Grassy, Acidic</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;6</td>
<td>Over Ripe (6)</td>
<td>(4) Green, Grassy, Acidic</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 to 5</td>
<td>Ripe (5)</td>
<td>(3) Strong, Strawberry</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 to 2</td>
<td>Under Ripe (1 to 3)</td>
<td>(2) Strong, Sweet, Fresh</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;6</td>
<td>Over Ripe (6)</td>
<td>(1) Strong, Alcohol, Musty</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>Ripe (5)</td>
<td>(8) Strawberry, Sweet</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>Ripe (6)</td>
<td>(7) Strawberry, Sweet</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td>1 to 2</td>
<td>Under Ripe (1 to 3)</td>
<td>(5) Green, Grassy, Acidic</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;6</td>
<td>Over Ripe (6)</td>
<td>(4) Green, Grassy, Fresh</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 to 5</td>
<td>Ripe (5)</td>
<td>(3) Strong, Strawberry</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;6</td>
<td>Over Ripe (6)</td>
<td>(2) Pungent, Strawberry, Musky</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 to 2</td>
<td>Under Ripe (1 to 3)</td>
<td>(1) Strong, Alcohol, Musty</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;6</td>
<td>Over Ripe (6)</td>
<td>(5) Green, Grassy, Acidic</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 to 5</td>
<td>Ripe (5)</td>
<td>(4) Green, Grassy, Fresh</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;6</td>
<td>Over Ripe (6)</td>
<td>(3) Strong, Strawberry</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 to 5</td>
<td>Ripe (5)</td>
<td>(8) Pungent, Strawberry, Musky</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;6</td>
<td>Over Ripe (6)</td>
<td>(7) Strawberry, Sweet</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 to 2</td>
<td>Under Ripe (1 to 3)</td>
<td>(6) Fresh, Acidic, Sharp</td>
<td>8.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;6</td>
<td>Over Ripe (6)</td>
<td>(5) Green, Grassy, Acidic</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 to 5</td>
<td>Ripe (5)</td>
<td>(4) Green, Grassy, Fresh</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;6</td>
<td>Over Ripe (6)</td>
<td>(3) Strong, Strawberry</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 to 2</td>
<td>Under Ripe (1 to 3)</td>
<td>(2) Pungent, Strawberry, Musky</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;6</td>
<td>Over Ripe (6)</td>
<td>(1) Strong, Alcohol, Musty</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 to 5</td>
<td>Ripe (5)</td>
<td>(5) Green, Grassy, Acidic</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;6</td>
<td>Over Ripe (6)</td>
<td>(4) Green, Grassy, Fresh</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 to 2</td>
<td>Under Ripe (1 to 3)</td>
<td>(3) Strong, Strawberry</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;6</td>
<td>Over Ripe (6)</td>
<td>(2) Pungent, Strawberry, Musky</td>
<td>2.1</td>
</tr>
</tbody>
</table>

1External shell colour was recorded against a Dole pineapple colour chart (2010)
2External colour was recorded against UC Davis colour charts. (Kader, and Cantwell, 2010)
3Numbers in brackets depict ripeness class and aroma scores

1 Max Force, Newtons
2.3.3. Quality, microbial and sensory evaluation

Quality, microbial, sensory evaluation and statistical procedures were carried out as described previously in Chapter 2 part I (section 2.3).

2.4. Results

Principal component analysis was carried out on the correlation matrix produced from twenty-seven quality attributes, previously identified as contributing factors to the quality and deterioration of fresh-cut fruits. The factor loadings for the different quality ratings were plotted based on the first two principal components (PCs) with attributes and samples illustrated as vector angles and symbols respectively. PCI accounted for a maximal amount of the total variance (inertia) meaning that under typical test conditions, PCI will be correlated with many of the observed variables loaded on that component. PCII will be uncorrelated with PCI and account for a maximal amount of the variance in the dataset not accounted for by PCI. The proportion of variance accounted for was deduced using the cumulative percent of variance criterion for solving the number of PCs to retain. For the current analysis the cumulative percent of variance must have accounted for at least 60% of inertia in order to be retained and subsequently interpreted. An exception to this was fresh-cut pineapple (extrinsic factors) where after several unsuccessful attempts at best-fit, 40% was deemed as the best percentage for maximum output and data interpretation. Following this, each solution was reviewed and interpreted in a simple rotation producing an orthogonal biplot for each effect/fruit studied. The proportions of variance produced for each biplot are presented in Table 2.6.

As previously outlined in Chapter 2 part I, poor quality attributes positively associated with increased deterioration were increased microbial counts, increased cell permeability and exudate levels, increased off-odour development, CO₂ accumulation and discolouration. Good quality attributes were characterised as good visual appearance, aroma, firmness and overall acceptability and, in most cases, were inversely correlated with poor quality attributes.
Table 2.6 Proportion of Cumulative Percentage Variance and Inertia for Biplots construed for each Fruit Type and Treatment

<table>
<thead>
<tr>
<th>Study</th>
<th>Fresh-cut Fruit</th>
<th>PC I (%</th>
<th>PC II (%</th>
<th>PC III (%)</th>
<th>PC IV (%)</th>
<th>Inertia (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physiological Age, Ripeness stage and Seasonality</td>
<td>Pineapple</td>
<td>42.5</td>
<td>19.7</td>
<td>11.9</td>
<td>6.4</td>
<td>80.5</td>
</tr>
<tr>
<td></td>
<td>Strawberry</td>
<td>41.9</td>
<td>21.7</td>
<td>15.6</td>
<td>8.8</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Packaging Type and Temperature</td>
<td>Pineapple</td>
<td>27</td>
<td>16.8</td>
<td>12.8</td>
<td>7.9</td>
<td>64.5</td>
</tr>
<tr>
<td></td>
<td>Strawberry</td>
<td>53.7</td>
<td>22.1</td>
<td>18.4</td>
<td>2.2</td>
<td>96.3</td>
</tr>
<tr>
<td></td>
<td>Kiwifruit</td>
<td>53.6</td>
<td>22.2</td>
<td>18</td>
<td>2.6</td>
<td>96.3</td>
</tr>
<tr>
<td></td>
<td>Cantaloupe Melon</td>
<td>44.6</td>
<td>36.2</td>
<td>12.8</td>
<td>4.1</td>
<td>97.8</td>
</tr>
<tr>
<td>Cutting Size and Dipping Treatment</td>
<td>Pineapple</td>
<td>28.4</td>
<td>15.2</td>
<td>12.2</td>
<td>8.0</td>
<td>63.9</td>
</tr>
<tr>
<td></td>
<td>Kiwifruit</td>
<td>44.2</td>
<td>29.4</td>
<td>14.6</td>
<td>4.8</td>
<td>72.0</td>
</tr>
<tr>
<td></td>
<td>Cantaloupe Melon</td>
<td>67.3</td>
<td>26.4</td>
<td>5.2</td>
<td>0.5</td>
<td>99.3</td>
</tr>
<tr>
<td></td>
<td>Strawberry</td>
<td>50.5</td>
<td>35.4</td>
<td>6.7</td>
<td>3.5</td>
<td>96.1</td>
</tr>
<tr>
<td></td>
<td>Kiwifruit</td>
<td>49.0</td>
<td>33.9</td>
<td>11.6</td>
<td>3.5</td>
<td>98.0</td>
</tr>
<tr>
<td></td>
<td>Cantaloupe Melon</td>
<td>65.8</td>
<td>24.3</td>
<td>8.5</td>
<td>0.9</td>
<td>99.5</td>
</tr>
</tbody>
</table>

1 Inertia is a measure of variation or ‘spread’ within a correlation matrix i.e. the total variance of the dataset (FactoMineR, 2008).

*a* data disregarded for subsequent interpretation

2.4.1. Effects of ripeness stage and season

The effects of ripeness stage and season were studied in fresh-cut pineapple and strawberry (Figure 2.3). Both fruits had similar patterns of deterioration, with fresh samples (Day 0) located to the left of the axis plane, migrating to the right as storage progressed (Day 7). Both ripeness stage and seasonality had large effects on deterioration patterns, with ripeness stage mostly affecting the rate, in particular for fresh-cut pineapple. Samples located left of the axes plane were characterised as having better visual appeal, aroma and overall acceptability while samples located to the right had decreased tissue stability, increased microbial counts and greater off-odour development.
Fresh-cut pineapple prepared from summer and autumn grown fruits (Del Monte Gold Extra Sweet, Costa Rica) were studied. There were significant effects of ripeness in both seasons (p<0.01). The plots show that autumn fruits were more centrally located in the axis plane, while summer fruits were positioned lower down. In Autumn, both under-ripe and ripe pineapple samples remained very central, not migrating far from good quality attributes during storage (i.e. they retained more of their fresh characteristics). By contrast, summer fruit had lower quality initially and deteriorated more rapidly during storage. Over-ripe fruits from both seasons deteriorated quite rapidly, as indicated by the large loading distances between sampling days.

Fresh-cut Irish grown strawberries (cv El Santa) were studied over four seasons. There were significant differences between ripeness stages (p<0.05) during storage, but no significant seasonal effects were observed (p>0.05). Autumn/Winter samples had better initial quality (were located higher up in ‘good quality’ axis plane) and had a slower rate of deterioration than Spring/Summer samples. Over-ripe fruit had poor initial quality (located lower down in the axis plane; Figure 2b) and moved rapidly towards poor quality attributes, remaining there throughout storage. Under-ripe fruits exhibited the slowest rate of deterioration as observed by small vector distances and were characterised as having better retained firmness and higher acidity levels, but their acceptability was poor.
(bii) Strawberry
Autumn & Winter

PC I 41.9%
PCC II 21.7%

-10
-1.5
-1.0

firmness

sugar/acid ratio

L*
a*
b*

Fmax

Fmean

psychrophiles

cell permeability

titratable acidity

overall acceptability

in-pack O2

aroma

appearance

yeasts and moulds

colour

package weight loss

lactic acid bacteria

percent soluble solids

off-odour

mesophiles
**Figure 2.3** Principal Component Analysis (PCA): Biplot of the loadings and scores of PC1 and PC2 illustrating the deterioration pattern of quality attributes for three physiological ages and season during storage at 4°C for (a) Fresh-cut pineapple, (bi) Fresh-cut strawberry (Spring & Summer) and (bii) Fresh-cut strawberry (Autumn & Winter).

**Key of abbreviations (Attributes):** CO₂ (carbon dioxide), O₂ (oxygen), F (puncture probe firmness - 6mm), S (Shear firmness), max (maximum firmness, Newton), mean (mean firmness, Newton), L* (CIE L* Lightness-Darkness), a* (CIE a* green-red) and b* (CIE b* blue-yellow).

**Key of Symbols:** ● Day 0; △ Day 1; ■ Day 4; × Day 7.

**Pineapple:**
- Summer → Under-ripe
- Autumn → Under-ripe

**Strawberry:**
- Spring → Under-ripe
- Summer → Under-ripe
- Autumn → Under-ripe
- Winter → Under-ripe
2.4.2. Effects of cutting size and dipping treatment

The effects of cut size and chemical dipping treatment (1% ascorbic acid; 1% citric acid) on quality deterioration of fresh-cut pineapple, kiwifruit and cantaloupe melon were determined. Both cut size and dipping treatment had significant effects (p<0.05) on overall quality deterioration (Figure 2.4a, 2.4b & 2.4c). In the case of pineapple (Figure 2.4a), samples tracked from left to right as they deteriorated; in the case of kiwi and cantaloupe melon they tracked from right to left. In general, the smaller the cut piece the greater the extent of deterioration. Samples which clustered around the middle of the plane had better initial quality than samples located lower down in the axis plane and were characterised as having better acceptability (appearance, aroma, firmness).

For fresh-cut kiwifruit (Figure 2.4b), un-dipped pieces were initially characterised as having lesser acceptability than dipped pieces due to brighter and firmer appearance of dipped flesh. However, dipped pieces had greater losses in acceptability and firmness as demonstrated by large vector angles in favour of increasing exudate, cell permeability, off-odours, colour (browning and/or translucency) and microbial counts and decreased firmness as storage progressed. The smallest dipped pieces (1/8) had the greatest quality change, while ½ un-dipped samples had the least change and were characterised as having lower microbial growth, least off-odour development and lowest exudate and cell permeability. When Day 4 samples were compared, quality was in the order of increasing cut size, with smallest sizes having poorest quality. This effect was accentuated in dipped samples.

In the case of un-dipped cantaloupe melon (Figure 2.4c), the smallest (10mm) cut pieces had the lowest starting quality, and this persisted to Day 1 and Day 4. The un-dipped samples, mostly positioned to the left of PC I, distanced themselves from initial fresh samples by a loss in appearance and aroma, coupled with increasing in-pack CO₂, off-odours and a loss in firmness. Dipping had only small effects on 25mm and 50mm pieces, but significantly improved the quality of 10mm pieces. These dipped 10mm pieces were positioned centrally to the axis plane, not migrating much from initial fresh-like characteristics during storage.
(b) Kiwifruit
un-dipped

PC II 29.4%
P I 44.2%

-1.0
-0.5
0.5
1.0
1.5
2.0

-1.0
-0.5
0.5
1.0

titratable acidity
driploss
package weight loss
ewards and moulds
table acid bacteria
mesophiles
exudate
pH
off-odor
Fmean
Fmax
cell permeability
psychrophiles

colour

a*
b*
c

in-pack CO₂

sugar-acid ratio

percent soluble solids

L*
in-pack O₂

overall acceptability

aroma
visual appearance

firmness
Figure 2.4 Principal Component Analysis (PCA): Biplot of the loadings and scores of PC1 and PC2 after analysis of effects of cut size and dipping on quality evaluation attributes for (a) Fresh-cut Pineapple, (b) Fresh-cut Kiwifruit, (c) Fresh-cut Cantaloupe melon during 7 Day storage at 4°C.

Key of abbreviations (Attributes): CO₂ (carbon dioxide), O₂ (oxygen), F (puncture probe firmness - 6mm), S (Shear firmness), max (maximum firmness, Newton), mean (mean firmness, Newton), L* (CIE L* Lightness-Darkness), a* (CIE a* green-red) and b*(CIE b* blue-yellow).

Key of Symbols:  

10mm + ⅛ cut size ➔
25mm + ¼ cut size ➔
50mm + ½ cut size ➔
2.4.3. Effects of packaging type and temperature

The effects of five packaging treatments with different gas permeabilities on quality at 4°C and 8°C were determined (Figure 2.5a, 2.5b, 2.5c & 2.5d). Both packaging type and temperature had significant effects (p<0.01 and p<0.05 respectively), observed as differences in the rate and extent of quality change. Storage was found to have more of a marked effect on deterioration patterns than packaging treatments.

For fresh-cut pineapple (Figure 2.5a), strawberry (Figure 2.5b) and kiwifruit (Figure 2.5c), samples (Day 0) were located to the left of the axis plane, characterised as having good visual appearance, aroma and overall acceptability. Samples located to the right (Day 7) had diminished quality with increased exudate, cell permeability, in-pack CO₂ and off-odour development and higher microbial counts. For fresh-cut cantaloupe melon (Figure 2.5d), the pattern of deterioration was the same, i.e. good to poor, albeit the direction was different (right to left).

Low respiring fruits such as fresh-cut pineapple and cantaloupe melon were best stored in HB (pineapple), OPP (pineapple & melon) and PA90 (melon only) where these fruits retained more of their fresh-like characteristics. Fresh-cut pineapple and cantaloupe melon stored in PA210 (highly permeable) and CS (highly impermeable) deteriorated most. Excessive modification of the CS in-pack atmosphere appeared to accelerate the rate of deterioration, while fruits packaged in micro-perforated PA210 film, which had little in-pack atmosphere modification, suffered rapid loss in original freshness, in this case reflected in loss of appearance and colour but without high levels of tissue breakdown.

When high respiring fruits such as strawberry and kiwifruit were packaged in HB, OPP and PA90, they lost their fresh-cut characteristics by Day 4, and were characterised as having increased exudate and ion leakage, increased weight-loss (strawberry) and poorer colour. For fruits packaged in CS, a much greater rate and extent of deterioration was observed, with significant losses in firmness (kiwifruit) (p<0.05) coupled with severe off-odour development (strawberry) and greatest in-pack CO₂ accumulation. At 8°C, a similar pattern to that at 4°C was observed, but the rate and extent of deterioration was considerably greater.
(a) Pineapple

- PC II 16.8%
- PC I 27%

- 4°C
- 8°C
- Day 0
- Day 1
- Day 4
- Day 7

- Sugar/acid ratio
- Overall acceptability
- Color
- pH
- Aroma
- Appearance
- Firmness
- In-pack CO₂
- Fmean
- Fmax
- Smean
- Tmax
- Psychrophiles
- Percent soluble solids
- In-pack CO₂
- Drip loss
- Off-odour
- Package weight loss
- Cell permeability
- Exudate
- Yeasts and moulds
- Lactic acid bacteria
Figure 3 Principal Component Analysis (PCA): Biplot of the loadings and scores of PC1 and PC2 illustrating the deterioration pattern of quality attributes for five packaging treatments across two temperatures during storage for (a) Fresh-cut Pineapple and (b) Fresh-cut Strawberry (c) Fresh-cut Kiwifruit and (d) Fresh-cut Cantaloupe melon.

Key of abbreviations (Attributes): CO₂ (carbon dioxide), O₂ (oxygen), F (puncture probe firmness - 6mm), S (Shear firmness), max (maximum firmness, Newton), mean (mean firmness, Newton), L* (CIE L* Lightness-Darkness), a* (CIE a* green-red) and b* (CIE b* blue-yellow).

Key of Symbols:

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Key Symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Barrier (HB) Film</td>
<td>□ △ □ □ □ □</td>
</tr>
<tr>
<td>Oriented Polypropylene (OPP)</td>
<td>○ △ □ □ ☒</td>
</tr>
<tr>
<td>Polyamide 90 (PA90)</td>
<td>○ △ □ □ ☒</td>
</tr>
<tr>
<td>Polyamide 210 (PA210)</td>
<td>○ △ □ □ ☒</td>
</tr>
<tr>
<td>Clamshell (CS)</td>
<td>□ △ □ □ ☒</td>
</tr>
</tbody>
</table>
2.5. Discussion

The data shows that PCA plots were effective in tracking differences in quality, and differences in patterns of deterioration resulting from a range of intrinsic and extrinsic factors. By comparing the length and direction of vectors and the position of plots on a given sampling day, the rates and extent of quality change could be compared. Some of the effects observed were large and can form the basis of optimising raw materials, processing and packaging of different fresh-cut fruits.

2.5.1. Effects of ripeness stage and season

Ripeness stage of fruit intended for fresh-cut processing is a critical factor in determining quality (Beaulieu and Lea, 2005; Cliffe-Byrnes and O'Beirne, 2005; Beaulieu and Gorny, 2004; Beaulieu et al., 2004; Soliva-Fortuny et al., 2002; 2004; Gorny et al, 1998). In fresh-cut pineapple, the PCA plots appeared to demonstrate clear effects of season on quality, and separated different patterns of deterioration due to ripeness stage. This is supported by previous reports of major seasonal effects on quality (Montéro-Calderón et al. 2008; Cao et al., 2010; Nielson and Leufvén, 2008; Mazur et al., 2012. The greater speed and extent of quality loss in over-ripe fruit was clearly apparent, with greater drip-loss, stronger off-odours and increased browning.

Samples prepared from ripe pineapple had greater initial quality and this was better retained during storage. By contrast, under-ripe fruits, although more visually appealing, had bland aroma, high acidity and greater firmness. Aroma scores gradually decreased with storage time, irrespective of physiological age and this decrease related well to the development of off-odours. Spanier et al (1998) observed that fresh-cut pineapple stored at 4°C had excellent visual appearance after 7 to 10 Days storage; however fruit in the lower portion of containers developed off-odours associated with microbial fermentation.

In fresh-cut strawberry, PCA indicated clear effects of season on initial quality and rate of deterioration. Effects of ripeness stage were less apparent than in pineapple. This may have been in part due to increases in firmness in some otherwise poor quality fruits. Such increases have been reported previously (Wright and Kader,
1997; Larsen and Watkins, 1995), though softening has also been reported (Montéro et al, 1996; Hernández-Muñoz et al, 2006). Differences may be due to the size of fruits studied.

2.5.2. Effects of cutting size and dipping treatment

As process severity increased, the rate and extent of deterioration also increased. PCA plots showed that larger un-dipped fruit pieces had best quality. The simple acid/antioxidant dips used in this work initially increased quality on Day 0, but subsequently led to more rapid deterioration during storage. This was most apparent in fresh-cut pineapple and kiwi, but less so in cantaloupe melon and probably attributed to the sub-optimal concentrations used. Dipped pieces had a marked increase in cellular sap and ion leakage which resulted in greater loss of firmness across all fruits. However, the results are complex with some smaller dipped cut pieces having better aroma (kiwifruit), improved colour (melon) and reduced browning/ translucency (pineapple) as a result of the greater surface area for diffusion. Therefore, particular consideration must be given when deciding the choice of cut and dip formulation which in turn must truly reflect the product’s needs.

2.5.3. Effects of packaging type and storage temperature

The plots showed that the type, rate and extent of deterioration were directly related to the types of atmospheres formed within packs, and to the storage temperatures. While information on precise optimum atmospheres is incomplete, previous studies by Chonhenchob et al, (2007a,b) and Martinez-Ferrer et al, (2002) found that fresh-cut fruit packaged under reduced O₂ and elevated CO₂ had longer shelf-life and better quality compared to storage in air. Achieving atmospheres in the optimum range for each fruit requires good compatibility between the gas barrier properties of the packaging films and the respiration rate of the product. The order of gas barrier properties of the packaging used was: CS>HB>OPP>PA90>PA210. Low respiring fruits such as pineapple needed materials in the higher barrier range (HB or OPP) to achieve technically useful atmosphere modification and good control of enzymatic
browning. When packaged in the more permeable micro-perforated PA films, there was little atmosphere modification, and acceptability of appearance declined rapidly. On the other hand, where CS, HB and OPP were used for high respiring fruits, the near anoxic environment combined with elevated CO₂ resulted in membrane damage, softening and increased translucency. CS packaging was extremely impermeable and the high CO₂ levels were damaging in all fruits except cantaloupe melon.

Deterioration in visual appearance was complex and due to a combination of discolouration, desiccation at the cut surfaces and sogginess of the flesh. In the highly micro-perforated PA films, the atmospheres remained mainly aerobic, displaying little or no change in-pack atmosphere modification during storage, with PA210 having a lesser acceptability than PA90. In the case of CS, HB and OPP packaging systems, the near anoxic environment resulted in elevated processes of firmness deterioration. In this instance, fresh-cut fruits had poor appearance not because of drying and discoloration, but due to increased tissue softening resulting in a more soft-mushy, water-soaked appearance with increased translucency. The damaging effects of mild temperature abuse were also apparent throughout; particularly in fresh-cut pineapple. Allong et al., (2001) demonstrated that a storage temperature of 5°C was more effective than 10°C in delaying ripening and microbial growth and better preserved the sensory quality of fresh-cut mango slices.

2.6. Conclusion

In conclusion, it is clear that the PCA plots showed some large differences in raw material quality, and in the rates and extent of deterioration. The largest effects observed were due to season, cut size and packaging and may have implications for raw material, process, and packaging optimisation. By comparing the effects of these intrinsic and extrinsic factors on rates and extent of deterioration, it is possible to extract estimates of effects on shelf life from the plots. Differences in shelf life of up to three days could be attributed to seasonal variation (pineapple). Reduced process severity increased shelf life by up to four days, and optimal packaging increased shelf life by about three days for all fruits.
2.7. **Benefits of PCA plots**

Recent studies have shown the effectiveness of PCA plotting in genetic classification, volatile aroma compound development, postharvest characterisation/spoilage and biodiversity studies (Chen *et al.*, 2013; Dong *et al.*, 2013; El Kar *et al.*, 2013; Wilson *et al.*, 2013; Hurtado *et al.*, 2012; Infante *et al.*, 2011 and Rocha *et al.*, 2010). In this study, PCA plots have produced useful information on quality and deterioration of fresh-cut fruits. They were effective in plotting initial quality, and quality differences between samples before and during storage. They highlighted the distinct processes of deterioration characteristic of each fruit type. They provided patterns of deterioration, indicating, for example, whether most deterioration occurred early or late in storage. They revealed similarities and differences in quality and patterns of deterioration resulting from cultivar or source of fruit.

It is concluded that an optimised method for tracking the deterioration pattern of fresh-cut fruits would allow coveted knowledge to be gained in the response of cut fruits to both intrinsic and extrinsic factors affecting quality. PCA can form the basis of more in-depth understanding of the effects of intrinsic and extrinsic factors on quality of fresh-cut fruits, and help optimise product quality. This could allow for careful planning and implementation of optimised processing and packaging conditions given a particular situation, i.e. inconsistent ripeness stage, seasonal and/or cultivar variations.
Chapter 3

Controlled and Modified Atmospheres:

*Quality, Microbial and Phytochemical Response of Fresh-cut Fruits*

3.1. Abstract

The effects of storage atmospheres on the quality, microbiology and levels of phytochemicals of fresh-cut pineapple, cantaloupe melon and kiwifruit were determined at 4°C for 7 Days. Products were stored either in controlled atmospheres (CA) of air, 5%O₂+5%CO₂ and 97%N₂+3%O₂ or in packages flushed with these atmospheres (MA). A CA of 5%O₂+5%CO₂ better maintained the colour, firmness and visual appeal of fresh-cut pineapple and cantaloupe melon, while a CA of 97%N₂+3%O₂ was better at maintaining fresh-cut kiwifruit quality.

Flushed packages had greater accumulation of CO₂ than product modified atmospheres (PMA) packs, with values for 97%N₂+3%O₂ and 5%O₂+5%CO₂ on Day 7 ranging from 10.5% to 14.5%, 7.6% to 9.4 % and 19% to 20.4% for fresh-cut pineapple, cantaloupe melon and kiwifruit. Flushing with 5%O₂+5%CO₂ and 97%N₂+3%O₂ caused a marked reduction in sensory scores (colour and firmness) of all fruits, with a 1-2 score reduction in visual appearance and colour, coupled with increased translucency. Fruits flushed with 5%O₂+5%CO₂ and 97%N₂+3%O₂ attained near anoxic (<1% and 1.5% O₂ respectively) atmospheres at end of storage. Effervescence was also noted upon opening of packs, especially those with high CO₂ accumulation.

Although flushing packs resulted in greater total carotenoids for fresh-cut kiwifruit and greater total phenolics and antioxidant activity of fresh-cut pineapple and cantaloupe melon initially (p<0.05), no significant effect of atmospheres was observed at end of storage (p>0.05). There was no significant effect of atmospheres on the total bacterial or *Listeria innocua* counts (p>0.05) with the exception of fresh-cut kiwifruit (Day 7 only) where a 0.5 to 1 log reduction in counts was observed for 5%O₂+5%CO₂ and 97%N₂+3%O₂ respectively.

The optimum CA atmospheres identified will form the basis of package design in Chapter 5.

**Keywords**: optimum atmospheres, gas flushing, anaerobiosis, deterioration, translucency, overall acceptability
3.2. Introduction

Fresh-cut fruit continue to respire and alter the in-pack atmosphere in which they are surrounded. Many recommendations for the controlled (CA) and modified atmosphere (MA) storage of fresh and fresh-cut fruits, have been made (Gorny, 2002; Saltveit, 2002).

The optimum O\textsubscript{2} and CO\textsubscript{2} atmospheres for fresh-cut pineapple, cantaloupe melon and kiwifruit, recommended by Gorny (2000), were 3-5% and 5-8%, 3% and 10% and 1-2% and 3-5%, respectively. These atmospheres have been found to have beneficial effects on postharvest quality in comparison to air packaging (Kader, 2012).

The effect of MAP on the physiology of fresh-cut produce is well documented (Toivonen and DeEll, 2002; Mir and Beaudry, 2004; Varoquaux and Ozdemir, 2005). In recent years, the increased marketing of fresh-cut fruits has renewed efforts to develop beneficial packaging for these novel products with successful applications made for fresh-cut apples (Soliva-Fortuny \textit{et al.}, 2005), pineapple (Marrero and Kader, 2006), melon (Bai \textit{et al.}, 2001; 2003) and kiwifruit (Rocculi \textit{et al.}, 2005).

A MA can be created passively by using appropriate permeable packaging materials compatible with the natural respiration of the fresh-cut commodity, or actively by flushing with specified gas mixtures. Passive MAP relies heavily on the relationship between the produce respiration rate and the package transmission rates to create and optimal in-pack gas atmosphere for a particular product, i.e. product-package compatibility. This process, also referred to as product modified atmosphere (PMA), generally takes a number of days to reach its desired target atmosphere (Finnegan \textit{et al.}, 2013).

The delay in achieving equilibrium, coupled with product-package incompatibility, is one of the major limitations facing PMA have prompted the development of active packaging approaches such as gas flushing (Forney, 2007).

Exposure to atmospheres outside optimal ranges may lead to anaerobic respiration with the concurrent production of undesirable metabolites and other physiological disorders (Zagory and Kader, 1988). Discolouration (browning,
whitening & translucency), microbial spoilage, off-odour development and dehydration are symptomatic of fresh-cut fruit deterioration. For fresh-cut kiwifruit, accumulation of CO$_2$ within packages has a negative impact on firmness (Finnegan et al., 2014b) while for fresh-cut pineapple, which is prone to enzymatic browning, the delay in O$_2$ reduction may be too long (Saltveit, 2003). Finnegan and O’Beirne, (2014b) concluded that low respiring fruits such as pineapple and cantaloupe melon need to be packaged in medium-to-high barrier films at low temperatures (4°C) to achieve technically useful atmosphere modification. Packaging in more permeable micro-perforated films had little in-pack atmosphere modification with a rapid loss in visual acceptability (discolouration/ firmness). Conversely, high respiring fruits such as kiwifruit when packaged in high barrier films achieved near anoxic atmospheres, with elevated CO$_2$ resulting in increased membrane damage, softening and increased translucency.

The objective of this study was to assess the effects of a number of gas atmospheres on the quality, microbiology and levels of phytochemicals of fresh-cut pineapple, cantaloupe melon and kiwifruit.
3.2. Materials and methods

3.2.1. Processing, packaging and storage of fresh-cut fruit

Whole fruits, pineapples (*Ananas comosus* cv Del Monte Gold MD2: #10), cantaloupe melon (*Cucumis melo* L. var *reiculatus*) and kiwifruit (*Actinidia deliciosa* cv *Hayward*) were purchased from a local fruit and vegetable wholesaler (Richardson’s Fruit and Vegetables, Old Clare St., Limerick, Ireland) on the morning of processing (Table 3.1) and stored at 4°C until used (1-2h). For pineapple, ripe fruit with a shell colour corresponding to stages 2 and 3 of the Dole pineapple colour chart (between 25% and 50% shell colour) were used for all experiments. For cantaloupe melon, fruits with a ½ to full slip (Appendix D), corresponding to a mature ripening to ripe melon, were used. For kiwifruit, fruits that were firm to touch and had excellent visual quality with no symptoms of deterioration (approx. 11.5% soluble solids) were used.

<table>
<thead>
<tr>
<th>Fruit</th>
<th>Cultivar/ Variety</th>
<th>Country of Origin</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pineapple</td>
<td>Del Monte Gold Extra Sweet</td>
<td>Costa Rica</td>
<td>Extra</td>
</tr>
<tr>
<td></td>
<td><em>Ananas comosus</em> L. Merr MD2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiwi</td>
<td><em>Actinidia deliciosa</em> cv Hayward</td>
<td>New Zealand</td>
<td>I</td>
</tr>
<tr>
<td>Melon</td>
<td><em>Cucumis melo</em> L. var <em>reiculatus</em></td>
<td>Costa Rica</td>
<td>I</td>
</tr>
</tbody>
</table>

All fruits were processed at room temperature (18-22°C). For fresh-cut pineapple, the peels of whole fruits were removed with a stainless steel knife which was sanitised in a 1% sodium hypochlorite (NaClO) solution after each fruit in order to minimise contamination of batches. The blossom and stem ends were removed and discarded and the fruit sliced transversely into rings (24mm). After slicing, the core from each ring was removed manually using a stainless steel cork borer. The slices were cut into triangular chunks of size 25mm using a hand-held stainless steel cutter (*Figure 1a*). For fresh-cut cantaloupe melon, both the slip and top end of the fruits were removed and the melon halved transversely. The seeds were carefully removed using a sanitised stainless steel spoon. Each half was cut into four longitudinal slices and the surrounding peel carefully removed from the flesh. Each section was next cut
by hand into relatively uniform trapezoidal chunks of size 25mm (Figure 1b). In the case of fresh-cut kiwifruit, the blossom and stem ends of whole fruits were removed and discarded and the rest of the peel carefully removed from the flesh using a sharp sanitised paring knife. Fruit were then cut into longitudinal halves, followed by transverse quarters (Figure 1c).

Figure 3.1 Cutting sizes used in Sample Preparation and Experimental Setup of Fresh-cut (a) Pineapple – 25mm, (b) Cantaloupe melon - 25mm and (c) Kiwifruit (¼).

Cut piece sizes for each individual fruit were pooled and sample packs (150g ± 5g) were prepared in duplicate, each from randomly selected fruit pieces in the lot. For effects of modified atmospheres, fruit samples were placed into rigid polylactic acid (PLA) containers (Biopak, UK) and inserted into pillow-pouch packages (20cm x 20cm x 20cm) prepared from a high-barrier (HB) double-laminate film (PET12/PE55 microns) having oxygen (OTR) and carbon dioxide (CTR) permeabilities of 62,814 and 212,776 mL.microns/m².day.atm, respectively. This film allowed desired atmospheres to be created with only the respiration of the product responsible for changes during storage.
Product modified atmospheres

For effects of modified atmospheres, packages were either hermetically heat sealed using an impulse bench-top heat sealer (Relco Ltd., UK) in air (PMA) or flushed with 5%O₂+5%CO₂ and/or 97%N₂+3%O₂ using a compensated vacuum technique before being sealed and stored at 3 to 5°C for 7 days. The flushing was performed on a form-fill machine where evacuation of air was followed by flushing with gas mixture before being heat sealed. Gas pressure was monitored and kept constant at an optimum rate of 4bar.

Controlled atmospheres

For effects of controlled atmospheres (CA), a flow-through atmosphere system was employed to study the effects of different gas atmospheres on fruit samples. Fresh-cut fruit samples, each in duplicate, were placed directly into HB packs. These packs had been previously perforated with 15 uniform perforations (slits) each of 1-inch in length (3 rows, 5 slits/ row). These perforations allowed for even distribution of the gas atmosphere surrounding the fresh-cut fruit pieces without drying the product out. The perforated packs were placed into 2-L chambers for each day of analysis (Day 0, 1, 4 and 7) for each of the following treatments: A = air, B = 5%O₂+5%CO₂ and C = 97%N₂+3%O₂. The flasks were hermetically sealed using a modified rubber stopper and connected to each of the three gas lines. The gas flow was maintained at 60-65ml per min and the chambers were stored at 3 to 5°C for 7 days.

Where microbial analyses of fresh-cut fruits were studied, inoculation occurred before packs were sealed and/or placed into control atmosphere chambers (Chapter 2.1 section 2.3.2).
3.2.2. Quality evaluation

Quality evaluation tests were carried out as outlined in Chapter 2.1 section 2.3.

3.2.3. Sensory evaluation

Sensory evaluation was carried out as outlined in Chapter 2.1 section 2.3.

3.2.4. Microbiological analyses

The different media used were prepared, plated and stored according to manufacturer’s instructions (Oxoid Ltd, Basingstokes, UK).

**Bacterial strains and culture conditions**

*Listeria innocua* strain NCTC 11288 cultures were maintained at -20°C in tryptone soya broth (TSB, Oxoid Ltd., CM0129, Fannin Healthcare, Dublin, Ireland) supplemented with 20% (v/v) glycerol. Resuscitation was achieved by thawing cultures at room temperature (17 to 25°C) followed by successive loop transfer activation (x2) in 10mL of TSB supplemented with 0.6% of Yeast Extract (Oxoid Ltd., L21) in sterile screw-cap tubes and overnight incubation at 37°C. Cultures contained approximately 10^8-10^9 bacteria mL^-1. After incubation, the cultures were centrifuged (5,000 x g, 15 min), and the cells were resuspended in phosphate buffer solution (1:10), (PBS, Oxoid Ltd., BR0014) mixed and further diluted in PBS (1:10) to allow for contamination of fresh-cut fruit pieces at initial levels of approximately 10^5-10^6 CFU g^-1 of fruit.

**Inoculation of fresh-cut fruits**

After appropriate dilutions, 100mL aliquots of cell suspensions were distributed uniformly over the fresh-cut fruits contained within each of the packages (Figure 3.2). Following inoculation, packages were actively flushed with the appropriate atmospheres and/or heat-sealed (section 2.1). After sealing, packs were gently shaken to assist distribution of the innocua.
Microbiological enumeration

Microbiological analyses were carried out initially on day of inoculation (Day 0) and at regular intervals throughout the storage period (Days 1, 4, 7). On each sampling day duplicate packs from each experiment were analysed for *Listeria* populations and total viable cell counts (TVCs). Each fresh-cut fruit pack was homogenised and from this homogenate, 25g of fruit was removed (under aseptic conditions) and transferred into a stomacher bag along with 225ml PBS for homogenised at high speed for 120s Steward stomacher 400, (AGB Scientific, Dublin, Ireland). Serial dilutions (10^{-1} to 10^{-4}) were prepared in PBS and were surface spread in duplicate on to the appropriate media. Numbers of *L. innocua* were determined on *Listeria* selective agar (LSA, Oxoid Ltd., CM856 containing a modified *Listeria* selective supplement) after 48h at 37°C. Total viable counts of mesophilic microflora were made on tryptone soya agar (TSA, Oxoid Ltd., CM131) after incubation at 37°C for 48h. Following incubation, colony-forming-units (CFU) were counted on plates that contained between 20-200 CFU. Results were expressed as colony-forming-units per gram (CFU/g) of fruit.
3.3.5. Antioxidant phytochemical compounds and antioxidant activity determination

**Methanolic extraction of antioxidant compounds**

Preparation of methanolic extracts of fresh-cut pineapple, cantaloupe melon and kiwifruit was carried out in duplicate from each fruit pack at set intervals (Day 0, 1, 4 & 7) during storage (Kenny and O’Beirne, 2010). Six-grams of homogenised fruit sample was added to 12mL of chilled methanol and homogenised at 20,000 rpm for 60s (Ultra-Turrax T-25) over ice before being centrifuged at 3,500 rpm for 10minutes at 4°C. Polytetrafluoroethylene (PTFE) syringe filters (pore size 0.22μm, Phenomenex, U.K) were used to filter the remaining supernatant. The filtered extract was collected into sterile vials and stored out of direct sunlight at -20°C until needed for quantification of total phenolics and total antioxidant activity.

**Determination of total phenolic concentration**

The total phenolic concentration (TPC) was determined in triplicate for each sample using the Folin-Ciocalteu (FC) method as described by Singleton and Rossi, (1965). The methanolic extract was mixed thoroughly and made to 1:5 dilutions. From this, 150μl was removed and placed in triplicate into a series of eppendorf tubes. Sample extracts were then mixed with 150μl of MeOH, 150μl of FC reagent (2N, Sigma-Aldrich Ireland Ltd.) and 1000μl of Na$_2$CO$_3$ (7.5%w/v) (Sigma-Aldrich Ireland Ltd.) in succession (mixed thoroughly after each addition). For sample blanks, 300μl of MeOH, 150μl of FC reagent and 1000μl of Na$_2$CO$_3$ were prepared, one per sample. All samples/blanks were incubated in darkness for 20 min at 25°C after which samples were centrifuged at 14,000rpm for 3 min and absorbance measured at 735nm. Total phenolic concentration was expressed as mean ± SD (milligrams) gallic acid equivalent (GAE) per 100mL of fresh-cut weight ($R^2 = 0.996$).
Determination of total antioxidant activity: radical scavenging capacity

Total antioxidant activity (TAA) in methanolic extracts was quantified using a modification of the 2, 2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay described by Goupy et al. (1999). Briefly, 0.7ml of DPPH (47.6μg/mL in methanol) was added to 0.7mL of suitably diluted sample (diluted in MeOH). A series of reagent blanks were used as reference samples consisting of 0.7mL DPPH (47.6μg L⁻¹ in methanol) and 0.7mL methanol. After 30 min incubation in the dark, the absorbance decrease was measured at 515nm. The instrument was auto-zeroed against methanol while a negative control (neat DPPH working solution) was also run simultaneously.

The efficient concentration (EC₅₀) which represents the amount of antioxidant necessary to decrease the initial DPPH concentration by 50%, representing a parameter widely used to measure antioxidant activity, was calculated from the calibration curve (Trolox ((R)-(+)6-hydroxy-2,5,7,8-tetramethyl-croman-2-carboxylic acid)) (Sigma-Aldrich Ireland Ltd.) (0 to 0.05mM) by linear regression with results expressed as mg of Trolox equivalent antioxidant capacity (TEAC) per 100mL of fresh-cut weight ($R^2=0.997$). Efficient antioxidants have high antiradical power, therefore, the amount of total antioxidant activity (ARP) is inversely related to the concentration of the sample required to reduce the initial concentration of DPPH by 50%. The ARP present was determined as the reciprocal value of the EC₅₀, representing a comparable term for the effectiveness of antioxidant and scavenging capacity. The ARP was recorded on a fresh-weight basis (g⁻¹) and graphed.

Determination of total carotenoids

Total carotenoids were extracted using an optimised method of Gross (1991) by homogenising 7g of fruit homogenate with 10mL of acetone containing (0.2%) butylated hydroxytoluene (BHT). Initial homogenate was filtered under vacuum through Whatman No. 4 filter paper under dim light and the residue recovered and re-extracted three times with combined filtrates brought to 40mL with extraction solution. Following extraction, samples were mixed to ensure homogeneity after which 1.5mL of samples (in triplicate) were centrifuged at 14,000rpm for 5 minutes.
at room temperature. Samples were measured at three different wavelengths, 470nm, 645nm and 662nm with the instrument auto-zeroed against extraction before use. Dilutions were made where necessary. Total carotenoids (fresh weight basis) were calculated and expressed as $\mu$g/g$^{-1}$ using the following equations:

(1.16) Chlorophyll $\alpha$ (C$\alpha$) : $(11.75)(A_{662}) - (2.35)(A_{645})$

(1.17) Chlorophyll $\beta$ (C$\beta$) : $(18.61)(A_{645}) - (3.96)(A_{662})$

(1.18) Total Carotenoids (µg/ml extract): \[
\frac{(1000)(A_{470}) - (2.27)(C\alpha) - (81.4)(C\beta)}{227}
\]

### 3.3.6. Statistical analysis

Statistical analysis was carried out as before (Chapter 2.1 section 2.3)
3.4. Results
3.4.1. Effects of atmosphere on quality

*Gas atmospheres*

Products were exposed to either controlled (CA) or modified atmospheres (MA) (Figure 3.2). In the case of packaged products, oxygen concentrations decreased to 0.2%-8.3%, 1.5%-16.1% and 0.4%-10.2% for fresh-cut pineapple, cantaloupe melon and kiwifruit, respectively, while carbon dioxide concentrations increased to 10-14.6%, 5.4%-9.4% and 16.1-20.4% (*Table 3.2*). For all fruits, packages flushed with 5%O₂+5%CO₂ had the greatest in-pack modification while PMA stored fruits had the least (*Figure 3.3*). Significant differences in O₂ concentrations was found between PMA and flushed packages on Day 7 (p<0.05).

*Table 3.2.** Controlled atmospheres (CA) and ranges of modified atmospheres (MA) developed within packs of fresh-cut pineapple, cantaloupe melon and kiwifruit during 7 Day storage at 4°C.*

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>O₂ (%)</th>
<th>CO₂ (%)</th>
<th>N₂ (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA</td>
<td>AIR</td>
<td>20.9</td>
<td>0.04</td>
<td>79.1</td>
</tr>
<tr>
<td></td>
<td>5%O₂+5%CO₂</td>
<td>5</td>
<td>5</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>97%N₂+3%O₂</td>
<td>3</td>
<td>-</td>
<td>97</td>
</tr>
<tr>
<td>MA/Flushed</td>
<td>PMA</td>
<td>20.4 - 8.3</td>
<td>1.2 - 10.0</td>
<td>78.4 - 81.7</td>
</tr>
<tr>
<td></td>
<td>5%O₂+5%CO₂</td>
<td>5.4</td>
<td>1.3</td>
<td>4.8 - 14.6</td>
</tr>
<tr>
<td></td>
<td>97%N₂+3%O₂</td>
<td>3.1</td>
<td>0.2</td>
<td>0.5 - 10.5</td>
</tr>
<tr>
<td></td>
<td>PMA</td>
<td>19.2 - 16.1</td>
<td>1.2 - 5.4</td>
<td>79.7 - 78.5</td>
</tr>
<tr>
<td></td>
<td>5%O₂+5%CO₂</td>
<td>5.8</td>
<td>3.2</td>
<td>4.9 - 9.4</td>
</tr>
<tr>
<td></td>
<td>97%N₂+3%O₂</td>
<td>4.3</td>
<td>1.5</td>
<td>1.1 - 7.6</td>
</tr>
<tr>
<td></td>
<td>PMA</td>
<td>19.1 - 10.2</td>
<td>1.2 - 16.1</td>
<td>79.7 - 73.7</td>
</tr>
<tr>
<td></td>
<td>5%O₂+5%CO₂</td>
<td>5.8</td>
<td>1.5</td>
<td>5.0 - 20.4</td>
</tr>
<tr>
<td></td>
<td>97%N₂+3%O₂</td>
<td>3.3</td>
<td>0.4</td>
<td>1.1 - 19.0</td>
</tr>
</tbody>
</table>
For fresh-cut pineapple, a steady rate of O\textsubscript{2} depletion was observed with flushed packages reaching extremely low O\textsubscript{2} concentrations of 1.3% and 0.2% on Day 7 (\textbf{Figure 3.3a}). Both PMA and 97%N\textsubscript{2}+3%O\textsubscript{2} flushed packs displayed similar trends during storage, with CO\textsubscript{2} levels higher in 97%N\textsubscript{2}+3%O\textsubscript{2} packs than PMA packs by Day 3 but with no significant differences observed at end of storage (p>0.05).

Fresh-cut cantaloupe melon, being a low respiring fruit, displayed the least in-pack atmosphere modification of all fruits studied (\textbf{Figure 3.3b}). Similarly to pineapple, PMA melon packs had the least in-pack atmosphere change, while 5%O\textsubscript{2}+5%CO\textsubscript{2} had the greatest. PMA stored melon had significantly different O\textsubscript{2} and CO\textsubscript{2} concentrations than flushed packs at end of storage (p<0.05) with values of 16.1% and 5.4% respectively. Fresh-cut melon stored in 5%O\textsubscript{2}+5%CO\textsubscript{2} had greatest CO\textsubscript{2} accumulation with a value of 9.4% on Day 7. For 97%N\textsubscript{2}+3%O\textsubscript{2} packs, O\textsubscript{2} levels decreased to near anaerobic levels (1.5%) on Day 7.

Fresh-cut kiwifruit had the greatest in-pack atmosphere modification over 7 Day storage (\textbf{Figure 3.3c}). Similarly to other fruits, in-pack O\textsubscript{2} levels within PMA packs (10%) were significantly different (p<0.01) to those for 5%O\textsubscript{2}+5%CO\textsubscript{2} (1.5%) and 97%N\textsubscript{2}+3%O\textsubscript{2} (0.4%) packs on Day 7. 5%O\textsubscript{2}+5%CO\textsubscript{2} packs had the greatest CO\textsubscript{2} accumulation with a value of 20.4% on Day 7 while PMA packs had the least (16%).
Figure 3.3 Changes in in-pack oxygen (O₂) and carbon dioxide (CO₂) of modified atmosphere packaged fresh-cut (a) pineapple, (b) cantaloupe melon and (c) kiwifruit during storage in Air, 5%O₂+5%CO₂ and 97%N₂+3%O₂ for 7 days at 4°C. The values are means for 6 determinations, separated by Fisher’s Least Significant Difference (LSD) (p<0.05). Error bars show SD. In-pack O₂, continuous lines, descending; in-pack CO₂, broken lines, ascending.
For all fruits studied, there was an increase in drip-loss during storage; the rate and extent of which was dependent in fruit type and atmosphere (Figure 3.4a). Fresh-cut pineapple accumulated the greatest volume of drip, followed by cantaloupe melon and kiwifruit. On Day 1 there was no significant effect of atmospheres in drip-loss (p>0.05). After 7 Days however, fresh-cut pineapple stored in PMA and flushed packs, had significantly higher drip-loss than samples stored in CAs. The high CO₂ of the 5%O₂+5%CO₂ flushed packs resulted in the highest volume of drip (9.25mL/pack) with no significant difference between PMA and 97%N₂+3%O₂ (p>0.05). An increase in drip-loss of 2.5-3.25mL was recorded for CA stored samples with no significant effect of atmospheres observed (p>0.05).

For fresh-cut cantaloupe melon, drip-loss was minimal for fruit stored in CA atmospheres (<4mL) (Figure 3.4b). On Day 1, no significant difference in volumes was noted, irrespective of atmosphere (p>0.05). After 7 Day storage, melon flushed with 97%N₂+3%O₂ had significantly higher drip levels (p<0.05; 6.25mL) than PMA (3.25mL) and 5%O₂+5%CO₂ (4mL) flushed packs, respectively.

Fresh-cut kiwifruit had the lowest drip-loss (Figure 3.4c). On Day 1, kiwifruit stored in CA atmospheres had a greater increase in drip than fruits stored in MA atmospheres, with 97%N₂+3%O₂ samples having a significant increase (2.25mL; p<0.05). After 7 Day storage, kiwifruit stored in 97%N₂+3%O₂ had significantly higher drip-loss levels (22%) than 5%O₂+5%CO₂ and Air stored samples (p<0.05). No significant difference in drip-loss levels was observed for fresh-cut kiwifruit flushed with different MAs (<1mL), irrespective of atmosphere (p>0.05).

Percent weight-loss (Figure 3.5) correlated well with previously reported drip-loss levels in that the greatest percentage weight-loss occurred for fresh-cut pineapple flushed with 5%O₂+5%CO₂ (17.5%; p<0.001), and fresh-cut cantaloupe melon flushed with 97%N₂+3%O₂ had the greatest loss (24%; p<0.001). For fresh-cut kiwifruit, fruit stored in a controlled atmosphere of 97%N₂+3%O₂ had the greatest weight-loss (17%; p<0.01).
Figure 3.4 Effects of controlled (CA) and modified (MA) atmospheres on drip-loss levels within packs of fresh-cut (a) pineapple, (b) cantaloupe melon and (c) kiwifruit during storage at 4°C. Broken red line (average fresh-cut drip-loss). Values are means for 6 determinations separated by Fisher’s LSD. Error bars show ± SD.
Figure 3.5 Effects of controlled (CA) and modified (MA) atmospheres on percentage weight loss within packs of fresh-cut (a) pineapple, (b) cantaloupe melon and (c) kiwifruit during storage at 4°C. Broken red line (maximum loss allowed). Values are means for 6 determinations separated by Fisher’s LSD and error bars showing ± SD. Columns with the same asterisk/ letters are not significantly different (p>0.05); where, NS (not significant), * (p<0.05), ** (p<0.01), *** (p<0.001).
**Effects on firmness**

Fresh-cut pineapple and cantaloupe melon had similar initial average firmness values of 4.69N and 4.08N, respectively, while fresh-cut kiwifruit had the lowest (1.84N).

Fresh-cut pineapple increased in firmness by Day 1 with no significant effect of atmosphere (p>0.05). After Day 1, there was a drop in firmness for flushed packs (p<0.05) with 5%O₂+5%CO₂ flushed packs having the greatest loss (Figure 3.6a). In CA storage, there was a significant increase in firmness (p<0.05), with 5%O₂+5%CO₂ having a significantly greater increase (p<0.01) than air and 97%N₂+3%O₂ (p>0.05).

Fresh-cut cantaloupe melon, fruits stored in CA and flushed with 5%O₂+5%CO₂ and 97%N₂+3%O₂ decreased in firmness by Day 1 (p>0.05). In contrast, firmness increased in air stored (p>0.05) and PMA (p<0.05) melon. After 7 Days storage, all flushed packs had significantly increased in firmness (p<0.05), with 5%O₂+5%CO₂ samples having the greatest increase and no significant difference in firmness levels between PMA and 97%N₂+3%O₂ observed (Figure 3.6b). There were minimal changes in firmness in CA stored melon (p>0.05).

Fresh-cut kiwifruit had the most significant loss of firmness (p<0.01) during storage (Figure 3.6c). After 1 Day, CA stored fruit had increased in firmness while flushed packs exhibited little or no change (p>0.05). On Day 7, a significant decrease in firmness was observed for all treatments (p<0.01) with no effects of atmospheres observed (p>0.05). In general, flushed packages had slightly better firmness than CA stored samples at end of storage.
Figure 3.6 Effects of controlled (CA) and modified (MA) atmospheres on firmness levels (N) of fresh-cut (a) pineapple, (b) cantaloupe melon and (c) kiwifruit during 7 Day storage at 4°C. Broken red line (average firmness fresh-cut). Values are means for 12 determinations separated by Fisher’s LSD. Error bars showing ± SD.
Effects on colour

Using the equations for $\Delta L^*$, $\Delta a^*$, $\Delta b^*$, chromaticity ($\Delta C$) and hue angle ($H^O$), derived from CIE $L^*$, $a^*$ & $b^*$, the colour differences during storage (Day 0 to Day 7) for each of the treatments studied are presented in Table 3.3, while the total colour differences ($\Delta E$) are presented in Figure 3.7. Colour change occurred for all fruits/atmospheres, with samples displaying medium ($\Delta E \geq 2$) to very obvious ($\Delta E \geq 6$) colour changes during storage.

For fresh-cut pineapple (Figure 3.7a), no significant effects of atmosphere on CIE Lab* colour coefficients were found ($p>0.05$), but significant effects on overall colour change ($\Delta E$), $\Delta a^*/\Delta b^*$ redness/yellowness (indicative of browning), $\Delta L^*$ (luminosity) and absolute colour difference ($\Delta H$) were noted ($p<0.05$) (Table 3.3). Pineapple flushed with 97%$N_2$+3%$O_2$ had the greatest overall colour change ($\Delta E$: 20.5; $\Delta H$: 0.03) while fruit flushed with 5%$O_2$+5%$CO_2$ had the least ($\Delta E$: 9.3; $\Delta H$: -2.9). In contrast, pineapple stored in CA atmospheres of 97%$N_2$+3%$O_2$ and 5%$O_2$+5%$CO_2$ had very similar colour differences, with $\Delta E$ values of 16 and 17, respectively; as did CA air stored (10.1) and PMA (11.4) packs.

For fresh-cut cantaloupe melon (Figure 3.7b), significant effects of atmospheres on overall colour change and hue (orangeness) were noted ($p<0.05$). Flushed melon packages had greater colour change than CA stored melon ($p<0.05$). Melon flushed with 97%$N_2$+3%$O_2$ displayed the greatest overall colour change ($\Delta E$: 27; $\Delta H$: 0.03). Interestingly, this fruit had the highest $\Delta a^*$ and $\Delta b^*$ (13) and $\Delta L^*$ (23) indicative of a lighter orange (more translucent) flesh than other samples. Fruit stored in CA 5%$O_2$+5%$CO_2$ had the least colour change with $\Delta E$ value of 2.6 and $\Delta H$ value of (-2). In contrast to previous sample, melon in this instance had the lowest overall colour change with $\Delta L^*$, $\Delta a^*$ and $\Delta b^*$ values of 1.7, (-1.8) and (-0.8) respectively, indicating little colour change from that of fresh-cut colour.

Figure 3.7c shows the $\Delta E$ values for fresh-cut kiwifruit. Significant differences in colour change was observed between CA and flushed packages ($p<0.01$) with CA samples, irrespective of atmosphere, displaying greater colour change.
Figure 3.7 Effects of controlled (CA) and modified (MA) atmospheres on the extent of colour change (ΔE Lab) of fresh-cut (a) pineapple, (b) cantaloupe melon and (c) kiwifruit during 7 Day storage at 4°C. Broken red line (>6; obvious colour change). Values are means for 24 determinations separated by Fisher’s LSD with error bars showing ± SD.
Table 3.3 Effect of controlled and modified atmospheres on colour indices of fresh-cut pineapple, cantaloupe melon and kiwifruit during 7 Day storage at 4°C.

<table>
<thead>
<tr>
<th>Fruit</th>
<th>Atmosphere</th>
<th>$\Delta E_{Lab}$</th>
<th>$\Delta H$</th>
<th>$\Delta C$</th>
<th>$H^0$</th>
<th>$\Delta L^*$</th>
<th>$\Delta a^*$</th>
<th>$\Delta b^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pineapple</td>
<td>AIR CA</td>
<td>10.13*</td>
<td>-3.08</td>
<td>8.24</td>
<td>1.54</td>
<td>-5.90</td>
<td>-0.52</td>
<td>-8.23</td>
</tr>
<tr>
<td></td>
<td>AIR MA</td>
<td>11.44*</td>
<td>-3.10</td>
<td>7.77</td>
<td>1.53</td>
<td>-8.39</td>
<td>-0.36</td>
<td>-7.77</td>
</tr>
<tr>
<td></td>
<td>5%O$_2$ + 5%CO$_2$ CA</td>
<td>17.14**</td>
<td>-3.08</td>
<td>17.10</td>
<td>1.55</td>
<td>-1.17</td>
<td>-1.07</td>
<td>-17.06</td>
</tr>
<tr>
<td></td>
<td>5%O$_2$ + 5%CO$_2$ MA</td>
<td>9.33*</td>
<td>-2.94</td>
<td>6.09</td>
<td>1.55</td>
<td>-7.07</td>
<td>-1.23</td>
<td>-5.97</td>
</tr>
<tr>
<td></td>
<td>97%N$_2$ + 3%O$_2$ CA</td>
<td>15.88**</td>
<td>-3.07</td>
<td>12.46</td>
<td>1.55</td>
<td>-9.85</td>
<td>-0.88</td>
<td>-12.43</td>
</tr>
<tr>
<td></td>
<td>97%N$_2$ + 3%O$_2$ MA</td>
<td>20.49***</td>
<td>0.03</td>
<td>12.00</td>
<td>1.55</td>
<td>16.61</td>
<td>0.36</td>
<td>11.99</td>
</tr>
<tr>
<td>Cantaloupe Melon</td>
<td>AIR CA</td>
<td>6.62*</td>
<td>0.67</td>
<td>4.67</td>
<td>1.09</td>
<td>-4.70</td>
<td>2.90</td>
<td>3.66</td>
</tr>
<tr>
<td></td>
<td>AIR MA</td>
<td>8.74*</td>
<td>3.14</td>
<td>7.39</td>
<td>1.53</td>
<td>4.68</td>
<td>0.03</td>
<td>7.39</td>
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<tr>
<td></td>
<td>5%O$_2$ + 5%CO$_2$ CA</td>
<td>2.56NS</td>
<td>-1.98</td>
<td>1.95</td>
<td>1.09</td>
<td>1.66</td>
<td>-1.79</td>
<td>-0.77</td>
</tr>
<tr>
<td></td>
<td>5%O$_2$ + 5%CO$_2$ MA</td>
<td>9.61*</td>
<td>-2.94</td>
<td>6.09</td>
<td>1.55</td>
<td>7.43</td>
<td>-1.24</td>
<td>-5.96</td>
</tr>
<tr>
<td></td>
<td>97%N$_2$ + 3%O$_2$ CA</td>
<td>5.51*</td>
<td>-1.74</td>
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<td>1.10</td>
<td>-5.48</td>
<td>-0.53</td>
<td>-0.09</td>
</tr>
<tr>
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<td>97%N$_2$ + 3%O$_2$ MA</td>
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<td>1.55</td>
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<td>12.97</td>
<td>12.97</td>
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<tr>
<td>Kiwifruit</td>
<td>AIR CA</td>
<td>11.33**</td>
<td>-3.07</td>
<td>5.56</td>
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<td>-9.87</td>
<td>-0.38</td>
<td>-5.55</td>
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<tr>
<td></td>
<td>AIR MA</td>
<td>14.01**</td>
<td>3.08</td>
<td>1.04</td>
<td>-1.41</td>
<td>-12.97</td>
<td>0.31</td>
<td>-5.30</td>
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<tr>
<td></td>
<td>5%O$_2$ + 5%CO$_2$ CA</td>
<td>16.96***</td>
<td>3.05</td>
<td>5.88</td>
<td>-1.42</td>
<td>-15.91</td>
<td>0.51</td>
<td>-5.86</td>
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<td></td>
<td>5%O$_2$ + 5%CO$_2$ MA</td>
<td>5.53*</td>
<td>3.08</td>
<td>1.04</td>
<td>-1.39</td>
<td>-5.43</td>
<td>0.07</td>
<td>-1.04</td>
</tr>
<tr>
<td></td>
<td>97%N$_2$ + 3%O$_2$ CA</td>
<td>12.31**</td>
<td>-2.23</td>
<td>4.11</td>
<td>-1.44</td>
<td>-11.61</td>
<td>-3.25</td>
<td>-2.51</td>
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<tr>
<td></td>
<td>97%N$_2$ + 3%O$_2$ MA</td>
<td>2.65NS</td>
<td>0.37</td>
<td>0.74</td>
<td>-1.38</td>
<td>-2.55</td>
<td>0.26</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Values are means for 24 determinations separated by Tukey’s LSD Where, for each individual fruit and colour index ($\Delta E$), values with the same symbols are not significantly different (p>0.05) NS (not significant); * (p≤0.05); ** (p≤0.01); *** (p≤0.001)
The greatest colour change occurred in fruit stored in a CA of 5%O₂+5%CO₂ (ΔE: 17; ΔH: 3.1) while kiwifruit flushed with 97%N₂+3%O₂ had the least (ΔE: 2.7; ΔH: 0.4). However, upon analysis of total colour change indices, it was found that flushed packages had more loss of green colour than CA stored fruit (Table 3.3). Fresh-cut kiwifruit stored in a CA of 5%O₂+5%CO₂ had greater loss of greenness, with Δa* and Δb* values of 0.51 and -5.9, respectively. In contrast, kiwifruit flushed with 97%N₂+3%O₂ increased in yellowness, with Δa* and Δb* values of 0.26 and 0.7, respectively, which was significantly different to all other samples (p<0.01). Furthermore, both CA and flushed samples lost luminosity, with CA stored kiwifruit having a significantly greater loss than flushed samples (p<0.05).

### Effects on percent soluble solids, pH and titratable acidity (%)

The effects of CA and MA atmospheres on the percent soluble solids (SS%), pH and titratable acidity (TA%) are presented in Table 3.4. For fresh-cut pineapple, cantaloupe melon and kiwifruit, no significant effects of atmospheres on SS% was observed (p>0.05). In terms of pH, no significant effects of atmosphere was observed during storage (p>0.05). Similarly, no significant effect of atmospheres on TA% was found for fresh-cut pineapple and kiwifruit (p>0.05). In contrast, flushing and/or CA storage in an atmosphere of 97%N₂+3%O₂ resulted in an overall increase in TA% for fresh-cut cantaloupe melon, with the greatest increase occurring in flushed packs from Day 0 to Day 1 (p<0.01). Figure 3.8 illustrates the effects of atmospheres on the sugar acid ratio (S:A). For fresh-cut cantaloupe melon, flushing and/or storage in 97%N₂+3%O₂ resulted in significant increase in S:A (Day 0 to Day 1) (p<0.01). For 5%O₂+5%CO₂, smaller increases were noted for both flushed and CA storage (44% and 113%, respectively). In contrast, both air stored and PMA packs decreased in S:A from Day 0 to Day 1 (~46%) with a gradual increase thereafter (p<0.05). For fresh-cut kiwifruit, flushing had no significant effect on S:A (Figure 3.7c). In contrast, for CA stored samples, an overall decrease was observed, with 5%O₂+5%CO₂ having greatest effect (p<0.05).
Table 3.4 Effects of controlled and modified atmosphere of percent soluble solids (SS\%), titratable acidity (%) and tissue pH of fresh-cut pineapple, cantaloupe melon and kiwifruit during 7 Day storage at 4°C. *n* = 18

<table>
<thead>
<tr>
<th>Storage Time (Days)</th>
<th>Storage Atmosphere</th>
<th>Pineapple</th>
<th>Cantaloupe Melon</th>
<th>Kiwifruit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SS%</td>
<td>TA%</td>
<td>pH</td>
</tr>
<tr>
<td>0</td>
<td>AIR CA</td>
<td>11.7</td>
<td>0.64</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>AIR MA</td>
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<td>0.63</td>
<td>3.7</td>
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<tr>
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<td>5%O₂; 5%CO₂ CA</td>
<td>12.0</td>
<td>0.59</td>
<td>3.7</td>
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<tr>
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<td>5%O₂; 5%CO₂ MA</td>
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<td>3.8</td>
</tr>
<tr>
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<td>97%N₂; 3%O₂ CA</td>
<td>11.9</td>
<td>0.53</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>97%N₂; 3%O₂ MA</td>
<td>13.0</td>
<td>0.48</td>
<td>3.9</td>
</tr>
<tr>
<td>1</td>
<td>AIR CA</td>
<td>9.3</td>
<td>0.63</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>AIR MA</td>
<td>11.7</td>
<td>0.54</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>5%O₂; 5%CO₂ CA</td>
<td>9.5</td>
<td>0.64</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>5%O₂; 5%CO₂ MA</td>
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<td>0.50</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>97%N₂; 3%O₂ CA</td>
<td>10.5</td>
<td>0.52</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>97%N₂; 3%O₂ MA</td>
<td>13.1</td>
<td>0.56</td>
<td>3.7</td>
</tr>
<tr>
<td>4</td>
<td>AIR CA</td>
<td>8.9</td>
<td>0.62</td>
<td>3.7</td>
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<td></td>
<td>AIR MA</td>
<td>11.6</td>
<td>0.52</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>5%O₂; 5%CO₂ CA</td>
<td>8.8</td>
<td>0.62</td>
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</tr>
<tr>
<td></td>
<td>5%O₂; 5%CO₂ MA</td>
<td>12.1</td>
<td>0.50</td>
<td>3.8</td>
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<tr>
<td></td>
<td>97%N₂; 3%O₂ CA</td>
<td>9.7</td>
<td>0.52</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>97%N₂; 3%O₂ MA</td>
<td>12.7</td>
<td>0.58</td>
<td>3.8</td>
</tr>
<tr>
<td>7</td>
<td>AIR CA</td>
<td>8.7</td>
<td>0.66</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>AIR MA</td>
<td>12.1</td>
<td>0.54</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>5%O₂; 5%CO₂ CA</td>
<td>8.5</td>
<td>0.62</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>5%O₂; 5%CO₂ MA</td>
<td>12.2</td>
<td>0.52</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>97%N₂; 3%O₂ CA</td>
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<td>0.57</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>97%N₂; 3%O₂ MA</td>
<td>13.0</td>
<td>0.57</td>
<td>3.8</td>
</tr>
</tbody>
</table>

SS% (percent soluble solids); TA% (titratable acidity, expressed as citric acid equivalent)
Figure 3.8 Effects of controlled (CA) and modified (MA) atmospheres on sugar/acid ratio values of (a) fresh-cut pineapple, (b) cantaloupe-melon and (c) kiwifruit during 7 Day storage at 4°C. The values are means for 12 determinations, separated by Fisher’s Least Significant Difference (LSD) (p<0.05). Error bars show SD. Broken red line denotes average Fresh-cut (Day 0) value.
3.3.2. Effects of atmospheres on sensory evaluation

There were gradual falls in scores for overall acceptability with time for all fruits, irrespective of atmospheres (Figure 3.9), however the rate of decrease was significantly greater for flushed packs (p<0.05).

For fresh-cut pineapple, (Figure 3.9a) flushing with an atmosphere of 97%N₂+3%O₂ was least beneficial, while PMA and/or CA storage in 5%O₂+5%CO₂ were best. Fresh-cut pineapple flushed with 97%N₂+3%O₂ had a 4 score lower acceptability, with concurrent reductions in scores for visual appearance (Figure 3.10a) and increased colour scores in comparison to PMA packs. Visual appearance scores dropped from excellent to good after initial flushing in 97%N₂+3%O₂, falling significantly (p<0.05) to below the level of marketability on Day 4 to below levels of usability by Day 7. Similarly, significant differences in colour scores were observed (Figure 3.11a), with 97%N₂+3%O₂ flushed packs (p<0.05) having the greatest colour change and PMA packs the least. These low acceptability scores were mainly due to increased translucency and a more water-soaked appearance. In contrast, fresh-cut pineapple stored in a CA of 5%O₂+5%CO₂ better maintained their characteristic fresh-cut colour and firmness (Figure 3.14a).

In terms of aroma and off-odour (Figure 3.12a; 3.13a), flushed pineapple packs had significantly reduced aroma scores (p<0.05), falling to unacceptable levels by Day 7 for 97%N₂+3%O₂ packs. For fresh-cut pineapple stored in CAs, similar aroma scores were noted (p>0.05) with 97%N₂+3%O₂ falling below level of marketability (5) on Day 7. No significant off-odours were noted in CA air stored or PMA packs, while for flushed packs, noticeable off-odours were noted on Day 7, in particular for 97%N₂+3%O₂ and 5%O₂+5%CO₂.
Figure 3.9 Effects of controlled atmospheres (CA) and modified atmospheres (MA) on overall acceptability scores of fresh-cut (a) pineapple, (b) cantaloupe melon and (c) kiwifruit during 7 Day storage at 4°C. Data are means for 6 determinations ± SD. Broken red line denotes level of marketability. Yellow, orange and green bars illustrate fresh-cut sensory quality (Day 0).
Figure 3.10 Effects of controlled atmospheres (CA) and modified atmospheres (MA) on the visual appearance scores of fresh-cut (a) pineapple, (b) cantaloupe melon and (c) kiwifruit during 7 Day storage at 4°C. Data are means for 6 determinations ± SD. Broken red line denotes level of marketability. Yellow, orange and green bars illustrate fresh-cut sensory quality (Day 0).
Similarly for fresh-cut cantaloupe melon, flushing with an atmosphere of 97%N₂+3%O₂ was least beneficial at retaining sensory characteristics, while PMA and/or CA air storage was the best (Figure 3.9b). In general, flushed melon packs had lower visual acceptability than CA stored melon, with a 2-3 score decrease in visual appearance following flushing with 97%N₂+3%O₂. This decrease resulted in acceptability falling from “very good” to “good”, with a gradual decline to below the level of usability by Day 7 (Figure 3.10b). Colour scores (Figure 3.11b) reflected this decrease in appearance well, with colour scores for 97%N₂+3%O₂ falling from very good to fair/acceptable after flushing, decreasing steadily to just below level of marketability on Day7. However, PMA stored melon had the greatest colour change during storage (p<0.05) with heightened translucency and deepening orange hue. These low acceptability scores were mainly due to increased translucency and a more water-soaked appearance. In contrast, fresh-cut melon stored in a CA of 5%O₂+5%CO₂ better maintained their characteristic fresh-cut colour. Flushing reduced the initial firmness of fresh-cut melon from “very firm” to “firm”, with a gradual decrease to/ below level of marketability on Day 7 (Figure 3.14a). Melon flushed with 97%N₂+3%O₂ were least firm of all samples, while CA air stored samples were firmest at end of storage. In terms of aroma and off-odour (Figure 3.12b; 3.13b), no significant effect of atmospheres was observed (p>0.05). In general, as aroma decreased, off-odours increased, with flushed packs having a greater loss in aroma and slightly more noticeable off-odours on Day 7, which were greatest for 97%N₂+3%O₂ and least for CA air stored fruit.

The overall acceptability of fresh-cut kiwifruit (Figure 3.9c) related well the changes in the individual sensory parameters. Flushing with an atmosphere of 97%N₂+3%O₂ resulted in lesser acceptability, with a 1.5 score reduction initially after flushing and a reduced level of marketability on Day 7 (Figure 3.10c). In contrast, a consistent decrease in visual appearance was observed for all CA samples, with all samples remaining marketable on Day 7. CA storage in air had best acceptability after 7 Days storage, with a CA of 5%O₂+5%CO₂ best at retaining visual appearance on Day 7, while kiwifruit flushed with 97%N₂+3%O₂ was worst (<0.05).
Figure 3.11 Effects of controlled atmospheres (CA) and modified atmospheres (MA) on the colour scores of fresh-cut (a) pineapple, (b) cantaloupe melon and (c) kiwifruit during 7 Day storage at 4°C. Data are means for 6 determinations ± SD. Broken red line denotes level of marketability. Yellow, orange and green bars illustrate fresh-cut sensory quality (Day 0).
Similarly, fresh-cut kiwifruit flushed with 97%N\textsubscript{2}+3%O\textsubscript{2} had the worst colour scores (Figure 3.11c) exhibiting a 2 score reduction from very good to good initially after flushing, and reduced marketability on Day 7. The low acceptability and colour scores were mainly due to increased translucency and softening. Fresh-cut kiwifruit stored in air (CA) better retained their initial fresh-cut colour. A gradual decrease in firmness was also observed (Figure 3.13c), with flushed packs having a bigger reduction in firmness than CA stored samples. A CA of 5%O\textsubscript{2}+5%CO\textsubscript{2} was best at maintaining fresh-cut kiwifruit firmness, while kiwifruit flushed with 97%N\textsubscript{2}+3%O\textsubscript{2} was worst (reduced level of usability on Day 7). In terms of aroma and off-odour (Figure 3.12c), no significant effects of atmospheres were noted (p>0.05). CA air and PMA were best at maintaining fresh-cut kiwifruit aroma; while a CA of 5%O\textsubscript{2}+5%CO\textsubscript{2} and 97%N\textsubscript{2}+3%O\textsubscript{2} flushing were the worst.
Figure 3.12 Effects of controlled atmospheres (CA) and modified atmospheres (MA) on the aroma scores of fresh-cut (a) pineapple, (b) cantaloupe melon and (c) kiwifruit during 7 Day storage at 4°C. Data are means for 6 determinations ± SD. Broken red line denotes level of marketability. Yellow, orange and green bars illustrate fresh-cut sensory quality (Day 0).
Figure 3.13 Effects of controlled atmospheres (CA) and modified atmospheres (MA) on the off-odour scores of fresh-cut (a) pineapple, (b) cantaloupe melon and (c) kiwifruit during 7 Day storage at $4^\circ$C. Data are means for 6 determinations ± SD. Broken red line denotes level of marketability. Yellow, orange and green bars illustrate fresh-cut sensory quality (Day 0).
Figure 3.14 Effects of controlled atmospheres (CA) and modified atmospheres (MA) on the firmness of fresh-cut (a) pineapple, (b) cantaloupe melon and (c) kiwifruit during 7 Day storage at 4°C. Data are means for 6 determinations ± SD. Broken red line denotes level of marketability. Yellow, orange and green bars illustrate fresh-cut sensory quality (Day 0).
3.3.3. Effects of atmosphere on microbial growth

The effect of atmospheres on the microbial load was determined for total bacterial counts (TBCs) (Figure 3.15) and *Listeria innocua* (Figure 3.16). For fresh-cut pineapple, there were significant reductions in TBCs (Figure 3.15a) and *Listeria innocua* counts (Figure 3.16a) \((p<0.05)\). In the case of fresh-cut cantaloupe melon, TBCs increased (Figure 3.15b) and *Listeria innocua* counts fell (Figure 3.16b) \((p<0.05)\).

In general, initial TBC counts for fresh-cut kiwifruit increased slightly from Day 0 to Day 1 (6.5 to 6.7 log CFUg\(^{-1}\)) with no significant changes thereafter \((p>0.05)\) (Figure 3.15c). An exception to this was for kiwifruit stored in a CA of 97%\(\text{N}_2\)+3%\(\text{O}_2\), which continued to increase after Day 1; exceeding the maximum limit for safe consumption on Day 7 (7.1 log CFUg\(^{-1}\)). Flushed kiwifruit packs had slightly higher *Listeria innocua* counts than CA stored kiwifruit (Figure 3.16c). After an initial increase (~0.5 log CFUg\(^{-1}\)) on Day 1, the populations within each atmosphere remained relatively consistent until Day 4, after which significant differences in responses were observed \((p<0.05)\). Both PMA and 97%\(\text{N}_2\)+3%\(\text{O}_2\) flushed packs increased by 0.4 and 0.3 log CFUg\(^{-1}\), respectively, while for 5%\(\text{O}_2\)+5%\(\text{CO}_2\) CA and flushed packs a 1 log CFUg\(^{-1}\) reduction was observed.
Figure 3.15 Effects of controlled and modified atmospheres on total bacterial counts (TBCs) of fresh-cut (a) pineapple, (b) cantaloupe melon and (c) kiwifruit during 7 Day storage at 4°C. Values are means for 12 determinations ± SD. Continuous line (CA); dashed line (MA). Dashed horizontal red line (maximum TVC limit: 7 log cfu/g⁻¹).
Figure 3.16 Effects of controlled and modified atmospheres on survival and growth of *Listeria (L.) innocua* on fresh-cut (a) pineapple, (b) cantaloupe melon and (c) kiwifruit during 7 Day storage at 4°C. Values are means for 12 determinations ± SD. Continuous line (CA); dashed line (MA).
3.3.4. Effects of atmosphere on levels of phytochemicals

Total carotenoids

Cantaloupe melon had the greatest fresh-cut total carotenoids (TC) concentration on Day 0 (1.73 µg g\(^{-1}\)), followed by pineapple (0.77 µg g\(^{-1}\)) and kiwifruit (0.52 µg g\(^{-1}\)), respectively (Figure 3.17). However, no significant effect of atmosphere was observed (p>0.05).

For fresh-cut pineapple, with the exception of PMA and 97%N\(_2\)+3%O\(_2\) flushed packs, there was an overall decrease in TC concentration during storage (p<0.05) with values ranging from 0.38 to 0.57 µg g\(^{-1}\) on Day 7.

For fresh-cut cantaloupe melon, after an initial decrease from Day 0 to Day 1, TC concentrations increased until Day 7 (p<0.05) with values nearing Day 0 values (1.73 µg g\(^{-1}\)).

For fresh-cut kiwifruit, no significant differences in TC concentrations were found during storage (p>0.05) with values ranging from 0.6 to 0.7 µg g\(^{-1}\).
Figure 3.17 Effects of controlled (CA) and modified (MA) atmosphere on total carotenoids (µg g\(^{-1}\)) in fresh-cut (a) pineapple, (b), cantaloupe melon and (c) kiwifruit during 7 Day storage at 4\(^{\circ}\)C. Values are means for 12 determinations ± SD. Vertical dashed red line (average fresh-cut TC concentration µg g\(^{-1}\)).
**Total phenolics**

Fresh-cut kiwifruit had the highest total phenolics (64.1 GAE mg kg\(^{-1}\)), followed by pineapple (52.8 GAE mg kg\(^{-1}\)) and cantaloupe melon (19.5 GAE mg kg\(^{-1}\)). There were no significant effects of atmospheres in fresh-cut pineapple and cantaloupe melon (p>0.05), but significant effects were observed for fresh-cut kiwifruit (p<0.05). PMA packs had significant increase while 97%N\(_2\)+3%O\(_2\) packs had a significant decrease during storage (p<0.05). Both CA and MA 5%O\(_2\)+5%CO\(_2\) fruit packs had the greatest increase on Day 4 (p<0.05) with values of 83.55 and 86.85 mg kg\(^{-1}\) falling to 79.38 and 79.47 mg kg\(^{-1}\) on Day 7, respectively.

**Total antioxidant activity**

Great variation in antiradical power (ARP) was observed between fresh-cut fruits studied (Figure 3.19). Fresh-cut kiwifruit had the highest ARP (0.090 g\(^{-1}\) fresh weight (FW)) followed closely by pineapple (0.084 g-1 FW) while fresh-cut cantaloupe melon had the lowest ARP (0.016 g\(^{-1}\) FW). No significant effects of atmospheres on ARP was observed for fresh-cut pineapple and cantaloupe melon but significant effects for fresh-cut kiwifruit were found (p<0.05).

For fresh-cut pineapple (Figure 3.19a), significant differences in the ARP of fruit flushed with 97%N\(_2\)+3%O\(_2\) and PMA packs was found on Day 7 (p<0.05) with values of 0.063 and 0.083 g\(^{-1}\) FW, respectively.

For fresh-cut kiwifruit, flushed fruit, irrespective of atmosphere, had slightly higher ARP than CA stored fruit during storage. On Day 1, a significant increase in ARP was found for CA air and PMA and CA/MA 5%O\(_2\)+5%CO\(_2\) kiwifruit (p<0.01). After Day 1, fresh-cut kiwifruit stored/flushed in/with 5%O\(_2\)+5%CO\(_2\) continued to increase with kiwifruit flushed with 5%O\(_2\)+5%CO\(_2\) peaking at Day 4 and having highest ARP at end of storage (0.140 g\(^{-1}\) FW). In contrast, fresh-cut kiwifruit stored in a CA of 97%N\(_2\)+3%O\(_2\) decreased in ARP after Day 1, having lowest ARP of all samples on Day 7 (0.087 g\(^{-1}\) FW) (p<0.05).
Figure 3.18 Effects of atmospheres on total phenolics, gallic acid equivalent (GAE) on a fresh weight basis (mg 100g\(^{-1}\)) in fresh-cut (a) pineapple, (b) cantaloupe melon and (c) kiwifruit during 7 Day storage at 4\(^\circ\)C. Values are means for 12 determinations ± SD. Vertical dashed red line (average fresh-cut PC concentration 100g\(^{-1}\) FW).
Figure 3.19 Effects of atmospheres on total antioxidant activity (mg 100g$^{-1}$) in fresh-cut (a) pineapple, (b) cantaloupe melon and (c) kiwifruit during 7 Day storage at 4°C. Values are means for 12 determinations ± SD. Vertical dashed red line (average fresh-cut ARP concentration mg 100g$^{-1}$ FW).
3.4. Discussion

In this study, the effects of storage atmospheres on the quality, microbiology and levels of phytochemicals of fresh-cut pineapple, cantaloupe melon and kiwifruit were determined. Storing and flushing fresh-cut fruits in a range of different atmospheres had significant effects on quality, and resulted in different microbiological responses and levels of phytochemicals. For flushed samples, these effects appeared to be directly related to the types of atmospheres formed within packages and were dependent on fruit type.

Fresh-cut fruits, especially kiwifruit, are difficult to package due to increased respiration rates brought about by processing. As a result, a range of different MAs were found within flushed packs during storage (Table 3.2). CO₂ levels were high, in particular for 5%O₂+5%CO₂ flushed packs; and O₂ levels were very low, especially for 97N₂+3%O₂ flushed packs, creating favourable conditions for anaerobic respiration. PMA storage represented the least modified of all packs, and produced a range of atmospheres in between these extremes.

Pineapple

The suggested optimum O₂ and CO₂ ranges for fresh-cut pineapple as recommended by Gorny, (1997) are 3-5% O₂ and 5-8% CO₂. In this study, fresh-cut pineapple flushed with air (PMA) developed near optimum O₂ and CO₂ concentrations during storage with values of 8% and 10% respectively, on Day 7. In contrast, pineapple flushed with 5%O₂+5%CO₂ had near anoxic O₂ levels on Day 7 (<0.5%) and had developed relatively high CO₂ levels (11%). Similarly, fruit flushed with 97%N₂+3%O₂ had near anoxic O₂ levels at end of storage (0.4%). Low O₂ (1-2%) can lead to the production of off-flavours/-odours, discoloration, potential growth of anaerobic bacteria with concurrent loss of visual quality.

The most significant effects of these sub-optimal atmospheres were direct effects on quality attributes such as drip-loss, colour change, firmness and sensory acceptability during storage (p<0.05). No significant effects on microbiology and/or levels of phytochemicals were observed (p>0.05).
The different responses to CA and MA appeared to be related to the benefits or stresses caused by the low O\textsubscript{2} and/or high CO\textsubscript{2} atmospheres. For example, sub-optimal O\textsubscript{2} levels of 0.2% and 1.3% and/or CO\textsubscript{2} levels of 10.5 and 15%, resulting from flushing with 97%N\textsubscript{2}+3%O\textsubscript{2} and 5%O\textsubscript{2}+5%CO\textsubscript{2}, caused physiological stress in pineapple, with translucency and minor flesh softening two of the major defects noted.

Deterioration of visual quality was complex and due to a combination of browning/ discoloration and increased translucency. Translucency is a physiological disorder characterised by dark and glassy flesh and is a principal sign of deterioration in MAP products such as pineapple (Chen and Paull, 2001). During storage, the high barrier film coupled with flushing created unfavourable atmospheres to be created. The main effects of reduced O\textsubscript{2}/ increased CO\textsubscript{2} in 5%O\textsubscript{2}+5%CO\textsubscript{2} CA and MA packs was a reduction in the rate of browning and better retention of yellow fruit colour as reflected in greater luminosity and higher chromaticity values. O’Connor-Shaw \textit{et al.}, (1994) reported that fresh-cut pineapple stored in round rigid polypropylene containers at 4\textdegree C showed no significant changes in sensory quality during the first 7 Days of storage. Spanier \textit{et al.}, (1998) conclude that fresh-cut pineapple stored in air at 4\textdegree C had excellent visual quality after 7 Days storage. However, they remarked that fruit in lower portions of the containers were of unacceptable quality, had greater translucency with noticeable off-odours. Marrero and Kader (2006) studied the influence of MA and storage temperatures on the post-cutting life of pineapple and concluded that excessive restriction of O\textsubscript{2} can lead to discolouration with the major colour changes including reduced chromaticity and luminosity. In this study, the very low O\textsubscript{2} (<2%) found in 97%N\textsubscript{2}+3%O\textsubscript{2} flushed packs, resulted in the greatest colour change with increased darkening of flesh coupled with increased translucency and a more water-soaked appearance. Discoloration from yellowing has also been previously reported (Mencarelli \textit{et al.}, 1990; Blanchard \textit{et al.}, 1996). Flushing considerably reduced the time at which equilibrium (EMA) was achieved; less than 2 days, compared to 5 days with PMA. This reduction was thought to induce a delay in discolouration (browning) as observed for PMA pineapple during early storage packs. Marrero and Kader, (2006) reported that pineapple chunks held in 1.5%O\textsubscript{2}+11%CO\textsubscript{2} at 0\textdegree C maintained good appearance during 14 Day storage, while
storage at 5°C resulted in anaerobiosis lending to poor appearance and off-odour development.

No significant effects of atmospheres on fresh-cut pineapple TC concentration were observed (p>0.05) while TP concentration increased significantly during storage, in particular for fruit flushed in 97%N₂+3%O₂ (p<0.05). This increase could be attributed to greater incidence of browning and overall colour change earlier observed for fruit flushed in this atmosphere. In line with these results, a gradual decline in antioxidant activity was observed for fresh-cut pineapple.

**Cantaloupe melon**

The rapid establishment of optimum atmospheres is critical for the prevention of subsequent physiological disorders such as discoloration and softening (Mahajan, 2006). In this study fresh-cut cantaloupe melon PMA packages were unable to attain beneficial in-pack atmospheres during storage. PMA relied heavily on the respiration of the product to regulate in-pack atmosphere with O₂ and CO₂ concentrations of 16% and 5% respectively, at end of storage. Fresh-cut melon flushed with 97%N₂+3%O₂ had O₂ and CO₂ levels of 1.5% and 8% respectively, at end of storage while for melon flushed with 5%O₂+5CO₂, O₂ and CO₂ levels were 3% and 9% respectively. These atmospheres are relatively in line with Gorny, (1997) who recommended an optimum atmosphere of 3%O₂ and 10%CO₂ to be beneficial at maintaining melon quality. In this study, melon flushed with 5%O₂+5%CO₂ better maintained its fresh-cut quality over other atmospheres.

During processing, many natural barriers to water-loss, i.e. the skin, rind and peel, are removed, leaving products very susceptible to water-loss and dehydration. For fresh-cut cantaloupe melon, the extent of processing is so severe that water-loss and softness can occur at much greater rates than that of the whole commodity. CA stored fresh-cut melon had more of a water-soaked appearance than MA stored fruit. For flushed packs, an overall increase in firmness was observed (p<0.05) with no significant effect of CA on melon firmness observed (p>0.05). Portela and Cantwell (1998) reported that firmness loss in melon cylinders during PMA storage at 5°C was 2.2lb, while CA air storage significantly reduced firmness loss.
Significant increases in both total bacteria counts (TBCs) and *L. innocua* populations were observed during storage (p<0.05) however no significant effects of atmospheres was observed (p>0.05). Fang *et al.*, (2013) previously reported that cantaloupe melon showed an immediate increase in populations of both background microflora and *L. monocytogenes* with little or no lag phase present following inoculation, and continued exponential growth until stationary phase was established. Francis *et al.*, (2007) showed that *L. monocytogenes* can survive and grow in fresh-cut products, notably those with high CO₂ atmospheres, while products flushed with an inert atmosphere also favoured growth over air storage (Francis and O’Beirne, 1998a,b).

Similarly to pineapple, fresh-cut cantaloupe melon flushed with 97%N₂+3%O₂ had the greatest colour change (p<0.01) while melon stored in a CA of 5%O₂+5%CO₂ had the least. Colour change in melon was minor and primarily related to increased translucency and loss of vivid pink-orange colour. Portela and Cantwell, (1998) reported that overall visual quality of fresh-cut melon stored in low O₂ alone or air was unacceptable after 9 Days storage at 5°C, while CA storage with elevated CO₂ (7.5%) maintained visual appearance. O’Connor-Shaw *et al.*, (1994) and Ayhan and Chism, (1998) found that, by the end of storage at 4°C and 2.2°C for 11 and 22 Days, respectively, fresh-cut cantaloupe melon chunks were paler than freshly cut chunks and were more translucent with decreased appearance scores. An active MAP of 4%O₂+10%CO₂ was found to better maintain the bright orange colour of fresh-cut cantaloupe melon (Bai *et al.*, 2001), where similar to this study (CA 5%O₂+5%CO₂), the initial luminosity, hue and chromaticity values remained relatively unchanged. Therefore, melon flushed or stored in 5%O₂+5%CO₂ is best at maintaining fresh-cut cantaloupe colour during storage. Bai *et al.*, (2003) also reported that melon chunks flushed with 5%O₂+5%CO₂ had better visual quality and aroma than PMA storage.

However, fresh-cut melon stored in air (CA) better maintained its sensory appeal with better aroma and firmness values; while 97%N₂+3%O₂ flushed packs had reduced sensorial traits. Fan *et al.*, (2008) suggested that appearance and aroma limited the shelf-life of fresh-cut cantaloupe melon under MAP storage. Similar to the current study, Ayhan and Chism, (1998) found that fresh-cut cantaloupe melon chunks stored in 95%N₂+5%O₂ in high barrier film at 2.2°C had developed off-odours and were translucent with decreased aroma.
Significant increases in total carotenoid concentrations were observed during storage (p<0.05). In ripe fruit, chloroplasts degenerate into chromoplasts, accompanied by increased synthesis of carotenoids (Matile et al., 1997). This change from chloroplast to chromoplast is particularly important in the case of fruits called *cartenogenic* fruits, characterised by this extensive new synthesis of carotenoids, usually accompanied by a change in the carotenoids profile (Ártés et al., 2000). This *de novo* synthesis of carotene has previously been described by Lee, (1996) and Berger et al., (2008). Weichmann (1986) reported that low O2 atmospheres enhanced the retention of carotene in carrots, air + 5%CO2 caused a loss, while air + 7.5%CO2 and/or higher caused *de novo* synthesis of carotene. These trends could also be attributed to an increased bioavailability due to tissue decay, as previously reported by Ding et al., (2001; 2002), Marrero and Kader, (2006) and Paiva and Russell, (1999).

**Kiwifruit**

Fresh-cut kiwifruit has the highest respiration rate of all fruits studied and as a result had the greatest in-pack atmosphere modification. Gorny, (1997), suggested that atmospheres in the range of 1-2%O2 and 3-5%CO2 were optimum. In this study, kiwifruit flushed with 5%O2+5%CO2, had O2 levels less than 1.5% on Day 7 while CO2 levels were ~18%. In the case of kiwifruit flushed with 97%N2+3%O2, O2 levels were less that 0.5% while CO2 levels were ~20%. Anaerobic respiration can also increase product susceptibility to physiological breakdown. Of particular importance are the possible effects on cell membranes which can affect firmness. As a consequence of the inadequate or injurious concentrations of O2 and/or CO2 developed, different symptoms of physiological injury and/or reduced quality occurred, with severe tissue softening and translucency.

An overall reduction in firmness was observed, irrespective of atmosphere with no significant effects observed on Day 7 (p>0.05). Unfavourable O2 and CO2 concentrations are likely to have contributed to this loss of firmness, as previously reported by Oms-Oliu et al., (2008) for fresh-cut pears. Furthermore, the duration of exposure to low O2 atmospheres can have a direct effect on membrane stability (Varoquaux et al., 1990). Soliva-Fortuny et al., (2002b) showed that high CO2 concentrations induce tissue breakdown and the formation of significant amounts of
exudate in fresh-cut apple and pear. Arpaia et al., (1994) showed that solubilisation of cell-wall softening related components was faster in air stored kiwifruit than in a CA of 2%O₂ + 5%CO₂.

There were no effects of atmospheres on microbial growth but flushing with 5%O₂+5%CO₂ significantly increased Listeria innocua counts on Day 7. Flushing with 5%O₂+5%CO₂ resulted in high CO₂ concentrations (>20%) to accumulate within packs. This concentration has previously been shown to promote the growth of pathogens like L. monocytogenes (Farber et al., 1991; Carlin et al., 1996).

In contrast to other fruits, fresh-cut kiwifruit flushed with 97%N₂+3%O₂ had least colour change, while when stored in 5%O₂+5%CO₂ had the greatest (p<0.05). Colour change for kiwifruit was a combination of degreening (increase in yellowness) coupled with increased translucency and slight browning of cut edges. All CA stored fruit developed a deeper green colour during storage, while flushed packs lost their green colour and became much more translucent. Loss of green colour has been reported to occur at 10% CO₂ with some evidence that 8% CO₂ is the upper limit for maintaining kiwifruit green colour (Arpaia et al., 1994). Yellowing (loss of chlorophyll) was found to be less appealing to panellists than an increase in green colour, contributing to reduced marketability and poor visual appeal on Day 7. In this instance, kiwifruit had poor acceptability due to a combination of deteriorative traits such as tissue softening which gave it a soft-mushy appearance and texture.

No significant effects of atmospheres on total carotenoids were observed for fresh-cut kiwifruit. However, fresh-cut kiwifruit flushed with 5%O₂+5%O₂ had significant increase in TP concentration during storage (p<0.01). The accumulation of phenolic compounds during storage has been previously observed (Babic et al., 1993; Howard and Griffin, 1993; Klaiber et al., 2005). This accumulation has been shown to result from wound-induced synthesis of PAL (Howard and Griffin, 1993). However, such relationships may also be attributed to the presence of other compounds (Aguayo et al., 2010; Yu et al., 2002) such as ascorbic acid which is found in abundance in kiwifruit.
3.5. Conclusion

It is conclude that:

- Atmospheres had significant effects of quality and sensory appeal but little effects on microbial growth or phytochemical content.
- Quality of fresh-cut pineapple and cantaloupe melon was best maintained under a CA of 5%O₂+5%CO₂.
- Quality of fresh-cut kiwifruit was better maintained under a CA of 97%N₂+3%O₂.
- Where low O₂ / elevated CO₂ were found within packs, quality suffered.
- The optimum atmospheres identified can be used as target atmospheres in package design (see Chapter 5).
Chapter 4

Volatile Aromatic Compound Changes in Fresh-cut Fruits

*Effects of Storage Time and Cut Size*

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4.1. Abstract

The effects of storage and cut size on volatile aromatic compounds (VACs) of fresh-cut pineapple, cantaloupe melon and kiwifruit were studied using headspace solid-phase microextraction (HS-SPME) gas chromatography mass-spectrometry (GC-MS). Fresh-cut fruits were packaged in a high barrier laminate pillow-pouch pack and stored for 14 days at 4°C. Anaerobic respiration was not initiated in any of the packs (>2% O₂) during the 14 Day storage. A total of 29, 23 and 35 odour-active compounds were detected of which 18, 16 and 20 were tentatively identified in the static headspace of packaged fresh-cut pineapple, cantaloupe melon and kiwifruit, respectively. Complex mixtures of esters (including acetate and thiol-esters), alcohols, aldehydes, monoterpenes, sesquiterpenes and hydrocarbons (HC) were observed with esters generally increasing during storage. Cut size (p<0.05) and storage time (p<0.01) had large effects on VAC profiles. Certain compounds such as ethyl acetate increased in concentration, while others such as α-pinene and/or methyl acetate decreased or showed no significant change (p>0.05) and were dependent on fruit type, cut size and storage time.

For fresh-cut kiwifruit, certain compounds such as methoxyacetone, diethyl carbonate, (3-Methyl-oxiran-2-yl)-methanol and ethyl benzoate were present only during the latter storage, while lactamide, 2-ethylfuran, limonene and 2,4-hexadienal were present only in fresh-cut samples (Day 0). Based on PCA interpretation, VAC changes during storage took place at greater rates for smaller cut pieces. Volatiles showed greater diversity in patterns with fruit type with a decrease or loss in some compounds (pineapple and kiwifruit) and an increase or emergence of others (cantaloupe melon and kiwifruit). Using PCA, the postharvest aroma shelf-life (SL) of fresh-cut pineapple and kiwifruit were 7 days for small pieces and up to 14 days for large cut pieces. For fresh-cut cantaloupe melon, aroma SL was limited to 4 and 7 days for small and large cut pieces due to presence of fermentative-like off-odours, which were more pronounced for smaller cut pieces. These off-odours were attributed to increased concentrations of existing volatiles rather than the emergence of new compounds.

Keywords: fresh-cut fruit, solid-phase microextraction, gas chromatography-mass spectroscopy, aroma, shelf-life.
4.2. Introduction

Fruit flavour is composed of two characteristics: (1) aroma, which is the combined effect of the presence of various volatiles in fruit, and (2) taste, which is determined by the contents of non-volatile compounds such as sugars and acids. It had been suggested by Kader, (2002, 2012) that the flavour attributes of fresh-cut fruits are usually lost or diminished before other deteriorative symptoms appear. The characteristic aroma associated with fresh-cut fruits is often short-lived due to enzymatic reactions that modify aroma composition.

The combination of different proportions of VACs and the presence or absence of certain trace components determines the aromatic properties of fruit (Ayala-Zavalla et al., 2004; Laohakunjit and Kerdechochueng, 2007) with non-characterising volatile esters quite common across species. Volatile compounds which make up the aroma of fruits are mainly esters, alcohols, aldehydes, ketones, lactones, terpenoids and hydrocarbons which can be classified as primary or secondary compounds, indicating whether they were present in intact fruit tissue or produced as a result of tissue disruption (wounding as a result of minimal processing). C$_{10}$ monoterpenes and C$_{15}$ sesquiterpenes are the most abundant group of compounds present in the aroma profile of fresh fruit. In some cases, they are also the key compounds determining characteristic aroma (El Hadi et al., 2013). Bound volatiles such as glucosides and/or glucosinolates, are recognised as a potential source of aroma compounds in kiwifruit (Actinidia deliciosa). Glucosides of aroma compounds in fruit are mainly O-β-D-glucosides and O-diglycosides, but triglycosides have also been identified (Sarry and Gunata, 2004; Reineccius, 2006). The proportion of free volatiles is usually much lower than that of glycosidically bound volatiles.

Based on AEDA analysis, the main volatile components reported for pineapple include esters, terpenes, ketones and aldehydes, notably ethyl 2-methylbutanoate, ethyl hexanoate, methyl hexanoate, 2,5-dimethyl-4-hydroxy-3(2H)-furanone (DMHF), decanal, ethyl 2-(methylthio)propionate, hexanoic acid, methyl ester, octanoic acid methyl ester and and methyl butanoate (Liu et al., 2011; Wei et al., 2011; Montero- Calderón et al., 2010).
In climacteric aromatic melon varieties, esters are prominent, together with sulphur-containing aroma compounds, sesquiterpenes, norisoprenes, short-chain alcohols (<C_{12}) and aldehydes (Burger et al., 2006; Obando-Ulloa et al., 2008). The most odour active VACs that have been identified for cantaloupe melon include ethyl-2-methyl butyrate, methyl 2-methylbutanoate, 3-methyl butyl acetate, ethyl butyrate, ethyl hexanoate, hexyl and benzyl acetate and some nine-carbon alcohols and aldehydes (Beaulieu and Grimm, 2001; Aubert and Bourger, 2004; Perry et al., 2009). Both aromatic and non-aromatic melon varieties possess amino acid derived volatiles which are major contributors to aroma (Burger et al., 2006). In aromatic varieties these volatiles are usually in abundance and mostly esterfied while in non-aromatic varieties they occur as aldehydes and alcohols (Verzera et al., 2011).

Kiwifruit appears to lack fingerprint volatiles. Instead they are characterised by a balance of esters, aldehydes and alcohols, in which branched volatiles or terpenoids are poorly represented (Warrington and Weston, 1990; Paterson et al., 1991). Based on AEDA and other techniques, more than 80 compounds have been identified as contributors to kiwifruit aroma. Methyl and ethyl butanoate, (Z)- and (E)-2-hexenal, hexanal, (Z)- and (E)-3-hexenol and methyl benzoate contribute most to an overall impression with (E)-2-hexenal been reported in some publications as the most abundant compound in ripe fruit (Young et al., 1983; Takeoka et al., 1987; Bartley and Schwede, 1989; Frank et al., 2007) with butanoate having a positive effect (Gunther et al., 2010; Carcia et al., 2013).

Many factors are known to affect volatile composition including intrinsic factors such as fruit type, cultivar, genetic make-up and maturity; extrinsic factors such as environmental conditions (pre- and post-harvest), exogenous ripening (applied ethylene), process severity (intact, sliced or homogenised), storage (Varoquaux and Wiley, 1994; Bolin et al., 1977; Wright and Kader, 1997; Ahvenainen, 2000; Bett et al., 2001; Martin-Belloso and Soliva-Fortuny, 2006; Artés-Hernández et al., 2007; Montero-Calderon et al., 2010; El Hadi et al., 2013; Finneghan et al, 2013) and the analytical method employed (Bruckner, 2008; Buttery, 1993).

Cutting of produce removes the natural protection of the epidermis and is a cause of major tissue disruption, destroying the internal compartmentalization as enzymes and
substrates, normally sequestered within the vacuole, become mixed with other cytoplasmic and nucleic substrates and enzymes. The presence of other enzymes (e.g. lipoxygenase) further alters these volatiles, in certain cases, giving rise to off-odours during prolonged storage (Montero-Calderón et al., 2010) which may be accompanied by flavour loss, discolouration, softening, gelling, shrinkage and an overall shorter SL.

Likewise, cut piece size may affect product quality and SL (Artes-Hernandez et al., 2007). The smaller the cut size the greater the respiration rate (Finnegan et al., 2013) and ethylene production, which stimulates the biosynthesis of enzymes related to accelerated ripening and senescence (Hyodo et al., 1978; Martínéz et al., 2006; Artés et al., 2007). Furthermore, increased surface area induces a higher rate of dehydration, and consequently a greater weight-loss. It also increases the synthesis of wound-response metabolites (lignin, cumarins and anthocyanins etc.) (Martin-Belloso and Soliva-Fortuny, 2006; Artés-Hernández et al., 2007).

Thus, the volatile composition is continuously changing in fruits. Current research on aroma and flavour has focused on the identification of volatiles produced by ripe fruits. A desirable, rich, fruity aroma, typical of most fruits, is often used by the consumer as an indicator of quality, ripeness and freshness. In contrast, fermented, mouldy, musty, acidic off-odours as well as insipid and bland aromas are indicators of spoilage, decay, under-ripeness and in general, inferior quality (Forney, 2001). Trace sulphur volatiles have also been recently identified that are thought to play significant roles in the flavour of some sub-/ tropical fruits such as pineapple, melons and kiwifruit (McGorrin, 2011; Schulbach et al., 2004). Therefore, the volatile composition of fruit provides consumers with a relatively good indication of produce quality. However, although these characteristics are highly influential to a consumers’ purchasing decision, there is limited knowledge of factors (intrinsic and extrinsic) affecting flavour development in MAP fresh-cut fruit produce.

The objective of the present study was to determine the extent of change of VACs in fresh-cut pineapple, cantaloupe melon and kiwifruit as affected by storage time and size reduction using principal component analysis (PCA), and use this data as a base for optimising aroma quality.
4.3. Materials and methods

4.3.1. Sample preparation – Processing and packaging of plant materials

Fresh fruit; pineapples (*Ananas comosus* cv Del Monte Gold MD2: #10), cantaloupe melon (*Cucumis melo* L. var *reiculatus*) and kiwifruit (*Actinidia deliciosa* cv *Hayward*) were purchased from a local fruit and vegetable wholesaler (Richardson’s Fruit and Vegetables, Old Clare St., Limerick, Ireland) on the morning of processing and stored at 4°C until required (1-2h). For pineapple, ripe fruit with a shell colour corresponding to stages 2 and 3 of the Dole pineapple colour chart (between 25% and 50% shell colour) were used for all experiments. For cantaloupe melon, fruits with a ½ to full slip, corresponding to a mature ripening to ripe melon, were used. For kiwifruit, fruits that were firm to touch and had excellent visual quality with no symptoms of deterioration (approx.11.5% soluble solids) were used.

All fruits were processed at room temperature (18-22°C). For fresh-cut pineapple, the peels of whole fruits were removed with a stainless steel knife which was sanitised in a 1% sodium hypochlorite (NaClO) solution between individual fruits in order to minimise contamination. The blossom and stem ends were removed and discarded and the fruit sliced transversely into rings (24mm). After slicing, the core from each ring was removed manually using a stainless steel cork borer. The slices were cut into triangular chunks of three different cut sizes (10mm, 25mm & 50mm) using a hand-held stainless steel cutter (*Figure 4.1a*). For fresh-cut cantaloupe melon, both the slip and top end of the fruits were removed and the melon halved transversely. The seeds were carefully removed using a stainless steel spoon (sanitised in a 1% NaClO solution between each fruit). Each half was cut into four longitudinal slices and the surrounding peel carefully removed from the flesh. Each section was subsequently cut into uniform trapezoidal chunks of varying size (*Figure 4.1b*). In the case of fresh-cut kiwifruit, the blossom and stem ends of whole fruits were removed and discarded and the rest of the peel carefully removed from the flesh using a sharp paring knife (sanitised in a 1% NaClO solution between each fruit). Fruits were then cut into longitudinal halves, followed by transverse quarters and then eights, depending on the size of the cut required (see *Figure 4.1c*).
Figure 4.1 Cutting sizes used in Sample Preparation and Experimental Setup of Fresh-cut (a) Pineapple – 10mm; 25mm and 50mm, (b) Cantaloupe melon- 10mm; 25mm & 50mm and (c) Kiwifruit- ⅛, ¼ and ½.
Cut piece sizes for each individual fruit were pooled and samples (150g ± 5g) were prepared in duplicate, each from randomly selected fruit pieces. Samples were placed into rigid polylactic acid (PLA) containers (Biopak, UK) and inserted into pillow-pouch packages (20cm x 20cm) previously constructed from a high-barrier (HB) double-laminate film (PET12/PE55 microns) having oxygen (OTR) and carbon dioxide (CTR) permeabilities of 62,814 and 212,776 mL.microns/m².day.atm, respectively. The packages were hermetically heat sealed using an impulse bench-top heat sealer (Relco Ltd., UK) and stored at refrigeration temperatures (3 to 5°C) for 14 days. Sealing allowed a passive MAP to develop within packs as a result of the natural respiration of the fruit. At set intervals during storage (Day 1, 4, 7 & 14) static headspace SPME analysis and physiochemical evaluations took place. Duplicate packs were analysed for each treatment and repeated twice (n = 4).

4.3.2. Sample Preparation - static headspace solid-phase micro-extraction

The contents of each pack (approx. 150g fruit tissue) was homogenised to a macerate using a stainless steel grater, stirred briefly using a sterile glass rod and allowed to stand for 1 minute before sampling (to allow foam to settle). Four grams of homogenate was transferred into a 20mL screw capped glass (amber) vial with a silicone/PTFE liner, 1.3 mm, 45 shore value (Apex Scientific Ltd., Maynooth, Co. Kildare, Ireland). This was done in duplicate per pack analysed.

Variability in analyte recovery with SPME was previously observed with various sampling regimes; thus variation was minimised and the procedure optimised prior to sampling by maintaining temperature, sample weight/volume, agitation speed, absorption and desorption times using the method by Montero-Calderon et al. (2010). The sample vials were equilibrated to 40°C for 5 minutes using pulsed agitation (3s at 650rpm). Sample introduction was carried out using a CTC Analytics GC Autosampler 80 (Agilent Technologies, Euro House, Little Island, Cork). A single 1cm x 50/30µm, 24 gauge StableFlex divinylbenzene/ Carboxen/polydimethylsiloxane (DVB/Carboxen/PDMS) fibre was used for all analysis (Supelco, Bellefonte, PA., USA). The SPME fibre was exposed to the headspace above the macerated sample for 5 minutes. The fibre was then retracted and injected.
via a Merlin microseal (Sigma Aldrich Ireland Ltd., Arklow, Wicklow, Ireland) on a multimode inlet using a Supelco SPME inlet (Sigma Aldrich Ireland Ltd.) at 260°C and desorbed for 2 minutes. The fibres were cleaned between samples using a bake out station at 270°C and carry over was assessed by running a blank sample between each treatment. The gas chromatograph-mass spectrometer was an Agilent Technologies 7890A with an Agilent 5975C Inert XL Mass Selective Detector (Agilent Technologies, Ireland) operating in scan mode within a mass range of 40-450amu at 2.5 scans s⁻¹ (MS Source: 230°C; MS Quad: 150°C). Ionisation was performed by electron impact at 70eV. The column was a HP-INNOWAX Polyethylene Glycol Column (60m x 250 µm x 0.5 µm) (Agilent Technologies, Ireland) and compounds were separated under the following conditions using helium as a carrier (1.2mL/min⁻¹): initial column temperature (40°C for 5 min), heated to 260°C at 20°C min⁻¹ and finally holding for 5 min. An auto-tune of the MS was carried out prior to each analysis to confirm that MS was operating optimally.

4.3.3. Physiochemical Analysis

In-pack gas atmosphere

On each sampling day, the headspace gas composition of packs was determined using a hand-held gas analyser (MAP-PAK Combi, AGC Instruments, Shannon, Co. Clare, Ireland). This instrument quantifies O₂ and CO₂ using an electrochemical sensor and a non-dispersive infrared sensor (NDIR). A 5mL sample was withdrawn by piercing each pack with the hypodermic needle through resealable tape.

Weight-loss (%)

Weight loss was determined on each sampling day as per Moneruzzman et al., (2008) and expressed as percentage difference of the weight on initial day of packaging (Day 0).
Percent soluble solids (SS %)

One millilitre of clear juice was taken from the macerated sample and the percentage of soluble solids measured using an Atago Digital Pocket Refractometer (Atago Co., Ltd., Tokyo, Japan).

Tissue pH and titratable acidity (TA %)

The pH of fresh-cut fruit pulp homogenate was directly measured using a calibrated Jenway 3510 pH meter. Titratable acidity was calculated as citric acid by titrating juice samples to pH 8.2 using 0.1N NaOH.

4.3.4. Volatile aromatic compound analysis

Individual volatile aromatic compounds were identified using mass spectral comparisons in the National Institute for Standards and Technology (NIST) mass spectral library 2008, (Agilent Technologies, Ireland). Individual compounds were assigned quantification and qualifier ions to ensure that only the individual compounds were identified. Quantification was performed by integrating the peak areas of the extracted ions using Agilent Chemstation; where increasing or decreasing relative peak areas demonstrated increasing or decreasing compound concentrations respectively.

4.3.5. Statistical analysis

Repeated measures ANOVA (SPSS Statistics 20, IBM, Chicago, IL. USA) was carried out to assess several measurements of the same fruit under different treatments and at different points in time. Factors were compared to determine differences in the means of response variables using a least significant difference (LSD) multi-comparison test, and significant differences were reported using Duncan’s test for homogeneity at p≤0.05.
For each cut size, PCA was performed on all VACs previously identified using UNSCRAMBLER software (Version 9.7, CAMO A/S, Trondheim, Norway). The analysis was performed on the response of each variable (VAC) to three cut sizes per fruit, each the mean of two replicates. The selection of variables was done according to the recurrence or not of the different VACs for each specific cut size during storage. In order to understand the relationship between the headspace aroma profile and cut size and storage time, a score for each sample was generated as a linear combination for each treatment. The contribution of each parameter to the PCA score was deduced from the parameters loading for the factor.
4.4. Results

4.4.1. In-pack gas atmosphere and physiochemical attributes of quality

The headspace gas compositional changes for fresh-cut pineapple, cantaloupe melon and kiwifruit as affected by cut size during storage are presented in Figure 4.2a, 4.2b & 4.2c respectively. During 14 Day storage, oxygen (O$_2$) concentrations decreased from normal air concentrations (20.9%) and CO$_2$ concentrations increased from 0.04% while aerobic conditions were maintained.

In fresh-cut pineapple, CO$_2$ levels were approximately 5, 10 and 20% on Days 4, 7 and 14, respectively while O$_2$ levels remained above 10%. No significant effects of cut size were found (p>0.05). Gas levels in fresh-cut cantaloupe melon were broadly similar except that smaller cut sizes had less O$_2$ and higher levels of CO$_2$ (up to 20% for 10mm cut size). Fresh-cut kiwifruit, having higher respiration rates, had very high CO$_2$ levels of 20 and 25% on days 7 and 14, respectively. Again, smaller cut sizes had higher CO$_2$ levels, however; O$_2$ levels were >5%.

Weight-loss was highly dependent on fruit type (Table 4.1). With the exception of fresh-cut cantaloupe melon, weight-loss increased with process severity, i.e. smaller cut pieces, while for fresh-cut kiwifruit weight-losses reported were relatively minor. Table 4.1 shows the physiochemical or non-volatile component changes of fruit flavour during 14 Day storage. Cut size and storage time had significant effects on flavour attributes such as percent soluble solids and acidity (p<0.001) and was highly dependent on fruit type (p<0.01).
Figure 4.2 Changes in in-pack headspace oxygen (O$_2$) and carbon dioxide (CO$_2$) concentrations of packaged Fresh-cut (a) Pineapple, (b) Cantaloupe melon and (c) Kiwifruit as affected by cutting size during storage (14 Days) at 4°C. The values are means for four determinations, separated by Fisher’s Least Significant Difference (LSD) (p<0.05). Error bars show ±SD. In-pack O$_2$, continuous lines, descending; in-pack CO$_2$, broken lines, ascending.
Table 4.1 Physiochemical properties of fresh-cut fruits during 14 Days storage at 4°C.

<table>
<thead>
<tr>
<th>Fruit</th>
<th>Cut Size</th>
<th>Weight-loss (%)</th>
<th>Soluble Solids (%)</th>
<th>Tissue pH</th>
<th>Titratable Acidity (%)</th>
<th>Sugar/Acid Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Day 0</td>
<td>Day 14</td>
<td>Day 0</td>
<td>Day 14</td>
</tr>
<tr>
<td>Pineapple</td>
<td>10mm</td>
<td>16&lt;sup&gt;a&lt;/sup&gt;</td>
<td>12.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>12&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.3&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>25mm</td>
<td>8&lt;sup&gt;b&lt;/sup&gt;</td>
<td>13.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>12.6&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.3&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>50mm</td>
<td>4&lt;sup&gt;c&lt;/sup&gt;</td>
<td>13.6&lt;sup&gt;c&lt;/sup&gt;</td>
<td>13.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.3&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Cantaloupe</td>
<td>10mm</td>
<td>4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8.4&lt;sup&gt;d&lt;/sup&gt;</td>
<td>6.8&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.9&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Melon</td>
<td>25mm</td>
<td>8&lt;sup&gt;b&lt;/sup&gt;</td>
<td>9.6&lt;sup&gt;c&lt;/sup&gt;</td>
<td>8.1&lt;sup&gt;d&lt;/sup&gt;</td>
<td>6.9&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.7&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>50mm</td>
<td>4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>8.3&lt;sup&gt;d&lt;/sup&gt;</td>
<td>6.9&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.7&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Kiwifruit</td>
<td>⅛</td>
<td>3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>12.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>11.4&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.6&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>¼</td>
<td>1&lt;sup&gt;a&lt;/sup&gt;</td>
<td>11.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>11.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.6&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>½</td>
<td>2&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>11.9&lt;sup&gt;a&lt;/sup&gt;</td>
<td>11.2&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.6&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

- Values are the means for 8 replicates.
- For each individual fruit type and attribute, same letters within a column(s) are not significantly different according to Duncan’s test for homogeneity at a 5% significance level (p<0.05).
- Titratable acidity % reported as citric acid equivalent.
4.4.2. Volatile aromatic compound profile for fresh-cut fruits

*Fresh-cut pineapple*

Table 4.2 shows the volatile aromatic composition in the headspace of fresh-cut pineapple during 14 days storage at 4°C. A total of 29 compounds were detected, of which 18 odour-active compounds were identified and used in further PCA calculations. Fresh-cut pineapple (Day 0 to 14) contained 72% esters, 11% acetate esters, 11% sesquiterpenes, 6% sulphur-ester of which methyl-2-methylbutanoate, methyl-3-(methylthio) propionate and α-copaene were the most abundant, respectively. Trace amounts of other compounds were found but their absolute values varied.

Ethyl acetate, methyl propionate, methyl isobutyrate, methyl butanoate, methyl-2-methylbutanoate, methyl caproate, methyl caprate and methyl heptanoate significantly increased (p<0.001) during 14 Days storage. Methyl-2E-hexenoate (*fruity*) and methyl valerate (*fruity, sweet*) decreased in concentration during storage; however, this decrease was not significant (p>0.05).

In contrast to fresh-cut cantaloupe melon and kiwifruit, larger fresh-cut pineapple pieces had higher VAC concentrations than smaller cut pieces, with ethyl acetate (*sweet, fruity*), methyl propionate (*sweet, fruity, rum-like*), methyl isobutyrate (*fresh, fruity, pineapple*), methyl valerate (*fruity, sweet*) and methyl caprate (*fruity*) in greater abundance. Smaller cut pieces had significantly lower levels of methyl acetate (*fruity*) than larger pieces (p<0.01) while methyl caprylate (*fruity*) and methyl-3-(methylthio) propionate (*pineapple*) were found in higher levels (p<0.001) in smaller cut pieces.
Table 4.2: Changes in volatile aromatic compound content (peak area) of fresh-cut pineapple during 14 Days storage at 4°C.

<table>
<thead>
<tr>
<th>IUPAC Name</th>
<th>RT min</th>
<th>CAS #</th>
<th>Descriptors</th>
<th>Day 0</th>
<th>Day 1</th>
<th>Day 4</th>
<th>Day 7</th>
<th>Day 14</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25mm</td>
<td>10mm</td>
<td>25mm</td>
<td>50mm</td>
<td>10mm</td>
</tr>
<tr>
<td>AE Methyl Acetate</td>
<td>5.833</td>
<td>79-28-9</td>
<td>Fruity, Banana, Pear</td>
<td>4.73E+07</td>
<td>1.38E+07</td>
<td>3.64E+07</td>
<td>3.59E+07</td>
<td>2.72E+07</td>
</tr>
<tr>
<td>AE Ethyl Acetate</td>
<td>6.134</td>
<td>141-78-6</td>
<td>Sweet, Fruity, Pleasant</td>
<td>3.09E+07</td>
<td>2.74E+07</td>
<td>3.31E+07</td>
<td>2.32E+07</td>
<td>2.34E+07</td>
</tr>
<tr>
<td>E Methyl Propionate</td>
<td>6.269</td>
<td>554-12-1</td>
<td>Sweet, Fruity, Rum-like</td>
<td>5.86E+07</td>
<td>6.22E+07</td>
<td>5.58E+07</td>
<td>8.06E+07</td>
<td>5.37E+07</td>
</tr>
<tr>
<td>E Methyl Isobutyrate</td>
<td>6.368</td>
<td>97-62-1</td>
<td>Fresh, Fruity, Pineapple</td>
<td>4.26E+07</td>
<td>6.47E+07</td>
<td>4.41E+07</td>
<td>5.09E+07</td>
<td>3.76E+07</td>
</tr>
<tr>
<td>E Methyl Butanoate</td>
<td>6.802</td>
<td>623-42-7</td>
<td>Sweet, Fruity, Pineapple</td>
<td>1.51E+07</td>
<td>1.88E+07</td>
<td>1.64E+07</td>
<td>1.99E+07</td>
<td>1.88E+08</td>
</tr>
<tr>
<td>E Methyl-2-methyl Butanoate</td>
<td>6.982</td>
<td>868-57-5</td>
<td>Fruity, Acetic</td>
<td>8.63E+08</td>
<td>8.00E+08</td>
<td>8.21E+08</td>
<td>8.86E+08</td>
<td>8.01E+08</td>
</tr>
<tr>
<td>E Ethyl-2-methylbutanoate</td>
<td>7.235</td>
<td>7452-79-1</td>
<td>Fruity</td>
<td>1.02E+07</td>
<td>2.36E+07</td>
<td>2.03E+07</td>
<td>2.07E+07</td>
<td>1.93E+07</td>
</tr>
<tr>
<td>E Methyl Caproate</td>
<td>8.333</td>
<td>106-76-7</td>
<td>Pineapple</td>
<td>1.65E+09</td>
<td>7.08E+08</td>
<td>5.63E+08</td>
<td>6.04E+08</td>
<td>5.53E+08</td>
</tr>
<tr>
<td>E Ethyl Caproate</td>
<td>8.682</td>
<td>123-66-0</td>
<td>Green, Sweet, Fruity</td>
<td>5.41E+07</td>
<td>7.99E+07</td>
<td>1.54E+08</td>
<td>8.17E+07</td>
<td>1.32E+08</td>
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<tr>
<td>E Methyl (2E)-2-hexenoate</td>
<td>8.896</td>
<td>13894-63-8</td>
<td>Fruity</td>
<td>3.25E+07</td>
<td>1.57E+07</td>
<td>1.44E+07</td>
<td>1.32E+07</td>
<td>1.97E+07</td>
</tr>
<tr>
<td>E Methyl Valerate</td>
<td>9.138</td>
<td>624-24-8</td>
<td>Flowery, Fruity, Sweet</td>
<td>1.10E+07</td>
<td>1.98E+07</td>
<td>3.00E+07</td>
<td>3.42E+07</td>
<td>5.27E+06</td>
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<tr>
<td>E Methyl Heptanoate</td>
<td>9.138</td>
<td>106-73-0</td>
<td>Fruity</td>
<td>5.76E+07</td>
<td>4.36E+07</td>
<td>3.22E+07</td>
<td>3.77E+07</td>
<td>4.31E+07</td>
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<tr>
<td>E Methyl Caprylate</td>
<td>9.926</td>
<td>111-11-5</td>
<td>Fruity, Citrus</td>
<td>3.66E+08</td>
<td>3.79E+08</td>
<td>3.67E+08</td>
<td>4.50E+08</td>
<td>3.86E+08</td>
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Table 4.2 continued

<table>
<thead>
<tr>
<th></th>
<th>Ingredient</th>
<th>R.T. (minutes)</th>
<th>AE</th>
<th>E</th>
<th>SE</th>
<th>ST</th>
<th>Total Peak Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Methyl Caprate&lt;sup&gt;1&lt;/sup&gt;</td>
<td>11.401</td>
<td>110-42-9</td>
<td>Fruity</td>
<td>1.81E+07</td>
<td>1.15E+07</td>
<td>1.10E+07</td>
</tr>
<tr>
<td>E</td>
<td>4-Methyl Decanoic acid&lt;sup&gt;1,3&lt;/sup&gt;</td>
<td>11.648</td>
<td>24323-24-8</td>
<td>Fruity</td>
<td>1.80E+07</td>
<td>1.95E+07</td>
<td>2.36E+07</td>
</tr>
<tr>
<td>SE</td>
<td>Methyl-3- (methylthio) propionate&lt;sup&gt;1,4,5&lt;/sup&gt;</td>
<td>11.085</td>
<td>13532-18-8</td>
<td>Pineapple</td>
<td>1.51E+07</td>
<td>5.02E+07</td>
<td>5.79E+07</td>
</tr>
<tr>
<td>ST</td>
<td>α-Copaene&lt;sup&gt;1,2,3&lt;/sup&gt;</td>
<td>11.042</td>
<td>3856-25-5</td>
<td>Woody</td>
<td>1.87E+07</td>
<td>2.75E+07</td>
<td>3.53E+07</td>
</tr>
<tr>
<td>ST</td>
<td>α-Cadinene&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>12.693</td>
<td>24096-05-1</td>
<td>Woody</td>
<td>2.01E+07</td>
<td>1.50E+07</td>
<td>1.88E+07</td>
</tr>
<tr>
<td></td>
<td>Total Peak Area</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.65E+09</td>
<td>2.71E+09</td>
<td>2.57E+09</td>
</tr>
</tbody>
</table>

Values are means of four replicate fresh-cut pineapple samples.
R.T. (retention time; minutes), AE (acetate ester), E (ester), SE (thiol-ester; sulphurous) and ST (sesquiterpene)

10mm (10mm cut size); 25mm (25mm cut piece size); 50mm (50mm cut piece size)

<sup>1</sup> - Montero-Calderon et al., (2010)
<sup>2</sup> - Zhang et al., (2009)
<sup>3</sup> - Liu et al., (2011)
<sup>4</sup> - Wei et al., (2011)
<sup>5</sup> - He et al., (2007)
**Fresh-cut cantaloupe melon**

Table 4.3 presents the volatile aromatic composition of the headspace of fresh-cut cantaloupe melon during 14 day storage at 4°C. Fresh-cut cantaloupe melon contained 88% esters (44% acetate esters) predominantly ethyl acetate, methyl-2-methylbutanoate, n-propyl acetate and methyl- and ethyl- butanoate and 6% alkenes and alcohols (fucoserratene and 3-nonen-1-ol, respectively). The results showed that esters were the most abundant volatile compounds, and that their relative peak areas were greatest for smallest cut pieces and increased during storage.

Ethyl acetate (*fruity, sweet*), ethyl propanoate (*fruity*), isopropyl propanoate (*fruity*), n-propyl acetate (*melon*) and methyl butanoate (*sweet*) increased significantly in concentration (p<0.001) during storage. Isobutyl acetate (*fruity, floral*) and benzyl acetate (*sweet*) were detected in fresh-cut samples only, while fucoserratene (*melon*) was found from Day 1 to Day 14.

Twenty-five millimetre cut pieces had greater concentrations of the former compounds in addition to ethyl caproate (p<0.001) than 10mm and 50mm pieces respectively. However, 25mm pieces had a significant loss of n-butyl acetate (p<0.01) and 2-nonen-1-ol (p<0.001) during storage, in contrast to 10mm and 50mm, which both displayed significant increases (p<0.01). Largest cut pieces (50mm) had significant losses in isoamyl acetate (p<0.01) while both 10mm and 25mm pieces had significant increases (p<0.001).
Table 4.3 Changes in volatile aromatic compound content (peak area) of fresh-cut cantaloupe melon during 14 Days storage at 4°C

<table>
<thead>
<tr>
<th>IUPAC Name</th>
<th>Category</th>
<th>Peak Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT min</td>
<td>CAS #</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AE</td>
<td>Methyl Acetate(^1)</td>
<td>5.831</td>
</tr>
<tr>
<td>AE</td>
<td>Ethyl Acetate(^2,3)</td>
<td>6.237</td>
</tr>
<tr>
<td>E</td>
<td>Ethyl Propanoate(^1,6)</td>
<td>6.585</td>
</tr>
<tr>
<td>E</td>
<td>Isopropyl Propanoate(^1,5,6)</td>
<td>6.641</td>
</tr>
<tr>
<td>E</td>
<td>Ethyl Caproate(^1)</td>
<td>8.672</td>
</tr>
<tr>
<td>AE</td>
<td>n-Butyl Acetate(^1)</td>
<td>7.35</td>
</tr>
<tr>
<td>AE</td>
<td>n-Propyl Acetate(^1)</td>
<td>6.705</td>
</tr>
<tr>
<td>E</td>
<td>Methyl Butanoate(^1,5,6)</td>
<td>6.797</td>
</tr>
<tr>
<td>E</td>
<td>Methyl-3-hydroxybutanoate(^1,3,4)</td>
<td>6.799</td>
</tr>
</tbody>
</table>

\(^1\) CAS: 599-16-3

\(^2\) CAS: 124-68-3

\(^3\) CAS: 123-82-2

\(^4\) CAS: 1487-49-6

\(^5\) CAS: 90-78-9

\(^6\) CAS: 89-62-7
<table>
<thead>
<tr>
<th>Table 4.3 Continued</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E</strong></td>
</tr>
<tr>
<td><strong>E</strong></td>
</tr>
<tr>
<td><strong>AE</strong></td>
</tr>
<tr>
<td><strong>AIHC</strong></td>
</tr>
<tr>
<td><strong>OH</strong></td>
</tr>
<tr>
<td><strong>AE</strong></td>
</tr>
<tr>
<td><strong>-</strong></td>
</tr>
</tbody>
</table>

Values are means of four replicate fresh-cut cantaloupe melon samples.
R.T. (retention time; minutes), E (ester), AE (acetate ester), AIHC (aliphatic hydrocarbon) and OH (alcohol);
10mm (10mm cut piece size); 25mm (25mm cut piece size); 50mm (50mm cut piece size)

1 – Burger et al., (2006)
2 – Obando-Ulloa et al., (2008)
3 – Beaulieu and Grimm, (2001)
4 – Aubert and Bourger, (2004)
5 – Perry et al., (2009)
6 – Verzera et al., (2011)
**Fresh-cut kiwifruit**

Table 4.4 presents the volatile aromatic composition of the headspace of fresh-cut kiwifruit during 14 day storage at 4°C. The volatiles detected included 42% esters (including 1 carbonate ester), 21% monoterpenes, 16% alkyl aldehydes, 15% alcohols and 3% of compounds each from amide and furan classes. The results showed that esters were the most abundant volatile compounds, and that their relative peak areas were greatest for smallest cut pieces, and that this increased during storage. Of the three fruits studied, fresh-cut kiwifruit exhibited the greatest change in aroma profile, with the emergence of certain volatiles (methoxyacetone, 3-methyl-oxiran-2-yl-methanol, ethyl-2methylbutanoate, diethyl carbonate and ethyl benzoate) and loss of others (lactamide, 2-ethylfuran, hexanal, camphene, limonene, 3-hexen-1-ol \((Z)\) and 2, 4-hexadienal).

Significant increases in ethyl acetate \((p<0.01)\), ethyl butanoate \((p<0.001)\), α-pinene \((p<0.01)\), ethyl-2-methylbutanoate \((p<0.05)\), ethyl caproate \((p<0.001)\) and 1-hexanol \((p<0.05)\) were observed during storage, while β-pinene showed a significant reduction in concentration \((p<0.01)\). Levels of 3-hexen-1-ol were significantly lower \((p<0.001)\) than 2-hexen-1-ol \((E,Z)\), \((p<0.05)\).

Limonene \((citrus)\) and 2,4-hexadienal \((green, citrusy)\) were only present in fresh-cut samples (Day 0) while camphene \((green, sweet, fruity)\) was detected up until Day 1. Fresh-cut samples also contained low quantities of lactamide and 2-ethylfuran which were absent from the profile on subsequent sampling days. Methoxyacetone \((sweet, cooling)\) and diethyl carbonate \((fruity)\) were detected in all packs, irrespective of cut size, form Day 7 to Day 14 while 3-methyl-oxiran-2-yl-methanol \((sweet, alcohol)\) was detected in Day 14 packs only.

Both ¼ and ½ pieces had significantly higher concentrations of ethyl acetate \((p<0.001)\) than ⅛ pieces \((p<0.01)\). In contrast ⅛ pieces had significantly higher levels of 1-hexanol \((p<0.05)\). Methoxyacetone, \((3\text{-}methyl\text{-}oxiran\text{-}2\text{-}yl)\)-methanol and ethyl benzoate levels were significantly higher in larger cut pieces \((p<0.05)\) while concentrations of diethyl carbonate levels were greatest in smaller cut pieces \((p<0.01)\).
Table 4.4 Changes in volatile aromatic compound content (peak area) of fresh-cut kiwifruit during 14 Days storage at 4°C.

<table>
<thead>
<tr>
<th>IUPAC Name</th>
<th>RT min</th>
<th>CA S #</th>
<th>Descriptor s</th>
<th>Day 0</th>
<th>Day1</th>
<th>Day4</th>
<th>Day 7</th>
<th>Day 14</th>
<th>Peak Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl Acetate&lt;sup&gt;1&lt;/sup&gt;</td>
<td>6.136</td>
<td>141-76-6</td>
<td>Sweet, Fruity, Pleasant</td>
<td>1.10E+0</td>
<td>1.21E+0</td>
<td>1.37E+0</td>
<td>1.05E+0</td>
<td>2.62E+0</td>
<td>2.53E+0</td>
</tr>
<tr>
<td>Methoxyacetone&lt;sup&gt;2&lt;/sup&gt;</td>
<td>6.348</td>
<td>5878-19-3</td>
<td>Sweet, Cooling</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(3-Methyl-oxiran-2-yl)-methanol&lt;sup&gt;3&lt;/sup&gt;</td>
<td>6.58</td>
<td>872-38-8</td>
<td>Sweet, Alcohol</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2-Ethylfuran&lt;sup&gt;4&lt;/sup&gt;</td>
<td>7.031</td>
<td>3208-16-0</td>
<td>Rum, ether</td>
<td>6.72E+0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ethyl Butanoate&lt;sup&gt;5, 6&lt;/sup&gt;</td>
<td>7.128</td>
<td>105-54-4</td>
<td>Sweet, Fruity, Citrus</td>
<td>1.15E+0</td>
<td>2.05E+0</td>
<td>1.96E+0</td>
<td>1.21E+0</td>
<td>1.54E+0</td>
<td>2.35E+0</td>
</tr>
<tr>
<td>(1R)(+)α-Pinene&lt;sup&gt;7, 8, 9&lt;/sup&gt;</td>
<td>7.194</td>
<td>7785-70-8</td>
<td>Harsh, Citrus, Terpenelike, Minty</td>
<td>2.42E+0</td>
<td>1.45E+0</td>
<td>1.62E+0</td>
<td>1.37E+0</td>
<td>5.74E+0</td>
<td>1.23E+0</td>
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<tr>
<td>Ethyl 2-methylbutanoate&lt;sup&gt;10, 11&lt;/sup&gt;</td>
<td>7.227</td>
<td>7452-79-1</td>
<td>Fruity, Sweet</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Hexanal&lt;sup&gt;10, 12&lt;/sup&gt;</td>
<td>7.523</td>
<td>66-25-1</td>
<td>Fruity, Fresh-cut Grass</td>
<td>8.20E+0</td>
<td>1.84E+0</td>
<td>1.40E+0</td>
<td>3.95E+0</td>
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209
<table>
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<tr>
<td>CE</td>
<td>Diethyl Carbonate</td>
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<tr>
<td>MT</td>
<td>1,3,4,5,7-Dimethyl-1,4-cyclohexadiene</td>
<td>8.150</td>
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<td>0.000</td>
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<tr>
<td>AL</td>
<td>2-Hexenal, (E)</td>
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<td>OH</td>
<td>3-Hexen-1-ol, (Z)-</td>
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<td>0.000</td>
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<tr>
<td>OH</td>
<td>2-Hexen-1-ol, (E,Z)-</td>
<td>9.951</td>
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<td>0.000</td>
<td>0.000</td>
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</tr>
<tr>
<td>E</td>
<td>Ethyl benzoate</td>
<td>12.24</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>
Values are means of four replicate fresh-cut kiwifruit samples.
R.T. (retention time; minutes), E (ester), A, (amide), MT (monoterpenes), AL (aldehyde), F (Furan), CE (carbonate ester) and OH (alcohol)

\( \text{ Total Peak Area } \)

\[
\begin{array}{cccccccccc}
2.22 \times 10^9 & 1.84 \times 10^9 & 2.04 \times 10^9 & 2.08 \times 10^9 & 1.72 \times 10^9 & 2.2 \times 10^9 & 2.17 \times 10^9 & 2.37 \times 10^9 & 2.77 \times 10^9 & 2.98 \times 10^9 & 3.52 \times 10^9 & 2.92 \times 10^9 \\
\end{array}
\]

\( \frac{1}{8} \) (one-eighth of whole fruit); \( \frac{1}{4} \) (one-quarter of whole fruit); \( \frac{1}{2} \) (one-half of whole fruit)

1 – Paterson et al., (1991)
2 – Warrington and Weston, (1990)
3 – Young et al., (1983)
4 – Takeoka et al., (1987)
5 – Bartley and Schwede, (1989)
6 – Gunther et al., (2010)
7 – Garcia et al., (2013)
8 – http://www.thegoodscentscompany.com/allodor.html
4.4.3. Principal component analysis

In order to obtain a more comprehensive understanding of the response of VACs to storage and cut size, principal component analysis (PCA) was carried out on the correlation matrix produced from 18, 16 and 20 volatile aromatic compounds produced for fresh-cut pineapple (Figure 4.3), cantaloupe melon (Figure 4.4) and kiwifruit (Figure 4.5). The factor loadings were plotted based on the first two principal components (PCI and PCII), with VACs and samples illustrated as vector angles and symbols, respectively. PCI accounted for the largest amount of total variance (inertia) meaning that under typical test conditions PCI was correlated with many of the observed variables loaded on that component. PCII was uncorrelated with PCI and accounted for the largest amount of total variance in the dataset not accounted for by PCI. A consistent trend was observed for all fruits studied in that the rotated factor pattern demonstrated a simple orthogonal structure, with VAC loadings on PCI and PCII measuring different constructs. Furthermore, VAC loadings on PCI and PCII share the same conceptual meaning, e.g. PCI refers to fresh aroma while PCII refers to stored or stale aroma, where appropriate. Observations close to each other are said to be positively correlated, meaning that their influence on the positioning of samples is similar and have similar characteristics, i.e. fresh, sweet, and rum-like, etc. Variables distant from each other across an axis plane are defined as being negatively correlated. Loading plot (a) shows the relationship between VACs during storage, while score plot (b) illustrates the relationship between the cut sizes for each of the fresh-cut fruits during storage.

All samples migrated in a similar pattern during storage; however the rate and extent of the pattern was dependent of fruit type and cut size.

Fresh-cut pineapple

For fresh-cut pineapple, the factor loadings were plotted based on the first two principal components (PCI and PCII) explaining 48% of the total variance (Figure 4.3a). Depending on the storage time and cut size, sample scores were separated out along the PCs according to their pace of aroma change (Figure 4.3b). Storage time had a larger effect on VAC patterns than cut size as illustrated by unique positioning
of the sample scores. PCII separated fresh pineapple (Day 1 and Day 4) from Day 7 and Day 14 samples, while PCI separated Day 1 and Day 4 samples from Day 7 and Day 14 samples. Furthermore, PCI also separated Day 7 from Day 14 samples. Samples to the right were characterised as having a sweeter pineapple aroma while samples to the left had a much stronger acidic and heady pineapple aroma.

Day 1 and Day 4 samples had negative loadings across PCI due to the low concentrations of VACs, which increased during storage. VACs associated with fresh-cut pineapple aroma were, methyl valerate (fruity, sweet), methyl- and ethyl-acetate (fruity, sweet), methyl isobutyrate (pineapple), methyl propionate (fruity, sweet), methyl butanoate (sweet, pineapple) and ethyl caproate (green, fruity, sweet). These VACs were highly correlated with early storage (Day 1 and 4) and negatively correlated with late storage (Day 7 and 14), signifying that as storage progressed, the former aroma notes decreased in intensity.

Positive loadings across PCI for samples stored for 7 and 14 days were attributed to higher concentrations of methyl caproate (pineapple), methyl caprate (fruity), methyl heptanoate (fruity), methyl, 2-methylbutanoate (fruity, acidic), copaene (rum-like, herbaceous, woody), 4-methyldecanoate (fruity) and the sulphurous compound 3-(methylthio)propanoic acid methyl ester (pineapple). Furthermore, PCI separated Day 7 samples from Day 1, 4 and 14 samples based on higher concentrations of methyl 2-E hexenoate (fruity). Here it was noted that PCI loadings were inversely correlated with early storage samples due to the unique positioning of samples scores.

As storage progressed, there was a loss in FC volatiles with samples moving in an upwardly manner, developing more pungent and intense pineapple aromas. Furthermore, FC samples were not well differentiated from samples stored for 1 or 4 Days meaning that by Day 4, samples still had characteristic fresh-cut aroma qualities.

Interestingly, on Day 14, largest cut pieces (50mm) were separated on PCII from 10mm and 25mm samples (PCI), signifying that larger cut pieces had a significantly different aroma profile than smaller cut pieces with lesser concentrations of sulphurous pineapple notes and greater intensities of sweet
pineapple notes. Ten millimetre cut pieces had the greatest aroma change of all samples as demonstrated by the unique positioning of VAC sample scores, with the biggest change occurring after Day 4. A similar trend in aroma change was also observed for both other samples. However, the rate was not the same indicating that process severity greatly affected aroma change. It is also suggested that the aroma shelf-life of fresh-cut pineapple, based on PCA observations is less than 4 days.
Figure 4.3 Principal Component Analysis: Loadings (a) and Scores (b) of the volatile aroma compounds for the biplot generated for fresh-cut pineapple stored for 0, 14, 7 and 14 days at 4°C.
**Fresh-cut cantaloupe melon**

For fresh-cut cantaloupe melon, PCI explained 39% of the total variance and PCII explained a further 15% (Figure 4.4). In general, PCI separated Day 0, 1, 4 and 7 samples from Day 14 samples (left to right) while PCII separated FC and Day 1 samples from Day 4 and Day 7 samples. FC and Day 1 samples have negative loadings across PCI due to the lower initial VAC concentrations. Smallest cut size samples (10mm) were largely separated from larger cut samples (25mm and 50mm) during storage. Ten-millimetre cut size samples had the fastest rate of change and 50mm, the least. Fifty-millimetre cut size samples had the greatest VAC change (Day 1 to Day 4) with minor change from Day 4 to Day 7, followed by a steady rate of change to Day 14. Twenty-five millimetre cut size had a steady rate of change from Day 1 to Day 7, and a substantial VAC change thereafter. However, it should be noted that a gradual increase in VACs occurred during storage, irrespective of cut size.

Positive loadings across both axes were attributed to increased concentrations of ethyl acetate (*sweet, fruity*), ethyl propanoate (*rich, fruity*), isopropyl propanoate (*fruity*), n-butyl acetate (*fruity*), n-propyl acetate (*melon, pungent*), methyl butanoate (*sweet, acrid*), methyl acetate (*fruity, banana, pear*), methyl-2-methylbutanoate (*fruity, acidic*), 2-methylbutyl acetate (*sweet, fruity*), 1.3-trans, 5-cis-octatriene (*melon*) and 3-nonen-1-ol (*green, melon*). Furthermore, isobutyl acetate and benzyl acetate were found in FC samples (Day 0) only.

PCI separated 10mm and 50mm Day 14 samples from Day 4 and Day 7 samples by higher concentrations of ethyl butanoate, 3-nonen-1-ol and methyl acetate. On Day 14, 25mm samples were separated from 10mm and 50mm by higher concentrations of ethyl propanoate (*rich, fruity*), n-propyl acetate (*melon, pungent*), n-butyl acetate (*fruity*) and ethyl caproate (*fruity*). Samples located to the left (early storage) were characterised as having a more pleasant, sweet, fruity melon aroma which gradually moved to the right in favour of a more pungent, acrid melon aroma as storage progressed.

Interestingly, 50mm cut pieces appeared to retain more of a fresh-cut melon aroma after 14 Days, characterised by PCA as having lesser concentrations of
pungent VACs. Fifty millimetre and 10mm samples stored for 1 Day had similar aroma qualities and were well differentiated from 25mm samples. By Day 4, 25mm and 50mm samples shared similar aroma qualities and were well differentiated from 10mm samples. By Day 7, none of the samples appeared to share similar aroma qualities with 10mm samples deviating considerably from 25mm and 50mm samples.

Based on PCA findings, it is suggested that fresh-cut cantaloupe melon aroma (50mm and 25mm pieces) have an adequate shelf-life of 7 Days storage, while for 10mm samples, shelf-life is limited to 4 Days due to a rapid increase in VAC concentration.
Figure 4.4 Principal Component Analysis: Loadings (a) and Scores (b) of the volatile aroma compounds for the biplot generated for fresh-cut cantaloupe melon stored for 0, 1, 4, 7 and 14 days at 4°C.
For fresh-cut kiwifruit, PCI explained 34% of the total variance while PCII explained 18% (Figure 4.5). In this case, there were very clear differences in patterns during storage. PCI separated FC, Day 1 and Day 4 kiwifruit samples from Day 7 and Day 14 samples, while PCII separated FC, Day 1 and Day 7 from Day 4 and Day 14, respectively. Furthermore, Day 1 samples were inversely correlated with Day 7 and Day 14 samples on PCII while Day 7 samples were inversely correlated with Day 14 samples on PCI. Samples to the left were characterised as having a greener aroma while samples on the right had a fruitier, sweeter, more pineapple-like aroma.

FC samples were negatively loaded on PCI and were the only samples to contain limonene, 2,4-hexadienal, 2-ethylfuran and lactamide. Day 1 samples had negative loadings across PCI with VACs such as camphene (green, herbal), hexanal (fresh-cut grass), 3-hexen-1-ol (grassy green), 2-hexenal (herbal green) and α-pinene (minty, acrid) corresponding to fresh-cut aroma. As storage progressed, there was a significant loss in green, grassy aroma notes (left) with samples migrating towards more fruity, sweet aroma volatiles on the right. By Day 4, samples had migrated away from green aroma notes, and by Day 7, were associated with ethyl propanoate (pineapple, fruity, rich), ethyl butanoate (sweet, fruity), β-pinene (woody, pine-like) and methoxyacetone (sweet, cooling).

On Day 14, all samples were highly associated with VACs such as ethyl acetate (sweet, fruity), ethyl caproate (green, sweet, fruity), ethyl isobutyrate (pineapple, fruity), diethyl carbonate (pleasant, fruity), 2-hexen-1-ol (sharp leafy green, fruity) and 3-methyl-oxiran-2-yl-methanol (alcohol-like). There was a clear distinction between storage times, with smaller effects due to cut size. Smallest cut pieces appeared to have the least developed aroma of all samples, but the fastest rate of change. ¼ samples had the greatest extent of aroma change over storage followed by ½ samples. On Day 1, the ½ cut sample was clearly differentiated from ¼ and ⅛ samples, with higher concentrations of VACs such as camphene (green, herbal), hexanal (fresh-cut grass) and 2-hexenal (herbal green). However, by Day 4, a similar pattern to that of ¼ was observed until Day 14, where all samples had similar aroma profiles. Interestingly, methoxyacetone, ethyl-2-methylbutanoate and diethyl carbonate were all only identified in packs from Day 7 to Day 14, while (3-methyl-
oxiran-2-yl)-methanol was detected in all packs on Day 14. Furthermore, after Day 1, no trace amounts of camphene, hexanal and 3-hexen-1-ol were detected.

Based on the PCA findings it is suggested that fresh-cut kiwifruit, irrespective of cut size, have an adequate aroma shelf-life of 7 Days. However, it should be noted that smaller cut pieces displayed the greatest rate and extent of aroma change during the storage period.
Figure 4.5 Principal Component Analysis: Loadings (a) and Scores (b) of the volatile aroma compounds for the biplot generated for fresh-cut kiwifruit stored for 0, 1, 4, 7 and 14 days at 4°C.
4.5. Discussion

4.5.1. In-pack gas atmosphere and physiochemical attributes of quality

In general, it was found that the smaller the cut size, the greater the in-pack atmosphere modification, with high respiring fruits such as kiwifruit having greater modification and low respiring fruit such as cantaloupe melon the least. However, none of the samples had developed anaerobic atmospheres, with lowest O$_2$ levels on Day 14 of 10%, 3% and 6% for pineapple (10mm), cantaloupe melon (10mm) and kiwifruit ($\frac{1}{8}$) respectively. Elevated CO$_2$ levels (>20%) were only observed between Days 7 and 14, suggesting the possibility of physiological disorders (increased membrane instability, ion leakage, exudate), in particular for smaller cut pieces, towards the end of storage-life.

Pesis (2005) suggested that tissue deterioration may initiate anaerobic respiration because of reduced mitochondrial activity associated with membrane damage and loss of cell ability to produce energy. The sudden change in CO$_2$ accumulation from Day 7 to Day 14 for pineapple (and kiwifruit) could be attributed to tissues switching to anaerobic respiration as previously shown by Montero-Calderon et al., (2010), with a sudden increase in CO$_2$ has been shown to be an intermediate product of fermentation (Budu et al., 2007, Oms-Oliu et al., 2007, Ke et al., 2004). In this study, no ethanol or acetaldehyde were detected in these packs during storage, however, precursors of ethanol formation (ethyl acetate) were detected in increasing concentrations towards end of storage-life. These findings further suggest that fresh-cut pineapple and kiwifruit were able to tolerate elevated CO$_2$ levels of 20-25% without initiating anaerobic respiration.

Water deficit has been found to induce the generation of certain volatiles (Kimmerer and Kozlovski, 1982) and loss of others (Toivonen, 1997). In this study, increased process severity increased the rate of water loss attributed to the greater surface area of smaller cut fruit, with larger cut pieces retaining and/or increasing VAC concentration. An exception to this was fresh-cut kiwifruit where little to no water loss was recorded and where the aroma profile of smaller cut pieces was greater than larger cut pieces.

Cut size showed significant effects on overall fresh-cut fruit flavour attributes such as percent soluble solids and acidity, and was highly dependent on fruit type.
An exception was tissue pH, where, similarly to Artés et al., (2000), pH values were maintained during MAP storage. Significant differences in percent soluble solids were found on Day 14 between 50mm cut pieces and 25mm and 10mm, respectively. For fresh-cut cantaloupe melon, 25mm pieces were significantly different (p<0.01) from 10mm and 25mm, respectively, while for fresh-cut kiwifruit, no significant differences were observed (p>0.05). Differences could be attributable to increased physiological change during storage as sugar/acid ratios showed that smaller cut pieces had greatest changes. In contrast, fresh-cut pineapple had sugar/acid ratio values highest for 50mm cut pieces, followed by 10m cut pieces and 25mm cut pieces.

4.5.2. Effects of storage time and cut size on volatile aromatic compounds

Storage time had a greater effect on VAC changes than cut size (p<0.01). The effects of cut size were also significant for fresh-cut pineapple (p<0.05), cantaloupe melon (p<0.01) and kiwifruit (p<0.01). To the best of our knowledge, this is the first time the aroma profile of fruits as affected by three distinct cut sizes has been investigated in this manner. All samples evolved a typical volatile profile during storage with some non-characterising volatile esters such as, ethyl acetate and butanoates, common across all three fruits in different quantities. The volatiles detected were broadly similar to those reported previously.

Fresh-cut pineapple

In this study, the reduction of esters due to wounding appeared to be an important reaction step in the loss of freshness during storage; this was also observed through PCA manipulations. Methyl-2-methylbutanoate (fruity, acidic), α-copaene (pineapple, woody) and methyl-3-(methylthio) propionate (pineapple) were the most abundant volatile compounds in fresh-cut pineapple. Over 280 VACs have been found in pineapple (Žemlička et al., 2013; El Hadi et al., 2013). Methyl-2-methylbutanoate and methyl-3-(methylthio) propionate were previously considered to be characteristic aroma compounds in fresh-cut pineapple (Wei et al., 2011). He et
al., (2007) reported that esters and hydrocarbons were the main compounds contributing to overall pineapple flavour. Other previous studies have reported that esters were the most abundant pineapple volatiles, in particular ethyl hexanoate (fruity), methyl butanoate (sweet) and 2-methyl butanoate (sweet, fruity) (Liu et al., 2011; Marta et al., 2010; Akioka et al., 2008; Tokitomo et al., 2005; Elss et al., 2005 and Umano et al., 1992). Takeota et al., (1991), Preston et al., (2003) and Liu et al., (2011) identified many sulphur-containing esters such as methyl-3-(methylthio) propionate among aromatic pineapple volatiles detected. In pineapple, this compound provides background ‘green’ notes; however its overall contribution to fruit aroma is considerably lower compared to most odour-active volatiles (Montero-Calderon et al., 2010). In the current study, it was found to be prevalent in older samples.

VACs associated with sweet, fruity fresh-pineapple aroma: methyl valerate (sweet, fruity), ethyl caproate (green, sweet, fruity), methyl isobutyrate (pineapple, fruity), methyl butanoate (sweet) and methyl propionate (sweet, fruity; rum-like) were dominant on Days 1 and 4. The subsequent change in the relative abundance of these volatiles was accompanied by the loss of some and emergence of others, with a reduction of certain esters found to be an important early reaction step in the loss of fresh-cut pineapple freshness during storage. As storage progressed further, the level of some esters fell and more intense heady aroma components appeared, including: methyl caprylate (fruity), methyl heptanoate (fruity), α-copaene (pineapple, woody), 4-methyldecanoate (fruity) and 3-(methylthio)methyl propionate (pineapple) indicating loss of sweet aroma during prolonged storage.

The stress-induced hydrolysis of polygalacturonide esters by pectin methyl esterase that takes place during solubilisation of the cell wall is well known. Lamikanra and Richard, (2004) demonstrated this stress effect in fresh-cut pineapple due to processing and noticed significant differences in VAC changes over 24h. Stress-induced enzymatic hydrolysis of esters involves their esterase-mediated conversions to acids and alcohols. Subsequent reactions involve fatty acid degrading enzymes and/ or alcohol dehydrogenase. Alcohols typically make a minor contribution to flavour unless present in relatively high concentration (Heath and Reineccius, 1986). The presence of some compounds with a sharp or pungent note reminiscent of rum, such as ethyl acetate and methyl propionate, when present in
high concentrations were detected in pineapple packs during latter storage. Voon et al., (2007) showed that these compounds were found to be highly correlated with perceived alcohol notes, while Larsen (1994) and Ueda and Bai (1993) showed that an increase in ethyl acetate and ethyl butanoate was associated with an ‘unnatural’ aroma in short-term CO₂ treated strawberries.

In agreement with the data presented for fresh-cut pineapple here, Beaulieu and Baldiwn (2002) and Montero-Calderon et al., (2010) observed a temporary increase in ester accumulation in fresh-cut apples and pineapple respectively, explained by the product response to wound stress and increased permeability of exposed fruit flesh allowing less resistance for volatile release, and increased oxidation. Larger cut pineapple pieces, in this study, had higher levels of VACs during storage, with esters such as methyl valerate, ethyl acetate, methyl caprate, methyl acetate, methyl isobutyrate, ethyl caproate and ethyl caproate in significantly higher concentrations (p<0.01) than for smaller cut pieces (10mm) at end of storage. Esters and sesquiterpenes were abundant in the aroma profile of fresh-cut pineapple with the thiol-ester 3-(methylthio) propionate also present in increasing concentrations with cut size during storage. These three compounds may be attributable to the different metabolic routes active in fresh-cut pineapple during storage i.e. LOX (lipid oxidation), MVA (mevalonate) and MEP (methyl-erythritol phosphate) pathways.

Zhang et al., (2009), Montero-Calderon et al., (2010) and Wei et al., (2011) reported that, although the volatile constituent aroma profile was the same across three cross-sectional pineapple pieces and between pulp and core flesh, respectively, their relative volatile content varied significantly (from top to bottom) owing to the progressive ripening nature of the fruit, and was attributable to differences in growing conditions, cultivation practices, harvest techniques etc. Such differences could also explain why ethyl hexanoate, 2,5 dimethyl-4-hydroxy-3(2H) furanone (DMHF) and 1-(E,Z)-3,5-undecatriene were not detected in this study despite being reported as key odourants in pineapple in other studies (Umano et al., 1992; Elss et al., 2005; Tokitomo et al., 2005). Lee and Nagy (1987) reported very small concentrations of DMHF in Costa Rican grown pineapples, as compared with those from Hawaii (cultivars not specified).
In summary, all pineapple pieces, irrespective of cut size, had an adequate aroma shelf-life over 7 days. Smaller cut pieces displayed a faster rate and slightly greater extent of aroma change than larger cut pieces. However, after 4 Days storage, all cut pieces lost their characteristic sweet, fresh pineapple aroma in favour of a stronger pineapple aroma. Based on these results, it is recommended that larger cut pieces be used for commercial production of fresh-cut pineapple products in order to better maintain the characteristic fresh-cut pineapple aroma.

**Fresh-cut cantaloupe melon**

In this study, an increase in ester formation during storage played an important role in the loss of overall sweet melon aroma; increasing with increased process severity. Ethyl acetate, n-butyl acetate, ethyl butanoate and methyl-2-methylbutanoate were identified in early storage (Days 0 to 1), contributing to overall sweet melon aroma. Levels of n-butyl acetate and 3-nonen-1-ol were also attributed to sweet melon aroma. However, levels of these compounds decreased over the 14 day storage period. More than 240 VACs have been identified in different melon varieties (Obando-Ulloa et al., 2008). Of those, volatile esters are prominent, together with sulphur-containing aroma compounds, sesquiterpenes, norisoprenes, short-chain alcohols, and aldehydes (Portnoy et al., 2008; Aubert and Bourger, 2004) with volatiles derived from amino acids the major contributors to cantaloupe melon aroma (Beaulieu and Grimm, 2001). Schieberle et al., (1990) also found that the fruity notes of melon were from ethyl-2-methylpropanoate, methyl-2-methylbutanoate and ethyl butanoate, and contributed to overall sweet melon aroma. Volatile esters, mainly acetate derivatives such as n-butyl acetate, n-propyl acetate and 2-methyl butyl acetate were found to be dominant in the aroma profile (33%), similar to the findings of Aubert and Bourger (2004). Sulphur-containing compounds, which are believed to play an important role in overall aroma expression in cantaloupe (Wyllie and Leach, 1992), were not detected in this study.

Volatile esters in melon mainly result from the esterification of alcohols and carboxylic acids, utilizing Co-A moiety of Co-A-ester as the acyl donor (Ueda et al., 1997; Shalit et al., 2001) with the mixture of esters produced by the fruit dependent
on alcohol acetyltransferase (AAT) activity (Yahyaoui et al., 2002), specificity and preference (El-Sharkawy et al., 2005; Lucchetta et al., 2007).

Many VAC biosynthetic pathways are also regulated by ethylene (C\textsubscript{2}H\textsubscript{4}) such as fatty acid and aldehyde reduction and the esterification step in aliphatic ester pathway. Fernandez-Trujillo et al., (2013) found that the pattern of many VACs was correlated with an upsurge in C\textsubscript{2}H\textsubscript{4} production. In this study, the VAC profile of fresh-cut cantaloupe melon appeared to follow an ethylene-dependent pattern due to the biosynthesis and degradation of volatiles as reported by previous authors (Ueda et al., 1997; Brecht, 1995). Ethylene produced upon wounding increases the permeability of membranes, reduces phospholipid biosynthesis (Watada et al., 1990; Brecht, 1995) and induces decompartmentalisation of previously sequestered enzymes and substrates such as phospholipase D (PLD), phosphatidic acid phosphatase (EC 3.1.3.4), lipolytic acyl hydrolase (EC 3.1.1.5) and LOX, which are lipid-degrading enzymes. The response of plant tissues, in particular melon, to wounding involves increased PLD activity (Flores et al., 2002). Melon fruit have been found to contain different PLD isoforms (Whitaker and Lester, 2006) having different effects on volatile production. Ethylene production also increases in proportion with process severity (Kader, 2002). Levels of ACC and ACC synthase activity also increase with increased C\textsubscript{2}H\textsubscript{4} as observed in fresh-cut cantaloupe melon (Abeles et al., 1992). Furthermore, ACC synthase 1 expression, which is normally expressed during ripening, was shown to be enhanced by mechanical stress (Olson et al., 1991; Zhang et al., 2005).

Wounding and the concurrent C\textsubscript{2}H\textsubscript{4} production can also speed up the onset of the climacteric, resulting in a difference in physiological ages between intact and cut tissues (Watada and Qi., 1999). In fresh-cut cantaloupe melon, smaller cut pieces displayed the most distinctive volatile pattern of all the cut sizes studied, with an intense cloying melon aroma developing very early on (by Day 4), suggesting that it had a significantly different physiological age than other cut sizes. The large amount of esters is also consistent with the strong dependence on C\textsubscript{2}H\textsubscript{4} biosynthesis of most of the esters catalysed by several alcohol acetyl transferases (Gonda et al., 2010; Galaz et al., 2013).
However, fresh climacteric melons such as cantaloupe have high aroma intensity but a short shelf-life (Perry et al., 2009). Processing and prolonged storage can promote or enhance the progressive enzymatic or chemical oxidation of certain aroma compounds, proceeding at different rates depending on the intrinsic or extrinsic properties of the fruit. Changes in the concentration of desirable aroma compounds can produce off-odour (Poll et al., 2006; Belitz et al., 2004). For example, Larsen and Watkins (1995) and Ueda and Bai (1993) showed that increases in ethyl acetate and ethyl butanoate was associated with an ‘unnatural’ aroma in short-term storage of strawberries. Zhu, et al., (2005) showed that the increased activity of alcohol acyltransferase (AAT) enhanced production of ethyl esters. This further promoted the final stage in ester biosynthesis, and may explain the rapid increase in melon ester accumulation during latter storage in this study. Moreover, Guichard et al., (1992) found that the level of ethyl esters in strawberries increased under elevated CO$_2$ atmospheres. In this study, ethyl acetate and ethyl butanoate had the greatest increase in concentration during storage, possibly contributing to the strong, cloying aroma noted in packs as a result of CO$_2$ accumulation in the order 10mm>25mm>50mm.

Furthermore, wounding results in a loss of membrane integrity with resultant turgor loss within cells as previously reported by Finnegan and O’Beirne, (2014b). As a consequence, smaller cut pieces were rendered more susceptible to microbial spoilage possibly giving rise to undesirable off-odours/ -flavours. Products of LOX pathway (Z)- and (E)- configured hydroperoxides can be metabolised to compounds that are crucial elements of plant defence (Schwab et al., 2008). However, many of the natural volatile compounds that control microbial growth are also products of the LOX pathway (Chung et al., 1993). Microorganisms have been reported to produce high levels of ethyl esters and alcohols on fresh-cut produce (Longo and Sanroman, 2006; Deetae et al., 2007). Previous studies by Finnegan and O’Beirne., (2014b) showed that cut size had major effect on bacterial and yeast growth in fresh-cut fruit, in particular in neutral fruits like cantaloupe melon, which may explain the extent of VAC change in the present study; increasing with increased process severity. The growth of certain bacteria, such as lactic acid bacteria has been shown to increase with increased process severity (Finnegan and O’Beirne, 2014b). This type of bacteria also controls off-odour development (Liu et al., 2008) which may help
explain the higher concentrations of ethyl esters in smaller cut pieces attributable to cloying aroma.

Isobutyl acetate (fruity, floral) is an isomer of n-butyl acetate produced from esterification of isobutanol with acetic acid. Isobutanol is produced naturally during the fermentation of carbohydrates (Peralta-Yahya et al., 2012) and also thought to be a by-product of the decay of organic matter (Atsumi et al., 2008). Isobutyl acetate was detected only in fresh-cut (FC) samples (Day 0). Ueda et al., (1997) found that cantaloupe melons of the reticulatus family had the capacity to convert isobutyl alcohol into isobutyl acetate. Because it was only present in FC samples, it was thought to be released as a direct effect of wounding.

In summary, the aroma shelf-life of fresh-cut cantaloupe melon pieces was limited strongly by increased process severity resulting in greater accumulation of esters during storage. Smaller cut pieces quickly lost their initial fresh aroma and by Day 4 had developed an intense cloying aroma. Larger cut pieces also developed a cloying aroma, however, at a much more reduced pace. Based on these results, it is recommended that larger cut melon pieces be used in commercial production in order to better maintain fresh-like aroma characteristics.

**Kiwifruit**

The wounding of fresh-cut kiwifruit was considered to have severe effects on plastids, which in turn caused a rapid deterioration in fruit appearance (colour-loss, translucency), firmness (rapid softening) and aroma development. This deterioration is thought to have caused rapid release of cell organelles such as chromoplasts and lipids which could act as precursors in VAC biosynthesis (see section 1.3.3). In previous studies, levels of VACs in kiwifruit were found to increase dramatically (Bartley and Schwede, 1989) following cutting, and Wang et al., (2011) related this increase to the increase in C₂H₄ production, even at low temperatures (Paterson et al., 1991). The main VAC profile changes observed during storage im this study were more complex than other fruits, with enhanced levels of (E)-2-hexenal over the formation of (Z)-3-hexenol during 14 day storage.
Over 80 VACs have been reported for kiwifruit (Garcia et al., 2011), of which 90% were reported to be lipid degradation products such as C₆ aldehydes and alcohols, esters and terpenoids (Zhang et al., 2009; Takeoka et al., 1986). Shiota (1982), Young et al., (1985; 1983) and Wang et al., (2011) identified ethyl butanoate (sweet, fruity), hexanal (freshly-cut grass), 2-(E)-hexenal (herbal, green), (Z)-3-hexenol (green, grassy), and 1-hexanol (grassy, green) as the major components of kiwifruit aroma. These VACs have been attributed to the grassy, green aroma of fresh-cut kiwifruit and the tropical, sweet, candy-like flavour (Wang et al., 2011). Sulphurous compounds such as methyl-2-(methylthio) acetate; ethyl (methylthio) acetate (Jordan et al., 2002), hydrogen sulphide (Young and Paterson, 1990; Paterson, 1991) and dimethyl trisulfide (Frank et al., 2007), although identified previously as odour-active compounds in ‘Hayward’ kiwifruit, were not detected in any packs during storage. In this study, ethyl acetate was found to be the most abundant ester which is in agreement with Paterson et al., (1991) who found that stored kiwifruit had ethyl acetate as their most abundant ester, in contrast to ethyl butanoate which was identified as the major ester in freshly harvested fruits.

Changes in VAC were similar to those reported previously by Zhang et al., (2009), partly attributable to the wound-ethylene response which increases with increased process severity. This caused the fruit pieces to age at a faster rate leading to a faster decrease in aldehydes responsible for green aroma, and an increase in esters responsible for fruity aroma. Smaller cut pieces had a greater green intensity initially (Day 0 to Day 1) with a more pleasant fruity aroma on Day 7. Similar results were also obtained by Bartley and Schwede (1989) who found that ethyl butanoate increased dramatically at the same time that (E)-2-hexenal decreased; the former contributing significantly to flavour of ripe kiwifruit. The differences in results of fresh-cut kiwifruit suggest that high levels of aldehydes were generated during sample preparation (maceration), providing an optimal condition for the action of LOX and a higher availability of FFA precursors (Paterson, 1991; Wang et al., 2011). In addition to forming green leaf volatiles in some fruits such as kiwifruit, LOX catalyses the peroxidation of certain FFA to form conjugated hydroperoxides, generating free radicals that can attack intact membranes thus causing further membrane damage. This may help explain the significant loss of kiwifruit firmness observed during storage, in particular for smaller cut pieces.
Certain aroma compounds, such as hexanal, are only released from kiwifruit upon cell disruption, when previously sequestered enzymes and substrates interact (Buttery, 1993). The initial increase in hexanal (Day 0 to Day 1) was thought to be a direct result of cell damage increasing with process severity and resulting in the formation of hydroperoxides during cutting (Galliard et al., 1977). Brilli et al., (2011) showed that wounding induces a differential production of green leaf volatiles over time. Membrane deterioration and the consequent oxidation of unsaturated fatty acids resulted in a fast transient evolution of C$_{6-9}$ aldehydes. In this study these C$_{6-9}$ aldehydes quickly decayed after fresh-cut processing as they are used as substrates for ADH reduction to their corresponding alcohols. Moreover, the formation of an aldehyde over an alcohol, as observed in this study, could also be attributed to the increased physiological age of smaller cut pieces, especially smaller cut pieces, under low O$_2$ and high CO$_2$ conditions within packs, as previously observed by Belitz et al., (2004).

Accumulation of limonene in fruit is a developmentally regulated process whereby limonene accumulation predominates in the early stages of development. At later stages of development competition with other pathways such as LOX, which appears to predominate the aroma profile of kiwifruit, may serve to limit monoterpenes accumulation (Bouwmeester et al., 1998). Sandermann and Bruns, (1965) hypothesised that limonene is an intermediate in the biosynthesis of carvone; however, Von Schantz and Elk (1971) and Von Schantz and Huhtikangan (1971) showed that limonene is no longer available as a precursor once it has been secreted into essential oil ducts. Due to its release upon cutting followed by rapid onset of LOX, this may help explain why limonene was only present in FC samples (Day 0). Furthermore, the compound 2,4-hexadienal is a LOX product of polyunsaturated fatty acids, such as linoleic acid, which undergoes auto-oxidation, especially during storage and naturally occurs in kiwifruit (Takeoka et al., 1986; 1987). In this study, it was present only in fresh-cut samples (Day 0) and its dissipation was attributed to rapid LOX. The increase in both pinene derivatives from Day 0 to Day 1 may be attributed to their role in stabilisation and protection of the plant membranes (Loreto and Velilova (2001). Their relative abundance throughout storage was also noted.
Wound respiration in some plant tissues is also attributed to \( \alpha \)-oxidation of fatty acids (Shine and Stumpf, 1974) which oxidises fatty acids to \( \text{CO}_2 \), and is responsible for the \( \text{CO}_2 \) release in some products (Rolle and Chism, 1987). Roma-Parada et al., (1991) found that 15% \( \text{CO}_2 \) damaged membrane integrity and accelerated loss of phospholipids (Duan et al., 2013) and polyunsaturated fatty acids from mitochondrial membranes and increased leakage of amino acids. In addition, \( \text{CO}_2 \) has also been found to have an uncoupling effect on oxidative phosphorylation (Fanestil et al., 1963) and can limit the energy supply needed for tissue survival, which may help explain the reduced rate of \( \text{CO}_2 \) concentration on Day 7 in fresh-cut fruit packs. Mathooko (1996) suggested that dissolved \( \text{CO}_2 \) can dissociate to carbonic acid in presence of water, existing only in equilibrium. This equilibrium is important for organisms to perform certain vital functions, which may explain why diethyl carbonate (a carbonate ester of carbonic acid and ethanol) was only present in kiwifruit packs from Day 7 to Day 14, thus suggesting the onset of fermentation in these packs.

Ethanol has been reported as a major volatile in stored kiwifruit; however ethanol was not found in this study. Ethanol is a precursor of ethyl acetate, and is normally formed at the beginning of fermentation, and its concentration gradually increases throughout the process. Although not directly acting as an odorant (Garcia et al., 2011), it has been suggested that as a metabolic precursor, ethanol would affect ethyl ester production (Burdon et al., 2005). Ethyl benzoate is an ester formed directly by the condensation of benzoic acid and ethanol (Luebke, 2011). This compound has a sweet, wintergreen, minty odour and during storage was only found in packs on Day 14. Methanol was detected in the headspace of kiwifruit packs on Day 14 storage only. Methanol detected in the headspace of olive brines was attributed to the activity of pectinolytic enzymes that cleave the methoxy group of pectin in the fruit (Montano et al., 1992). Interestingly methoxyacetone was also only detected in packs on Day 14 suggesting that perhaps it was released in par with the pectinolytic activity in fresh-cut kiwifruit. To the best of our knowledge, these compounds have not before been found in fresh-cut kiwifruit samples and could be used as potential indicators of anaerobic respiration in fruit packs.
In summary, the aroma shelf-life of fresh-cut kiwifruit appears to be compromised greatly by wounding and intermittently by the concurrent release of ethylene, which appears to cause increased membrane deterioration and accelerated the loss of green aromas. Smaller cut pieces had better initial green aroma which quickly dissipated in favour of a sweet fruity aroma with an aroma-life of 7 Days. Larger cut pieces retained more of their initial green aroma for longer, but developed less of a sweet aroma during storage. The compounds formed during latter storage could be used as signalling compounds of anaerobic respiration in kiwifruit packs. Based on the data presented above, it is recommended that medium (1/4) cut pieces be used in commercial production practices in order to better maintain fresh green aromas yet allow for development of sweet fruity aromas over a shelf-life of 7 Days.
4.6. Conclusion

The main processes involve in aroma loss appeared to be a direct effect of wounding with stress induced hydrolysis of esters, increased ethylene biosynthesis and lipid oxidation the main contributing factors.

It is concluded that:

- The VAC content of fresh-cut pineapple, cantaloupe melon and kiwifruit varied during storage with differences more quantitative that qualitative.
- Cut size had a deleterious effect on aroma shelf-life.
- A reduction of esters due to wounding appears to be an important step in the loss of fresh pineapple aroma, with stress-induced hydrolysis playing a major role in this loss.
- For fresh-cut cantaloupe melon, wounding appeared to increase the rate of physiological age in an ethylene dependent manner, with increases in ester formation giving rise to undesirable aromas during storage.
- In fresh-cut kiwifruit, wounding appeared to accelerate the rate of lipid oxidation, resulting in loss of green aromas and influencing overall aroma development during storage.
- The data shows that larger cut pieces result in greater aroma shelf-life.

Given the variability in cut piece size, reduction of which gives rise to increasing surface area to volume ratios, the correlations between this and aroma loss would be of interest to future work endeavours.
Chapter 5

Respiration and Product-Package Compatibility

5.1 Abstract

The effects of intrinsic (fruit type, cultivar, origin, physiological age and seasonality) and extrinsic factors (cut size, blade sharpness, dipping treatments and time) on the respiration rate ($R_{CO_2}$) of a number of fresh-cut fruits were determined. The $R_{CO_2}$ was measured at $4^\circ$C for 24h in air using a flow-through system. In general, $R_{CO_2}$ showed an initial increase in respiration rate ($R_i$) followed by a peak and a gradual decline to steady-state ($R_{eq}$) within 24h. The high initial rate was thought to be due to the wound-response to processing which was short-lived and highly affected by fruit type and processing severity. An exception to this was fresh-cut strawberry and kiwifruit which continued to increase or decrease respectively throughout storage without the initial increase in $R_{CO_2}$. $R_i$ was affected to a greater extent by intrinsic factors, such as physiological age and season, in particular in fresh-cut pineapple and strawberry. Reducing the cut size significantly increased $R_i$ and $R_{eq}$ in most fruits ($p<0.05$). Cutting with a razor sharp blade versus a blunt blade decreased $R_i$, while only caused a slight reduction in $R_{eq}$ ($p>0.05$) for pineapple. Neither cut size nor origin affected the $R_i$ or $R_{eq}$ of fresh-cut kiwifruit. A mathematical model based on exponential decay was developed in order to predict respiration rate of fresh-cut fruits over time. The model parameters ($R_i$ and $R_{eq}$), were found useful in comparing respiration rates for each of the factors studied.

The target oxygen and carbon dioxide transmission rates required in MAP design were estimated for fresh-cut pineapple, covering variability in respiration rate due to intrinsic and extrinsic factors studied. This model proved to be a good fit with experimental data thus, aiding in the successful package design of fresh-cut pineapple.

Keywords: fresh-cut produce, respiration, wound-response, equilibrium, perforation-mediated modified atmosphere packaging
5.2 Introduction

Respiration is the metabolic process by which fresh and fresh-cut fruits obtain the energy needed to fuel biochemical processes (Meyer et al., 1973). Aerobic respiration involves the oxidative degradation of carbohydrates and organic acids to simpler molecules including carbon dioxide (CO$_2$) and water vapour and the production of energy (ATP) and heat (Fonseca, 2000). In anaerobic respiration (<2% O$_2$), ethanol production involves decarboxylation of pyruvate to CO$_2$ without oxygen (O$_2$) uptake (Fonseca, 2002). Thus, respiration rate is a significant factor in physiological ageing, product quality and shelf-life. Control of respiration rate is an important factor in establishing an effective atmosphere modification for optimising the shelf-life of fresh-cut fruits.

Many factors affect the respiration rate of fresh-cut fruit including intrinsic factors such as cultivar, seasonality, origin and physiological age, and extrinsic factors such as process severity (cut size/shape, blade sharpness), storage temperature, gas compositions and storage time. Wounding caused by fresh-cut processing can lead to modifications of metabolism and increases respiration rate (Antoniolli et al., 2006). This is attributable to increased surface area exposed after cutting, allowing for a more rapid diffusion of O$_2$ to the internal cell compartments, thus increasing the metabolic activity of the wounded cells (Zagory, 1999). The type of equipment used in fresh-cut processing may also affect the physiological response of the tissues. In addition, certain pre-treatments can alter the respiration rate. For example, dipping in ascorbic acid and sucrose has been shown to reduce the R$_{CO2}$ and improve the visual quality of fresh-cut fruits (Liu et al., 2007; Gonzalez-Aguilar et al., 2004).

Packaging is an integral part of the commercial food supply chain. For shelf-life extension of fresh-cut produce, different packaging materials and technologies are used. Modified atmosphere packaging (MAP) assists in preservation by reducing respiration rate and the onset of quality deterioration. Respiration rate can be reduced by decreasing O$_2$ and increasing CO$_2$ levels surrounding the packaged commodity (Kader, 1986; Mathooko, 1996; Fonseca et al., 2002; Saltveit, 2003; Tijskens et al., 1999; 2003).
However, when a fresh-cut product is sealed in an impermeable package, the respiration process causes rapid depletion of O$_2$ and accumulation of CO$_2$ inside the package. This could eventually lead to anaerobic respiration and undesirable product quality. Likewise, when the package is highly permeable, then there is little to no in-pack atmosphere modification, and little effect on product quality and loss of shelf-life (Lee et al., 1996; Ártés et al., 2007; Finnegan and O’Beirne, 2014b).

The rate of respiration plays a major role in packaging design. It is known that beneficial MAs within fresh-cut fruit packages are attained by correctly choosing packaging materials that will provide the appropriate levels of O$_2$ and CO$_2$ in the packs. Low O$_2$ and elevated CO$_2$ concentrations within an MA package may reduce the respiration rate of certain produce and improve its SL. Therefore, a properly designed package entails matching the gas permeability properties of the packaging film to the respiration rate of the fresh-cut fruit. The goal of MAP in this instance is to establish an optimal equilibrium modified atmosphere (EMA). However, products vary on their tolerance to O$_2$ and CO$_2$ concentrations and, as a result, the target ranges of O$_2$ and CO$_2$ must be chosen accordingly for each product. Subsequently, each MA packaging system must be designed appropriately for each individual fresh-cut fruit product in order to provide these optimal storage conditions. At a given temperature, these two gases approach steady-state or equilibrium, which is when the rate of gas permeation through the package matches the rate of respiration of the product, i.e. product-package compatibility.

While many commercial polymers are available, few meet the specific permeability requirements for packaging these perishable commodities. One way of overcoming this is the use of micro-/ macro-perforations. The use of macro-perforations is a potentially useful technique for postharvest preservation of respiring produce. In this technique, instead of solely relying on polymeric films with or without micro-perforations, a package is designed in which the regulation of the gas exchange is achieved via deliberate diffusion windows, i.e. single or multiple perforations through a low permeable or impermeable film (Emond and Chau, 1990; Emond, 1992, Silva et al., 1999). Thus, a polymer’s oxygen transmission rate (OTR), and carbon dioxide transmission rate (CTR) are key attributes. In this technique, the gas transmission rates of polymeric films are determined by the size of the individual holes, their position and frequency. The number of perforations required is directly
proportional to the desired OTR (i.e. as the OTR requirements increase, so too do the number of holes) (Mahajan et al., 2006; 2007).

Several respiration rate mathematical predictive models have been proposed for use in packaging design (Lee et al., 1991; Fonseca et al., 2002; Saltveit et al., 2003; Mahajan and Goswami, 2001, 2002, and Caleb et al., 2012). More recently, respiration rate has been related to the degree of cutting (Zhu et al., 2001) and notably to wound-induced respiration (Surjadinata and Cisneros-Zevallos, 2003). However, there are various limitations to the development of such models, including limited number of experimental observations, inconsistent raw materials resulting in inherent biological variation, and the dynamic response of stored or fresh-cut produce to environmental changes (Caleb et al., 2013). Another major limitation of respiratory rate modelling is of the lack of adequate respiratory data, with the data available either based in O₂ consumption or CO₂ production rates in a steady-state environment (Fonseca et al., 2002; Mahajan et al., 2006) which do not consider the surge in respiration observed after processing. Therefore, MAP design requires a suitable model to predict these responses as an accurate function of time, temperature, processing and gas composition (Mahajan et al., 2006; Caleb et al., 2013).

The objective of this study was to quantify the effects of intrinsic and extrinsic factors on R\textsubscript{CO₂} for a number of fresh-cut fruits. Using this data, a simple exponential decay mathematical model was elucidated for R\textsubscript{CO₂}, considering the effect of intrinsic and extrinsic factors. This model was then used to demonstrate the principles involved in the design of a macro-perforated MAP system for fresh-cut pineapple. The validity and effectiveness of this model in the design of a MAP for creating previously defined optimum EMA for fresh-cut pineapple was demonstrated. The model could then be used to estimate the target OTRs and CTRs required for optimum packaging for fresh-cut fruits.
5.3. Materials and methods

5.3.1. Plant materials and intrinsic factors

To evaluate the effects of intrinsic factors, fresh, whole fruits were collected from a local wholesaler (Richardson’s Fruit and Vegetables, Limerick, Ireland) on the morning of each trial and allowed to equilibrate to testing temperatures. The various intrinsic factors studied are outlined in Table 5.1 and 5.2. To evaluate seasonal variation in respiration rate, fresh-cut pineapple and strawberries were analysed during Summer (May-Aug 2010), Autumn (Sept-Oct 2010), Winter (Nov-Jan 2010/11) and Spring (Feb-Mar 2011). For experiments where the effects of physiological age (PA) were evaluated, the respiration rates of under-ripe: UR (green), ripe: R (half green/yellow) and over-ripe: OR (fully yellow) fruit were compared. In the case of strawberries, PA refers to the stage of ripening at harvest, whereas for pineapple, PA refers to the state of ripeness at processing. For over-ripe fruit, fresh intact ripe fruits were purchased up to 5 days in advance of the trial and allowed to over-ripen at an average room temperature of 22°C before being stored at testing temperatures (5°C) the day before the trial. Ripe fruit were used for all other experiments except where otherwise stated. All fruits were selected based on their initial visual quality (external appearance), pulp firmness and percent soluble solids (SS%). External colour was assessed using descriptors developed by Kader and Cantwell, (2010). Aroma was evaluated using descriptive sensory techniques where 9 = excellent, normal characteristic aroma, 7 = very good, normal to slightly off, 5 = limit of marketability, distinctive off-odour but still OK to eat, 3 = fair, limit of usability, strong off-odours, slightly anaerobic, becoming offensive and 1 = poor, inedible, very strong off-odours, very fermented-like, Firmness was determined using a TA.XT Plus Texture Analyser (Stable Micro Systems, Surrey, UK) fitted with a 6mm flat tipped cylindrical probe. One reading was taken from each of three cut-fruit pieces per fruit sampled. TSS% was measured using an Atago Digital Pocket Refractometer (Atago Co., LTD., Tokyo, Japan) previously standardised using distilled water (0% SS). Approximately 50g of fruit pieces were homogenised and after a settling period the clear juice measured for SS%.
5.3.2. Processing and extrinsic factors

Fresh-cut fruits were processed at room temperature (22°C) on a surface previously sanitised with a 1% Virkon® solution. Peels, husks, stems and hulls, where appropriate, were manually removed using a stainless steel knife which was previously sanitised in a 1% sodium hypochlorite (NaClO) solution (and again after each fruit). Each fruit was cut accordingly depending on the trial studied (Figure 5.1). For effects of cut size, fresh-cut pineapple, cantaloupe melon and honeydew melon were sliced, de-seeded/de-cored and cut into chunks of three different sizes (50, 25 and 10mm) using a hand-held stainless steel slicer. For fresh-cut kiwifruit, the whole fruit was carefully peeled before being cut in half (longitudinal), into quarters (transverse) and eights (longitudinal), where appropriate. For fresh-cut strawberries, whole fruits had the calyx removed and were de-hulled before being cut into half pieces (longitudinal). For all other experiments fruits were processed into 25mm, ¼, or ½ (or whole grapes) cut piece sizes where appropriate. For different degrees of sharpness a stainless steel slicer (razor sharp, sharp and blunt knife) was used. The effect of pre-dipping pre-treatment using 1% ascorbic acid: citric acid on respiration rate of fresh-cut fruits (pineapple, cantaloupe melon and kiwifruit) was tested and compared with un-dipped samples. The dipping solution was prepared using chilled distilled water and fruits were submerged in the solution for 2 minutes with slight agitation and allowed to drain for 2 minutes.
Table 5.1: Intrinsic characteristics (physiological age and seasonality) of intact fruits used in this study and their initial quality attributes

<table>
<thead>
<tr>
<th>Type/ Source</th>
<th>Season</th>
<th>Physiological age</th>
<th>Aroma</th>
<th>Firmness, N</th>
<th>Percent soluble solids</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>External colour¹, %</td>
<td>Ripeness class</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Del Monte Gold™ Extra Sweet, Pineapple, MD2, Costa Rica ¹</td>
<td>Spring</td>
<td>0 to 25</td>
<td>Under Ripe (0 to 1)</td>
<td>Acidic, Fresh, Sharp, Insipid</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25 to 50</td>
<td>Ripe (2 to 3)</td>
<td>Sweet, Pineapple</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90 to 100</td>
<td>Over Ripe (5 to 6)</td>
<td>Pungent, Strong, Musty</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>0 to 25</td>
<td>Under Ripe (0 to 1)</td>
<td>Acidic, Fresh, Sharp, Insipid</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25 to 50</td>
<td>Ripe (2 to 3)</td>
<td>Sweet, Pineapple, Fresh</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90 to 100</td>
<td>Over Ripe (5 to 6)</td>
<td>Strong, Musty, Acrid</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>Autumn</td>
<td>0 to 25</td>
<td>Under Ripe (0 to 1)</td>
<td>Fresh, Acidic, Sharp</td>
<td>8.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25 to 50</td>
<td>Ripe (2 to 3)</td>
<td>Sweet, Pineapple</td>
<td>7.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90 to 100</td>
<td>Over Ripe (5 to 6)</td>
<td>Pungent, Strong, Musty</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td>25 to 50</td>
<td>Ripe (2 to 3)</td>
<td>Insipid, Sweet, Acidic</td>
<td>7.5</td>
</tr>
<tr>
<td>Fyffe’s Super Sweet™, Pineapple, MD2, Brazil ¹</td>
<td>Summer</td>
<td>25 to 50</td>
<td>Ripe (2 to 3)</td>
<td>Sweet, Insipid, Pungent</td>
<td>6.9</td>
</tr>
<tr>
<td>Agricola Agromonte, Pineapple, MD2, Honduras ¹</td>
<td>Autumn</td>
<td>25 to 50</td>
<td>Ripe (3)</td>
<td>Pineapple, Sweet, Sharp</td>
<td>7.4</td>
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<tr>
<td>Strawberry El Santa, Ireland ²</td>
<td>Spring</td>
<td>1 to 2</td>
<td>Under Ripe (&gt;9)</td>
<td>Green, Grassy, Acidic</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 to 5</td>
<td>Ripe (5)</td>
<td>Strawberry, Sweet, Crisp</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;6</td>
<td>Over Ripe (1 to 3)</td>
<td>Strong, Strawberry</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>1 to 2</td>
<td>Under Ripe (&gt;9)</td>
<td>Green, Grassy, Acidic</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 to 5</td>
<td>Ripe (5)</td>
<td>Strawberry, Sweet, Fresh</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;6</td>
<td>Over Ripe (1 to 3)</td>
<td>Strong, Strawberry, Musty</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>Autumn</td>
<td>1 to 2</td>
<td>Under Ripe (&gt;9)</td>
<td>Green, Grassy, Acidic</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 to 5</td>
<td>Ripe (5)</td>
<td>Strawberry, Sweet</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;6</td>
<td>Over Ripe (1 to 3)</td>
<td>Strong, Strawberry</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td>1 to 2</td>
<td>Under Ripe (&gt;9)</td>
<td>Green, Grassy, Acidic</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 to 5</td>
<td>Ripe (5)</td>
<td>Strawberry, Sweet</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;6</td>
<td>Over Ripe (1 to 3)</td>
<td>Pungent, Strawberry, Musty</td>
<td>2.1</td>
</tr>
</tbody>
</table>

¹ External shell colour was recorded against a Dole pineapple colour chart
² External colours recorded using UC Davis Postharvest Quality Produce Fact Sheets [http://postharvest.ucdavis.edu/producefacts/](http://postharvest.ucdavis.edu/producefacts/)
Table 5.2 Intrinsic characteristics (origin and cultivar) of intact fruits used in this study and their initial quality attributes.

<table>
<thead>
<tr>
<th>Type</th>
<th>Origin</th>
<th>Cultivar</th>
<th>Physiological age</th>
<th>Aroma</th>
<th>Firmness, N</th>
<th>Percent Soluble Solids</th>
</tr>
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<td>Strawberry</td>
<td>Spain</td>
<td>Camarossa</td>
<td>5</td>
<td>Ripe (5)</td>
<td>11.1</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>Morocco</td>
<td>Camarossa</td>
<td>4 to 5</td>
<td>Ripe (5)</td>
<td>9.6</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>Egypt</td>
<td>Festival</td>
<td>5</td>
<td>Ripe (5)</td>
<td>7.0</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>Ethiopia</td>
<td>Orly</td>
<td>6</td>
<td>Ripe (5)</td>
<td>4.4</td>
<td>9.1</td>
</tr>
<tr>
<td>Kiwifruit</td>
<td>Italy</td>
<td>Hayward</td>
<td>3</td>
<td>Ripe (4)</td>
<td>1.49</td>
<td>7.5</td>
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<tr>
<td></td>
<td>New Zealand</td>
<td>Hayward</td>
<td>3</td>
<td>Ripe (5)</td>
<td>2.75</td>
<td>7.3</td>
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<td>Cantaloupe Melon</td>
<td>Costa Rica</td>
<td>N/A</td>
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<td>8.23</td>
<td>7.7</td>
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<tr>
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<td>Italy</td>
<td>N/A</td>
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<td>Ripe (5)</td>
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<td></td>
<td>Brazil</td>
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<td>7.2</td>
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<td>Honeydew Melon</td>
<td>Costa Rica</td>
<td>N/A</td>
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<td>Ripe (4)</td>
<td>6.3</td>
<td>7.9</td>
</tr>
<tr>
<td></td>
<td>Brazil</td>
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<td>Ripe (5)</td>
<td>7.2</td>
<td>7.3</td>
</tr>
<tr>
<td>Orange</td>
<td>Morocco</td>
<td>Midknight</td>
<td>4</td>
<td>Ripe (&gt;9)</td>
<td>2.3</td>
<td>12</td>
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<td>Apple</td>
<td>France</td>
<td>Granny Smith</td>
<td>6</td>
<td>Ripe (5)</td>
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<td></td>
<td>France</td>
<td>Royal Gala</td>
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<td>Ripe (5)</td>
<td>13.3</td>
<td>13.5</td>
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<tr>
<td>Grape</td>
<td>Spain</td>
<td>Crimson*</td>
<td>5</td>
<td>Ripe (5)</td>
<td>5.9</td>
<td>18.3</td>
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<tr>
<td></td>
<td>Greece</td>
<td>Thompson*</td>
<td>3</td>
<td>Ripe (4)</td>
<td>5.4</td>
<td>16.4</td>
</tr>
</tbody>
</table>

*see [dles](http://postharvest.ucdavis.edu/producefacts/)

2 External colours recorded using UC Davis Postharvest Quality Produce Fact Sheets [http://postharvest.ucdavis.edu/producefacts/](http://postharvest.ucdavis.edu/producefacts/)
Figure 5.1 Cutting sizes/shapes used in sample preparation of fresh-cut (a) Pineapple – 10mm, 25mm & 50mm; (b) Cantaloupe melon- 10mm, 25mm & 50mm and (c) Honeydew melon – 10mm, 25mm & 50mm; (d) Kiwifruit- \( \frac{1}{2}, \frac{1}{4}, \) & \( \frac{1}{8} \), (e) strawberry – whole with stem, whole without stem, halves & slices (approx. 4/ berry); (f) orange – segment; (g) – red and green apple – wedges (16/fruit) and (h) red and green grape – whole (de-stemmed).
5.3.3. Measuring respiration rate: Experimental setup and procedure

The effect of intrinsic and extrinsic factors on the respiration rate of a variety of fresh-cut fruit was determined at 4°C in air. A custom made flow-through respirometer system was employed (Barry-Ryan, 1996). It consisted of eight chambers connected to a compressed air cylinder (certified <1ppm ethylene, BOC gases, Limerick, Ireland) via a Saffire 230 Series 3 flow regulator (Murex, Herts, England) housed in a refrigerator (Figure 5.2). Six of the eight chambers, 2-L conical flasks constructed from heavy duty pyrex glass (Series 22; AGB Scientific, Dublin, Ireland), were filled with 500g of fresh-cut product. Two chambers were left empty and used as controls. Each chamber was hermetically sealed with a rubber bung (d: 67mm). The wide neck enabled plant tissue to be easily placed in and removed from the chamber and the gas tight seal was able to withstand pressure of 2bar. Through regulation of pressure at the cylinder head and adjusting the fine metering valves (Nupro, USA), the airflow was controlled (10-15mL/min), in order to prevent the accumulation of more than 0.2% CO₂ in the chamber and to prevent the accumulation of ethylene, humidified and sub-divided into eight separate lines serving each of the chambers. The CO₂ concentrations at the outlets of each chamber were sampled every 85 min using an automated sampler and quantified using a gas chromatograph (Model GM250, AGC Instruments LTD, Ireland) fitted with a CTR1 column (Alltech, USA) with helium (CP-grade, BOC gas, Limerick, Ireland) at 60mL min⁻¹ used as the carrier gas. The detector current was set at 100mAmgs, and detector temperature was run under ambient temperatures (25°C). The detector had sensitivity to O₂ of ≥ 100ppm and to CO₂ of ≥ 200ppm. The experiment was conducted for 24 hours. All samples were run in duplicate and experiments were repeated three times.

Data from the GC was integrated using Trend Vision Chromatography Software (AGC Instruments LTD, Shannon, Co. Clare, Ireland) which allowed continuous automated sampling and processing of the data over 24 hours. The data collated was used to calculate the respiration rates (mL.CO₂/kg.h) of the samples, taking into account the level of CO₂ and O₂ in the inlet air, flow rates and sample weights. The CO₂ production rates of fresh-cut pineapple was measured in duplicate; replicated three times and deduced using the following equation:
\[ R_{CO_2} = \frac{V_f \times 60}{W \times 100} \times (CO_2^{out} - CO_2^{in}) \] (1.19)

Where; \( R_{CO_2} \) is respiration rate; mL CO\(_2\) kg\(^{-1}\) hr\(^{-1}\)
\( V_f \) is gas flow rate, mL/min
\( W \) is the weight of fruit; kg
\( CO_2^{out} \) = CO\(_2\) concentration at the outlet of respirometer; %
\( CO_2^{in} \) = CO\(_2\) concentration at the inlet of respirometer; %

**Figure 5.2** Flow-through respirometer apparatus (Barry-Ryan, 1996)

### 5.3.4. Validation: Packaging of fresh-cut pineapple chunks

Modified atmosphere packaging (MAP) is a dynamic process during which the \( R_{CO_2} \) of the product and gas permeability of the package determines the changes in O\(_2\) and CO\(_2\) levels inside the package. The steps involved in MAP design are outlined in Chapter 1.7. Briefly, package design involves determination of intrinsic properties of the product, i.e. respiration rate, product mass and density, optimal storage conditions, and package characteristics, i.e. film permeability, package geometry and storage. Subsequently, simulation is carried out to predict O\(_2\) and CO\(_2\) concentrations inside designed packages and to explore different scenarios related to variability within variables such as raw material (origin, season, physiological age), processing
(cut size/shape, dipping treatment) and/or temperature variation during storage. The final step is validation of the package under real-life conditions in order to define product-package compatibility (Torreiri et al., 2009; Mahajan et al., 2007; 2006).

Assuming that there is no gas stratification inside the package and that the total pressure is constant, the differential mass balance equations (Mahajan et al., 2007) that describe O₂ and CO₂ concentration changes in a package containing a respiring product are:

\[ \frac{d(O_2)}{dt} = O_{TR} \cdot \text{A} \cdot (O_{2}^{\text{out}} - O_{2}^{\text{in}}) - \text{RO}_{2} \cdot M \tag{1.20} \]

\[ \frac{d(CO_2)}{dt} = C_{TR} \cdot \text{A} \cdot (CO_{2}^{\text{out}} - CO_{2}^{\text{in}}) + \text{RCO}_{2} \cdot M \tag{1.21} \]

Equations (2) and (3) were used to predict O₂ and CO₂ concentrations, respectively inside a package containing 0.15 kg of fresh-cut pineapple chunks. The package system was a pouch of 20 x 20 cm (area: 412.9 cm²). The product was stored at 4°C and the recommended ranges of O₂ and CO₂ for fresh-cut pineapple were assumed to be 5%O₂+5%CO₂ (chapter 3). The respiration rate model was developed considering all of the factors and was used for predicting O₂ and CO₂ inside the packages at 4°C.

“Solver” was used to aid in the prediction of the respiration rate. Solver is part of a suite of commands sometimes referred to as ‘what-if-analysis’: a process of changing values in cells to see how those changes affect the outcome of formulas in a worksheet. With Solver it is possible to find the predicted respiration rate of a particular product using the sum of the residuals (ΣRes-CO₂) as the optimal value in the set target cell i.e. the difference between experimental and predicted RCO₂. Solver then works with a group of predefined cells, namely; Rᵣ, Rₑq and α, that are directly related to the formula in the target cell. Since the experimental data for fresh-cut pineapple is known, (average RCO₂ 2-5 mL kg⁻¹ hr⁻¹), the value of the coefficients is kept in line with the variable results obtained (usually to a minimum of 1 and max of 100). In the case of fresh-cut pineapple, considering all possible variable factors, values of 1.5, 5 and 0.2 were chosen as Rᵣ, Rₑq and α, respectively. Solver adjusted these values in the by changing cells specified (also called the adjustable cells) to produce a result specified by the target cell. In this instance, the value of the target
cell, i.e. \( \Sigma \text{Res}_{\text{CO}_2} \), was required to be as small as possible so \( \text{min} \) was chosen in order to minimise the sum of squares (\( \Sigma R^2 \)) and produce a good fit.

In order to estimate the target barrier properties required for packaging of fresh-cut pineapple chunks, the Equations (1.20) and (1.21) were treated at steady-state condition making the accumulation term equal to zero. Hence,

\[
\text{RO}_2 \cdot W = \text{OTR} \cdot A \cdot (O_{2\text{out}} - O_{2\text{in}}) \quad (1.22)
\]

\[
\text{RCO}_2 \cdot W = \text{CTR} \cdot A \cdot (CO_{2\text{in}} - CO_{2\text{out}}) \quad (1.23)
\]

Where, \( V_f \) is the free volume inside the package, \( O_{2\text{out}} \) is the \( O_2 \) concentration outside the package (20.9%); \( O_{2\text{in}} \) is the \( O_2 \) concentration inside the package; \( CO_{2\text{out}} \) is the \( CO_2 \) concentration outside the package (0.03%) and \( CO_{2\text{in}} \) is the \( CO_2 \) concentration inside the package. \( A \) is the net breathable area of packaging film, m\(^2\), \( W \) is the weight of pineapple chunks, kg. \( R_{O_2} \) and \( R_{CO_2} \) are the respiration rate for \( O_2 \) consumption and \( CO_2 \) production, respectively. \( RQ \) was assumed to be one. \( OTR \) and \( CTR \) are required transmission rates for \( O_2 \) and \( CO_2 \), respectively expressed in ml/m\(^2\).day.atm.

For validation of predicted gas composition, un-optimised, optimised, pillow pouch packages and clamshell containers were evaluated. For un-optimised and optimised packages, approximately 150g (±5g) of fresh-cut pineapple (25mm cut piece size) was placed inside a 250cc rigid polylactic acid (PLA) container (Biopak, UK) and the appropriate film (oriented polypropylene: OPP) carefully sealed around the rim of the container (Figure 5.3a, 5.3b) using an strong adhesive (Evo-stik multipurpose clear adhesive 32g, Bostik, UK.) . For optimised packs, the required number of perforations was added to the lidding film after sealing using a disposable hypodermic needle (18g x 40\( \mu \)m; Fisher Scientific Ltd.), before being stored. Clamshell containers were commercially construed from recycled polyethylene terephthalate (rPET) into which the same net weight/ cut piece size of fresh-cut pineapple was placed before being hermetically clamped shut and stored for analysis (Figure 5.3c). Pillow-pouch packages were made from a high-barrier laminate flexible film, commercially used for cheese packaging (Amcor Flexibles, Gloucester, UK). The film consisted of a double laminate (PET12/PE55 microns) and had \( O_2 \) and \( CO_2 \) permeabilities of 2473 and 8377 cc.mil/m\(^2\).day.atm respectively. An impulse bench-top heat sealer (Relco Ltd, UK) was used to prepare the pouches. The
dimensions for each of the test packages were 20cm x 20cm. Sealing allowed for a passive MAP to develop within packs as a result of the respiration of the fruit. Approximately 150±5g samples were placed in a 250 cc rigid polylactic acid (PLA) container (Biopack, UK) which was then heat sealed within the pillow pouch packages (Figure 5.3d). All laboratory packaged fresh-cut fruits were stored at 4°C for a period of 7 days. The gas composition within packs was measured using a gas analyser (Systech Instruments, UK). Gas sample was withdrawn by piercing the pack with the hypodermic needle through the septum. The mean values for O₂ and CO₂ concentrations of triplicate packs were recorded.

![Diagram](image)

Figure 5.3 Packaging systems used for package simulation and validation (a) macroscopic holes in combination with polymeric film; (b) non-perforated lidding film; (c) impermeable clamshell container and (d) pillow-pouch package. Black and red arrows illustrate O₂ and CO₂ movement respectively.

5.2.5. Statistical analysis

The experimental results were presented as the mean and standard deviation for three measurements. A two-way analysis of variance using Fisher’s Least Significant Difference (LSD) multi-comparison test to determine significant differences between factors studied (SPSS Statistics 19, IBM, Chicago). Statistically significant differences were reported at P ≤ 0.05.
Table 5.3 Product and package characteristics for fresh-cut pineapple

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<thead>
<tr>
<th>Product Characteristics</th>
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<tr>
<td>Fruit Type</td>
<td>Pineapple</td>
</tr>
<tr>
<td>Variety/ Cultivar</td>
<td>DelMonte Gold Extra Sweet MD2</td>
</tr>
<tr>
<td>Cut size/ shape, mm</td>
<td>25, triangular chunk</td>
</tr>
<tr>
<td>Product weight (M), kg</td>
<td>0.150 ±5</td>
</tr>
<tr>
<td>RR Model[^a]</td>
<td>Exponential decay</td>
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<td>Respiration rate; $R_{CO_2} (R_{eq}; mL CO_2 kg^{-1} h^{-1})$</td>
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<td>$O_2$ maximum ($Y_{omax} O_2$), atm</td>
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<tr>
<td>$CO_2$ minimum ($Y_{omin} CO_2$), atm</td>
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<td>$CO_2$ maximum ($Y_{omax} CO_2$), atm</td>
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<tr>
<td>Height (h), m</td>
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</tr>
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<td>Film name</td>
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</tr>
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<td>Film area, (A), cm$^2$ ($\pi r^2$)</td>
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<tr>
<td>Film thickness, (x), µ</td>
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<tr>
<td>Total volume ($V_t$), m$^3$</td>
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<tr>
<td>Produce volume ($V_p$), m$^3$</td>
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</tr>
<tr>
<td>Free volume ($V_f$), m$^3$</td>
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<td>Fill, %</td>
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</tr>
<tr>
<td>OTR, mL/m$^2$. day. atm</td>
<td>7300 - 12500</td>
</tr>
<tr>
<td>CTR, mL/m$^2$. day. atm</td>
<td>13900 - 23500</td>
</tr>
<tr>
<td>Beta required, ($\beta$)</td>
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<tr>
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</tr>
<tr>
<td>Diameter of perforation/ hole (D), µm</td>
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<td>External gas atmosphere, $CO_2$, ($CO_2^{out}$), %</td>
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</tr>
</tbody>
</table>
5.4. Results

5.4.1. Effects of fruit type, storage time and intrinsic and extrinsic factors on respiration rate

The respiration rates ($R_{CO_2}$) of a variety of (a) climacteric and (b) non-climacteric fresh-cut fruits over a 24h period are illustrated in Figure 5.4. At 4°C, initial respiration rate ($R_i$) values for climacteric fruit (Figure 5.4a) were in the range of 1.48 to 7.32 mL CO$_2$ kg$^{-1}$ hr$^{-1}$ with steady-state ($R_{eq}$) ranging from 0.85 to 5.67 mL CO$_2$ kg$^{-1}$ hr$^{-1}$ (achieved in <12hours). For non-climacteric fruit (Figure 5.4b) $R_i$ ranged from 0.85 to 12.99 mL CO$_2$ kg$^{-1}$ hr$^{-1}$, while $R_{eq}$ ranged from 0.95 to 11.02 mL CO$_2$ kg$^{-1}$ hr$^{-1}$.

![Figure 5.4](image)

Figure 5.4 Effects of raw material type on respiration rate (RCO$_2$) of (a) Climacteric and (b) Non-Climacteric fresh-cut fruits stored in air at 4°C. Values are means for three determinations ± SD (error bars) separated by Fisher’s LSD (p<0.05). (25mm – cut pieces).
In Figure 5.4a, the R\textsubscript{CO\textsubscript{2}} of both fresh-cut kiwifruit and red apple pieces increased initially (R\textsubscript{i}) until equilibrium (R\textsubscript{eq}) was established. For all melon and green apple, R\textsubscript{CO\textsubscript{2}} decreased until R\textsubscript{eq} was achieved. R\textsubscript{i} was in the order of honeydew melon > kiwifruit > galia melon > red apple > cantaloupe melon > green apples while Req was in the order of kiwifruit > red apple > honeydew melon > galia melon > cantaloupe melon > green apple. For non-climacteric fruit (Figure 5.4b), fresh-cut Agromonte pineapple had the highest R\textsubscript{CO\textsubscript{2}} initially (12.99 mL CO\textsubscript{2} kg\textsuperscript{-1} hr\textsuperscript{-1}) that decreased until equilibrium was reached (18.42 mL CO\textsubscript{2} kg\textsuperscript{-1} hr\textsuperscript{-1}). Del Monte pineapple and red grapes also increased in R\textsubscript{CO\textsubscript{2}} with values of 2.63 and 1.13 mL CO\textsubscript{2} kg\textsuperscript{-1} hr\textsuperscript{-1} at equilibrium respectively. Both fresh-cut strawberry halves and orange segments increased initially (8.58 and 6.14 mL CO\textsubscript{2} kg\textsuperscript{-1} hr\textsuperscript{-1}) until a peak was observed (14.64 and 9.01 mL CO\textsubscript{2} kg\textsuperscript{-1} hr\textsuperscript{-1}) then decreased until equilibrium was achieved (11.02 and 6.04 mL CO\textsubscript{2} kg\textsuperscript{-1} hr\textsuperscript{-1}) respectively.

**Figure 5.5** Effects of physiological age and season on the initial (R\textsubscript{i}) and steady-state (R\textsubscript{eq}) respiration rate of fresh-cut pineapple cv DelMonte Gold Extra Sweet (MD2) stored in air at 4°C for 24h. Values are means for three determinations ± SD. UR (under-ripe), R (ripe) and OR (over-ripe).
**Pineapple**

The effects of physiological age and seasonality on the $R_i$ and $R_{eq}$ of fresh-cut pineapple were determined (Figure 5.5). Physiological age affected the $R_{CO_2}$ of fresh-cut pineapple in the order of over-ripe > ripe > under-ripe across all seasons. An exception to this was fresh-cut Summer pineapple, where the $R_i$ was in the order of under ripe > ripe > over ripe ($p<0.05$) with no significant differences in $R_{eq}$ recorded ($p>0.05$). For Spring, Autumn and Winter over-ripe pineapples, a significant effect on $R_i$ was observed ($p<0.05$) with Autumn fruit displaying the highest $R_i$ of all ($p<0.001$). In general, Summer fruit (under-ripe and ripe) displayed the greatest $R_i$ of all fruits (14.78 and 12.63 mL CO$_2$ kg$^{-1}$ h$^{-1}$) with Spring fruit having the lowest values of 3.04 and 4.81 mL CO$_2$ kg$^{-1}$ h$^{-1}$. Overall, no significant differences in the $R_{eq}$ values for all fruit studied was found ($p>0.05$) with values in the range of 1.32 to 4.06 mL CO$_2$ kg$^{-1}$ h$^{-1}$.

![Figure 5.6](image)

**Figure 5.6** Effects of country of origin on the initial ($R_i$) and steady-state ($R_{eq}$) respiration rate of fresh-cut pineapple cv MD2 stored in air at 4°C for 24h. Values are means for four determinations ± SD.

**Figure 5.6** shows the effects of country of origin on the initial ($R_i$) and steady-state ($R_{eq}$) respiration rate of fresh-cut pineapple. Initial respiration rate values differed significantly ($p<0.05$) with values of 10.72, 7.81 and 4.77 mL CO$_2$ kg$^{-1}$ h$^{-1}$ for Honduras, Brazilian and Costa Rican grown fruit respectively. After 24h, no significant differences in $R_{eq}$ values were observed ($p>0.05$), ranging from 1.89 to 2.45 mL CO$_2$ kg$^{-1}$ h$^{-1}$. 

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Figure 5.7 Effects of cut blade sharpness on the initial (R\textsubscript{i}) and steady-state (R\textsubscript{eq}) respiration rate of fresh-cut pineapple \textit{cv} DelMonte Gold Extra Sweet (MD2) stored in air at 4\textdegree C for 24h. Values are means for three determinations ± SD.

Figure 5.7 shows the effect of cut blade sharpness on the initial and steady-state respiration rate of fresh-cut pineapple. As anticipated, use of the stainless steel chopper and sharp knife resulted in slightly lower respiration rates than use of the blunt knife, however, no significant differences were found (p>0.05) with R\textsubscript{i} values of 5.96, 5.91 and 6.95 mL CO\textsubscript{2} kg\textsuperscript{-1} h\textsuperscript{-1}, respectively. Similarly, no significant difference in R\textsubscript{eq} values were observed (p>0.05) with final values ranging from 1.78 to 2.18 mL CO\textsubscript{2} kg\textsuperscript{-1} h\textsuperscript{-1}.

Figure 5.8 Effects of cut size and dipping treatment on the initial (R\textsubscript{i}) and steady-state (R\textsubscript{eq}) respiration rate of fresh-cut pineapple \textit{cv} DelMonte Gold Extra Sweet (MD2) stored in air at 4\textdegree C for 24h. Values are means for three determinations ± SD.
**Figure 5.8** illustrates the effect of cut size and dipping treatment (1% ascorbic acid and 1% citric acid) on the respiration rates ($R_i$ and $R_{eq}$) of fresh-cut pineapple. Cut size affected $R_i$ with larger 50mm cut pieces having significantly lower $R_i$ values (5.83 mL CO$_2$ kg$^{-1}$ h$^{-1}$) ($p<0.05$) than smaller 25mm and 10mm cut pieces (7.01 and 7.41 mL CO$_2$ kg$^{-1}$ h$^{-1}$, respectively). Dipping the cut pieces caused a marked reduction in $R_i$, having more of an effect on smaller cut pieces. Dipping 10mm cut pieces resulted in a 58% reduction in $R_i$ (2.92 mL CO$_2$ kg$^{-1}$ h$^{-1}$) while a 41% reduction was observed for 50mm cut pieces (3.45 mL CO$_2$ kg$^{-1}$ h$^{-1}$). Dipping also resulted in lower $R_{eq}$ values for all cut sizes ($p>0.05$), with $R_{eq}$ values ranging from 1.76 to 2.42 mL CO$_2$ kg$^{-1}$ h$^{-1}$ for dipped fruit and 2.74 to 3.21 mL CO$_2$ kg$^{-1}$ h$^{-1}$ for undipped fruit ($p>0.05$).

**Figure 5.9** Effects of physiological age and season on the initial ($R_i$) and steady-state ($R_{eq}$) respiration rate of fresh-cut strawberry cv El Santa (Irish) stored in air at 4°C for 24h. Values are means for three determinations ± SD.
Chapter 5

Strawberry

The effects of physiological age and season on the initial and steady-state respiration rate of fresh-cut strawberry halves are presented in Figure 5.9. Physiological age affected the $R_i$ in the order of over ripe > ripe > under ripe ($p<0.01$) with a smaller effect of season observed ($p<0.05$). Under-ripe fruit had the lowest $R_i$ with values of 6.48, 11.75, 14.39 and 6.07 mL CO$_2$ kg$^{-1}$ h$^{-1}$ for Spring, Summer, Autumn and Winter fruit, respectively. In contrast, over-ripe fruit had the highest $R_i$ with values ranging from 12.2 to 22.2 mL CO$_2$ kg$^{-1}$ h$^{-1}$ in Spring and Summer to 18.55 to 14.79 mL CO$_2$ kg$^{-1}$ h$^{-1}$ in Autumn and Winter. Ripe Summer strawberry halves had the greatest $R_i$ of all (22.14 mL CO$_2$ kg$^{-1}$ h$^{-1}$). Steady-state ($R_{eq}$) respiration values were significantly different with respect to physiological age ($p<0.05$) with no significant effects of season observed ($p>0.05$). Values ranged from 6.66 to 12.83 mL CO$_2$ kg$^{-1}$ h$^{-1}$ in Spring, 8.36 to 12.80 mL CO$_2$ kg$^{-1}$ h$^{-1}$ in Summer, 8.03 to 13.40 mL CO$_2$ kg$^{-1}$ h$^{-1}$ in Autumn, and 5.07 to 11.85 mL CO$_2$ kg$^{-1}$ h$^{-1}$ in Winter.

Figure 5.10 Effects of cultivar and country of origin on the initial ($R_i$) and steady-state ($R_{eq}$) respiration rate of fresh-cut strawberry stored in air at 4°C for 24h. Values are means for three determinations ± SD.
**Figure 5.10** shows the effects of cultivar and origin on the $R_i$ and $R_{eq}$ of fresh-cut strawberry halves. For $R_i$, no significant effect of cultivar and/or origin was found ($p>0.05$) with values ranging from 8.88 to 11.23 mL CO$_2$ kg$^{-1}$ h$^{-1}$. Similarly, no significant effect on $R_{eq}$ was noted, with values ranging from 8.41 to 10.22 mL CO$_2$ kg$^{-1}$ h$^{-1}$. An exception to this was Egyptian cv Festival and Irish cv El Santa whose respiration rate continued to increase during storage with $R_{eq}$ values of 9.07 mL CO$_2$ kg$^{-1}$ h$^{-1}$ ($p>0.05$) and 16.7 mL CO$_2$ kg$^{-1}$ h$^{-1}$ recorded ($p<0.05$) respectively.

**Figure 5.11** Effects of cutting and season on the initial ($R_i$) and steady-state ($R_{eq}$) respiration rate of fresh-cut strawberry cv El Santa (Irish) stored in air at 4°C for 24h. Values are means for three determinations ± SD.

**Figure 5.11** illustrates the effects of cutting and season on the $R_i$ and $R_{eq}$ of fresh-cut strawberry halves. In general, Summer fruit had slightly higher RCO$_2$ than Autumn fruit. Removing the stem decreased the RCO$_2$, but the change was not significant ($p>0.05$). Initial and steady-state respiration values ranged from 8.48 to 8.62 mL CO$_2$ kg$^{-1}$ h$^{-1}$ and 12.3 to 13.27 mL CO$_2$ kg$^{-1}$ h$^{-1}$ in Autumn and 8.33 to 8.79 mL CO$_2$ kg$^{-1}$ h$^{-1}$ and 12.97 to 12.63 mL CO$_2$ kg$^{-1}$ h$^{-1}$ in Summer. Halving the fruit caused a marked increase in $R_i$ (26%), with values of 10.44 to 12.79 CO$_2$ kg$^{-1}$ h$^{-1}$ and 16.72 to 17.44 mL CO$_2$/ kg$^{-1}$ h$^{-1}$ in Summer and Autumn, respectively. A similar trend was also
noted for \( R_{eq} \) (p<0.01) although no significant differences between seasons were observed (p>0.05). Slicing the fruit into 4 slices increased \( R_{i} \) even further (30%) with no significant difference in values observed (p>0.05) between seasons. In contrast, significant differences were observed between \( R_{eq} \) for sliced strawberries, with values of 20.78 and 14.62 mL CO\(_2\) kg\(^{-1}\) h\(^{-1}\) for Summer and Autumn fruit respectively (p<0.05). However, no significant differences were found between \( R_{i} \) and \( R_{eq} \) for Autumn fruit studied (p>0.05).

**Kiwifruit**

The effects of origin, cut size and dipping treatment on the respiration rate (\( R_{i} \) and \( R_{eq} \)) of fresh-cut kiwifruit is reported in Figure 5.12. The \( R_{CO_2} \) of fresh-cut kiwifruit increased during storage. This increase was almost 50% of its initial value. Cutting and dipping slightly increased the \( R_{i} \) and \( R_{eq} \) of fruits, but the effect was not significant (p>0.05). Larger cut fruits (\( \frac{1}{2} \)) had greater \( R_{i} \) values, while smaller cut fruits (\( \frac{1}{8} \)) had greater \( R_{eq} \) values (p>0.05). No significant effect of origin was noted (p>0.05) with Italian fruit displaying slightly higher values than New Zealand fruit. Based on these results, the average \( R_{i} \) and \( R_{eq} \) values were 4.5 and 8.3 mL CO\(_2\) kg\(^{-1}\) h\(^{-1}\) respectively.

**Melon**

Figure 5.13 shows the effects of origin and cut size on the \( R_{i} \) and \( R_{eq} \) of fresh-cut honeydew melon. The respiration rate for melon decreased with time to approximately 50% of its initial value at equilibrium. Among origins studied, Costa Rican melon had slightly higher \( R_{i} \) values than those from either Brazil or Honduras. In general, the smaller the cut piece size the greater the \( R_{i} \) with values ranging from 5.78 to 7.41 mL CO\(_2\) kg\(^{-1}\) h\(^{-1}\) and 3.28 to 4.20 mL CO\(_2\) kg\(^{-1}\) h\(^{-1}\) for 10mm and 50mm cut pieces, respectively. At equilibrium (\( R_{eq} \)), no significant differences, irrespective of origin or cut size, was found (p>0.05).
Figure 5.12 Effects of origin, cut size and dipping treatment (1% ascorbic acid + 1% citric acid) on the initial ($R_i$) and steady-state ($R_{eq}$) respiration rate of fresh-cut Italian and New Zealand kiwifruit stored in air at 4°C for 24h. Values are means for three determinations ± SD. D (dipped), UD (undipped).

Figure 5.13 Effects of origin and cut size on the initial ($R_i$) and steady-state ($R_{eq}$) respiration rate of fresh-cut honeydew melon stored in air at 4°C for 24h. Values are means for three determinations ± SD.
Figure 5.14. Effects of cut size and origin on the initial ($R_i$) and steady-state ($R_{eq}$) respiration rate of fresh-cut cantaloupe melon stored in air at 4°C for 24h. Values are means for three determinations ± SD.

Similar to honeydew melon, the respiration rate of fresh-cut cantaloupe melon decreased with time, to between 74 and 89% of its initial value (Figure 5.14). However, the respiration rate in this instance was almost three times greater than that of honeydew melon, with an average $R_i$ value of 14.08 mL CO$_2$ kg$^{-1}$ h$^{-1}$. The $R_{eq}$ was also higher with an average value of 2.5 mL CO$_2$ kg$^{-1}$ h$^{-1}$. In general, the smaller the cut size the higher the $R_{CO_2}$ with $R_i$ and $R_{eq}$ values ranging from 8.02 to 20.35 mL CO$_2$ kg$^{-1}$ h$^{-1}$ and 1.19 to 4.17 mL CO$_2$ kg$^{-1}$ h$^{-1}$ respectively. Costa Rican cantaloupe melon had significantly higher $R_i$ values (p<0.001) than other origins tested, with no significant differences between cut sizes observed (p>0.05). At equilibrium ($R_{eq}$), no significant differences, irrespective of origin or cut size, were found (p>0.05).
5.4.2. Case Study – Package design procedure for fresh-cut pineapple

A case study is presented to illustrate the use of the experimental respiration data in MAP design for fresh-cut pineapple.

The first step in the design of any MAP is to determine the respiration rate of the intended product. In this instance, the respiration rate (R$_{CO_2}$) of fresh-cut pineapple as affected by intrinsic and extrinsic factors (Figure 5.5 to 5.8) were determined as outlined in section 5.2.

The parameters of the respiration rate model were estimated by non-linear regression (MS Excel, 2007, USA) analysis of the experimental data obtained through the study of intrinsic and extrinsic factor effects on fresh-cut pineapple. This model for respiration is usually a function of O$_2$, CO$_2$ and temperature. Based on the intrinsic and extrinsic data attained for fresh-cut pineapple, a mathematical model based on the exponential decay (Equation 1.24) was applied to predict changes in respiration rate with time for all the factors studied.

\[
R_{CO_2}^{eq} = R_{CO_2}^i + \left( R_{CO_2}^i - R_{CO_2}^{eq} \right) e^{-(\alpha t)} \quad (1.24)
\]

where; $R_{CO_2}$ is the respiration rate at any time (t), mL kg$^{-1}$ h$^{-1}$; $R_{CO_2}^i$ is the initial respiration rate, mL kg$^{-1}$ h$^{-1}$; $R_{CO_2}^{eq}$ is the respiration rate at equilibrium time, ml/kg.h; t is the storage time, h and $\alpha$ is constant coefficient.

A secondary model was built by combining Equations (1.19) and (1.24) yielding Equation (1.25):

\[
CO_2^{out} = \frac{[R_{CO_2}^{eq}+(R_{CO_2}^i-R_{CO_2}^{eq})e^{-\alpha t}]}{V_f \times 60} W \times 100 + CO_2^{in} \quad (1.25)
\]

The experimental data obtained at various times during storage was fitted with Equation (1.25). The model parameters such as $R_{CO_2}^i$, $R_{CO_2}^{eq}$ and $\alpha$ were estimated using Solver in Microsoft Excel (MS Excel, 2007, USA).
The estimated values of respiration constants ($R_{CO_2}^i$ and $R_{CO_2}^{eq}$) are summarized in Table 5.4 and 5.5 for intrinsic and extrinsic factors, respectively. On average, $R_i$ and $R_{eq}$ values were 8.52±4.68 and 2.64±0.68 mL kg$^{-1}$ h$^{-1}$ respectively. Although initial increases in $R_{CO_2}$ were observed for all treatments, $R_{eq}$ ranged from 1.6 to 4 mL kg$^{-1}$ h$^{-1}$. The constant coefficient $\alpha$ varied from 0.11 to 0.27, indicating that the ratio of $R_{CO_2}^i$ and $R_{CO_2}^{eq}$ was close to 3. The experimental and predicted $R_{CO_2}$ for under-ripe, ripe and over-ripe fresh-cut pineapple chunks is presented in Figure 5.15. The mathematical model (Equation 4) appropriately described the influence of storage time on respiration rate as shown by the high $R^2$ values between 85.9 and 99.89%.

![Figure 5.15](image-url)

**Figure 5.15** Typical changes in respiration rate of fresh-cut pineapple chunks as a function of storage time and degree of physiological age (symbols: experimental values; line: predicted values).
Table 5.4 Effect of intrinsic characteristics on respiration rate of fresh-cut pineapples at 4°C.

<table>
<thead>
<tr>
<th>Type/Source</th>
<th>Season</th>
<th>Physiological age (Ripeness class)</th>
<th>$R_i$</th>
<th>$R_{eq}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Del Monte Gold&lt;sup&gt;(R)&lt;/sup&gt;, Extra Sweet, Costa Rica</td>
<td>Spring</td>
<td>Under ripe</td>
<td>3.11&lt;sub&gt;a&lt;/sub&gt;</td>
<td>1.76&lt;sub&gt;b&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ripe</td>
<td>4.80&lt;sub&gt;b&lt;/sub&gt;</td>
<td>2.72&lt;sub&gt;hij&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Over ripe</td>
<td>10.39&lt;sub&gt;cd&lt;/sub&gt;</td>
<td>3.92&lt;sub&gt;lm&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>Under ripe</td>
<td>15.29&lt;sub&gt;f&lt;/sub&gt;</td>
<td>3.32&lt;sub&gt;klm&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ripe</td>
<td>13.13&lt;sub&gt;c&lt;/sub&gt;</td>
<td>2.99&lt;sub&gt;ijk&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Over ripe</td>
<td>10.35&lt;sub&gt;cd&lt;/sub&gt;</td>
<td>3.58&lt;sub&gt;klm&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>Autumn</td>
<td>Under ripe</td>
<td>5.85&lt;sub&gt;b&lt;/sub&gt;</td>
<td>2.15&lt;sub&gt;hi&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ripe</td>
<td>8.75&lt;sub&gt;c&lt;/sub&gt;</td>
<td>2.92&lt;sub&gt;ijk&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Over ripe</td>
<td>23.27&lt;sub&gt;g&lt;/sub&gt;</td>
<td>4.01&lt;sub&gt;m&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td>Ripe</td>
<td>10.75&lt;sub&gt;d&lt;/sub&gt;</td>
<td>2.44&lt;sub&gt;hi&lt;/sub&gt;</td>
</tr>
<tr>
<td>Fyyfe’s Super Sweet&lt;sup&gt;(R)&lt;/sup&gt;, Brazil</td>
<td>Summer</td>
<td>Ripe</td>
<td>8.57&lt;sub&gt;c&lt;/sub&gt;</td>
<td>2.76&lt;sub&gt;ijk&lt;/sub&gt;</td>
</tr>
<tr>
<td>Royal Coast Gold&lt;sup&gt;(R)&lt;/sup&gt;, Costa Rica</td>
<td>Winter/Spring</td>
<td>Ripe</td>
<td>10.75&lt;sub&gt;d&lt;/sub&gt;</td>
<td>2.45&lt;sub&gt;hi&lt;/sub&gt;</td>
</tr>
<tr>
<td>Agro Monte, Honduras</td>
<td>Autumn</td>
<td>Ripe</td>
<td>13.83&lt;sub&gt;ef&lt;/sub&gt;</td>
<td>3.07&lt;sub&gt;ijk&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

*Numbers with the same letters are not significantly different (p>0.05)

Table 5.5 Effect of processing and extrinsic factors on respiration rate of fresh-cut pineapple at 4°C.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Variations</th>
<th>$R_i$</th>
<th>$R_{eq}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ml CO&lt;sub&gt;2&lt;/sub&gt; kg&lt;sup&gt;-1&lt;/sup&gt; h&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>ml CO&lt;sub&gt;2&lt;/sub&gt; kg&lt;sup&gt;-1&lt;/sup&gt; h&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Cut size*</td>
<td>10 mm chunk</td>
<td>2.93&lt;sub&gt;a&lt;/sub&gt;***</td>
<td>2.00&lt;sub&gt;lg&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>25 mm chunk</td>
<td>4.98&lt;sub&gt;b&lt;/sub&gt;</td>
<td>2.40&lt;sub&gt;gh&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>50 mm chunk</td>
<td>3.43&lt;sub&gt;a&lt;/sub&gt;</td>
<td>1.59&lt;sub&gt;f&lt;/sub&gt;</td>
</tr>
<tr>
<td>Blade sharpness**</td>
<td>Razor sharp knife&lt;sup&gt;†&lt;/sup&gt;</td>
<td>6.19&lt;sub&gt;cd&lt;/sub&gt;</td>
<td>1.57&lt;sub&gt;f&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>Sharp knife</td>
<td>6.17&lt;sub&gt;cd&lt;/sub&gt;</td>
<td>2.12&lt;sub&gt;gh&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>Blunt knife</td>
<td>7.68&lt;sub&gt;c&lt;/sub&gt;</td>
<td>2.38&lt;sub&gt;ghi&lt;/sub&gt;</td>
</tr>
<tr>
<td>Dipping pre-treatment</td>
<td>10 mm chunk</td>
<td>7.02&lt;sub&gt;de&lt;/sub&gt;</td>
<td>3.21&lt;sub&gt;j&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>25 mm chunk</td>
<td>7.42&lt;sub&gt;e&lt;/sub&gt;</td>
<td>2.89&lt;sub&gt;ijd&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>50 mm chunk</td>
<td>5.95&lt;sub&gt;c&lt;/sub&gt;</td>
<td>2.74&lt;sub&gt;hij&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

* No dipping treatment applied; sharp blade used.
** Cut size 25mm chunk
*** Numbers with the same letters are not significantly different (p>0.05)
5.4.3. Implications for packaging

Considering the variability in respiration rate, the predicted range of O\(_2\) and CO\(_2\) was found to be 12.3-16.2% and 5.1-9%, respectively after 7 Days (Figure 5.16).

![Figure 5.16](image)

**Figure 5.16** Package gas simulations based on variability in respiration rate due extrinsic and intrinsic factors. The dotted lines shows the possible range of O\(_2\) and CO\(_2\) obtained based on respiration rate variability and continuous lines shows that without any variability in respiration rate.

Intrinsic factors (physiological age and season) greatly influenced in-pack gas atmosphere composition (Figure 5.17). A gradual decline in O\(_2\) and increase in CO\(_2\) concentrations were recorded within all packages.

![Figure 5.17](image)

**Figure 5.17** The effects of physiological age and seasonality on in-pack (a) oxygen and (b) carbon dioxide concentrations of fresh-cut pineapple chunks stored within a high barrier film at 4°C. Values are means for four determinations. Vertical lines represent ±SD. Key HB = high barrier film; UR = under ripe; R = ripe; OR = over ripe; Aut = Autumn season; Sum = Summer season; continuous line, descending (O\(_2\)) dashed line, ascending (CO\(_2\)).
The effects of cut size and dipping treatment on in-pack O₂ and CO₂ levels at 4°C were also determined. Figure 5.18 shows a gradual decrease and increase in O₂ and CO₂ respectively, within both un-dipped and dipped packages, with greater modification observed for smaller cut pieces.

Figure 5.18. The effects of cut size and dipping treatment (1%AA:CA) on in-pack oxygen and carbon dioxide concentrations of packaging of fresh-cut pineapple chunks stored within a high barrier film at 4°C. Values are means for four determinations. Vertical lines represent ±SD. Key: HB (high barrier film); AA (Ascorbic acid); CA (Citric acid); 10 (10mm), 25 (25mm) and 50 (50mm) cut sizes; UD (un-dipped) and D (dipped); continuous line, descending (O₂), dashed line, ascending (CO₂).

Considering the variability of respiration rate (2.64±0.68 ml CO₂ kg⁻¹ h⁻¹ at equilibrium), the target barrier properties required for packaging 150 grams of fresh-cut pineapple chunks were estimated. Based on the results of chapter 3, the recommended modified atmosphere for fresh-cut pineapple was 5%O₂ + 5%CO₂. For a market size tray (12x7 cm) with heat sealable film at the top (breathable area = 64cm²), the target range of OTR and CTR required to reach an equilibrium within the recommended atmosphere range was found to be 7300-12500 and 13900-23500 ml/m².day.atm, respectively for one mil of film thickness (Table 5.3). The transmission rates required would have to be doubled for 2 mil thick film.

As there is no flexible film to match the required transmission rates, any packaging film selected would have to be adjusted to include precise perforations for that particular product. The number and size of the holes was estimated from the
target OTR and CTR and their respective gas diffusion coefficients as reported by Mahajan et al., (2007). Without making a hole, there is a risk of anoxia and also high CO$_2$ concentration inside the package over longer periods of storage. The gas transfer coefficients through perforations can be described as follows (Equations 1.26 and 1.27):

\begin{align}
\text{P}_{\text{O}_2} &= N_p \times \frac{\varepsilon}{T^2} \times a \times D_{\text{p}}^b \times L_c^c \tag{1.26} \\
\text{P}_{\text{CO}_2} &= N_p \times \beta \times \frac{\varepsilon}{T^2} \times a \times D_{\text{p}}^b \times L_c^c \tag{1.27}
\end{align}

where; $a = 6.4 \times 10^{-6}$; $b = 1.45$, $c = -0.598$, $\beta = 1.14$; $D_{\text{O}_2} = 16.4 \times 10^{-6}$ m$^2$s$^{-1}$ and $D_{\text{CO}_2} = 20.6 \times 10^{-6}$ m$^2$s$^{-1}$.

The microscopic perforation in the polymeric film represents an alternative route for gas transport, which is in parallel to the barrier formed by the plastic material. The total flow through polymeric film having $N_H$ number of holes is (Equation 1.28):

\begin{equation}
\text{Total permeation} = \{\text{permeation through film}\} \times \{\text{permeation through 1 hole} \times N_H\} \tag{1.28}
\end{equation}

Macroscopic perforations in polymeric films have diameters in the order of $10^{-4}$ m or greater, whereas the mean-free path of gas molecules at atmospheric pressure is much less $(1$ or $2) \times 10^{-7}$ m (Fishman et al., 1996). Therefore, transport through the perforation may be treated as macroscopic diffusion in a cylindrical pathway filled with air. If the distance between perforations is much greater than their radius, the diffusive path length becomes the length of the pore plus the radius of the hole:

\begin{align}
\text{P}_{\text{O}_2} &= \left[\frac{\text{P}_{\text{O}_2}^{\text{film}} + \pi R_H^2 \times D_{\text{O}_2} \times N_H}{(e \times R_H)}\right] \tag{1.29} \\
\text{P}_{\text{CO}_2} &= \left[\frac{\text{P}_{\text{CO}_2}^{\text{film}} + \pi R_H^2 \times D_{\text{CO}_2} \times N_H}{(e \times R_H)}\right] \tag{1.30}
\end{align}

where; $P_{\text{O}_2}$; $P_{\text{CO}_2}$ is the permeability for O$_2$; CO$_2$ mL.mil.m$^{-2}$.day$^{-1}$.atm$^{-1}$; $R_H$ is the radius of the hole, m; $D_{\text{O}_2}$;$D_{\text{CO}_2}$ is the diffusivity of O$_2$; CO$_2$ in air, m$^2$s$^{-1}$; $e$ is the thickness of the film, $\mu$m and $N_H$ is the number of holes required.
Based on these calculations, a package containing at least one micro-hole of size 70 microns is needed in order to achieve the target O₂ and CO₂ transmission rates required for packaging of fresh-cut pineapple chunks (Table 5.3). In this instance, a rigid type poly lactic acid (PLA) container with a micro-perforated lidding film in combination with macroscopic perforations (as shown in Figure 5.3a) was selected for validation in the present case study. The rigid container was assumed to be more suitable for consuming a ready-to-eat product, such as the fresh-cut pineapple. In addition to the ‘optimised’ packaging system described above, control packaging systems were concurrently evaluated within this study to demonstrate the effectiveness (or not) of the optimised film. A non-perforated lidding film (Figure 5.3b), impermeable clamshell container (Figure 5.3c) and a high barrier pillow-pouch package (Figure 5.3d) were employed to mimic sub-optimal packaging systems.

Of the commercial polymers available, oriented polypropylene (OPP) was chosen as the lidding film, with a thickness of 25.4µm and a permeability of 1,100 cc O₂/ m².day.atm (β: 3.09). The surface area of the lidding film in systems (a) and (b) was equal to the surface area (A) of the container top (πr² = 9.5x10⁻³m²). High-barrier film was used to produce pillow-pouch packages (A = 825.8cm²) while recycled polyethylene terephthalate (RPET) was the polymer used in clamshell containers (250cc).

![Graph showing in-pack gas atmosphere validation of fresh-cut pineapple packs at 4°C. 25mm cut piece size.](image)

Figure 5.19 In-pack gas atmosphere validation of fresh-cut pineapple packs at 4°C. 25mm cut piece size. ○ Shows the EMA time (approx. 3.75 days for optimised packs). ● highlights the near optimum O₂ and CO₂ range attained by optimised packs on Day 7. Continuous line, descending (O₂), dashed line, ascending (CO₂).
Clamshell containers (impermeable) attained the fastest rate of EMA, in approximately 1.75 Days (Figure 5.19). However, the EMA was not maintained with CO₂ levels continuing to increase thereafter, reaching 24% by Day 7. In addition, O₂ levels continued to decrease reaching near anoxic levels on Day 7 (0.06%). Un-optimised packages (no holes) also attained sub-optimal in-pack gas atmosphere concentrations during storage, achieving EMA by Day 2 but with increasing CO₂ levels thereafter (26% on Day 7). O₂ levels rapidly depleted reaching anoxic levels (0%) on Day 7. Pillow-pouch packages showed the least in-pack atmosphere modification of all packs studied with O₂ and CO₂ levels of 12% and 6.5%, respectively, at end of storage. Optimised packages (1 hole) displayed favourable in-pack gas atmospheres during storage, achieving EMA in approximately 3.75 Days. At end of storage, packs had attained near optimum gas levels (3-5%O₂ + 5-8% CO₂) with O₂ and CO₂ values of 9% and 12%, respectively.
5.5. Discussion

5.5.1. Effect of fruit type and storage time on respiration rate.

Figure 5.3 shows the respiratory activity ($R_{CO_2}$) of fresh-cut fruits over a 24h period. The range $R_{CO_2}$ values obtained for most fruits were in line with previous studies. The $R_{CO_2}$ of fresh-cut fruit was found to vary between cultivar and species and was generally much higher initially, peaking to a maximum with time ($T_x$) and decreasing to an equilibrium value depending on the type of fruit studied. The initial rates were affected by raw material type, quality and process severity, however, similar trends to equilibrium were observed.

These high initial rates were due to wounding and a short-lived stress response. When $R_i > R_{eq}$, wound-induced respiration exhibits a 3-phase response; including, an increase, a maximum peak and a decline as observed for fresh-cut pineapple and strawberry. However, when $R_i \approx R_{eq}$, then wound-induced respiration rate increases and there is no decline as observed for fresh-cut strawberry and kiwifruit. Finally, when tissues show little increase in respiration rate, the $R_{eq}$ values remain very low, as observed for red and green grapes. Thus, $R_i$ contributes to initial in-pack modification while $R_{eq}$ contributes more to equilibrium modified atmosphere (EMA).

In this study, fresh-cut pineapple showed a gradual steady decline in $R_{CO_2}$ until an equilibrium was achieved in approximately 12-20h. For fresh-cut strawberry, $R_i$ increased until a peak was reached at ~10h, followed by a gradual decline until $R_{eq}$ was achieved in <24h. Fresh-cut honeydew melon reached equilibrium in 11-13h while cantaloupe melon took longer, on average, 13-24h. For fresh-cut kiwifruit, origin had little effect on the time it took to achieve equilibrium, ranging from 17-22h.

Overall, climacteric fruits had lower $R_i$ values than non-climacteric fruits with values ranging from 2.12 to 8.21 mL CO$_2$ kg$^{-1}$ hr$^{-1}$ while non-climacteric fruit had lower $R_{eq}$ values ranging from 0.85 to 3.70 mL CO$_2$ kg$^{-1}$ hr$^{-1}$. Different varieties of the same product can exhibit different $R_{CO_2}$ (Fidler and North, 1967; Song et al., 1992; Fonseca et al., 2002). Significant differences in $R_i$ values between both ripeness classes were obtained, with average values of 5.42 and 6.65 mL CO$_2$ kg$^{-1}$ hr$^{-1}$ for climacteric and non-climacteric fruits ($p<0.05$) respectively. However, no
significant differences in $R_{eq}$ were obtained with average values of 2.73 mL CO$_2$ kg$^{-1}$ hr$^{-1}$ and 4.28 mL CO$_2$ kg$^{-1}$ hr$^{-1}$, respectively (p>0.05).

Climacteric fruits such as apple, kiwifruit and melon, once cut, had slightly elevated respiration rates. Significant differences were observed in $R_{CO_2}$ of both green and red apple varieties (P<0.001) with average values of 0.98 and 4.53 mL CO$_2$ kg$^{-1}$ hr$^{-1}$ recorded respectively. Fresh-cut kiwifruit pieces had significantly higher steady-state respiration rates compared with all other fruits tested (P<0.001) with a value of 8.01 mL CO$_2$ kg$^{-1}$ hr$^{-1}$. No significant differences (P<0.05) were obtained for both fresh-cut honeydew and galia melon varieties with average $R_{CO_2}$ values of 4.16 and 3.87 mL CO$_2$ kg$^{-1}$ hr$^{-1}$ respectively. In contrast, significant values were obtained for fresh-cut cantaloupe melon (P<0.01) which had an average $R_{CO_2}$ value of 1.75 and mL CO$_2$ kg$^{-1}$ hr$^{-1}$.

For fresh-cut pineapple (Del Monte Gold #10) the respiration rate was relatively low to begin with and declined slowly during storage. This is in contrast to fresh-cut strawberry halves which demonstrated a dramatic increase in respiration until $R_{eq}$ was achieved. In addition, significant differences were obtained (P<0.01) for both pineapple varieties tested with average $R_{CO_2}$ values of 3.52 and 6.20 mL CO$_2$ kg$^{-1}$ hr$^{-1}$ for Del Monte Gold (MD2) and Agricola Agromonte (MD2) respectively. Fresh-cut pineapple (Agromonte) (NCL) had the highest $R_i$ initially of all fruits tested (13 mL CO$_2$ kg$^{-1}$ hr$^{-1}$) which saw a dramatic decline thereafter until equilibrium was reached (3.7 mL CO$_2$ kg$^{-1}$ hr$^{-1}$), similar to that of Del Monte Gold (3.3 mL CO$_2$ kg$^{-1}$ hr$^{-1}$). The large differences in $R_{CO_2}$ values obtained are likely attributed to the diverse fruit sizes. Agricola Agromonte were marketed as Extra-Large (XL) Pineapple (185mm*130mm) while Del Monte Gold pineapple as ‘size 10’ (150mm*110mm). Gorny et al. (2000) showed that pear sizes greatly affected respiration rate with smaller pears having smaller respiration rate than larger fruit. Similarly, increased fruit size could be attributed to increased cell size, volume and number resulting in greater starch availability for sugar conversion. Interestingly, the RR of halved strawberries continued to increase throughout the initial testing period until a plateau was reached (8-12h) after which time a gradual decrease was observed.
For both red and green grape varieties the \( R_{\text{CO}_2} \) was low ranging from 1.99 and 0.95 mL \( \text{CO}_2 \) kg\(^{-1}\) hr\(^{-1}\) initially, and 1.34 and 0.85 mL \( \text{CO}_2 \) kg\(^{-1}\) hr\(^{-1}\) at equilibrium, respectively. By contrast with other fresh-cut fruit in which membranes and cells are damaged, grapes, even though removed from the stem, have their protective membrane/tissues left intact which prevents direct tissue or cellular interaction of its succulent inner flesh (Kader, 1989).

It is known that wounding triggers key enzymes from the respiration pathway, such as phosphofructokinase (Hajirezaei and Stitt, 1991) and cytochrome oxidase (Nanos et al., 1994), by increasing and decreasing their activity through time, allowing an increase and decrease in respiration rate depending on the product. Wounding may also enhance the synthesis of different enzymes within plant tissues such as phenylalanine-amonia-lyase (PAL) activity (Saltveit, 1997; Toivonen and DeEll, 2002). Wound-induced respiration may also be associated in-part to \( \alpha \)-oxidation of long-chain fatty acids from membrane deteriorative processes (Laties, 1964; Laties, 1978). Escalona et al. (2007) found that the \( R_{\text{CO}_2} \) of fresh-cut kohlrabi sticks increased immediately after cutting (10 ml/kg.h), decreasing steadily to 3-5 ml/kg.h by end of storage at 0°C in air. Iqbal et al. (2008) demonstrated that the \( R_{\text{CO}_2} \) of sliced and shredded carrots decreased from 8.6 and 10.8 mL \( \text{CO}_2 \) kg\(^{-1}\) h\(^{-1}\) to 3.6 and 3.39 mL \( \text{CO}_2 \) kg\(^{-1}\) h\(^{-1}\), respectively during 31 h of storage at 4°C.

5.4.2. Effect of intrinsic factors on respiration rate of fresh-cut fruits.

The \( R_{\text{CO}_2} \) of fresh-cut fruit was found to vary with physiological age (PA), origin, season, cultivar and species. \( R_i \) was affected to a greater extent by PA and origin than by season, and each factor had a considerable effect on the rate at which equilibrium was achieved.

The \( R_i \) of fresh-cut pineapple in the present study was found to vary significantly (\( P<0.05 \)) in contrast to \( R_{\text{eq}} \) which did not (\( P>0.05 \)). The average of \( R_{\text{CO}_2} \) for fresh-cut pineapple ranged from 5.85 mL \( \text{CO}_2 \) kg\(^{-1}\) h\(^{-1}\) for Autumn under-ripe to 23.27 mL \( \text{CO}_2 \) kg\(^{-1}\) h\(^{-1}\) for Autumn over-ripe and 3.11 ml/kg.h for Spring under-ripe to 10.39 mL \( \text{CO}_2 \) kg\(^{-1}\) h\(^{-1}\) for Spring over ripe. This shows an approximately 50% lower \( R_i \) value in Spring. However, the values for \( R_{\text{eq}} \) did not differ significantly irrespective season or PA.
Likewise, cultivar effects on $R_{\text{CO}_2}$ were also found for fresh-cut strawberry and kiwifruit but the effects were not significant ($p>0.05$). An exception to this was Irish grown *El Santa* where the $R_{\text{eq}}$ value of 16.7 mL CO$_2$ kg$^{-1}$ h$^{-1}$ was approximately 82% higher than the average $R_{\text{eq}}$ of 9.18 mL CO$_2$ kg$^{-1}$ h$^{-1}$ for other cultivars. For fresh-cut strawberries there was a 45 to 59% increase in $R_i$ between Spring and Summer fruits, respectively. As in the case of pineapple, the values for $R_{\text{eq}}$ we affected by physiological age ($p<0.05$) but not by season ($p>0.05$). In addition, the $R_i$ for both fresh-cut strawberry and kiwifruit was greater than the $R_{\text{eq}}$.

For fresh-cut melon, there were significant effects of origin on $R_i$ ($p<0.001$) but not on $R_{\text{eq}}$ ($p>0.05$).

Variations in consistent raw material supply throughout the year can greatly affect the quality of fresh-cut fruit products. Kader, (1987) explained the differences in respiratory activity in terms of genotype variation, which produced differences among plant parts and that this influenced their gas diffusion characteristics and respiration rates.

Gorny *et al.* (2000) compared the $R_{\text{CO}_2}$ of four different cultivars of sliced pears at 10°C. Among the four cultivars tested, Bartlett pear slices had the highest $R_{\text{CO}_2}$ and no differences in $R_{\text{CO}_2}$ values were observed among the three other cultivars tested. Manolopoulou and Papadopoulou (1998) reported $R_{\text{CO}_2}$ in the range of 1.0 to 2.5 mL kg$^{-1}$ h$^{-1}$ for four different kiwifruit cultivars stored at 0°C. Al-Mughrabi *et al.*, (1995) and Caleb *et al.*, (2012) reported the possible influence of physiological differences between cultivar responses to storage conditions. At 15°C, Caleb *et al.*, (2012) observed a spike in $R_{\text{CO}_2}$ initially and suggested a possible influence of ethylene as previously outlined by Devlieghere *et al.*, (2003).

As a consequence of differences in respiration rates, different MA’s would develop within packs initially, which would have a profound effect on overall quality and shelf-life. A higher respiration rate generally implies a faster rate of deterioration and subsequent quality loss. However, Cliffe-Byrnes and O’Beirne (2005) reported that the $R_{\text{CO}_2}$ of ‘dry’ coleslaw mix prepared with shredded cabbage, *cv Marathon* was significantly higher than that prepared with *cv Lennox* but that the storage life of Marathon was better than Lennox. They concluded that the reason was clearly more complex and that pre-harvest factors, such as climate conditions and cultural
practices, may have affected the morphological and compositional characteristics of
the given genotypes, which in turn influenced the respiration rates.

5.5.3. Effect of extrinsic factors on respiration rate of fresh-cut fruits.

Cut size had a considerable effect on $R_i$ and $R_{eq}$, with smaller cut pieces having
higher rates than larger pieces ($p<0.05$). In contrast, smallest pieces had highest $R_i$
and $R_{eq}$. For fresh-cut pineapple, blade sharpness had no significant effect on $R_{CO_2}$.

For fresh-cut strawberry, significant effects of cutting were observed, with
sliced strawberry having the greatest $R_{CO_2}$ in Summer (20.8mL CO$_2$ kg$^{-1}$ hr$^{-1}$) and
halved strawberry having highest in Autumn (17.5mL CO$_2$ kg$^{-1}$ hr$^{-1}$) ($p<0.05$). In
contrast, whole strawberry with stem removed had lowest $R_{CO_2}$ in both seasons, with
values of 12.6 and 12.3mL CO$_2$ kg$^{-1}$ hr$^{-1}$ respectively ($p>0.05$).

In the case of fresh-cut melons, there were significant effects of cutting on $R_i$
($p<0.05$) but not on $R_{eq}$ ($p>0.05$).

Cutting fruit releases previously bound enzymes and other vacuolar substrates
which can cause an increment in ripening and respiration coupled with faster
deterioration (Kader, 2012). Cut size and dipping decreased the time to reach
equilibrium, by almost 40%, with average times ranging from 7-15h depending on
fruit type. Wounding plant cells and tissues induces elevated ethylene production
rates that may stimulate $R_{CO_2}$ and consequently accelerate deterioration and
senescence (Brecht, 1995). The $R_{CO_2}$ may gradually increase over time until a
maximum value is reached (fresh-cut strawberry) and then start to decrease again to
either the initial value or higher as was the case of fresh-cut kiwifruit. Watada et al
(1990) showed that the $R_{CO_2}$ of intact kiwifruit was about 12.5 ml/kg.h and slicing to
1cm thickness caused a 2-fold increase which sustained for 36 h at 20°C. Lamikanra
(2002) studied the effect of angle cut for fresh-sliced banana and reported an increase
in $R_{CO_2}$ coinciding with an increase in angle cut which was directly related to the
shelf-life. Aguayo et al. (2004) compared cut melon to whole melon, and found that
wounding caused an increase in $R_{CO_2}$, and that this was more pronounced at 5°C than
at 0°C. Gorny et al., (2000) compared the CO$_2$ and ethylene production rates of
fresh-cut pears as influenced by cultivar, and showed that wounding increased the 
$R_{\text{CO}_2}$ of all cultivars, and that there was a strong effect of cultivar.

In addition to size reduction, the sharpness of the processing blade is also
known to play a major role in the rate of $R_{\text{CO}_2}$, with blunt blades showing higher $R_{\text{CO}_2}$
than sharp blades. A reduction in mechanical injury will result in better keeping
quality of fresh-cut produce by maintaining the cellular integrity and avoiding loss of
internal substrates (Artes et al., 2007). Increased mechanical injury can damage
many layers of tissue, increasing the mechanical shock or “initial stress response”
(Cantwell and Suslow, 2002). In this study however, no significant effects for blade-
sharpness on $R_{\text{CO}_2}$ was observed (p>0.05) with blunt blades having slightly higher
$R_{\text{CO}_2}$ than razor/ sharp blades. This is in contrast to Portela and Cantwell (2001) who
found that cutting cantaloupe melon pieces with a sharp borer, resulted in extended
shelf life at 5°C compared to cutting with a blunt borer and highlighted the fact that
although $R_{\text{CO}_2}$ values were affected only slightly by cutting treatment, blunt cut
pieces had higher electrolyte leakage (amongst other quality parameters tested) than
sharp cut pieces.

Pre-treatment steps during minimal processing are known to affect the $R_{\text{CO}_2}$ of
fresh-cut produce, with effects depending on the commodity, dipping concentration
of agents used and wash water temperature among other variables (Brody et al.,
2008). For fresh-cut pineapple, dipping resulted in a significant reduction in $R_i$, especially for smaller cut pieces (p<0.05) while no significant effect on $R_{\text{eq}}$ (dipped
and un-dipped) was observed (p>0.05). For fresh-cut kiwifruit, in general smaller cut
sizes had lowest $R_i$ initially and greatest $R_{\text{eq}}$ ultimately. However, no significant
effects of cutting and/or dipping were observed (p>0.05), with $R_{\text{eq}}$ values
significantly greater than $R_i$ values (p<0.05) at end of storage, irrespective of cut
size. Dipping times normally range from 1 to 5 minutes (Soliva-Fortuny and Martin-
Belloso, 2003). In this study, fruit pieces were dipped (~20°C) for 2 minutes with 2
minutes draining, resulting in a marked increase in $R_{\text{CO}_2}$. In fruits where the action of
polyphenol oxidase is the main cause of browning, the cold chain must be
maintained and dipping is usually carried out at temperatures ≤ 20°C (Soliva-Fortuny
and Martin-Belloso, 2003). In this present study, it is suggested that the increase in
$R_i$ is the result of greater surface area of the smaller cut pieces allowing for greater
diffusion of the dipping solution resulting in greater $R_{\text{eq}}$ at end of storage.
5.4.4. Product-package compatibility

Simulation of the gas atmosphere composition is an important tool in package design. Its aim is to predict O\textsubscript{2} and CO\textsubscript{2} changes inside the package to verify that the variables were correctly optimised (Mahajan et al., 2006). Due to the weak respiration rate of fresh-cut pineapple chunks, equilibrium modified atmosphere was not achieved (Figure 5.16).

In the current study, the predictions of the model represented a good match with the experimental results. For example, the greater the physiological age of the fresh-cut pineapple chunk, the greater the CO\textsubscript{2} accumulation. In Summer, over-ripe fruit had the greatest in-pack CO\textsubscript{2} levels (10.4%) and lower levels of O\textsubscript{2} (9.3%).

However, due to the weak respiration rate of fresh-cut pineapple chunks, equilibrium modified atmosphere was not achieved during the 7 Day storage period using high barrier film alone (Figure 5.16–5.18). In all situations, the time taken to reach equilibrium was too long in relation to product shelf-life. Indeed, a shelf-life of 7 Days is suggested at 4\textdegree{}C. Thus, the selected variables, i.e. package volume and product weight, do not guarantee an appropriate EMA, since the time taken to reach equilibrium was too long. A wider range of \( \beta \), especially those below 3, is necessary to better match the respiration behaviour of many fresh-cut products (Mahajan et al., 2006). The \( \beta \) value of many polymeric films is greater than the respiratory quotient, resulting in more CO\textsubscript{2} leaving the package than O\textsubscript{2} entering, thus causing the free volume to shrink during storage. Therefore, it was necessary to decrease the \( \beta \) value of the film in order to produce an atmosphere within the optimum range for fresh-cut pineapple by making precise perforations in the polymeric film. Perforations allow a convective non-selective influx of air to balance the total pressure inside the package with the air outside, with the concurrent change in in-pack atmosphere. The number of perforations required and their diameter depends on the permeability and area of the film.

Since fresh-cut pineapple has a low respiration rate, it was still quite difficult to achieve equilibrium modified atmospheres within an appropriate time period in relation to shelf-life. The “perm-selectivity” of the perforated packaging film alone, i.e. the ratio of CTR to OTR, is 1.0 as opposed to the original required target of 2.0.
To deal with this situation, it is necessary to make a compromise with one of the gases, normally CO$_2$, and design a package based on O$_2$. However, the perm-selectivity range of most commercially available polymeric films is quite narrow (approximately 4) and therefore not suitable. Some biodegradable films, such as wheat-gluten films, have much higher perm-selectivity, up to 18.0 (Cagnon et al., 2012). However, further tests are necessary to explore the application of such films for packaging of fresh and fresh-cut produce.

5.6. Conclusion

In conclusion, most fresh-cut fruits studied had high initial respiration rates. These initial high rates were due to a transitionary stress response as a result of processing which peaked and then stabilised at equilibrium over time. The largest intrinsic factor effect was physiological age, in the order of over-ripe> ripe> under-ripe. The largest effect of extrinsic factors studied was due to cut size in the order of smallest cut piece to largest. Using the average range of respiration rates found and considering the optimum needs of different fruits, the permeability requirements of packaging systems can be defined. A mathematical model based on exponential decay was found to be useful for predicting the package gas composition and also to estimate the target OTR and CTR required for packaging of fresh-cut pineapple chunks. A similar approach can be used to design packages which deliver optimum MA$_s$ to other fresh-cut fruits.
Chapter 6

Summary and Conclusions
6.1. **Summary**

The objective of this thesis was to contribute to improving the quality of fresh-cut fruits by identifying how raw material use, processing technology and packaging systems might be optimised.

Principal component analysis (PCA) was employed to help characterise and interpret large datasets generated during storage. The biplots produced were effective in characterising patterns of deterioration and in tracking differences in quality in terms of the rates and extent of change as affected by intrinsic and extrinsic factors. They showed that ripeness stage/physiological age of raw materials was an important parameter in fresh-cut pineapple and strawberry quality, while geographical origin was important for fresh-cut melon and kiwifruit. In terms of extrinsic factors studied, cut size was a major determinant for consistent end-product quality, with smaller cut pieces deteriorating faster than the larger cut pieces.

Packaging fresh-cut fruits within films of different permeability had significant effects on quality and produced products of different shelf-lives. Low respiring fruits such as pineapple and melon needed materials in the higher barrier range (HB and OPP) in order to achieve technically useful atmosphere modification and good control of discolouration. When packaged in more permeable micro-perforated films (PA90 and PA210), there was little atmosphere modification, and acceptability of appearance declined rapidly. On the other hand, where CS, HB and OPP films were used to package high respiring fruits such as kiwifruit and strawberry, a near anoxic environment developed, and combined with elevated CO\(_2\) within packs, resulted in membrane damage, softening and poor appearance. Increasing storage temperature from 4\(^\circ\)C to 8\(^\circ\)C resulted in a faster rate and extent of deterioration with reduced shelf-life.

In chapter 3, the effects of a large number of controlled and modified atmospheres were studied. There were significant effects of on quality and sensory appeal, but little effect on microbial growth or phytochemical content. Exposure to atmospheres outside optimal ranges (<2%O\(_2\) and >15%CO\(_2\)), resulted in physiological disorders such as discolouration, browning, increased softening, aroma loss and off-odour development. For fresh-cut pineapple and cantaloupe melon, storage in a controlled atmosphere of 5%O\(_2\)+5%CO\(_2\) was best at maintaining quality,
while for fresh-cut kiwifruit, quality was better maintained under a controlled atmosphere of 97%N₂+3%O₂. These optimum atmospheres identified were used as target atmospheres in chapter 5.

In chapter 4, the extent of change of volatile aromatic compounds in fresh-cut pineapple, cantaloupe melon and kiwifruit, as affected by storage time and cut size, were determined and further characterised using PCA. The data showed that storage time (p<0.01) and cut size (p<0.05) had large effects. The pos-tharvest aroma shelf-life of fresh-cut pineapple and kiwifruit was found to be 7 days for small cut pieces and up to 14 days for larger cut pieces. However, for fresh-cut kiwifruit, smaller pieces had a greater rate of change, with under developed aroma. In fresh-cut cantaloupe melon, aroma shelf-life was limited to 4 Days for small cut pieces and 7 Days for larger cut pieces. This was due to the presence of fermentative like off-odours, and was more pronounced for smaller cut pieces. These off-odours were attributed to increased concentrations of existing volatiles rather than the emergence of new compounds. It is concluded that larger cut pieces are best for maintaining the overall fresh-cut aroma of fruits.

In chapter 2, achieving a technically useful package proved to be a difficult task, while results from chapter 3 showed that besides low temperatures, attaining and maintaining the desired optimum modified atmosphere within packages, was critical in achieving consistently high quality. In chapter 5, developing an optimised packaging system for a particular fresh-cut fruit product was achieved. Firstly, the effect of intrinsic and extrinsic factors on the respiration rate of a number of fresh-cut fruits was determined. In general, the respiration rate of fresh-cut fruit showed an initial increase (Rᵢ), followed by a peak (Rₚ) and a gradual decrease to steady-state (Rₑq) within 24h. The high initial rates were thought to be due to a short-lived stress response and was highly affected by fruit type, processing and time.

Using this respiration data, a mathematical model based on exponential decay was developed. The elucidated model parameters, Rᵢ and Rₑq, were found to be useful in comparing respiration rates for each of the factors studied. Taking fresh-cut pineapple as an example, the target oxygen and carbon dioxide transmission rates required in MAP design were estimated using the optimum target MA (chapter 3) and taking into consideration the variability in the previous respiration rate
measurements due to the intrinsic and extrinsic factors. The model proved to be a good fit with experimental data and could be successfully applied to other fresh-cut fruits in order to achieve product-package compatibility.
6.2. Conclusion

The key determinants of quality in fresh-cut fruits were:

- The use of raw materials of optimum maturity, particularly for fresh-cut pineapple and strawberry products.
- The use of raw materials of most suitable geographic origin, particularly for fresh-cut melon and kiwifruit products; noting seasonal variations where appropriate.
- Minimising process damage, notably by using larger cut sizes.
- The use of optimum storage atmospheres by selecting packaging with appropriate gas barrier properties and ultimately, by employing precise package design methodology to ensure that optimal gas atmospheres are maintained throughout storage.
- Storage at 4°C or below.

Attention to these details will significantly improve the quality of fresh-cut fruit products available to Irish and international consumers. This in turn will contribute to the ideation, viability and success of these novel fruit products in the marketplace for years to come.
These Appendices are an introduction to the preliminary experimentations which determined how this project would progress and/or were supplementary data central to the structure of the major chapters and discussions in this dissertation.
Appendix A – Questionnaire

This Appendix (A) gives a brief overview of consumer’s attitudes and preferences towards fresh, and in particular, fresh-cut fruit products. Appendix A is also an introduction to preliminary experimentation (Appendix B) which determined how subsequent research chapters (2-5) would progress and were central to general discussions.

Introduction

The strive for convenience and value for money is ever present, however, the stagnant economic climate in which we reside has slowed sales of fresh and fresh-cut fruits in recent times. These purchases are often viewed as indulgent, luxurious and impulsive with the majority of consumers seeking value for money over nutrition leading to significant differences in dietary patterns. One approach to achieving optimum fruit intake is to serve attractive and convenient fruit based snacks that could easily be eaten out of context of main meals. Therefore optimising already available fresh-cut fruit based snacks may be a valid solution to increasing fruit intakes amongst consumers. Several reports have highlighted the possibility of raising product profiles of fresh-cut fruit by presenting them in a more attractive way. However, this attractiveness, coupled with the increased pace of technology change, has resulted in inferior quality packs that are, in actual fact, not highly sought after by consumers in many cases. In this aspect, sensory and consumer preferences of fresh-cut fruit products are highly appropriate disciplines to engage in.

The purpose of this questionnaire was to gain an understanding of the forces that drive consumer purchases with respect to fresh and fresh-cut products. Key areas pertaining to fresh-cut fruit product quality needs and deterioration that might be opened to technical intervention, were identified. Other latent information gathered by this questionnaire aimed to identify consumer segments, strategies and habits which inadvertently would help stimulate the viability of these products, increase fresh-cut sales, all the while improving consumption patterns.
Appendix A.1.: Copy of Ethics Approval Certificate

UNIVERSITY of LIMERICK

O L L S C O I L L U I M N I G H

16th July 2013

Prof. David O’Beirne
Department of Life Sciences
University of Limerick


Dear David,

The Faculty of Science and Engineering Research Ethics Committee has approved the above application.

Yours sincerely

Dr. Thomas Waldmann
Chair
Science & Engineering Research Ethics Committee

c.c. Elizabeth Finnegan
Appendix A.2: Design methodology

This questionnaire was sent out during two seasons over a 6 month period (Summer/Autumn 2013 and Winter/Spring 2013/14). The research and information gathered used both quantitative and qualitative methodology in order to get a sense of consumer attitudes in Ireland regarding fresh-cut fruit products. Through primarily random consumer evaluations, one of the aims of this study was to try and define and elucidate important attitudes and determinants as well as consumer responses towards fresh-cut fruit products. It was hoped to try and develop optimisation strategies for these products, targeted at consumers.

Many determinants, both conscious and insentient, contribute to consumer food choice. Sensory attributes, as well as social and cultural influences; mood and emotions; product expectations generated from information and packaging; situational and market factors; learning and previous learning experiences; and our bodily state, all contribute to this choice. Therefore, given the huge number of factors involved, predicting consumer food choice is very difficult (Cardello 1995; Gibson 2006). In this survey, consumer attitudes and behaviour towards fresh-cut products were assumed to be highly dependent several determinants, such as, on the product itself (visual appearance, overall quality perception), the person perceiving the product (age, gender, marital status, and occupation), whether or not they consumed fresh-cut fruits and their attitudes towards fresh-cut fruit products) and interrelated determinants i.e. product cost, value for money and safety. These determinants are only a few of many determinants that could possibly affect consumer choices. Other determinants include social context, exposure, labelling and use of media for effective knowhow and were studied to a minimal context. However the previous determinants studied were chosen as they were of high importance from a sensory and consumer science perspective.

In context, the overall aim of this evaluation was to assess consumers’ attitudes and responses toward fresh-cut fruits. It was pre-determined that these responses are highly affected by the initial visual quality of the packs, the perceived complexity of the fresh-cut fruit products as well as expectations and perceived determinants of the consumer. The outputs should provide coveted knowledge about consumers and their attitudes in recent times towards fresh-cut fruit products. For research, as well as industry innovation, this knowledge is valued in a sector where consumers have
immense influences over the viability of particular products through their own attitudes, preferences and choices. Furthermore, this knowledge should help improve our understanding of fresh-cut fruit quality and perception by consumers and help generate optimum products, with selective availability with exceptional quality and sustained SL.
Appendix A.3 Copy of Questionnaire entitled:
“A context for change: Consumers Attitudes and Preferences Concerning Fresh-cut Fruit Products.”

Explanatory Cover Letter (Email):

Hi all,

I seek participants from the ages of 18-65 to partake in a short 10 minute questionnaire entitled: A context for change: consumer attitudes and behaviours concerning fresh-cut fruit products.

The survey endeavours to assess consumer’s attitudes and preferences concerning Fresh-cut Fruits.

Please click on the below link to complete the questionnaire.

http://www.surveymonkey.com/s/RR6FX2J

Thanking you in advance for your time.
Kind regards
Elizabeth

N.B.: By clicking the above link, the participant is deemed to consent, though he or she can withdraw at any time.
Explanatory cover letter (Questionnaire):

Thank you in advance for your kindness in partaking in this questionnaire and in helping me with my research. I am a postgraduate researcher in the Food Science Research Centre within the Department of Life Sciences, at the University of Limerick. I am currently carrying out studies in the area of fruit quality research. I am very interested in your attitudes and preferences towards fresh-cut fruit products.

Nowadays, strive for convenience is ever present, however, the stagnant economic climate in which we reside has slowed sales of fresh-cut fruit in recent times. These purchases are often viewed by many as indulgent, luxurious and impulsive, with the majority of consumers seeking value for money over nutrition, leading to significant differences in dietary patterns.

The purpose of this survey was to gain an understanding of the forces that drive consumer purchases with respect to fresh and fresh-cut products. Key areas pertaining to fresh-cut fruit product quality needs and deterioration and that might be opened to technical intervention, will be identified. Other latent information gathered by this questionnaire aims to identify consumer segments, strategies and habits which inadvertently would help stimulate the viability of these products, increase fresh-cut sales, all the while improving consumption patterns.

This questionnaire will cover questions relating to consumer purchasing, attitudes towards fresh-cut fruits in terms of the attributes influencing consumer intentions to purchase, as well as the factors that influence consumer preferences concerning these commodities. There is no right or wrong answer. Your opinion is what matters most. The answers are completely confidential and will not connect you to your responses in any way. Participants have the right not to answer questions and can withdraw from the survey at any time. Should you have any queries regarding this questionnaire please don’t hesitate to contact us. The relevant contact details of the primary researcher, primary supervisor and the Chairperson of the Science & Engineering Research Ethics Committee (S&E REC) are given below.

Primary researcher: Elizabeth.Finnegan@ul.ie
Primary supervisor: David.OBeirne@ul.ie
Chair of S&E REC: Thomas.Waldmann@ul.ie  Phone: +353(0)61-202802.
Copy of Questionnaire

1. Tell me a bit about yourself...
   Gender: Female □ Male □
   Age: 18-25 □ 26-40 □ 41-65 □ >65 □
   Marital status: single □ cohabiting □ married □
                   separated □ divorced □ widowed □
   Occupation: □
   Lifestyle: □
   Local shopping district: □
   Average weekly spend on groceries (€): 0-50 □ 50-100 □ 100-150 □
                                           150-200 □ >200 □
   Average weekly spend on fresh fruit and vegetables (not including fruit drinks or prepared salad, fruit and/or vegetables) (€): 0-50 □ 50-100 □ 100-150 □
                                           150-200 □ >200 □

Additional information (children, etc):

2. How often do you consume fresh fruit?
   Never □
   Less than (<) once a month □
   Daily □
   Once a week □
   2 to 3 times a week □
   More than (>) 5 times a week □
   1 to 3 times a month □
   More than (>) 5 times a month □

   If you selected ‘Never’, please indicate reason(s) as to why.

3. When you think of FRESH-CUT FRUIT products, what do you think of?
   Please list as many FRESH-CUT FRUIT products as you can!
4. Please rank in order of choice your preferred or regularly used source of information on fresh-cut fruit products.

<table>
<thead>
<tr>
<th>Source</th>
<th>Preferred</th>
<th>Regular</th>
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<tr>
<td>Health Practitioner</td>
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<tr>
<td>Package Labelling</td>
<td></td>
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<tr>
<td>Friends (word of mouth)</td>
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<td>TV</td>
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<td>Radio</td>
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<td>Internet</td>
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<tr>
<td>Social Media/ Magazines</td>
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<td></td>
</tr>
<tr>
<td>Supermarket Staff</td>
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</tr>
</tbody>
</table>

5. How often do you purchase fresh fruit in a processed format?

- Never
- Less than (<) once a month
- Daily
- Once a week
- 2 to 3 times a week
- More than (>5) times a week
- 1 to 3 times a month
- More than (>5) times a month

If you selected ‘Never’, please indicate reason(s) as to why.

6. When are you most likely to purchase fresh-cut fruits?

- Periods of good weather (sunny)
- Periods of bad weather (rain)
- All year round
- None of the time

If you selected ‘None of the time’, please give a reason(s) as to why.
7. **What influences your decision to purchase fresh-cut fruits? You may select more than one!**

- Visual appeal of product
- Lifestyle
- Health promoting benefits
- Curiosity
- Weather
- Word of mouth
- Value/price
- Other (please specify below)

---

8. **Where do you consume the majority of fresh-cut fruit products**

- At home
- On the go (travelling – car, bus, train, etc.)
- In the office
- Recreational activities (i.e. picnics)

---

9. **If you purchased a fresh-cut product, please rate your overall satisfaction of the product in terms of the following:**

- Quality
- Flavour (Taste & Aroma)
- Value for money (price)

<table>
<thead>
<tr>
<th>Satisfied</th>
<th>Very satisfied</th>
<th>Neither satisfied nor dissatisfied</th>
<th>Dissatisfied</th>
<th>Very dissatisfied</th>
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If you were ‘dissatisfied’ or ‘very dissatisfied’ with your purchase please give a reason(s) as to why.

---

10. **Based on your overall level of satisfaction (Be it positive or negative), are you likely to purchase a fresh-cut fruit product(s) again?**

- YES
- NO

Please give a brief explanation as to why you selected ‘YES’ or ‘NO’.
Consumer analysis is the sensory method that deals with affective and subjective measurements of products. The main objective when using this method is to try to quantify the relative preference or degree of acceptance of a set of products (Lawless and Heymann 2010). This can be done either by determining consumer preference for one product over another (preference testing), or by allowing respondents to rate a certain product on a hedonic scale according to their liking or other relevant affective parameters (acceptance testing) (Lawless and Heymann 2010). Acceptance testing gives interval or ratio data directly unlike preference methods, where choices are given and intervals are indirectly measured (Thurstone 1928). The results retrieved in consumer analysis depend greatly on the evaluation techniques used.

Opinion differs as to which of the existing testing methods are the best and it seems to be heavily dependent on particular factors such as sample size and product (Hein et al., 2008; Jaeger et al., 2008; Lim, 2011). In this study, some 66% of 100 participants were female while the remaining 34% were male. Of those, 29% ranged in age from 18-25, 48% from 26-40, and 23% 41-65 and lived moderately active (45%), active (24%) and stressed (13%) lifestyles respectively. Their occupancies ranged from students, educators, healthcare professionals and financiers (in order of percentage).

In general, respondents believe that fresh and fresh-cut fruits are good for you, are somewhat nutritious, prevent diseases, promote energy, and are convenient while some passed comment that processed foods were for “lazy” people. On the other hand, they highlighted that some whole fruits are not so hard to prepare (you can pop a whole apple or banana in your bag for lunch without need for processing), have more superior taste and are better value for money than their processed counterparts. However respondents did comment that some larger fruits like pineapple and melon, although cheaper, are not something they would buy unless they had the time and amenities to prepare them as they were not efficient in terms of convenience and portion control for a particular individual on the go.
When asked “When you think of Fresh-cut Fruits what do you think of?” respondents were very detailed and listed a wide variety of fruits. Although, it is worth mentioning that many fruits are not, in a technical sense, “fresh-cut”. Figure A.1 shows the more popular fresh-cut fruits listed by consumers.

![Figure A.1 Percentage of “Fresh-cut” Fruits recognised by respondents. (n=90)](image)

It is obvious that the more common fruits traditionally found in fresh-cut form had the greatest popularity amongst respondents with apple, pineapple and melon coming out as clear favourites. However, it wasn’t surprising that many respondents listed strawberries and grapes as fresh-cut, as these fruits, although not minimally processed to the extremes of pineapple or melon are commonly used fresh-cut fruit salad components. Overall, respondents were very aware of the choices of fruits available to them and it is clear looking through the list that the availability of certain exotic fruits is very prevalent in Irish supermarkets. This may be due to the travelling experiences of consumers which in turn provoke supermarkets to accommodate the need for variety/choice.

With 91% of respondents stating they spend in the range of €0-€50 and a further 7% stating they spend a staggering €50-€100 per weekly shop on fresh fruit and vegetables, it was interesting to find out what percentage of those actually consumed fresh fruit on a daily basis, especially when 63% of person’s asked were single and only 30% married (with children). Figure A.2 shows that a pleasing 61% of those asked, said they consume fresh fruit on a daily basis with 14% saying they
consume fruit 2-3 times a week. A further 11% stated they eat fresh fruit once per week and a worrying 6% claimed they would only eat fresh fruit less than once a month and only do so because it is recommended to. Interestingly, a survey carried out by Bord Bia (2010) found similar results with the average consumer spending €26 on fruit, however an increase in portions being consumed suggested falling prices at retail levels corresponding to earlier suggestions regarding price and profitability.

![Figure A.2](image1.png)

**Figure A.2** Fresh Fruit consumption patterns (n=100)

![Figure A.3](image2.png)

**Figure A.3** Percentage frequency of purchases of Fresh-cut Fruits (n=99)

However, when asked “How often do you purchase fruit in a processed format?” results were not as appetising. **Figure A.3** shows the average percentage purchases of fresh-cut fruit (excluding juices, tinned/canned and frozen fruit) and details that 40% of people surveyed only purchased fruit in FC format less than once a month.
with a surprising 31% stating they ‘NEVER’ purchase fresh-cut fruits while only 16% admitted to purchasing fresh-cut packs once a week.

Outlining their reasons as to their previous answer, a pattern in potential barriers was observed and these are displayed in Figure A.4 below. Some of the chief obstacles preventing consumers purchasing these products were price, nutritional and environmental concerns, freshness and trust. Some of the comments made were:

- “More expensive than buying whole fruit and cutting yourself; whole melon costs on average 69c in supermarkets while fresh-cut melon costs €2 and what you are getting is the weight equivalent of one slice; price versus volume = rip-off”.
- “Overpriced!! Would only purchase when travelling (e.g. at airports) if there was no other option available i.e. whole apple, banana or orange”.
- “I am led to believe that buying fruit already prepared does not provide the same level of nutrition as whole fruits. For example: most of the vitamin C of the cut fruit will be diminished after 20 minutes of its exposure to fresh air!”
- “Not so fresh, occasionally the unsold, bad fruits are used in the production of these products. Don’t look or taste or smell the same preparing whole fruit yourself.”
- “I don’t like the preservatives/ additives they put on them to keep them fresh while the plastic package (toxic) is bad for the environment, so I will not buy these products.”

![Figure A.4](image-url) Potential barriers for consumers when purchasing fresh-cut fruits. (n=70)
In Ireland, many fruits are sold as raw, intact products. Whole pieces of fruits (apples) and a small selection of fresh-cut fruit (sliced apple, combination packs) are such examples. However, in most instances, these fresh-cut fruit products are normally displayed alongside or relatively near whole products. Besides developing an actual fresh-cut fruit product, it would lead one to assume that marketing and exploitation of these products needs to be reviewed as pricing and promotion are high regarded as unequal with significant differences in prices between that of the whole product visibly recognisable and highly observed by consumers. However, while cost and quality remain fundamental obstacles that need to be challenged, the latter obstacles are areas that are gravely misconceived. Most people are of the understanding that the fruits themselves are “bad” quality and are “tampered” with in some way with added ‘harmful preservatives and additives’ to make them more appealing and fresher looking for longer. In a general sense this is not always the case for majority of fresh-cut products in the market as food labelling regulations request that all additives and preservatives are cited on packages.

In terms of environmental concerns, most producers are aware that cutting their carbon footprint will not only do wonders for the environment but also their reputation and in turn favour their profit margins. Some 30% of consumers remarked that some fresh produce had too much packaging and that they would only resort to purchasing packaged fruits if indeed there was no other option available to them.

Fruit used for fresh-cut processing must be of the highest quality in order to reach the consumer in as fresh like of state as possible (Warren, 2012). For that reason high grades and classes can only be used in processing refuting the claims made by many respondents that the fruit used for fresh-cut production are usually “bad” quality and fruits that are unsold in supermarkets. One can understand peoples’ misconceptions regarding the aforementioned topic when purchasing substandard packages of fresh-cut fruits. The lack of flavour/taste and inferior visual quality is something that processors are trying to amend. Trust and confidence in a particular product is something that is hard to achieve, especially since the recent horse meat scandal that has rocked Europe (2013) and major Listeria outbreak of 2012 in Colorado affecting cantaloupe melons that resulted in many deaths. If consumers see that the products in which they are expected to purchase are not of superior standard or consistent quality how can they trust the product?
In addition, the Irish consumer market is also highly weather dependent, with many consumers admitting to only purchasing and consuming fresh-cut fruit products during periods of good weather (39%) and being less interested when the weather is bad (rainy) (4%) which given our climatic reputation does no favours for the industry. Product profile in Ireland is at present limited to a few fruit e.g. soft and pome fruits. In peak season, fresh native fruits such as strawberries are available in surplus and while in glut season (off-season) the Irish availability depends heavily on imports and availability of these produce in certain regions (Bord Bia, 2009). Therefore, technology (such as fresh-cut) has become a necessity to improve consumption of horticultural commodities in glut season. However some 33% of consumers did state that weather was not a barrier and that they would purchase fresh-cut fruit products all year round because they wanted to, provided the product looked good and of sound quality. Similarly, Bourke (2010) found that 57% of consumers said they varied their fresh fruit and vegetable purchases according to season.

Respondents were then asked to list their preferred and regularly used sources of information regarding fresh-cut products (Figure A.5).

**Figure A.5** Preferred and regular sources of information regarding food products.

In terms of preferred sources, food packaging/ labelling led the way with 47% while the internet was the least preferred source coming it at only 19%. A similar trend followed through with regularly used sources with 58% of respondents relying heavily on food packaging/ labelling as their regular source of information on
products while social media sources came were regarded as unreliable by some people and came in at 19%. From this it is clear that trust in the food producer (in terms of packaging) is of utmost importance to the consumer when trying to educate themselves on a product/service. The supermarket and word of mouth are also heavily relied upon; therefore in-store product display and quality need to be superior if a product is to do well.

When asked “What influences your decision to purchase fresh-cut fruits?” those who answered based their decision on price>visual-appeal>health benefits>lifestyle>curiosity (Figure A.6).

![Figure A.6 Factors influencing decisions to purchase fresh-cut fruits (n=82)](image)

**Figure A.6** Factors influencing decisions to purchase fresh-cut fruits (n=82)

Again, cost remains as the biggest factor influencing purchasing decisions with 31% of consumers making it their first priority. Visual appeal of the product comes a close second with 21% of consumers remarking that if they can see that the fruit is very fresh and reasonably priced they are more likely to purchase it. Appearance is of great importance in our acceptance and rejection of a food. It is often the first major stimulus that is presented to the consumer and the main one influencing consumer expectations and choosing whether or not to look out for a particular product again. If something looks appetising then it should taste appetising. The visual properties produce positive sensations leading to acceptance or negative sensations leading to rejection. To increase intake of a fruit by introducing fresh-cut fruit products, consumers need to firstly be attracted to them, secondly have them as their first
choice and lastly consume them and more importantly enjoy them. In competition with other food brands and products, the appearance of fresh-cut fruit sometimes loses out where packaging needs are concerned as most consumers view the contained products as inferior quality to intact counterparts. Therefore, it is no surprise that the health promoting benefits of fresh-cut comes third in the list of purchasing priorities with 15% of consumers perceiving that whole fruits contain more nutritional value than cut fruit. Lifestyle factors ranked fourth in order of influential priorities with 8% of respondents commenting that convenience and mood as their sole rationale for making this decision. Curiosity, word of mouth and the weather had no significant contribution to consumers’ rationale for decision making ranking 5th, 6th and 7th respectively.

As convenience is behind much of the innovation of fresh-cut products, people were asked ‘Where do you consumer the majority of your fresh-cut fruit purchases?’ Interestingly, Figure A.4 illustrated that of the 84% people who admitted to purchasing FCF products, 44% consume these products at home, while 38% admitted to eating them on-the-go with only 13% and 5% eating them in the office or on picnics respectively. When asked to rate their overall satisfaction of their a fresh-cut fruit product based on quality, flavour/taste and value for money people had more of a concern over their value for money rather than on the quality of the end-product (Figure A.7).

![Figure A.7 Overall satisfaction rating of fresh-cut product (n=83)](image-url)
These results are consistent with previous comments made by consumers with 42% of respondents being dissatisfied with their value for money. In terms of quality and flavour, 50% of respondents were satisfied with the overall quality of the products they purchased while 24% and 27% were neither satisfied nor dissatisfied with the quality and flavour. Most people who said they were dissatisfied remarked on quantity versus value for money as unacceptable while others highlighted that the product was too cold resulting in a lack of characteristic taste. Others commented on the fact that some fruits (example melon) are either unripe or over-ripe, while some remarked that you can’t estimate for quality by looking at pieces of cut fruit and with the packs (majority of the time) the fruits don’t taste good so they represent poor value for money. Bourke, 2010 found that display/ or in-store influence has diminished somewhat since 2006 with planned purchasing and price being more influential overall in 2010. Availability of quality produce on display is the largest influencing factor generating sales. Fresh appearance is also a key consideration with 16% of influence being attributed to this aspect.

Therefore, given the opportunity to purchase fresh-cut fruit again the majority was in favour of doing so (70%) while the remaining 30% said ‘no’ remarking that unless processors incorporate premium brands e.g. pink lady apples and high quality raw materials in to their packs, they will continue to purchase whole fruits. Others said they would only purchase the product again if it was on special offer; some people remarked on the inclusion of a ‘spork’ in ALL packs, as eating with your fingers is not very hygienic (especially when you are on the go). Some people would like to see more variety in terms of exotic fruits instead of the more traditional fruits which one could buy anywhere while others said they would only purchase a pack if they were truly stuck for something to eat with no other choices available. Bourke, 2010 found that 71% of respondents would be encouraged to increase their variety of purchases if prices were cheaper. 35% would need to be more aware of choices while 30% said if free in-store sampling were available they would be more likely to expand their purchases.

In summary, the quality of commercially produced fresh-cut fruits is relatively poor (in the eyes of the consumer). In terms of consumer attitudes and behaviours regarding fresh-cut fruit, a lot needs to be exercised in terms of educating the public on the topic. Getting value for money has and always will be at the
forefront of the consumers’ agenda when it comes to making purchasing decisions and this over-rides any nutritional benefits these novel products may bring. It can be seen that there is great market potential in fresh-cut fruits to steer us from bad eating habits, however we need to broaden our definition of ‘fresh-cut’ as well as marry these new trends and incorporate innovation into developing novel processing equipment in order to achieve superior quality. In order for a novel fresh-cut fruit product to succeed in the marketplace, it should provide good eating quality and be highly appealing to a range of ages.

**Future Prospects and Technical Needs**

There are a number of marketing strategies aimed at increasing sales; however, the fundamental ones based on the outcomes of this questionnaire are undoubtedly:

- Quality
- Price
- Safety

It has been said that the quality and variety of fruits available to the Irish consumer is excellent. In this context however, *including the “right cultivar” for the “right consumer”* is of critical importance (De la Calle *et al.*, 2010). Moreover, it is known that the fresh-cut processing industry continuously needs to improve their technical support by renewing their processing techniques by introducing novel, emerging and alternative processing and preservation strategies which endeavour to reduce production losses and provide safer and higher quality products. Fruits are forecast to have a barely positive volume growth between 2012 and 2016 even though industry bodies, supported by government agencies, are striving to argue that peoples’ attitudes toward fruits needs to change and that fruit should be a part of everyday diets (Euromonitor International, 2012). Price and value for money play a key factor in this, however while volumes might increase, market value has come down so there is more pressure than ever on producers to come up with safe, innovative products at a reasonable price. In suit, 53% of food companies claim to be diversifying their product range, with 62% investing in new product development (NPD) (Grant Thornton, 2011). Standards still need to be met; and innovation and quality, and convenience and safety, will always warrant concern.
Appendix B - Supplementary Information for Chapter 1

This Appendix (B) contains supplementary data for Chapter 1 (Review of Literature) including table of available fruits for fresh-cut production in Ireland (Table B.1), the market for Irish fresh-cut fruit (B.2) and evaluation of commercial fresh-cut fruits (B3).
### Appendix B.1 Table of acceptable fruit varieties and their corresponding origins available to Irish processors

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<tr>
<th>Fruit</th>
<th>Apple</th>
<th>Melon</th>
<th>Pineapple</th>
<th>Grape</th>
<th>Orange</th>
<th>Kiwifruit</th>
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<td>Granny Smith</td>
<td>Cantaloupe</td>
<td>Champaka Smooth Cayanne</td>
<td>Flame seedless</td>
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Appendix B.2 The market for fresh-cut fruit

It has been regarded that consumers are increasingly aware of the health benefits of fresh fruits. Dietary guidelines in recent times have contributed to a worldwide increase in the consumption of fresh fruits as sources of key vitamins, antioxidants and dietary fibre; all of which are known for their own specific health promoting benefits in alleviating and preventing some common known illnesses. Fresh fruit consumption plays an integral part in maintaining a healthy diet. Fresh fruit, if consumed daily in sufficient amounts, could prevent such major diseases such as coronary heart disease, diabetes and even certain cancers. Moreover, consumption of fresh fruit and vegetables is a key component of school curriculum’s designed to tackle the epidemic of obesity (Matthews, 2006). The importance of fruit in the Irish diet was highlighted in a recently published North/South Ireland Food Consumption Survey. Fruit (and nuts) was found to contribute to only 6% of daily dietary carbohydrate intake and 8% of daily dietary fibre intake.

Since the 1980’s the concept of the food pyramid has evolved and transformed itself drastically (Figure B.1a). The traditional long-standing food pyramid contains the four normal food groups and rations within them your recommended daily values (RDV) for each group. People were once encouraged to eat 3-5 servings of vegetables and 2-4 servings of fruit. In 2005, the US food pyramid has had a drastic makeover (Figure B.1b) and as well as been made aware of the importance of healthy eating, the pyramid also promotes our RDV for exercise (USDA, 2005). The Irish nutrition and dietetic institute (INDI) recommend that persons consume 5 or more portions of fruit and vegetables per day (Department of Health, 2012). The world health organisation (WHO) and the Food and Agriculture Organisation recommend the intake of a minimum of 400g of fruits and vegetables a day.

Figure B.1 Food Pyramid Concepts 1980 (a) and 2012 (b).
Consumers are encouraged to eat a rainbow of fruit and vegetables as variety is the key to acquiring all the essential vitamins, minerals, fibre, antioxidants and phytonutrients all present in different quantities in colourful produce. Green fruit and vegetables contain adequate amounts of vitamins C & E and useful amounts of fibre, calcium, magnesium, folate as well as high levels of healthy mono-unsaturated fat. Blue or purple fruits and vegetables contain anthocyanins which as antioxidants help neutralise free radicals which are responsible for cell damage. White or pale yellow fruits and vegetables are good sources of potassium which maintains fluid balance and allicin which stimulates the immune system. Orange fruits and vegetables are rich sources of beta- (β) carotene which is an antioxidant that is converted into vitamin A (when in short supply). Red fruits and vegetables are rich in vitamin C and contain lycopene.

In the last few decades there have been some major changes in food consumption habits. With the sustained promotion of the healthy eating benefits of fruit consumption, there has been renewed commercial interest and a surge of research in the area of fresh-cut produce. There has been increased consumer attraction to the benefits of eating fresh fruit in recent times and this coupled with travelling experiences and increased media exposure to ethnic foods helped to develop a growing market for exotic and minor fruits.

The effects of poor diets on health and has led authorities to devise strategies to boost consumption and increase the awareness through campaigns aimed at the general public to the benefits of eating fresh fruit and vegetables. The 5-a-day campaign introduced by the National Health Service (NHS) in the UK is one most generally recognised. The 5-a-day programme aims to change the way people think and highlight the benefits of eating more fruit and vegetables. It entitles school-going children to one free piece of fruit or vegetable per day (NHS, 2009). Supermarkets have also gotten behind the initiative, with Marks and Spencer introducing the 5-a-day logo on all their ready meals provided they contain at least 1 of 5-a-day (Figure B.2).
International travelling has led the exposure of people to new foods and food related experiences. Tropical fruits in particular, are of rapid demand in societies where the effects of climate affect their growth (Chonhenchob et al., 2007). Moreover, the growing diaspora of populations and proliferation of foreign travel, immigration and urbanisation fuels the demand and growth of tropical fruit within the EU, in particular the UK (James and Ngarmsak, 2011). Nowadays, many fruits including tropical fruits can be consumed just hours after being harvested thanks to advances in technology and food processing techniques and increased importation in Ireland. In 2003, fruit and vegetable imports into the Republic were valued at €344 million. (SafeFood, 2007) with fresh-cut pineapple, melon (in particular watermelon and cantaloupe) and mixed fruit combinations dominating worldwide market shares (Figure B.3).

Fruits such as blueberries, cranberries and pomegranates are examples of ‘super’ fruits which are now being included in fresh-cut packages. The problem is, with the
inclusion of these new tropical fruits with our traditional fruits, product inconsistency problems are emerging. However, innovation of fresh-cut fruits is at the cutting-edge of food processing technology. Emerging consumer trends offer new revenue and profit opportunities for companies. The desire for fresh-like products has toughened the demand for mildly processed commodities which have good sensorial appeal and high nutrient quality. The fresh fruit and vegetable market is of particular relevance since the EU is the largest importer of fresh fruit and vegetables in the world, accounting for 27% of the value of world fruits and vegetable imports (intra-EU trade excluded) in 2007 (UN, 2008). Global trade in fresh fruit and vegetables has increased by 16% from 2003 to 2007 with the EU share of world imports increasing from 26% to 35% for fruits and from 10% to 15% for vegetables in the same period. Typical for fresh fruit, price data is highly volatile with regular incidences of extreme values recognised by processors and consumers alike. This may be caused by the high variability of market supplies resulting from irregular size and timing of harvest caused by changing weather conditions, and seasonality of the supply. Also, the short-run supply elasticity is low and can be balanced out only to a low degree by storage due to the high perishability of the products. Furthermore, seasonally changing composition of the supply of differing origin may imply changing price regimes prevailing in a market throughout a year. These particularities may pose an extra challenge to processing of fresh-cut fruit, especially in Ireland where imports are heavily relied on. For example, seasonally restricted supply implies that the quality of certain commodities is discontinuous which often than not results in inconsistent end-product quality.

Food industries in recent years have focused intensely on cost reduction and improved operation efficiency. All the while, there is a continued need for these novel products to be marketed in a well-defined way to appropriate consumers (Grant Thornton, IBR, 2011). Fresh-cut apples were first fruit introduced to restaurants in the 1980s and marketed as pre-prepared produce in this fast moving foodservice sector (Rabobank, 2009). In the 5 years prior to 2009, the market of fresh-cut ready to eat fruits observed consummate growth. The UK, which is the market leader in fresh-cut produce in Europe, exemplifies how the market may flourish in continental Europe. In 2008, the continental European fresh-cut fruits and vegetable market was estimated as €3.4 billion. Figures for market trends in the UK
show a greater than 30% increase in two years with an estimated worth of £8.34billion (Research and Markets, 2009). The retail market in Ireland displayed a similar market pattern and is the most important market for sales of fresh produce. In 2005, the soft fruit sector in Ireland was worth close to €290 million (Dept. of Agriculture and Food Annual Report, 2005). In 2007, the Irish retail market for fresh produce was valued at €1.2billion which was a 14.2% increase compared to 2005 while the retail value of prepared products in Ireland amounted to €55million with fruit making up 45.4% of sales (Bord Bia, 2007).

In Asian markets, fresh-cut fruit is more commonly sold in open-air markets and food stalls and is becoming popular in some supermarkets. Often these products are displayed without refrigeration so their SL is frequently not extended beyond their point of display for immediate consumption. Interestingly this does not compromise on quality with FC produce only being processed in volumes by need rather than excess (James and Ngarmsak, 2011). In Japan and Korea, the fresh-cut produce market reached approximately US $2.6 billion in 2005 and $1.1 billion in 2006, respectively. In the US, the per capita consumption of fresh fruits increased dramatically by 19% in 1999 with sales from 2000 to 2006 jumping from $10billion to $16billion respectively (Research and Markets, 2009; Rabobank, 2009).

This trend in increased consumption was expected to continue through to 2020, with fruit consumption increasing to 27% (Clemens, 2004). A number of consumer market research reports in the past predicted that the demand for FC products would continue to increase both in Europe and the US, with food service facilities and school lunch programs being major customers (Euromonitor International, 2012).
Table B.2 Sale of fresh-cut fruit in millions by geography; in the period from 2004-2009.

<table>
<thead>
<tr>
<th>Millions</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ireland</td>
<td>(€)</td>
<td>0.86</td>
<td>1.03</td>
<td>1.19</td>
<td>1.36</td>
</tr>
<tr>
<td>UK</td>
<td>(£)</td>
<td>114.0</td>
<td>136.0</td>
<td>156.06</td>
<td>173.23</td>
</tr>
<tr>
<td>USA</td>
<td>($)</td>
<td>582.0</td>
<td>717.50</td>
<td>781.36</td>
<td>787.40</td>
</tr>
<tr>
<td>Western EU</td>
<td>($)</td>
<td>273.40</td>
<td>379.50</td>
<td>489.90</td>
<td>564.50</td>
</tr>
<tr>
<td>Worldwide</td>
<td>($)</td>
<td>1,404.20</td>
<td>1629.90</td>
<td>1810.80</td>
<td>1980.30</td>
</tr>
</tbody>
</table>

(Source: Euromonitor International, 2010)

Table 1.1 illustrates Ireland’s fresh-cut fruit financial sales status and compares it to that of the UK, US, Western Europe and the total world’s sales. It shows steady growth in fresh-cut fruit market 2005-2009, however, in a European and international context, both the fresh-cut fruit market, as seen in Table B.2, and the horticultural industry on the island of Ireland are quite small. Nevertheless, they play a significant economic role as an important, indigenous industry providing full-time employment for around 4500 in the Republic (Bord Bia, 2010). Therefore, continued support and growth of this sector is imperative.

Table B.3 illustrates forecasted sales of fresh-cut fruits per annum from 2011-2015 which shows a steady increase for Ireland.

<table>
<thead>
<tr>
<th>Millions</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ireland</td>
<td>(€)</td>
<td>1.58</td>
<td>1.62</td>
<td>1.65</td>
<td>1.67</td>
</tr>
<tr>
<td>UK</td>
<td>(£)</td>
<td>198.71</td>
<td>203.58</td>
<td>208.05</td>
<td>212.11</td>
</tr>
<tr>
<td>USA</td>
<td>($)</td>
<td>826.98</td>
<td>892.31</td>
<td>1,101.18</td>
<td>1,096.79</td>
</tr>
</tbody>
</table>

(Source: Euromonitor International, 2010)

Table B.3 illustrates Ireland’s forecasted sales per annum from 2011 to 2015 (Euromonitor International, 2010) and compares it to United Kingdom and United States of America, showing expected sales increase. However, due to the economic circumstances in recent time, sales for fresh-cut fruit are now showing slight decline. In the EU, ongoing low profitability at producer and processor levels has been causing significant declines in the production base for some agricultural products.
such as fresh-cut fruits. From an Irish perspective, any further losses in the Irish supply base will have further long-term consequences for the security of urban and local supplies of certain products on a year round basis (Bord Bia, 2010).

**Impact of economic decline on Fresh and Fresh-cut Fruit commodity sales**

The global market has seen massive changes over the past few of years that forecasted sales as presented in Table B.3 could not have perceived. However, while the EU market has seen unprecedented growth over the last decade, the Irish market has yet to flourish. Many of the fresh-cut fruit products sold in Ireland are regarded as “high-value” or “luxury” items. In each sector of the fresh-cut market, producers compete on quality, variety of fruits, range of products, novelty packages and of course price (Appendix A). The global recession has hit fresh food sales hard and this has impacted greatly on peoples’ behaviour directly. Fresh and fresh-cut fruit sales have not been exempt from these shifts in attitude or behaviour with the economic downturn causing stagnation (in some cases even decline) in fresh fruit sales, with minimal growth rates the best most products can expect.

Let’s look at the paradox that is Ireland, and problems accumulating to changes in consumer attitudes in recent times:

- IMF (>€85 billion) bailout to be footed by tax payers – announced in November 2010.
- Approximately €20 billion taken from Irish economy following subsequent budget cuts (2011-2012).
- Reduced services and quality of life with recruitment freezes and closures in public sector services; Gardaí, HSE, Fire Stations and Post Offices etc.
- Falling house prices coupled with implementation of household and water taxes leaving >50,000 mortgages in arrears and placing greater than one-third of house owners in negative equity.
- Record breaking rainfall and floods (June 2012/ March 2013) leading to catastrophic horticultural losses and product yields with increased prices for perishable goods.
- Increase in the numbers of people seeking emigration (numbers not seen since mid-80s).
Therefore, given all these misfortunes hitting our economy in recent times, it is not surprising that people are becoming ever cautious about their money and how they choose to spend it. Finnegan, 2013 (Appendix A.1), highlighted a number of potential barriers for consumers when buying fresh and FCF. These included (in order of importance):

1. Cost
2. Lack of knowledge about raw materials
3. Nutritional status (Fresh Intact versus Fresh-cut)
4. Inferior quality products (Appearance and Flavour)
5. Food safety issues (news headlines, *Listeria* outbreaks etc)
6. Lack of convenience (exclusion of a ‘spork’ in some packs) and variety.

There is clear evidence that many consumers are trading down their standard weekly shop in favour for value and cutting back on so-called “luxuries” in favour of specific food essentials. Fruit sales in the UK and Ireland declined overall in 2011 with consumers worryingly moving away from healthy foods in favour of cheaper alternatives (canned, frozen and preserved preferences) (Euromonitor International, 2012). This comes as no surprise with pubs and restaurants reporting lower bodies as people opt for eating and drinking at home (Vintners Federation of Ireland, 2012). FCF lost both dollar sales and volume at retail level in the third quarter of 2009 compared to the previous year, according to United Fresh Produce Association’s Fresh Facts on Retail report prepared by The Perishables Group.

In Ireland, decline in fresh fruit and vegetable purchases have been reported across all demographics, though especially in lower income households. The most popular fruits of apples, bananas and oranges all suffered declines in 2011 coupled with figures from the UK’s Department for Environment, Food and Rural Affairs (DEFRA) showing poor households in the UK cutting back the most. Those in the lowest income bracket bought almost a third (30%) less fruit in 2011 than in 2006. A similar trend was observed in Ireland in 2006-2010 as reported by Bourke (2010), who found that the incidence of shoppers purchasing from convenience stores has fallen back by 6%, potentially driven by changes in consumers’ discretionary spending power. Shoppers are becoming less loyal and impulsive and more restrained in their shopping behaviour shopping around for cheaper prices more
often. Furthermore, the level of volatility in global food commodity prices generates significant unease for Irish producers in terms of market returns. While the rise in global food prices, which reached a peak in 2008, is to be welcomed by certain industry sectors, it comes with the negative effect of surging raw material and logistic costs for the minimally processed and prepared food sector (Bourke, 2010). This has hit fresh food prices hard, especially those imported tropical and subtropical fruits and vegetables. Bigger retailers have been able to absorb these shocks much better than smaller independent retailers who suffered drastic decline in their market share as they have their already lesser margins cut even more. At the same time, small independent retailers and mid-market companies are becoming increasingly dependent on suppliers and channel partners for innovation, while larger multiples enjoy the financial scale necessary for NPD and technology investment (Grant Thornton, 2011). With growing market competition and greater access to information, shoppers have evolved to cope with the volatility in food prices giving shoppers increased power to shop around and demand more value for their money. This coupled with slower consumer spending means “The Smart Shopper” is coming increasingly to the fore as a key consumer lifestyle trend in Ireland (Bord Bia, 2009-2011).

Furthermore, against the unimaginable backdrop of the financial crisis which is being portrayed in the media, our food producers and retailers are also struggling to respond accordingly (Bord Bia, 2009-2011). High commodity prices combined with sluggish consumer spends limit the ability of food companies to raise their prices. Retailers are keen to drive costs down in any way they can in order to retain some profit. However, maintaining consumer acceptance at this lower cost is a major challenge to the fresh-cut industry. This may help explain the inferior quality fresh-cut fruit packs which grace our supermarket shelves and the negative response of consumers towards them. Christie (2010) highlighted that nearly every category of the fresh-cut segment lost both volume and dollar sales, with average prices also falling. In effect supermarket multiples are acute to stress they are stocking as much locally produced, Irish food as possible (when in season).

With the Irish climate naturally restricting the growth of many fruits, fruits such as citrus fruits, bananas, grapes and pineapples etc., imports are therefore a necessity to supply the all-year round market needs and demand from major
supermarket multiples such as Superquinn, Dunnes Stores, Tesco and Marks and Spencers. Fruits are widely distributed and depending on their distribution are classified into sub-tropical; tropical and temperate. The main advantage of Irish grown fruit is freshness, quality and local availability, however, these traits are sometimes hard to achieve as the location of growers (and processors) is influenced by a range of factors including soil type and climate and this in turn determines crop variety.

As well as tropical fruit imports there are certain domestic fruits, that even though can be successfully grown in Ireland, need to be imported to meet domestic market needs. This can be attributed to seasonal climatic and long-term storage constraints. In addition, EU import prices of some kinds of fresh fruits (oranges) are highly influenced by the EU entry price system (EPS). In combination with ad valorem taxes of up to 20% the EPS aims to protect EU growers of 15 kinds of selected fruits and vegetables against international competition. Although the amount of locally produced fresh fruit and vegetables has in many instances not increased, there has been a proliferation in marketing exploits amongst retail multiples deliberately engineered to show they are more committed to buying directly from the Irish economy than others. In actual fact, this has been in response to fluctuating global prices with many retailers favouring buying goods as close to home as possible rather than risk ambiguity regarding inflation and transport costs (Euromonitor International, 2012).

Widespread domestic production of certain fruit and vegetables such as strawberries and mushrooms exists, however, fruit crops grown in Ireland tend to be seasonal and are categorised under two broad descriptions. Fruits grown on trees or in orchards are referred to as ‘Top’ fruit or fruit grown ‘above the ground’ (e.g. apples, pears & plums), and ‘Soft’ fruit which is the generic description for fruit and berries grown on runners, canes or bushes or ‘at or near the ground’ (e.g. strawberries, raspberries & blueberries). With the majority of fruit crops being seasonal, the arrival of new season Irish grown fruit on the market is widely anticipated by consumers each year thus increasing the demand for fruits, especially soft fruits, in the summer months, hence the term ‘summer fruit’. The main crops grown for further processing in Ireland are apples, strawberries, raspberries and blackcurrants which are commonly used for cider production, juicing, jam making, baking and canning and not FC
production. The most important fresh market retail fruit lines sold are eating and
cooking apples, strawberries and raspberries.

Nevertheless, the need for convenience and freshness and high nutritional
value products still lives on with consumers seeking stronger relationships than ever
with the products and brands they regularly buy.
Appendix B.3: Evaluation of commercial fresh-cut fruit packs

Based on the findings from Appendix A, the quality evaluation of commercially available fresh-cut fruits was undertaken. Fresh-cut fruits were purchased from numerous multiples in the Limerick, Offaly and Westmeath regions, namely, Tesco, Dunnes Stores, SuperValu and Marks and Spencer.

The results from this study aimed to identify ‘key’ problematic fruits of interest, identify what typical deterioration symptoms were observed and assess the general quality of fresh-cut fruits as a whole.

Abstract

An evaluation of commercially available fresh-cut fruit packs was conducted from October 2008 to March 2010. A range of fresh-cut fruit packs from a range of popular supermarkets were evaluated. These evaluations gave valuable insights into the main fruit types, species and cultivars used in fresh-cut processing in Ireland and provided information on sources, seasonality, availability, commercial production practices, product specifications and processing/packaging difficulties. The review and evaluation helped to identify technical needs, quality problems and problematic fruits of interest, all of which were subsequently investigated in latter studies.

Materials and methods

Quality evaluation tests were performed as outline in Chapter 2.2. Additional remarks on pack size (g), geometry, fruit types, combinations (%) and fruit shape observations were also made.
Results

In-pack gas analysis

Figure B.4 In-pack gas atmosphere concentration ranges (O\textsubscript{2} and CO\textsubscript{2}) for selected commercial fresh-cut fruit packs from different multiples.

Figure B.5 Product per package volume

Figure B.4 illustrates the in-pack O\textsubscript{2} and CO\textsubscript{2} ranges for different fresh-cut fruit products from different multiples. In-pack atmosphere concentrations from Multiple
D were nearest the optimal atmosphere winder with Multiple A and B products being significantly outside this optimum window. In general, the amount of product per package volume was found to be between 0.4 to 0.6 g mL \(^{-1}\) \(\text{Figure B.5}\).

\begin{figure}
\centering
\includegraphics[width=\columnwidth]{image}
\caption{In-pack \textit{O}_2 and \textit{CO}_2 concentrations for selected commercial fresh-cut fruit packs.}
\end{figure}

In terms of individual products from different multiples, \textit{O}_2 concentrations ranged from 19.5% to 10.1% for all packs. \textit{CO}_2 concentrations ranged from 4.2% - 11.5% \(\text{Figure B.6}\). Marks and Spencer had the highest \textit{O}_2 concentrations of all packs analysed on day 0 (19.5%) with Dunnes Stores tropical fruit salad having 15% and Dunnes Stores fresh fruit salad having the lowest at 10.1%. \textit{CO}_2 values correlated with \textit{O}_2 values with 4.6% for Marks and Spencer, 9.5% for Dunnes Stores tropical fruit salad and 11.5% for Dunnes Stores fresh fruit salad.
Great variation in fruit combinations were noted for a typical fresh fruit salad packs (various sizes) with 4 to 7 combinations observed (Figure B.7). Red grapes were found in all packs (8-12%) while pineapple and cantaloupe melon chunks, green apple wedges, and orange slices were present in majority of packs, ranging from 30-50%, 8-29%, 12-27% and 12-22% depending on pack size. Fresh-cut kiwifruit (8%) and whole blueberries (1%) were present in small percentages for pack (b), fresh-cut
honeydew melon (25%) was found in pack (c), while whole (de-hulled) strawberries (20%) were present in pack (d).

**Drip-loss levels**

![Drip-loss volumes in a variety of individual and mixed fresh-cut fruit salad packs.](image)

*Juicy Fruit Twist* (pineapple, apple, strawberry). *Hawaiian salad* (pineapple chunks, cantaloupe melon chunks, red and green apple wedges, orange slices, red grapes and pomegranate arils).

Drip-loss levels were more of a concern for multiple fruit packs (>4), especially those containing fresh-cut pineapple, melon and orange (**Figure B.8**). Individual pineapple packs had the most drip with values ranging from 6 to 11mLs. Packs containing 3 or less fruit combinations had much lower drip levels ranging from 0.2 to 3mLs depending on the fruit combinations.
General observations

Fresh-cut Fruit Salad Packs

- Film was hard to peel off in all packs.
- Label was transparent and flexible (plastic). In some cases (Tesco) was printed onto lidding film, while for M&S packs label was attached to lidding film and of various sizes depending on the product and pack size.
- Label size was the same for all product ranges (Tesco, Dunnes and SuperValu).
- Tray size was varied for all products evaluated.
  - Volume ranging from ~250-450cm$^3$
- Film material appeared to be the same for all packs.
- No micro-perforations evident
- Excessive drip-loss accumulation in all packs (especially those containing pineapple).
- Less liquid in melon and grape packs
- Most apple wedges were coated in a citric acid/ ascorbic acid dip (although not cited on all packs).
- Fruit proportions were within levels cited on packs.
- CO$_2$ was within optimal for pineapple and melon/grape packs.
- O$_2$ was above optimum range for all products.
- Fruit shape and size varied depending on the multiple and/product, especially in mixed fruit packs.
  - possibly attributed to hand-cut processing as stated on some packs.
- Poor aroma with strong odours detected upon opening mixed packs.
- Poor visual quality of most mixed fruit packages due to accumulation of drip-loss which resulted in certain fruit pieces having a water-soaked appearance and texture. In addition, colour bleed was evident in packs where strawberries were found, resulting in a pinkish/ reddish tint on lighter coloured fruit pieces.
- At end of storage life, sub-optimal atmospheres were found in almost all packs (elevated CO$_2$ and excessively low O$_2$) which heightened the poor aromas previously detected in packs.
- Packs where berries were found had greatest atmosphere change while melon packs had the least.
- Fresh-cut kiwifruit had significant loss in fresh-cut firmness and visual appeal (grey, dull colour, loss of greenness and increased translucency and yellowness).
- Fresh-cut pineapple pieces had darkening at cut edges and were translucent in appearance.
- Melon pieces had a bouncy texture (especially cantaloupe) and were translucent in appearance.
- Orange segments looked drier in appearance with a whitened flesh.
- Grapes appeared to be darker in colour with some showing symptoms of skin cracking/ bursting.
- Apples wedges showed increased browning of cut surfaces.
Colorimetry

Table B.4 Overall colour change (DE), browning (BI) and whitening (WI) index values for individual fresh-cut fruit pieces contained within a commercial mixed fruit pack during 7 Day storage at 4°C.

<table>
<thead>
<tr>
<th>Fruit</th>
<th>ΔE</th>
<th>BI</th>
<th>WI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D0</td>
<td>D7</td>
<td>D0</td>
</tr>
<tr>
<td>Green apple</td>
<td>4.97</td>
<td>29.79</td>
<td>41.65</td>
</tr>
<tr>
<td>Red apple</td>
<td>2.41</td>
<td>31.62</td>
<td>35.70</td>
</tr>
<tr>
<td>Red grape</td>
<td>1.22</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cantaloupe melon</td>
<td>25.59</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pineapple</td>
<td>3.33</td>
<td>71.26</td>
<td>81.79</td>
</tr>
<tr>
<td>Orange</td>
<td>3.00</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table B.4 shows that there was minor to severe colour change during storage which varied with fruit type. Both red and green apple varieties increased in DE with green apples showing greater colour change than red apples. This correlated well with increasing BI values which were also greater for the green apple variety. A similar increase was also observed for fresh-cut pineapple which had minor colour change (DE 3.33), indicative of browning. In contrast cantaloupe melon had the greatest overall colour change of all fruits with minor increase in WI scores. Fresh-cut orange had very minor colour change (3) but had high increase in WI values, corresponding to increase in whitening of segments. Red grapes, which were whole, had the least colour change of all fruits (1.22).
The percent soluble solids content varied for different fruit types with only minor changes observed during storage (Figure B.9). Values for red grape ranged from 10.4% – 12.1% with a minor decrease observed during storage. For cantaloupe melon a noticeable decrease was observed on Day 1 followed by a rapid increase which remained relatively constant thereafter with values ranging from 9.5% – 12.8%. Values for pineapple on Day 7 ranged from 8.7% to 9.9%. The soluble solids content for orange, strawberry, kiwi and blueberry ranged from 9.8% - 14.3% on Day 7 with gradual decreases between days 0 and 4. Blueberry and grapes had the highest soluble solids of all fruits with values ranging from 19% and 18% on Day 0 falling to 14% and 17% on Day 7 respectively.
**Microbial enumeration**

![Graphs showing microbial enumeration](image)

**Figure B.10** Effects of packaging on (a) Mesophilic Counts, (b) Psychrophilic Counts, (c) Lactic Acid Bacteria Counts & (d) Yeast and Mould Counts for commercially prepared fresh fruit salad over 7 days storage at 4°C.

In **figure B.10 (a)**, mesophilic counts show that melon had the highest counts on Day0 (6.7 CFU/g) and red grapes (5.0 CFU/g) had the lowest. However on Day 7 red grapes had counts of 6.20 CFU/g while green apple had the highest count (7.6 CFU/g). It appears that pineapple had the lowest growth counts on day 7 (5.7
CFU/g). All apple varieties had similar counts ranging from 7.15-7.20 CFU/g on day 0 which ranged from 6.46 – 7.57 CFU/g on day 7.

In Figure B.10 (b), psychrophilic counts for melon were the highest counts on day 0 (6.79 CFU/g), while red grapes had the lowest (5.16 CFU/g). Both values corresponded with previous mesophilic counts in Figure B.10 (a). On Day 7 pineapple appeared to have the highest count (8.10 CFU/g) while all other fruits averaged out the same having 7.48 CFU/g.

From the above Figure B.10 (c), it is evident that pineapple and green apple had the highest counts (5.23 and 5.18 CFU/g) on day 0. Orange and melon had the lowest counts (4.15 CFU/g respectively) while all other fruits having counts which ranged from 4.30 – 4.72 CFU/g. On Day 3 all values increased with counts ranging from 5.19 – 6.82 CFU/g and by Day 7 all fruits saw a decrease with pineapple having the lowest (4.31 CFU/g). All other fruits had counts ranging from 5.21 – 5.70 CFU/g.

From the above Figure B.10 (d), yeast and mould counts for melon green apple were the highest recorded with counts of 6.05 and 5.92 CFU/g respectively on Day 0. All other fruits had counts ranging from 5.76 – 5.89 CFU/g. From day 3 to day 7 all fruits saw a steady increase in counts ranging from 6.48 – 7.48.
Figure B.11 Sensory evaluation scores for individual fresh-cut fruits within a commercial mixed fruit salad pack. (a) visual appearance, (b) colour, (c) overall acceptability, (d) aroma, (e) off-odour and (f) firmness.
The above Figure B.11 (a-f) illustrates the sensory scores evaluated throughout storage. Scores for visual appearance decreased throughout storage. For fresh-cut orange, green apple and cantaloupe were good on Day 0 however kiwi and pineapple were least preferred by panellists (acceptable). By Day 7, kiwi, green apple and honeydew had reduced usability with orange, blueberry and red grapes having reduced marketability. Scores for aroma saw a steady decline throughout storage. Blueberry, orange and red grapes appeared to have best aroma while cantaloupe and kiwi had the least noticeable aroma. By Day 7, honeydew melon, orange and red apple appeared to retain the best aroma while kiwi, green apple and strawberry had the least desirable. Cantaloupe saw no change in aroma from Day 0-7. Initially slight off odours were detected for strawberry, blueberry, kiwi and red grapes. All other fruits had no detectable off odour until Day 4 where red apple scored the highest. On Day 7, orange, and honeydew melon had the least off odour while red grapes and strawberry had the most noticeable off odours. On day 0, all fruit scored relatively “good” in terms of colour. Green apple had the best colour followed by blueberry. However, after 7 Days, red grapes, orange and pineapple had the best colour score and kiwi, green and red apples had the worst. Initially on Day 0, the texture of all fruits was good with red grapes, orange and blueberry having the best texture while red apple and pineapple had the worst. On Day 3, orange appeared to retain a good texture while kiwi and red apple decreased. Red grapes appeared to improve in texture on Day 3. By Day 7, orange and blueberry retained the best texture while kiwi, honeydew and cantaloupe had the least favourable texture. Overall likeness of packs incurred a steady decrease during storage. Green apple and strawberry were liked the best on Day 0, while red apples, red grapes and kiwi were least liked. On day 3 all fruits saw a rapid decrease with likeness scores ranging from 3-5 for all fruits. By Day 7, a further decrease was observed with blueberry, green apple and red apple and red grapes scoring best and kiwi scoring worst.
Conclusion

The quality of commercial packs was poor and they appeared to deteriorate quite quickly, especially when multiple fruits were mixed. There was little atmosphere modification initially that decreased to sub-optimal levels during storage. Juice leakage from pineapple, orange and melon resulted in very wet packs and poor product appearance (water-soaked and translucent), especially for fruit where lower portions were submerged in the exudate.

As a result, the sensory quality of all packs was poor, deteriorating during storage. However, commercial packs of mixed fruits had greater deterioration than individually packaged fruits.

Figure B.12 Selection of commercial fresh-cut fruit products available in Irish supermarkets.
Appendix C - Supplementary Information for Chapter 2


The additional information for this chapter (2) presents the supporting raw data used in principal component analysis of fresh-cut pineapple, strawberry, kiwifruit and cantaloupe melon as affected by various intrinsic and extrinsic factors. The data presented are the means for 2 experimental replicates unless otherwise stated. For each quality evaluation test, as presented in Tables C.2-C.14, the values are the means for the following determinations (Table C.1):

<table>
<thead>
<tr>
<th>Quality Test</th>
<th>Abbreviations</th>
<th>Unit</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-pack O₂</td>
<td>O₂</td>
<td>%</td>
<td>6</td>
</tr>
<tr>
<td>In-pack CO₂%</td>
<td>CO₂</td>
<td>%</td>
<td>6</td>
</tr>
<tr>
<td>Drip-loss</td>
<td>Drip</td>
<td>mL</td>
<td>6</td>
</tr>
<tr>
<td>Pack weight-loss</td>
<td>PkWt</td>
<td>%</td>
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</tr>
<tr>
<td>Total soluble solids</td>
<td>BRIX (SS)</td>
<td>%</td>
<td>18</td>
</tr>
<tr>
<td>Titratable acidity*</td>
<td>TA</td>
<td>%</td>
<td>18</td>
</tr>
<tr>
<td>pH</td>
<td>pH</td>
<td></td>
<td>18</td>
</tr>
<tr>
<td>Sugar acid ratio</td>
<td>S:A</td>
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<td>18</td>
</tr>
<tr>
<td>Exudate</td>
<td>Ex</td>
<td>g</td>
<td>12</td>
</tr>
<tr>
<td>Cell permeability</td>
<td>Cell Per</td>
<td>g</td>
<td>12</td>
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<tr>
<td>Luminosity</td>
<td>CIE L*</td>
<td></td>
<td>36</td>
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<tr>
<td>Redness/Greenness</td>
<td>CIE a*</td>
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<td>36</td>
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<tr>
<td>Blueness/Yellowness</td>
<td>CIE b*</td>
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<td>Visual Appearance</td>
<td>App</td>
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<td>Colour score</td>
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<td>Aroma score</td>
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<td>24</td>
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<td>Off-odour score</td>
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<td>Firmness score</td>
<td>TEX</td>
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<tr>
<td>Overall Acceptability</td>
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<td>Maximum shear force</td>
<td>ECK&lt;sub&gt;max&lt;/sub&gt; ¹</td>
<td>N</td>
<td>40</td>
</tr>
<tr>
<td>Mean shear force</td>
<td>ECK&lt;sub&gt;mean&lt;/sub&gt; ¹</td>
<td>N</td>
<td>40</td>
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<tr>
<td>Maximum probe firmness</td>
<td>P&lt;sub&gt;max&lt;/sub&gt; ²</td>
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<td>16</td>
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<td>Mean probe firmness</td>
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<td>Total mesophilic count</td>
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<td>Total psychrophilic count</td>
<td>Psychro&lt;sub&gt;logCFUg⁻¹&lt;/sub&gt;</td>
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<td>Yeast and Mould count</td>
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*reported as citric acid equivalent; ¹ Extended Craft Knife; ² Probe, N (Newtons).
Table C.2: Raw data used for principal component analysis of effects of geographical origin on fresh-cut pineapple quality.

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<th>Treatment</th>
<th>Gas Analysis</th>
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<th>Pack Weight</th>
<th>BRIX</th>
<th>pH</th>
<th>TA</th>
<th>SIA</th>
<th>Extract</th>
<th>Cell Per</th>
<th>Colour</th>
<th>Sensory</th>
<th>Texture</th>
<th>Microbial Enumeration</th>
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</thead>
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<td>P-CR0</td>
<td>20.75 0.25 11.0 6.03 12.33 2.64 0.59 25.04 0.50 0.94 76.00 25.47 1.74 8.23 1.17 9.00 1.00 52.50 9.29 7.22 5.49 0.46 6.70 4.35 0.00 4.56 5.64</td>
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<tr>
<td>P-B0</td>
<td>20.95 0.30 2.08 6.03 11.33 3.40 0.59 25.04 0.58 1.01 73.33 37.25 2.17 10.00 1.00 9.00 1.00 50.00 9.00 5.76 5.98 0.22 5.49 6.00 0.00 6.02 6.32</td>
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<tr>
<td>P-H0</td>
<td>20.30 0.25 3.39 0.00 12.38 3.39 0.05 20.39 1.17 2.45 72.73 35.36 1.06 7.67 1.00 8.00 1.00 80.33 7.42 5.25 6.00 0.00 5.74 5.98</td>
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<td>P-CR1</td>
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<td>P-B1</td>
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<tr>
<td>P-H1</td>
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<td>18.50 2.87 7.50 0.75 12.00 0.38 0.40 15.07 0.44 2.80 73.02 35.03 0.02 2.83 1.17 3.00 2.00 26.67 2.67 5.62 7.97 11.00 7.1 6.00 0.00 5.56 4.96</td>
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<tr>
<td>P-CR7</td>
<td>15.85 6.40 2.83 2.11 11.99 3.39 0.02 14.51 0.40 1.51 75.33 30.75 0.00 1.51 2.60 3.00 162 45.09 3.08 2.60 3.00 1.10 5.00 5.00 5.00 6.00</td>
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<tr>
<td>P-B7</td>
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<tr>
<td>P-H7</td>
<td>12.10 7.70 10.00 7.75 12.30 3.22 0.58 13.52 3.82 3.92 73.81 36.63 0.03 3.33 2.42 6.05 1.42 27.50 6.67 5.40 5.17 7.79 5.45 5.00 5.18 6.34</td>
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</tbody>
</table>

Data is the mean for 3 experimental replicates.

Abbreviations: P (Pineapple), CR (Costa Rica), B (Brazil), H (Honduras), D0 (Day 0), D1 (Day 1), D4 (Day 4) and D7 (Day 7).
Table C.3: Raw data used for principal component analysis of effects of ripeness stage and season on fresh-cut pineapple quality.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>GA Concentration</th>
<th>Diploss</th>
<th>Pack Loss</th>
<th>BBRK</th>
<th>pH</th>
<th>TA</th>
<th>S constituent</th>
<th>Color</th>
<th>Sensory</th>
<th>Microbial Enumeration</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (P)</td>
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<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>60</td>
<td>70</td>
<td>80</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td>UR (UR)</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>60</td>
<td>70</td>
<td>80</td>
<td>90</td>
<td>100</td>
<td>110</td>
</tr>
<tr>
<td>R (R)</td>
<td>50</td>
<td>60</td>
<td>70</td>
<td>80</td>
<td>90</td>
<td>100</td>
<td>110</td>
<td>120</td>
<td>130</td>
<td>140</td>
</tr>
<tr>
<td>OR (OR)</td>
<td>80</td>
<td>90</td>
<td>100</td>
<td>110</td>
<td>120</td>
<td>130</td>
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<td>170</td>
</tr>
<tr>
<td>S (S)</td>
<td>150</td>
<td>160</td>
<td>170</td>
<td>180</td>
<td>190</td>
<td>200</td>
<td>210</td>
<td>220</td>
<td>230</td>
<td>240</td>
</tr>
<tr>
<td>A (A)</td>
<td>250</td>
<td>260</td>
<td>270</td>
<td>280</td>
<td>290</td>
<td>300</td>
<td>310</td>
<td>320</td>
<td>330</td>
<td>340</td>
</tr>
</tbody>
</table>

Abbreviations: P (Pineapple), UR (Under-ripe), R (Ripe), OR (Over-ripe), S (Summer), A (Autumn)
Table C.4: Raw data used for principal component analysis of effects of cut size and dipping treatment on fresh-cut pineapple quality.

| Treatment           | Gas Analysis | Driploss | Pack Weight | BRX | pH  | TA | Aroma | Eubact | Cell Per | Sensory | Texture | Microbial Enumeration |
|---------------------|--------------|----------|-------------|-----|-----|----|-------|--------|----------|----------|---------|----------|----------------------|
|                     | CO2          | CO2      | In [mg/l]   | pH  | A.S.| E.A. | pH    | a`    | b`      | App      | Coll     | OD       | ECKmax   | ECKmean | Pmax | Pmean | LAB | Y&M |
| P-50mm-UD-D0        | 20.25        | 0.25     | 1.00        | 0.06| 12.32| 3.44| 0.59  | 5.19  | 0.47    | 1.71     | 0.31    | 6.60     | 10.59    | 0.00  | 1.01  | 0.01  | 0.05  |
| P-25mm-UD-D0        | 20.55        | 0.20     | 2.26        | 0.00| 11.34| 3.40| 0.59  | 5.38  | 0.88    | 1.18    | 0.00    | 0.00     | 3.79     | 0.00  | 1.00  | 0.00  | 0.00  |
| P-10mm-UD-D0        | 20.30        | 0.25     | 3.25        | 0.01| 12.38| 3.38| 0.65  | 5.30  | 1.17    | 2.45    | 2.73     | 3.06    | 0.06  | 8.57  | 0.00  | 1.00  | 0.00  | 1.62  |
| P-50mm-D-0          | 20.20        | 0.35     | 2.97        | 0.60| 10.26| 3.92| 0.24  | 14.46 | 0.84    | 4.02    | 7.10     | 36.09   | 0.29  | 0.25  | 0.00  | 1.00  | 0.00  | 0.00  |
| P-25mm-D-0          | 20.60        | 0.50     | 6.90        | 0.78| 11.95| 3.33| 0.68  | 17.35 | 1.24    | 3.77    | 65.27    | 35.65   | 1.56  | 8.01  | 1.00  | 6.03  | 1.00  | 0.00  |
| P-10mm-D-0          | 20.60        | 1.10     | 2.40        | 0.00| 14.62| 3.24| 0.53  | 5.23  | 4.75    | 3.82    | 65.91    | 32.03   | 0.04  | 8.00  | 1.00  | 6.63  | 1.00  | 0.00  |
| P-50mm-UD-D1        | 20.65        | 0.80     | 2.80        | 0.25| 12.85| 3.55| 0.65  | 15.93 | 0.20    | 3.26    | 76.08    | 56.55   | 1.17  | 7.17  | 1.39  | 7.42  | 1.26  | 0.25  |
| P-25mm-UD-D1        | 19.65        | 0.60     | 2.12        | 1.24| 12.65| 3.55| 0.65  | 15.23 | 0.20    | 3.26    | 76.08    | 56.55   | 1.17  | 7.17  | 1.39  | 7.42  | 1.26  | 0.25  |
| P-10mm-UD-D1        | 19.65        | 0.80     | 2.80        | 0.25| 12.85| 3.55| 0.65  | 15.23 | 0.20    | 3.26    | 76.08    | 56.55   | 1.17  | 7.17  | 1.39  | 7.42  | 1.26  | 0.25  |
| P-50mm-D-1          | 19.65        | 0.80     | 2.80        | 0.25| 12.85| 3.55| 0.65  | 15.23 | 0.20    | 3.26    | 76.08    | 56.55   | 1.17  | 7.17  | 1.39  | 7.42  | 1.26  | 0.25  |
| P-25mm-D-1          | 19.65        | 0.80     | 2.80        | 0.25| 12.85| 3.55| 0.65  | 15.23 | 0.20    | 3.26    | 76.08    | 56.55   | 1.17  | 7.17  | 1.39  | 7.42  | 1.26  | 0.25  |
| P-10mm-D-1          | 19.65        | 0.80     | 2.80        | 0.25| 12.85| 3.55| 0.65  | 15.23 | 0.20    | 3.26    | 76.08    | 56.55   | 1.17  | 7.17  | 1.39  | 7.42  | 1.26  | 0.25  |

Abbreviations: P (Pineapple), 50mm, 25mm & 10mm (50mm, 25mm & 10mm cut piece size), UD (Un-dipped), D (Dipped)
Table C.5: Raw data used for principal component analysis of effects of packaging film and temperature on fresh-cut pineapple quality.

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<th>Treatment</th>
<th>Gas Analysis</th>
<th>Emploco</th>
<th>Pack Weight</th>
<th>RHIX</th>
<th>pH</th>
<th>TA</th>
<th>SIA</th>
<th>Emul</th>
<th>Cell Pal</th>
<th>Colon</th>
<th>Seewong</th>
<th>EoMax</th>
<th>EoMax</th>
<th>Enmax</th>
<th>Pmax</th>
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<th>Melso</th>
<th>Psicho</th>
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<th>Lamv</th>
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<td>60.000</td>
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<td>0.000</td>
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<td>80.000</td>
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Abbreviations: P (Pineapple), HB (high barrier film), OPP (oriented polypropylene), PA90 and PA210 (micro-perforated films), CS (clamshell container)
Table C.6: Raw data used for principal component analysis of effects of geographical origin and cultivar on fresh-cut strawberry quality.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Gas Analysis</th>
<th>Diploss</th>
<th>Pack Weight</th>
<th>BRIX</th>
<th>pH</th>
<th>TA (mg%)</th>
<th>SGA</th>
<th>Starch</th>
<th>Ethanol</th>
<th>Cell Per</th>
<th>Cell Wall</th>
<th>Colour</th>
<th>App</th>
<th>Col</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
<th>Sensoric</th>
<th>Texture</th>
<th>Microbial Enumeration</th>
</tr>
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<td>SD - El Santa</td>
<td>23.26</td>
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<td>0.00</td>
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<td>0.00</td>
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<td>0.00</td>
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<td>3.52</td>
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<td>4.53</td>
<td>2.93</td>
<td>4.52</td>
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</tr>
</tbody>
</table>

Abbreviations: SB (strawberry), ES (El Santa), F (Festival), Cam (Camarosa), Mor (Morocco), Eth (Ethiopia)
Table C.7: Raw data used for principal component analysis of effects of physiological age and season on fresh-cut strawberry quality.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>CT &amp; Analysis</th>
<th>Diploters</th>
<th>Pack Weight</th>
<th>Brix</th>
<th>pH</th>
<th>TA</th>
<th>SFA</th>
<th>EVS</th>
<th>Cell Per Fr.</th>
<th>Colour</th>
<th>Arg</th>
<th>b*</th>
<th>Cell Cal</th>
<th>xE</th>
<th>Tissue</th>
<th>Microbial Examinations</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
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<td>0.99</td>
<td>0.52</td>
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<td>0.62</td>
<td>2.94</td>
<td>90.6</td>
<td>46.1</td>
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</tr>
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<td>0.99</td>
<td>0.52</td>
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<td>1.69</td>
</tr>
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<td>3.66</td>
<td>0.99</td>
<td>0.52</td>
<td>3.7</td>
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<td>64.61</td>
<td>1.76</td>
<td>4.77</td>
<td>1.69</td>
</tr>
</tbody>
</table>

Abbreviations: S (strawberry), UR (under-ripe), R (ripe), OR (over-ripe), Sp (Spring), Sum (Summer), Aut (Autumn), Win (Winter)
Table C.8: Raw data used for principal component analysis of effects of packaging type and temperature on fresh-cut strawberry quality.

| Treatment | Gas Analyzer | Disposal | Fill Weight | pH | TA | SGA | Exudate | Cell Per Res | Colour S*  | S* | L*  | App | Col | Ac | OD5 | TEX | Oa | Opa | Faw | Ewan | LAB | YAM |
|-----------|--------------|----------|-------------|----|----|-----|---------|-------------|------------|----------|-----|-----|-----|-----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| S-HD-4-HD | 15.30         | 2.85     | 0.00        | 0.67 | 3.10 | 12.69 | 0.14    | 2.60 | 47.90 | 27.79 | 20.61 | 9.80 | 4.80 | 6.00 | 5.60 | 70.00 | 5.00 | 18.80 | 7.20 | 4.60 | 0.00 | 6.54 | 4.77 |
| S-HD-4-HD | 18.08         | 2.55     | 0.00        | 0.60 | 3.20 | 12.62 | 0.09    | 2.31 | 43.40 | 41.45 | 32.42 | 9.00 | 4.80 | 9.60 | 5.60 | 70.00 | 3.90 | 14.41 | 7.31 | 4.60 | 0.00 | 4.56 | 4.92 |
| S-OPP-4-HD | 15.00        | 2.60     | 0.00        | 0.67 | 3.10 | 12.69 | 0.14    | 2.60 | 44.19 | 38.70 | 22.65 | 9.80 | 6.00 | 5.60 | 5.60 | 70.00 | 5.00 | 13.31 | 7.20 | 4.75 | 0.00 | 4.51 | 4.92 |
| S-OPP-4-HD | 15.20        | 2.60     | 0.00        | 0.67 | 3.10 | 12.69 | 0.14    | 2.60 | 46.09 | 44.22 | 32.21 | 9.80 | 6.00 | 5.60 | 5.60 | 70.00 | 5.00 | 13.31 | 7.20 | 4.75 | 0.00 | 4.51 | 4.92 |
| S-CS-4-HD | 15.95         | 2.75     | 0.00        | 0.67 | 3.10 | 12.69 | 0.14    | 2.60 | 46.09 | 44.22 | 32.21 | 9.80 | 6.00 | 5.60 | 5.60 | 70.00 | 5.00 | 13.31 | 7.20 | 4.75 | 0.00 | 4.51 | 4.92 |
| S-CS-4-HD | 16.20         | 2.75     | 0.00        | 0.67 | 3.10 | 12.69 | 0.14    | 2.60 | 46.09 | 44.22 | 32.21 | 9.80 | 6.00 | 5.60 | 5.60 | 70.00 | 5.00 | 13.31 | 7.20 | 4.75 | 0.00 | 4.51 | 4.92 |
| S-CS-4-HD | 15.95         | 2.75     | 0.00        | 0.67 | 3.10 | 12.69 | 0.14    | 2.60 | 46.09 | 44.22 | 32.21 | 9.80 | 6.00 | 5.60 | 5.60 | 70.00 | 5.00 | 13.31 | 7.20 | 4.75 | 0.00 | 4.51 | 4.92 |
| S-CS-4-HD | 16.20         | 2.75     | 0.00        | 0.67 | 3.10 | 12.69 | 0.14    | 2.60 | 46.09 | 44.22 | 32.21 | 9.80 | 6.00 | 5.60 | 5.60 | 70.00 | 5.00 | 13.31 | 7.20 | 4.75 | 0.00 | 4.51 | 4.92 |

Abbreviations: S (strawberry), HB (high barrier film), OPP (oriented polypropylene), PA90 and PA210 (micro-perforated films), CS (clamshell container)
Table C.9: Raw data used for principal component analysis of effects of geographical origin on fresh-cut kiwifruit quality.

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<th>Pack Weight</th>
<th>Brix</th>
<th>pH</th>
<th>TA</th>
<th>S/A</th>
<th>Exudate</th>
<th>Cell Perc</th>
<th>Colour</th>
<th>Sensory</th>
<th>Texture</th>
<th>Microbial Enumeration</th>
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<td></td>
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<td></td>
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<td>0.00</td>
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<td>0.82</td>
<td>1.47</td>
<td>0.24</td>
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<td>45.08</td>
<td>10.83</td>
<td>-1.77</td>
</tr>
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<td>12.09</td>
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<td>3.41</td>
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<td>1.53</td>
<td>37.24</td>
<td>16.32</td>
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</table>

Abbreviations: KW (kiwifruit), NZ (New Zealand)

Data is the mean for 3 experimental replicates.
Table C.10: Raw data used for principal component analysis of effects of cut size and dipping treatments on fresh-cut kiwifruit quality.

<table>
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<th>Gas Analysis</th>
<th>Diploss</th>
<th>Pack Weight</th>
<th>BRAD</th>
<th>pH</th>
<th>TA</th>
<th>SPAD</th>
<th>Exudate</th>
<th>Cell Per</th>
<th>Colour</th>
<th>K*</th>
<th>N*</th>
<th>App</th>
<th>Col</th>
<th>Ac</th>
<th>OD600</th>
<th>F6X</th>
<th>OA</th>
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Abbreviations: KW (kiwifruit), 50mm, 25mm & 10mm (50mm, 25mm & 10mm cut piece size), UD (Un-dipped), D (Dipped)
Table C.11: Raw data used for principal component analysis of effects of packaging type and temperature on fresh-cut kiwifruit quality.

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<th>TA</th>
<th>SA</th>
<th>Ewadate (Fatg)</th>
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Abbreviations: KW (kiwifruit), HB (high barrier film), OPP (oriented polypropylene), PA90 and PA210 (micro-perforated films), CS (clamshe Contestake container)
Table C.12: Raw data used for principal component analysis of effects of geographical origin on fresh-cut cantaloupe melon quality.

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<td>6.10</td>
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<td>0.13</td>
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<tr>
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<tr>
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<td>3.50</td>
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<td>130.54</td>
<td>2.03</td>
<td>2.00</td>
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<td>17.22</td>
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</table>

Abbreviations: CM (Cantaloupe melon)
Data is the mean for 3 experimental replicates.
Table C.13: Raw data used for principal component analysis of effects of cut size and dipping treatment on fresh-cut cantaloupe melon quality.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Gas Analysis</th>
<th>Dipless Pack Weight</th>
<th>BRIX</th>
<th>pH</th>
<th>TA</th>
<th>SIA</th>
<th>Waerude</th>
<th>Cell Per</th>
<th>Colour</th>
<th>Sensory</th>
<th>Texture</th>
<th>Microbial Enumeration</th>
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<tr>
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<td>6.24</td>
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<td>1.42</td>
<td>85.54</td>
<td>41.59</td>
<td>15.23</td>
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</tbody>
</table>

Abbreviations: CM (cantaloupe melon), 50mm, 25mm & 10mm (50mm, 25mm & 10mm cut piece size), UD (Un-dipped), D (Dipped)
Table C.14: Raw data used for principal component analysis of effects of packaging type and temperature on fresh-cut cantaloupe melon quality.

<table>
<thead>
<tr>
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<th>BRIX</th>
<th>pH</th>
<th>TA</th>
<th>S/A</th>
<th>Eatable</th>
<th>Coll Per</th>
<th>Colour</th>
<th>Sensory</th>
<th>Texture</th>
<th>Microbial Enumeration</th>
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<td>CO2</td>
<td>Limp</td>
<td>PMW(tg)</td>
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<td>P</td>
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<td>17.49</td>
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</tbody>
</table>

Abbreviations: S (strawberry), HB (high barrier film), OPP (oriented polypropylene), PA90 and PA210 (micro-perforated films), CS (clamshell container)
Appendix C.2: Supplementary data for Chapter 2.2: Characterising
deterioration patterns in fresh-cut fruits using principal component analysis II:
effects of ripeness stage, seasonality, processing and packaging

In Chapter 2.II, PCA plots accurately illustrated the deteriorative patterns of quality change for a number of fresh-cut fruits as affected by packaging type and storage temperature. Information on ‘actual’ gas accumulation patterns within the different packaging systems was warranted in order to better interpret PCA data. The additional information for this chapter, presented in Appendix C.2, illustrates the effects of packaging type and storage temperature on in-pack gas atmosphere modification analysis of fresh-cut pineapple, strawberry, kiwifruit and cantaloupe melon. These results were central to the structure of Chapter 2.II as the resulting in-pack atmosphere changes formed the basis for many of the subsequent quality, sensorial and microbiological investigations discussed.

Abstract

In this study, in-pack oxygen (O\textsubscript{2}) levels decreased while carbon dioxide (CO\textsubscript{2}) levels increased with time at both 4\textdegree O\textsubscript{C} and 8\textdegree O\textsubscript{C}. As the permeability of the film decreased, little to no in-pack atmosphere modification occurred with lower steady-state CO\textsubscript{2} and higher O\textsubscript{2} levels established. Use of clamshell (CS) containers resulted in statistically different gas concentrations compared with high barrier, oriented polypropylene and micro-perforated films (p<0.05) at both temperatures. This was especially true for fresh-cut pineapple (p<0.01) where at 4\textdegree O\textsubscript{C}, O\textsubscript{2} levels were near anaerobic by Day 4. Similarly, for high respiring fruits such as fresh-cut kiwifruit and strawberry, CO\textsubscript{2} levels were greater than 25% and 35%, respectively on Day 7 (p<0.05). At 8\textdegree O\textsubscript{C}, steady-state CO\textsubscript{2} were even higher, while O\textsubscript{2} levels were anaerobic by Day 7. An exception to this was fresh-cut cantaloupe melon, where, irrespective of film type and temperature, had relatively stable in-pack gas atmosphere modification change during storage. In summary, packaging within a low barrier film (HB) proved to be most beneficial for fresh-cut pineapple and cantaloupe melon, while OPP and PA90 were more beneficial for fresh-cut kiwifruit and strawberry, respectively. Elevating the storage temperature to 8\textdegree O\textsubscript{C} resulted in loss of all benefits.
**Materials and methods**

In-pack gas atmosphere analysis was performed as outlined in Chapter 2.2.

**Results**

The effects of using five packaging films of different permeabilities on the in-pack gas atmosphere concentrations of fresh-cut pineapple, strawberry, kiwifruit and cantaloupe melon were determined at 4°C and 8°C (Figure C1-4). Rapid gas levels were observed during the first 1 to 4 Days of storage, after which steady-state gas concentrations were established in most packs. In general, as the permeability of the film increased, modification decreased, while, when permeability decreased, modification increased, in some instances being excessive, especially for high respiring fruits.
For fresh-cut pineapple, fruit stored in CS containers had the most significant decrease and increase in O$_2$ and CO$_2$ concentrations, respectively (p<0.001). Oxygen levels were near anoxic by Day 4 while CO$_2$ levels exceeded 10%. By Day 7, CO$_2$ levels at 4°C were 16% while at 8°C were 24% (Figure C.1). Micro-perforated films had the least atmosphere modification (p>0.05) with O$_2$ and CO$_2$ levels ranging from 19-20% and 1-1.4% at 4°C and 19-20% and 0.9-2% at 8°C for PA90 and PA210, respectively.

Figure C.1 Effects of packaging type and temperature on in-pack (a) O$_2$ and (b) CO$_2$ concentrations of fresh-cut pineapple stored for 7 Days.
Strawberry:

Figure C.2 Effects of packaging type and temperature on in-pack (a) O\(_2\) and (b) CO\(_2\) concentrations of fresh-cut strawberry halves stored for 7 Days.

For fresh-cut strawberry, significant effects of micro-perforated films on in-pack gas atmosphere modification was observed (p<0.05) (Figure C.2). Fruit stored in CS containers rapidly declined in O\(_2\) concentrations by Day 1 (p<0.01), with fruit stored at 8\(^\circ\)C displaying anaerobic conditions on Day 7. In contrast, micro-perforated PA films had little-to-no O\(_2\) atmospheric change, while CO\(_2\) levels ranged from 10-13% and 4.5-6% for PA90 and PA210, respectively. Fruit stored in HB and OPP had atmospheres in between these extremes, with HB ranges greater than OPP.
Kiwifruit:

(a) Effects of packaging type and temperature on in-pack (a) O$_2$ and (b) CO$_2$ concentrations of fresh-cut kiwifruit stored for 7 Days.

Figure C.3 Effects of packaging type and temperature on in-pack (a) O$_2$ and (b) CO$_2$ concentrations of fresh-cut kiwifruit stored for 7 Days.

A gradual decline in O$_2$ concentrations was observed for fresh-cut kiwifruit during storage (Figure C.3). A rapid decline in O$_2$ was noted from Day 0 to Day 1 for fruit stored in CS packs falling to 14% and 12% at 4°C and 8°C respectively. This decrease was coupled with increases in CO$_2$ to 9% and 15% and continued until end of storage where O$_2$ levels were less than 1% while CO$_2$ levels were 28% and 30% at 4°C and 8°C, respectively. With the exception of micro-perforated PA90 and PA210 packs at 4°C, all other packs had similar atmosphere change until end of storage, ranging from 8% to 11% O$_2$ and 13% to 19% CO$_2$. 
Cantaloupe melon:

Figure C.4 Effects of packaging type and temperature on in-pack (a) \( O_2 \) and (b) \( CO_2 \) concentrations of fresh-cut cantaloupe melon stored for 7 Days.

Although similar to other fruits, in that modification was greater at higher temperatures, fresh-cut cantaloupe melon had the least in-pack modification of all fruits studied (Figure C.4). The greatest decrease and increase in \( O_2 \) and \( CO_2 \) was observed in CS packs, where values of 4.5% and 10.5% and 9.5% and 12% were noted at 4\(^\circ\)C and 8\(^\circ\)C, respectively. In contrast, micro-perforated packs displayed the least modification with \( O_2 \) and \( CO_2 \) values at 4\(^\circ\)C and 8\(^\circ\)C ranging from 11.5 to 17% and 2.3% to 6%, and 14.5% to 19% and 7.3% to 19.5%, respectively.
Discussion

The kinetics of O\(_2\) and CO\(_2\) changes within packs depended mainly upon the respiratory nature of the fresh-cut fruit, the permeability of the packaging film and the temperature at which the packs were stored. Fresh-cut fruits are notoriously difficult to package, due to high respiration rates, a direct result of fresh-cut processing. As a result the range of atmospheres that were found within packages varied significantly. HB and OPP films are widely used by the MA packaging sector; however their gas permeabilities range from very low to low. As a result, a range of MAs were found within these packs, with lower respiring fruit (pineapple and melon) attaining better beneficial (near optimum) atmospheres than higher respiring fruits (strawberry and kiwifruit). Similarly, clamshell containers are nowadays commonly used to package fresh-cut fruits due to their convenience for both storage and consumption. The permeability of this packaging system is extremely low and coupled with the variable respiratory nature of different fresh-cut fruits produced sub-optimal atmospheres, resulting in faster deterioration and an inferior end-product quality with diminished shelf-life (Chapter 2). In general, CO\(_2\) levels within CS packs were high (>10%) and O\(_2\) levels were very low (<2%), creating conditions favourable for anaerobic respiration. In contrast, micro-perforated packs, in particular PA210, represented a somewhat unmodified atmosphere, while PA90 packs produced a range of atmospheres in between these extremes (proving most beneficial for fresh-cut strawberries in that near optimum atmospheres, as recommended by Gorny, (1997) were achieved).

Increasing the storage temperature is said to bring about increases in the permeability of packaging films (Brandenberg, 2012); however, these increases are usually insufficient to compensate for the increased product respiration (Kader, 1989). Increasing the storage temperature from 4\(^\circ\)C to 8\(^\circ\)C brought about an increase in in-pack atmosphere modification for all packs. As a result, more extreme MAs were produced (near/ anoxic environment + >20% CO\(_2\)), which caused a marked reduction in the quality of most fruits (Chapter 2).
Conclusion

In conclusion, none of the packaging treatments evaluated produced recommended optimal atmospheres. However, at 4°C, packaging within a low barrier film (HB) was better at attaining near optimum atmospheres (as recommended by Gorny, 1997) for fresh-cut pineapple and cantaloupe melon, while OPP and PA90 were more beneficial for fresh-cut kiwifruit and strawberry, respectively. Increasing storage to 8°C, however, resulted in a loss of those packaging benefits and heightened the already detrimental effects of incompatible packaging (CS).

In general, the atmospheres produced were insufficiently modified to be technically beneficial to the product. Therefore, actively modifying the atmospheres to assess potential benefits and/or identifying target atmospheres in order to achieve equilibrium modified atmosphere (EMA), i.e. product-package compatibility, is warranted.

References

See reference section.
Appendix D – Product Specifications

This Appendix (D) gives a brief overview of the problematic fruits central to this research and lists some key product specifications for raw material intake. A schematic illustration of the fresh-cut production chain is also included.
Product Specifications for Fresh-cut Fruit
A brief question and answer session with one of Ireland’s leading fresh-cut producer, Mr Paddy O’Callaghan, CEO Nature’s Best LTD, was held at Fresh Connex (Berlin, 2012). He highlighted some of the more interesting in-house troubles facing fresh-cut processing in Ireland (and Europe) in recent times.

The main problems identified were:

i. Inconsistent raw material supply chain, i.e. variations in incoming product quality and fruit maturity, seasonal variations in cultivar etc.,

ii. Miscommunication between producers, suppliers and processors,

iii. Over-packing of certain fruits during transport leading to inferior quality at warehouse,

iv. Temperature abuse during transit,

v. Failure of suppliers to distinguish between physical, physiological and pathological causes of injury (scald on apples deemed suitable for FC processing; internal browning, bruising, contamination etc. on some products received at goods inwards),

vi. Mismanagement of temperature and refrigerated storage at retail level,

vii. Wariness on behalf of consumers regarding the product(s),

viii. Limited yields, high waste and high production costs = no profit $\rightarrow$ reason for forfeiting the industry,

ix. Limited use of postharvest treatments to prolong shelf-life (ex. Apples – CaCl$_2$ to inhibit browning),

x. Limited packaging materials, NPD, R&D, most of which are not optimised for FCF storage, innovation and marketing,

xi. Huge variety of cut sizes due to hand-cut processing,

xii. Value for money questionable?

xiii. Inferior quality products when compared to intact commodities,
Figure D.1 Generic Process Flow Diagram identifying suggested Critical Control Points (CCPs) for RTE fresh-cut Fruits and Vegetables

Appendix D.1. Pineapple

Introduction

Pineapple (Ananas comosus) is a composite, non-climacteric fruit that shows low to moderate rates of respiration and ethylene production (Dull et al., 1967). After banana and citrus fruits, pineapple is one of the most important tropical fruits consumed in the world today.

Each pineapple plant gives a single fruit before producing suckers which could be used for future planting. The plant itself is a perennial herb 50-100cm high with narrow, tapering pointed leaves arranged in a spiral rosette crowded onto a tightly clasped central stem. The pineapple fruit is terminal and cylindrical with a compound structure at the apex of the stem. It is formed by fusion of the berry-like fruitlets that develop from the flowers. Because it is apex, the fruit bears a compressed, leaf shoot called the crown (Bartholomew et al., 2003). It is important that fruits are produced under optimum conditions as the internal and external quality of fruit at harvest is dependent on several intrinsic and extrinsic factors.
Figure D.2 Cross-sectional view of pineapple plant

Taken from:
Schematic Illustration of Harvest and Postharvest Unit Processing for Pineapples

Figure D.3 Schematic Illustration of Harvest and Postharvest Unit Processing for Pineapples

Taken from
http://www.iica.int/Eng/regiones/caribe/trinidadytobago/Documents/pineapple_publication.pdf
Minimum Quality Requirements for Fresh-cut Pineapple Processing

**Varieties Considered:** Champaka MD2 Smooth Cayenne

**Countries of Origin:** Costa Rica Brazil

**External Conditions:**
- No extremely misshapen fruit (extreme bottlenecks)
- No soft, bruised or mouldy fruit.

No shell defects which can affect internal quality e.g. cracked shells, scars, and malformed fruit (section VI).

Fruit must also to be free from all visible contamination by dust and spray residues.

**With/without Crown** - The quality of the crown is an indicator of freshness and therefore crowns should be green with turgid leaves without withered appearance.

**Internal Conditions:**
- No internal browning.
- No translucent flesh.
- MD2 Flesh Maturity A - B.

**Texture:** Soft but not too crunchy. Not dry.

**Flavour:** Characteristic of the variety (sweet/acidic).

**Sugar Level:** Minimum brix levels measured 50mm from base of crown:
- Champaka 10%
- MD2 minimum 11%, maximum 15.5%

**pH:** 3.2 – 3.8

**Sizes:**
- Count sizes 8 in a 18kg net box
- Count sizes 5, 6, 7, 8 in a 10kg box.

**Delivery Temperature:** 8 - 10°C

**FCF Storage Temperature:** 0 - 4°C

To be delivered in food-grade cardboard containers which minimise damage during transit. All deliveries to be made on Blue Chep pallets.

**Processing:** 25mm triangular cut sizes is recommended

**Optimum Yield:** 35% flesh after removal crown, skin and core.

- Pallets to be checked in a spiral pattern covering all sides of the pallet.
- Fruit must not be grown from genetically modified plants. Fruit must not have been irradiated at any point.
- **Use of Ethephon is permitted:** A wax which may contain polyethylene/paraffin or carnauba/paraffin-based may also be applied.
- **X** may be due to insufficient irrigation, extensive refrigerated storage at temperatures <7°C, low RH%, incorrect application of ethephon and marketing delays.
- All produce must conform to THE CONTROL OF PESTICIDES REGULATIONS 1986 and THE PESTICIDES (MAXIMUM RESIDUE LEVELS IN CROPS, FOOD AND FEEDING STUFFS) REGULATIONS 1994.

**Any deviations from this Specification must be notified prior to supply.**
Appendix D.2 - Cantaloupe Melon

Introduction

Cantaloupe melon belongs to the *Cucumis melo* L. var Nada group and includes two different types; (1) true cantaloupes (*Cucumis melo cantalupensis*), and (2) American Cantaloupes (*Cucumis melo reticulatus*) (Figure 1). True cantaloupes are only found in Europe (native to Italy) and have a beige coloured skin covered in a well-defined grey netting. They have a very sweet pale orange flesh. American cantaloupes are very similar, however are not technically cantaloupes but a netted member of the muskmelon family. They have a green-grey skin covered in netting, protecting a sweet pale orange flesh. In Australia and New Zealand cantaloupes are called rockmelons. Cantaloupe melon is a warm season vining crop, generally requiring 80 to 120 days of warm conditions from seed to maturity. Best melon quality is obtained in areas with high temperatures, high light, minimal rainfall, and relatively low humidity during the growing season.

![Cross-Sectional View of Cantaloupe Melon](image)

*Figure D.4 Cross-Sectional View of Cantaloupe Melon*
Maturity Indices for Cantaloupe Melon

Cantaloupe melons are a temperate, climacteric fruit. They are harvested by maturity and not by size. Commercial maturity is ideally at the firm-ripe stage or "3/4 to full-slip" when a clear abscission (slip separation) from the vine occurs with light pressure. Melons will ripen when taken off the plant (provided they are mature enough when picked) but do not increase in sugar content. Cultivars may vary in their external color during maturity. This skin color typically transitions from gray to dull green when immature, deep uniform green at maturity, and light yellow at full ripeness.

Table D.1 Ripeness Class and Characteristics (adapted from Produce Fact Sheets, UC Davis)
Harvest and Postharvest Operations and Production Practices

Figure D.5 Schematic Illustration of Harvest and Postharvest Operations, Production Practices and Risk Factors in Microbial Food Safety of Fresh and Fresh-cut Cantaloupe Melon

Taken from:
http://www.fda.gov/Food/FoodScienceResearch/SafePracticesforFoodProcesses/ucm091106.htm
Minimum Quality Requirements for Fresh-cut Cantaloupe Melon Processing

Varieties Considered: Cantaloupe Cantaline Charentais

Class I or Class II fruit as described below.

Countries of Origin: Spain Brazil Italy Israel South Africa Costa Rica France

External Conditions: Cantaloupe - Full or partial netting. All melons to be free from soil and evidence of mould or rot. Fruit also to be free from all visible contamination by dust and spray residues.

Class I Fruit: No visible skin markings.
Class II Fruit: Skin scarring, but no rots, moulds, splits or marks which penetrate the flesh.

Internal Conditions: No translucent flesh or extreme colour graduation from centre to skin. No thick green line between skin and flesh. Maximum skin thickness: 10mm. Flesh to be orange in colour.

Texture: No soft or over-ripe fruit acceptable. Also, no firm, crunchy fruit.

Flesh to have initial resistance when eaten but should soften readily in the mouth.

Flavour: High flavour profile desired. Flesh to be sweet and scented but not pungent or whiney.

Sugar Level: Minimum average brix level of 11 when 3 samples taken from the seed pod side, centre and outer skin side of a melon slice.

Maximum brix level of 15.

pH: 5 – 6.5

Sizes: Count sizes 3, 4, 5 in a 5kg net box, or count sizes 4, 5, 6 in 7.5kg.

Delivery Temperature: 8-10°C

Packaging: To be delivered in foodgrade cardboard containers, which minimise damage during transport. All deliveries to be made on blue Chep pallets.

Processing: 25mm trapezoidal chunks is recommended.

Optimum Yield: 55% flesh after removal of outer-skin and seeds.

- Pallets to be checked in a spiral pattern covering all sides of the pallet.
- Fruit must not be grown from genetically modified plants. Fruit must not have been irradiated at any point.
- A wax which may contain polyethylene/paraffin or carnauba/paraffin-based may also be applied.
- All produce must conform to THE CONTROL OF PESTICIDES REGULATIONS 1986 and THE PESTICIDES (MAXIMUM RESIDUE LEVELS IN CROPS, FOOD AND FEEDING STUFFS) REGULATIONS 1994.

Any deviations from this Specification must be notified prior to supply.
Appendix D.3 Kiwifruit

Introduction

The kiwifruit (*Actinidia deliciosa*) is a large, woody, deciduous vine, native to the Yangtze Valley of China. Fruit from the vine are classified as sub-tropical and climacteric in nature, about the size and shape of a large hen’s egg, with a fuzzy, dull-brown skin. Inside, the flesh is emerald green and dotted with rows of black edible seeds. Fruit texture is similar to that of ripe strawberry and the flavour resembles that of a strawberry and pineapple blend (sweet and sharp). Kiwifruit grow on branches of kiwi vines which can be compared to grapevine tendrils. They have a unique and temperamental growing cycle (Figure 1) and will only grow in ideal conditions i.e. fertile, moist and slightly acidic soils, in a sunny climate with not too much wind. *Actinidia* deliciosa will not tolerate winter temperatures much lower than 10°F, however well-hardened, mature vines have been known to survive temperatures approaching 0°F obtained gradually over a number of weeks.

Almost all kiwifruit cultivars grown in commercial orchards outside of China are descended from two female plants and one male plant and *Hayward* fruits are borne from a female vine. However, different Male polliniser cultivars of *Actinidia* deliciosa exist. Most male cultivars have been selected to coincide in flowering with *Hayward*. Effective pollination, seed set and full-sized fruit require coincident flowering of males and females. However weather conditions have a major effect on the time of flowering of males and for that reason, different males are being selected for the different growing countries.

![Figure D.6 Mid-cross Sectional View of Kiwifruit](image)

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Figure D.7  Schematic Illustration of Harvest and Postharvest Operations, Production Practices and Risk Factors in Microbial Food Safety of Fresh and Fresh-cut Kiwifruit

Taken from: http://www.fda.gov/Food/FoodScienceResearch/SafePracticesforFoodProcesses/ucm091106.htm
Minimum Quality Requirements for Fresh-cut Kiwifruit Processing

Varieties Considered: Hayward
Class 1 fruit only.

Countries of Origin: Italy France Chile
New Zealand Greece

External Conditions: Fruit must be free from damage or injury caused by pests, weather, disease or other physical damage. Fruit also to be free from all visible contamination by dust and spray residue.

Internal Conditions: Sound intact condition with no excessive white core or translucency. No woody cores.

Texture: Fruit to have a firm texture with a slight ‘give’. Minimum pressure of 3lbs by penetrometer, using the 8mm head. Core and flesh maximum pressure of 6lbs.

Flavour: Characteristic sweet, juicy flavour to be present. Predominately acidic flavoured fruit not acceptable.

Sugar Level: Minimum brix level of 8.

pH: To be agreed.

Sizes: Count size 33, 36, 39 in a 3kg box. Count size 90, 100, 110 in a 10kg box. Other sizes by prior arrangement only.

Delivery Temperature: 8 - 10°C

Packaging: To be delivered in foodgrade cardboard containers, which minimise damage during transport. All deliveries to be made on blue Chep pallets.

Processing: ¼ cut fruit pieces is recommended

Optimum Yield: 75% flesh after removal of the skin.

- Fruit must not be grown from genetically modified plants.
- Fruit must not have been irradiated at any point.
- Pallets to be checked in a spiral pattern covering all sides of the pallet.
- All produce to conform to THE CONTROL OF PESTICIDES REGULATIONS 1986 and THE PESTICIDES (MAXIMUM RESIDUE LEVELS IN CROPS, FOOD AND FEEDING STUFFS) REGULATIONS 1994.

Any deviations from this Specification must be notified prior to supply.
Strawberry

Introduction

Strawberry fruit (*Fragaria spp.*) is a temperate, climacteric fruit produced from a low-growing, herbaceous plant with a fibrous root system and a crown from which basal leaves arise. The leaves are compound with three leaflets, sawtooth-edged and fuzzy. The flowers are generally white, rarely reddish, and borne in small clusters on slender stalks arising from the axils of the leaves. As a plant ages, the root system becomes woody, and the ‘mother’ crown sends out runners that touch the ground, thus enlarging the plant (Figure 1).

In a botanical sense, strawberries are the greatly enlarged stem-end, or receptacle, in which are particularly embedded the many true fruits, or achenes (pips). The plant succeeds on a wide range of soils and situations however, most countries developed their own varieties, especially suited for a particular climate, day-length, altitude or type of production required. The soil should be well drained (plants won’t survive in water saturated ground) and rich, with well-rotted manure so as to be as free as weeds as possible with potassium, in some form, also added. Regular attendance of soil is advisable to help improve aeration, drainage and increase moisture-holding capacity. Although a harvestable crop is attainable with as little as six hours of sunlight per day, larger harvest yields and the best quality strawberries come from plants with a good luminance exposure.

![Cross sectional view of strawberry](image)

**Figure D.8** Cross sectional view of strawberry
Harvest and Postharvest Operations and Production Practices

Figure D.9 Schematic Illustration of Harvest and Postharvest Operations, Production Practices and Risk Factors in Microbial Food Safety of Fresh and Fresh-cut Strawberry Fruit

Taken from: http://www.fda.gov/Food/FoodScienceResearch/SafePracticesforFoodProcesses/ucm091106.htm
Minimum Quality Requirements for Fresh-cut Strawberry Processing

Varieties Considered:  
Chandler  Yael  Camarosa  
Selva  Evita  
El Santa by special arrangement

Countries of Origin:  
U.K.  France  Holland  
Spain  Belgium  U.S.A.  
South Africa  Morocco

External Conditions:  
Whole fruit should be sound with no mould, soft or wet spots present.  
Berries without leaves should show no detachment or subsequent damage.  
Colour to be minimum 90% red with no green or excessive white shoulders.  
Fruit must be free from damage or injury caused by pests, weather, disease or other physical damage.  
Fruit also to be free from all visible contamination by dust and spray residue.  No sand, soil or straw.

Internal Conditions:  
No boxy fruit with large cervices in the central core.  
No discoulouration.

Texture:  
Firm and dry to the touch, eats with little resistance.  
No soft berries.

Flavour:  
Characteristic sweet flavour to be present.  
Predominately acidic fruit not acceptable.

Sugar Level:  
November to mid-Jan minimum brix level of 6.  
Mid-Jan to end-Oct minimum brix level of 8.

Sizes:  
Berry size between 15 and 25mm.

Packaging:  
No shrink-wrapped fruit.  
To be delivered in food-grade containers, which minimise damage during transport.  No polystyrene trays.  
All deliveries to be made on blue Chep pallets.

Delivery Temperature:  
8 - 10°C  
Processing:  
Medium whole sized fruit with caylex removed is recommended

Optimum Yield:  
95% with caylex removed.

- Fruit must not be grown from genetically modified plants.  
- Fruit must not have been irradiated at any point.  
- Pallets to be checked in a spiral pattern covering all sides of the pallet.  
- All produce to conform to THE CONTROL OF PESTICIDES REGULATIONS 1986 and THE PESTICIDES (MAXIMUM RESIDUE LEVELS IN CROPS, FOOD AND FEEDING STUFFS) REGULATIONS 1994.

Any deviations from this Specification must be notified prior to supply.


Amiot, M.J., Tacchini, M., Aubert, S., Nicholas, J. (1995) Influence of cultivar, maturity stage, and storage conditions on phenolic composition


(TomloxC) involved in the generation of fatty acid-derived flavour compounds. *Plant Physiology*, 136: 2641-2651.


Available[online]:https://www.allianz.com/media/economic_research/publications

http://factominer.free.fr/classical-methods/principal-components-

respiration rate and physiochemical change of fresh-cut apple stored

Fallico, B., Lanza, M.C., Maccarone, E., Nicolosi Asmunado, C. and
Rapisarda, P. (1996) Role of hydroxycinnamic acids and vinyl-phenols
in the flavour alteration of blood orange juices. J. Agric. Food Chem.,
44, 2654-2657.

surface pasteurisation of whole fruit on shelf-life and quality of fresh-cut


Fang, T., Y. Liu, and L. Huang (2013) Growth kinetics of Listeria
monocytogenes and spoilage microorganisms in fresh-cut cantaloupe.
Food Microbiology 34:174-181.

guide’. available[online]:
[20.10.2010].


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Oms-Oliu, G., Soliva-Fortuny, R., & Martín-Belloso, O. (2008b) Physiological and microbiological changes in fresh-cut pears stored in high oxygen active packages compared with low oxygen active and passive modified atmosphere packaging. *Postharvest Biology and Technology*, 48, 295–301.


beverages and oils consumed in Italy assessed by three different in vitro assays. *The Journal of Nutrition*, 133, 2812-2819.


http://www.researchandmarkets.com/research/d77bfa/fruit_vegetables.
Accessed 31.05.2013.


Thurstone, L.L. (1928) Attitudes can be measured. American Journal of Sociology. 33, 529-554.


