

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

**EFFECTS OF POSTHARVEST TREATMENTS ON
STORAGE QUALITY OF LIME (*CITRUS*
LATIFOLIA TANAKA) FRUIT**

**A thesis presented in partial fulfilment of the requirements for the degree of
Doctor of Philosophy in Food Technology
at Massey University, New Zealand**

**THAMARATH PRANAMORNKITH
2009**

Abstract

Limes (*Citrus latifolia* Tanaka) are an attractive fruit crop but generally suffer a loss in value as their colour changes from green to yellow. Various approaches were taken to slow degreening including low temperature storage, use of controlled atmosphere (CA) environments, and treatment of fruit with physiologically active agents such as gibberellic acid (GA₃). However, the cold storage life of lime fruit can also be restricted by a number of factors including chilling injury (CI) and rots. Various pretreatments such as the use of fungicide (thiabendazole, TBZ) and hot water dipping (HWD) and several postharvest regimes based on temperature conditioning (step down technique) and intermittent warming (IW) regimes were further investigated to protect the fruit against rots and CI during cold storage. The objective of this study was to determine what storage conditions and pretreatments would permit long term storage of NZ limes with minimal loss of quality.

CA storage (10% O₂ with 0 or 3% CO₂) was compared to regular air storage (RA) and IW (varying durations) treatments across a range of temperatures. Although some CA storage regimes could assist in delaying degreening, none of the treatments provided protection against CI. CA storage at 3% CO₂ delayed yellowing and gave better fruit quality than the low CO₂ treatment. High CO₂ CA treatments at 5 or 7°C decreased the rate of colour change compared to other constant temperature treatments but did not protect against CI. CI limited storage of fruit under all conditions at constant low temperatures.

Including fungicide (TBZ) in the dip water reduced the incidence of rots and had a secondary effect on protection against CI of lime fruit. However, fungicide use may sometimes exacerbate stresses such as heat injury on lime peel. Hot water dipping has been shown previously to hold potential as a storage pretreatment, but this technique may give risk of damage on produce if it is dipped at too high a temperature. Some HWD treatments did delay degreening, but there was no major effect on CI. HWD at > 47°C for ≥ 4 min caused heat injury to NZ limes. All HWD treatments showed severe CI (>15%) after 10 weeks of cold storage; and HWD fruit stored under RA at 13°C did not

show any CI but showed some pitting ($\leq 10\%$) and degreened rapidly. Overall no suitable HWD treatment for limes was identified in this trial.

This project identified the critical periods and temperature conditions for successful IW of limes. The IW conditions successfully delayed losses in quality of lime fruit provided the first warming period was applied within the first 20 days of storage. At least 2-cycle IW was required to maintain lime quality during long term storage. Some benefits were found after just one cycle of IW treatment but there were not enough to extend storage life.

IW storage benefited fruit quality and provided the highest overall fruit quality of all postharvest treatments tested. The degreening of lime during cold storage at 5°C could be delayed by IW treatments in which the fruit were stored at 5°C for 12, 16 or 20 days then moved to 15°C for 2 days. Both 2- and 6-cycle IW treatments proved satisfactory for maintaining colour on the green and yellow side of lime for 12 weeks of storage. IW treatments in which fruit were warmed within 20 day of cold storage did not show significant CI symptoms after 12 weeks of storage, and the 2-cycle IW treatment showed only a low percentage of CI fruit at this time. A 2-cycle IW treatment was almost as effective as 6 cycles, and a step down treatment also showed some promising results, indicating that it may be possible to further optimize the time and duration of variable temperature storage regimes to meet both quality requirements and the constraints of temperature management in commercial coolstores. The application of these regimes to other citrus species may also be beneficial. There are a number of physiological explanations that may account for the effectiveness of IW including positive effects on heat shock protein (HSP) and cell membranes. Nutritional factors such as vitamin C and flavonoid compositions were also investigated and fruit that did not show visible CI were found to retain at-harvest levels of these factors. Practical ways of implementing IW are discussed.

In order to understand the effectiveness of IW on degreening, I used a logistic model to describe degreening of lime peel. This modelling approach demonstrated that IW did not change the mechanism of lime degreening based on the similarity between the hue values predicted by the model and the actual hue values measured during lime storage. The activation energy (E_a) for degreening based on either hue angle (H°) or colour score (CS) during air storage was estimated to be ~ 53 and ~ 86 KJ.mol⁻¹, respectively. Relationship

between colour (H° and CS) and chlorophyll content, relationship between reflectance spectra (%), chlorophyll content and H° of lime fruit stored under different conditions are presented and discussed. This data allowed deduction to be made about the changes in individual pigments that are driving colour change during “good” and “bad” storage.

Acknowledgements

I would like to express my profound gratitude to both of my academic supervisors Associate Professor John Mawson, Institute of Food, Nutrition & Human Health, Massey University and Dr. Julian Heyes, New Zealand Institute for Plant & Food Research Limited (PFR), Palmerston North for their knowledge, guidance, advice and support throughout the study period. I have very much appreciated their assistance, encouragement and friendship, not only for my study but also as they have helped me with obstacles I faced since I arriving NZ. This research and my study would not have succeeded without their help and support. I am thankful that both of you have nurtured, taught me much scientific knowledge. I have very much enjoyed study and discussion with both of you which provided me an opportunity to establish my knowledge and always learn new things in the field of postharvest technology. I wish to thank you both very much for your patience, critical reading and many suggestions for my thesis writing.

My gratitude for the help and very useful discussions I received from Fresh Technology staff, Institute of Food, Nutrition & Human Health, Massey University, particularly Dr. Bruce MacKay, Sue Nicholson and Dr. Jinquan Feng. I would like to thank all Fresh Technology staff for their friendship. I would like to make a special thank you to Peter Jeffery who helped me in harvesting lime fruit and introduced me to some interesting places. I also thank you for the help with any problems related to my computer. I also would like to thank you Associate Professor John Bronlund, School of Engineering and Advanced Technology for his kind help and support.

I sincerely thank you Dr. Ross Lill, Dr. Erin O'Donoghue, Dr. Nigel Gapper and Dr. Lian-Heng Cheah for the help and very useful discussions about my work, Dr. Nigel Joyce for identification of flavonoid peaks by liquid chromatography mass spectrometry (LCMS), and Dr. Duncan Hedderley and Dr. Andrew McLachlan for assistance with principal component analysis (PCA) of flavonoid compounds of lime juice. I wish to say thank you very much to Dr. Kees and Mrs Helge van Epenhuijsen for their friendship - thank you for inviting me to your home, it was very warm and also thank you very much Kees for your help including the many items I borrowed from the entomology lab.

I would like to express my thanks to Tatyana Pinkney, Sheryl Somerfield, and Steve Arathoon who provided me technical assistance, training, help and support throughout my study periods. I would like to make a special thank you to Bruce Bycroft, Brent Page, Paul Shakespeare and Ken Somerfield for their help and friendship. I would like to thank all those PFR staff for making the place a friendly place to work during my study. I acknowledge the kind hospitality of Carol Dolman and Maryanne Nation for their help with administrative work.

I gratefully acknowledge the Asian Development Bank (ADB) for my PhD scholarship. I am deeply grateful for the support received from the Institute of Food, Nutrition and Human Health (IFNHH), Massey University. I also acknowledge The Clark Fletcher Memorial Citrus Bursary for the scholarship.

I wish to acknowledge Keith Pyle for providing the limes necessary for the study in 2004 and his helpful suggestions about lime.

I would like to thank my friends, Weerawate Utto, who I really enjoy talking with on every topic during my study period. Thanks also to Dr. Pisit Dhamvithee and Pierre Vernerey for lab assistance. I also would like to thank all my friends for their friendship and support, I cannot list all of your name here. I would like to make a special thank you to Mr. Maxwell Townley, who passed away. I deeply acknowledge his help and friendship during my living in NZ.

I thankfully express my acknowledgement to Associate Professor Sirichai Kanlayanarat, King Mongkut's University of Technology Thonburi, Thailand, who gave me a very good opportunity to study overseas. His support and assistance helped me very much during my PhD study in New Zealand. I would like to take this opportunity to thank you my Thai supervisor for his best wishes, best opportunity from the past until now.

Finally, I would also like to acknowledge the help and support I received from my parents (Pisit and Jumrus), my brothers (Sakol and Ruttapol) and sister (Pennapa), who always gave me moral support and love.

Table of Contents

Abstract.....	iii
Acknowledgements.....	vii
Table of Contents.....	ix
List of Figures.....	xv
List of Tables.....	xxix
Abbreviations.....	xxxix
<i>CHAPTER 1</i>	1
Introduction.....	1
<i>CHAPTER 2</i>	3
Literature review.....	3
2.1 Lime cultivars and their characteristics.....	3
2.2 Lime production.....	4
2.3 Consumers' acceptance of lime.....	5
2.4 Major quality changes of citrus fruit after harvest.....	6
2.4.1 The development of citrus fruit.....	6
2.4.2 Colour, soluble solids content and acidity.....	8
2.4.3 Firmness.....	11
2.4.4 Respiration and ethylene production rates.....	11
2.4.5 Nutritional quality.....	12
2.4.5.1 Vitamin C.....	12
2.4.5.2 Flavonoids.....	13
2.5 Disorders of citrus during storage.....	17
2.5.1 Introduction.....	17
2.5.2 Pitting and chilling injury (CI).....	18
2.6 The current understanding of the chilling injury in plants.....	18
2.6.1 Definition and causes of CI.....	18
2.6.2 Symptoms of CI.....	19
2.6.3 Different factors influencing CI.....	19
2.6.4 Original hypothesis.....	19
2.6.5 Ir- and reversible concepts.....	20
2.6.6 Revised hypothesis – the primary and secondary responses.....	21
2.6.7 Differences between the chilling sensitive and chilling tolerant plants.....	21

2.6.8 Reactive oxygen species (ROS).....	22
2.6.9 Effects of hormones to CI:.....	24
2.6.9.1 Polyamines.....	24
2.6.9.2 Ethylene.....	25
2.6.9.3 Absciscic acid.....	26
2.6.10 Protective mechanism.....	27
2.6.10.1 Transgenic.....	27
2.6.10.2 Heat shock proteins (HSPs).....	27
2.7 Rots.....	27
2.8 Heat injury (HI).....	28
2.9 Techniques for extending storage life of citrus fruit.....	30
2.9.1 Introduction.....	30
2.9.2 Prestorage treatment.....	31
2.9.2.1 Application of fungicide.....	31
2.9.2.2 Application of gibberellic acid (GA ₃).....	32
2.9.2.3 Heat treatment.....	33
2.9.3 Post-harvest techniques for improving storage life.....	34
2.9.3.1 Low temperature storage.....	34
2.9.3.2 Modified atmosphere (MA) and controlled atmosphere (CA) storage.....	35
2.9.3.3 Intermittent warming (IW).....	38
2.9.3.4 Temperature conditioning (TC) or step down technique.....	40
2.10 Aims and project objectives.....	41
CHAPTER 3.....	43
Methods and materials.....	43
3.1 Fruit supply and handling.....	43
3.1.1 Harvest 1 (H1).....	45
3.1.2 Harvest 2 (H2).....	45
3.1.3 Harvest 3 (H3).....	45
3.1.4 Harvest 4 (H4).....	45
3.1.5 Harvest 5 (H5).....	46
3.2 Schematic overview of experimental programme.....	46
3.3 Storage regimes.....	48
3.3.1 Glass jar storage system (H1).....	49
3.3.2 Polycarbonate box storage system (H2, H3 and H4).....	50

3.3.3 Cylindrical storage container system (H5)	53
3.4 Colour measurement	54
3.4.1 Introduction.....	54
3.4.2 Chromameter.....	55
3.4.3 Spectrophotometer	56
3.4.4 Comparison of colour measurements.....	56
3.4.5 Colour score (CS, %)	58
3.5 Disorders	58
3.5.1 Chilling injury (CI)	59
3.5.2 Pitting.....	59
3.5.3 Heat injury (HI).....	60
3.6 Rots	61
3.7 Other quality parameter measurements	61
3.7.1 Compression firmness (CF)	61
3.7.2 Respiration and ethylene production rate	62
3.8 Chemical assessments	63
3.8.1 Flavonoids (Polyphenolic compounds).....	63
3.8.2 Ascorbic acid	64
3.8.3 Chlorophyll content	65
3.9 Statistical analysis.....	66
CHAPTER 4.....	67
Effects of gas atmosphere and GA ₃ on lime (<i>Citrus latifolia</i> Tanaka) storage life	67
4.1 Behaviour of lime fruit under regular air (RA) storage	67
4.1.1 Introduction.....	67
4.1.2 Colour changes during RA storage	68
4.1.2.1 Introduction.....	68
4.1.2.2 Trends in hue in RA storage	69
4.1.2.3 Effect of inclusion of ethylene absorbent	75
4.1.2.3.1 Introduction.....	75
4.1.2.3.2 Colour changes of limes with C ₂ H ₄ absorbent during RA storage	75
4.1.2.4 The effect of GA ₃ on lime stored in RA	76
4.1.2.5 Colour score (CS) of lime under RA storage.....	77
4.1.3 Disorders under RA	79
4.1.3.1 Introduction.....	79

4.1.3.2 CI symptoms after storage of NZ lime under RA.....	80
4.1.4 Disorders under RA after storage and shelf life.....	82
4.1.4.1 Introduction.....	82
4.1.5 Rots under RA.....	84
4.1.5.1 Introduction.....	84
4.1.6 Compression firmness (CF) under RA	87
4.1.6.1 Introduction.....	87
4.1.6.2 Association of CF with disorders or mass loss	87
4.2 Behaviour of lime fruit under CA storage	90
4.2.1 Introduction.....	90
4.2.2 Colour changes during CA storage	90
4.2.2.1 Trends in hue in CA storage	90
4.2.2.2 Colour score under CA storage.....	92
4.2.3 Disorders under CA	94
4.2.4 Rots under CA.....	96
4.2.5 Compression firmness under CA	97
4.3 Discussion.....	98
CHAPTER 5	107
Intermittent warming and hot water dipping as possible strategies to extend lime (<i>Citrus latifolia</i> Tanaka) storage life.....	107
5.1 Introduction.....	107
5.2 Experimental overview	108
5.3 Intermittent warming (IW).....	108
5.3.1 Trends in hue under IW conditions.....	108
5.3.2 Colour score under IW condition.....	113
5.3.3 Disorders under IW condition.....	114
5.3.4 Disorders after shelf life.....	117
5.3.5 Rots under IW condition.....	118
5.3.6 Compression firmness.....	122
5.3.7 Respiration and ethylene production rate	123
5.4 Hot water dipping (HWD)	126
5.4.1 Trends in hue in HWD conditions	128
5.4.2 Colour score under HWD conditions.....	133
5.4.3 Disorders during storage following HWD	134

5.4.4 Rots under HWD conditions	137
5.4.5 Compression firmness under HWD conditions	139
5.5 Overall acceptability of limes after storage	139
5.6 Discussion	141
CHAPTER 6	157
Kinetics and mechanism of colour change	157
6.1 Introduction	157
6.2 Methodology: Use of the logistic equation to describe degreening	158
6.3 Variability in colour change profiles	159
6.3.1 Individual vs. mean hue data	159
6.3.2 Further consideration of mean hue data	162
6.4 Temperature kinetics of degreening	167
6.4.1 Hue angle	167
6.4.2 Colour score	170
6.5 Applying degreening models in the prediction of colour change by IW	173
6.5.1 H° and Time	174
6.5.2 CS and Time	175
6.6 How is colour related to pigment concentration?	176
6.6.1 Introduction	176
6.6.2 The relationships between hue, colour score and chlorophyll	177
6.6.3 Relationship between reflectance spectra (%), chlorophyll content and hue angle	179
6.6.3.1 Introduction	179
6.6.3.2 Reflectance spectra on the green and yellow side of limes	180
6.6.3.3 Comparison of differences in reflectance spectral data of the high H° fruit set versus the low H° fruit set at T = 0 and T = 12 weeks	185
6.6.3.4 Implications of difference spectra for the underlying pigment changes during postharvest storage	186
6.7 Do changes in pigment differ between IW and HWD?	192
6.8 Discussion	193
CHAPTER 7	199
Phytochemical composition of lime (<i>Citrus latifolia</i> Tanaka) fruit during storage	199
7.1 Introduction	199
7.2 Methodology	199

7.3 Effect of different postharvest treatments and storage on vitamin C content.....	200
7.4 Effect of postharvest techniques on lime phytochemicals after storage	201
7.4.1 Flavonoids of lime and their identification	202
7.4.2 Principal components analysis (PCA)	204
7.4.3 Latent vector analysis	207
7.5 Changes in composition of selected lime flavonoids.....	208
7.5.1 Introduction.....	208
7.5.2 Changes of composition of individual flavonoids	209
7.5.3 Changes in hesperidin concentration	211
7.6 Discussion	212
<i>CHAPTER 8</i>	217
Overall discussion and conclusions	217
References	229
Appendix I	255
Appendix II	257
Appendix III.....	259
Appendix IV.....	261

List of Figures

Figure 2.1 A: Schematic drawing of a mature citrus fruit emphasizing the vascular arrangement. B: Diagrammatic equatorial cross-section through a citrus fruit.....	8
Figure 3.1 Schematic overview of experimental programme.....	48
Figure 3.2 The gas mixer used to prepare gas atmospheres for CA trials.	49
Figure 3.3 Limes in CA storage using glass jars.	50
Figure 3.4 Limes during shelf life at $20 \pm 2^{\circ}\text{C}$	50
Figure 3.5 Limes in RA or CA and IW conditions during storage using polycarbonate boxes.....	51
Figure 3.6 H3 fruit stored under RA at 5, 7, 15 and $20 \pm 1^{\circ}\text{C}$ and IW conditions were washed for 3 min in 20°C cold water to which the fungicide TBZ (1,500 ppm) was added.	52
Figure 3.7 Selected H3 fruit were treated hot water dipping (HWD) at $52-53^{\circ}\text{C}$; H5 fruit were dipped at $42-57^{\circ}\text{C}$, for 2-6 min.	52
Figure 3.8 H5 fruit were washed (or cool down after HWD) for 3 min in 15°C cold water to which the fungicide TBZ (1,200ppm) was added (A) then left to air-dry at room temperature for one night (B).....	53
Figure 3.9 Limes in RA storage using cylindrical storage containers.	54
Figure 3.10 The CIE chromaticity diagram showing approximate colour regions from 400 nm to 700 nm wavelength.	55
Figure 3.11 Correlation between hue (H°) of limes (♦) on the green (G) and yellow (Y) side and of paint colour cards (□) as measured by chromameter and spectrophotometer.	57
Figure 3.12 Colour score grading system for lime fruit ranging from green fruit = 0% yellow ($H^{\circ} \geq 115^{\circ}$) and yellow fruit = 100% yellow ($H^{\circ} \leq 95^{\circ}$).	58
Figure 3.13 Grading scale for the percentage of surface area showing CI symptoms following Kluge <i>et al.</i> (2003): 1 = <5%; 2 = 5 – 25%; 3 = 25 – 50%; 4 = >50%.....	59
Figure 3.14 Grading scale for the extent of pitting symptoms: 1 = <5% surface area affected, 1-2 pits; 2 = 5-10% area affected, > 2 pits; 3 = 10-15% area affected, >2 pits; 4 = >15% area affected, >2 pits.	60

Figure 3.15 Grading scale for the percentage of surface area showing HI symptoms: 1 = <5%; 2 = 5 – 25%; 3 = 25 – 50%; 4 = >50%.....	61
Figure 3.16 Examples of the different types of rot observed on limes during storage.	62
Figure 4.1 Hue angle in NZ limes stored under RA on the green side (A) or yellow side (B) at 2, 5 and 13°C, H1. H° _C (chromameter data).....	70
Figure 4.2 Hue angle in NZ limes stored under RA on the green side (A) or yellow side (B) at intermediate temperatures ranges 5, 7, 9 and 13°C, H2..	70
Figure 4.3 Colour change for NZ limes stored under RA on the green side (A) or yellow side (B) at 5, 7, 15, and 20°C, H3. H° _S (spectrophotometer data).....	71
Figure 4.4 Colour change for NZ limes stored under RA on the green side (A) or yellow side (B) at 5°C across all runs. All H° of fruit from H1-H2 were adjusted for H° between chroma meter and spectrophotometer whereas the H° of H3 fruit were adjusted for only the beginning value.....	72
Figure 4.5 Colour change for NZ limes stored under RA on the green side at 7°C (A) or at 13°C (B) across three different harvest (H2, H3 & H4 at 7°C and H1, H2 & H5 at 13°C). All H° of fruit from H1-H2 were adjusted for H° between chroma meter and spectrophotometer whereas the H° of H3 fruit were adjusted for only the beginning value	73
Figure 4.6 Colour changes for NZ limes stored under RA on the green side (A) or yellow side (B) at 5 and 7°C with and without C ₂ H ₄ , absorbent, H4.....	76
Figure 4.7 Colour change for NZ limes stored under RA on the green side (A) or yellow side (B) at 2, 5 and 13°C with and without GA ₃ , H1. H° _C (chromameter data).....	77
Figure 4.8 CS after harvest for NZ limes stored under RA at 2, 5 and 13°C until 10 weeks of storage, H1.	77
Figure 4.9 CS after harvest for NZ limes stored under RA at 5, 7, 9 and 13°C until 8 weeks of storage, H2 (A) or at 5, 7, 15 and 20°C until 12 weeks of storage, H3 (B).	78
Figure 4.10 Correlation between H° and CS for NZ limes stored under RA on the green side (A) or association between H° (◇) on the green side and CS (□) (B), stored at 20°C, H3.	79
Figure 4.11 Incidence of pitting injury and CI after 8 (left) and 10 (right) weeks of storage for H1 fruit and RA storage at low and non-chilling temperatures.....	80

Figure 4.12 Incidence of pitting injury and CI after 6 (left) and 8 (right) weeks of storage for H2 fruit and RA storage.....	81
Figure 4.13 Incidence of pitting injury and CI after 8 (left) and 10 (right) weeks of storage for H4 fruit.....	82
Figure 4.14 Incidence of pitting injury and CI after 8 (left) and 10 (right) weeks of storage plus 3 days shelf life at 20°C for H4	83
Figure 4.15 Incidence of rots after 8 (left) and 10 (right) weeks of storage for the fruit stored under RA at 2, 5 and 13°C, H1.....	85
Figure 4.16 Incidence of rots after 6 (left) and 8 (right) weeks of storage for the fruit stored under RA at 5, 7, 9 and 13°C, H2.....	86
Figure 4.17 Incidence of rots after 10 (left) and 12 (right) weeks of storage for the fruit stored under RA at 5, 7, 15 and 20°C, H3.....	86
Figure 4.18 CF for NZ limes stored under RA at 2, 5 and 13°C after shelf life for 3 days after 8 and 10 weeks of storage, H1.....	88
Figure 4.19 Association between CF of the fruit stored for 8 and 10 weeks plus 3 days shelf life at 20°C and CI scores of fruit at 8 and 10 weeks of storage for NZ limes stored under RA at 2 and 5°C, H1.	88
Figure 4.20 Association between CF of the fruit stored for 8 and 10 weeks plus 3 days shelf life at 20°C and all types (CI-1-CI-4) of mass loss at 8 and 10 weeks of storage for NZ limes stored under RA at 2, 5 and 13°C, H1.....	89
Figure 4.21 Colour change for NZ limes stored under RA at 5°C and 0 or 3% CO ₂ with 10% O ₂ CA at 2 or 5 and 13°C on the green side (A) or yellow side (B), H1.	92
Figure 4.22 Colour change for NZ limes stored under RA at 5°C and 3% CO ₂ with 10% O ₂ CA at intermediate temperatures ranges 5, 7, 9 and 13°C on the green side (A) or yellow side (B), H2.	92
Figure 4.23 CS after harvest for NZ limes stored under RA at 5°C and 0 or 3% CO ₂ with 10% O ₂ CA at 2 and 13°C or 3% CO ₂ with 10% O ₂ CA at 5°C until 12 weeks of storage, H1.	93
Figure 4.24 CS after harvest for NZ limes stored under RA at 5°C and 3% CO ₂ with 10% O ₂ CA at 5, 7, 9 and 13°C until 8 weeks of storage, H2.	93
Figure 4.25 Incidence of pitting (top) and CI (bottom) of lime stored under RA at 5°C and 0 or 3% CO ₂ with 10% O ₂ CA at 2 and 13°C or 3% CO ₂ with 10% O ₂ CA at 5°C after 8 (left) and 10 (right) weeks of storage, H1	94

Figure 4.26 Incidence of pitting (top) and CI (bottom) of lime stored under RA at 5°C and 3% CO ₂ with 10% O ₂ CA at 5, 7, 9 and 13°C after 6 (left) and 8 (right) weeks of storage, H2.....	95
Figure 4.27 Incidence of rots of lime stored under RA at 5°C and 0 or 3% CO ₂ with 10% O ₂ CA at 2 and 13°C or 3% CO ₂ with 10% O ₂ CA at 5°C after 8 (left) and 10 (right) weeks of storage, H1.	96
Figure 4.28 Incidence of rots of lime stored under RA at 5°C and 3% CO ₂ with 10% O ₂ CA at 5, 7, 9 and 13°C after 6 (left) and 8 (right) weeks of storage, H2.	96
Figure 4.29 CF for NZ limes stored under RA at 5°C and 0 or 3% CO ₂ with 10% O ₂ CA at 2 and 13°C or 3% CO ₂ with 10% O ₂ CA at 5°C, H1.....	97
Figure 5.1 Colour change for NZ limes stored under RA at 2, 5 and 13°C and an IW condition at 2°C, for 3 weeks and 13°C for 1 week on the green side (A) or yellow side (B), H1.....	109
Figure 5.2 Colour change for NZ limes stored under RA at 5, 7 and 13°C and IW conditions at 5°C for 3 weeks and 13°C for 1 week or at 7°C for 3.50 weeks and 20°C for 3 days on the green side (A) or yellow side (B), H2.....	109
Figure 5.3 Colour change for NZ limes stored under different RA storage at 5, 7, 15 and 20°C and IW conditions at 5°C for 12 days and 15°C for 2 days with and without fungicide or 7°C for 12 days and 20°C for 2 days or 7°C for 3.50 weeks and 20°C for 3 days on the green side (A) or yellow side (B), H3.	110
Figure 5.4 Colour change for NZ limes stored under RA at 5°C, a step-down technique by stored the fruit at 10°C for 2 weeks then stored at 5°C until the end of storage and different IW conditions (5°C, 12 days and 15°C, 2 days) regimes plus C ₂ H ₄ ethylene absorbent and different warming frequency (1, 2 or 6 cycles) on the green side (A), or yellow side (B), H4...	111
Figure 5.5 Colour change for NZ limes stored under RA at 5°C and different IW conditions (5°C, 12 days and 15°C, 2 days) regimes plus C ₂ H ₄ ethylene absorbent (6 cycles) and other different IW conditions at different durations (16, 20 and 24 days for the first warming at 5°C and 15°C, 2 days) on the green side (A), or yellow side (B), H4.....	112

Figure 5.6 Comparison of CS after harvest for NZ limes stored under RA at 5°C and different IW conditions for 1 day, 2, 4, 6, 8, 10 and 12 weeks of storage, H2, 3 and 4.	113
Figure 5.7 Incidence of pitting (top) and CI (bottom) after 8 (left) and 10 (right) weeks of lime stored under RA at 2, 5 and 13°C and an IW condition (2°C for 3 weeks and 13°C for 1 week), H1	115
Figure 5.8 Incidence of pitting (top) and CI (bottom) after 6 (left) and 8 (right) weeks of lime stored under RA at 5, 7 and 13°C and IW conditions (5°C for 3 weeks and 13°C for 1 week or 7°C for 3.5 weeks and 20°C for 3 days), H2.	115
Figure 5.9 Incidence of pitting (no CI) after 8 (left) and 10 (right) weeks of lime stored under RA at 5, 7, 15 and 20°C and IW conditions (5°C for 12 days and 15°C for 2 days with and without the fungicide or 7°C for 12 days and 20°C for 2 days or 7°C for 3.5 weeks and 20°C for 3 days), H3	116
Figure 5.10 Incidence of pitting (top) and CI (bottom) after 10 (left) and 12 (right) weeks of lime stored under RA at 5°C with C ₂ H ₄ absorbent and the step-down treatment (10°C for 2 weeks and then moved to 5°C) and IW conditions (5°C for 12 days and 15°C for 2 days) with different warming durations for 1, 2 or 6 cycles and added with C ₂ H ₄ absorbent, H4.....	116
Figure 5.11 Incidence of pitting (top) and CI (bottom) after 8 (left) and 10 (right) weeks of lime stored under RA at 5°C with C ₂ H ₄ absorbent and the step-down treatment (10°C for 2 weeks and then moved to 5°C) and IW conditions (5°C for 12 days and 15°C for 2 days) with different warming durations for 1, 2 or 6 cycles and added with C ₂ H ₄ absorbent, H4.....	117
Figure 5.12 Incidence of rots after 8 (left) and 10 (right) weeks of storage for the fruit stored under RA at 2, 5 and 13°C and an IW condition (2°C for 3 weeks and 13°C for 1 week), H1.....	118
Figure 5.13 Incidence of rots after 6 (left) and 8 (right) weeks of storage for the fruit stored under RA at 5, 7 and 13°C and IW conditions (5°C for 3 weeks and 13°C for 1 week or 7°C for 3.5 weeks and 20°C for 3 days), H2.....	119
Figure 5.14 Incidence of rots after 10 (left) and 12 (right) weeks of storage for the fruit stored under RA at 5, 7, 15 and 20°C and IW conditions (5°C for 12 days and 15°C for 2 days with and without the fungicide or 7°C for 12 days and 20°C for 2 days or 7°C for 3.5 weeks and 20°C for 3 days), H3...	119

Figure 5.15 Incidence of rots after 10 (left) and 12 (right) weeks of storage for lime stored under stored under RA at 5°C with C ₂ H ₄ absorbent and the step-down treatment (10°C for 2 weeks and then moved to 5°C) and IW conditions (5°C for 12 days and 15°C for 2 days) with different warming durations for 1, 2 or 6 cycles and added with C ₂ H ₄ absorbent, H4.....	120
Figure 5.16 Incidence of rots after 10 (left) and 12 (right) weeks of storage for the fruit stored under RA at 5°C with C ₂ H ₄ absorbent and IW conditions (5°C for 16, 20 and 24 days, respectively and 15°C for 2 days with C ₂ H ₄ absorbent), H4.....	121
Figure 5.17 CF for NZ limes (A) stored under RA at 5°C and IW conditions (5°C for 3 weeks and 13°C for 1 week or 7°C for 3.5 weeks and 20°C for 3 days, H2. (B) stored under RA at 5°C and IW conditions (5°C for 12 days and 15°C for 2 days or 7°C for 12 days and 20°C for 2 days and 7°C for 3.5 weeks and 20°C for 3 days, H3. (C) stored under RA at 5°C and IW conditions (5°C for 12 days and 15°C for 2 days) regimes plus C ₂ H ₄ ethylene absorbent and different warming frequency (1, 2 or 6 cycles), H4..	122
Figure 5.18 Respiration rate (measured at 15°C) of limes stored under RA at 5°C (with and without C ₂ H ₄ absorbent) and different IW conditions (5°C, 12 days and 15°C, 2 days) regimes plus C ₂ H ₄ absorbent and different warming frequency (1, 2 or 6 cycles), H4..	125
Figure 5.19 Ethylene production (measured at 15°C) rate of limes stored under RA at 5°C (with and without C ₂ H ₄ absorbent) and different IW conditions (5°C, 12 days and 15°C, 2 days) regimes plus C ₂ H ₄ absorbent and different warming frequency (1, 2 or 6 cycles), H4.....	125
Figure 5.20 Temperature profiles for the outer flesh surface and core of limes during dipping into hot water at 47°C for 2, 4 and 6 min then into 19°C water.	126
Figure 5.21 Temperature profiles for the outer flesh surface and core of limes during dipping into hot water at 52°C for 2, 4 and 6 min then into 19°C water.	127
Figure 5.22 Colour change for NZ limes stored under RA at 5 and 15°C and pre-treated limes with 52-53°C HWD then stored under RA at 5°C with and without the IW condition (5°C for 12 days and 15°C for 2 days) and/or with and without C ₂ H ₄ absorbent on the green side (A) or yellow side (B), H3.....	128

Figure 5.23 Colour change for NZ limes stored under RA at 5°C and pre-treated limes with different HWD conditions (47°C or 52°C for 2, 4 or 6 min, respectively) then stored at 5°C on the green side (A) or yellow side (B), H5.	129
Figure 5.24 Colour change for NZ limes stored under RA at 5°C and pre-treated limes with HWD at 42°C for 2 min, 47 and 52°C for 4 min without fungicide, 57°C for 6 min then stored under RA at 5°C on the green side (A) or yellow side (B), H5.	130
Figure 5.25 Colour change for NZ limes stored under RA at 5°C and pre-treated limes with HWD at 42, 47 and 52°C for 2 min then stored under RA at 5°C on the green side (A) or yellow side (B), H5.	131
Figure 5.26 Colour change for NZ limes stored under RA at 5°C and pre-treated limes with different HWD conditions at 47 and 52°C dipped for 4 min with and without fungicide then stored under RA at 5°C on the green side (A) or yellow side (B), H5.	131
Figure 5.27 Colour change for NZ limes stored under RA at 5°C and pre-treated limes with different HWD conditions at 47, 52 and 57°C dipped for 6 min then stored under RA at 5°C on the green side (A) or yellow side (B), H5.	132
Figure 5.28 Colour change for NZ limes stored under RA at 5 and 13°C and pre-treated limes with different HWD conditions at 47 and 52°C dipped for 6 min then stored under RA at 13°C on the green side (A) or yellow side (B), H5.	133
Figure 5.29 CS after harvest for NZ limes stored under RA at 5°C and pre-treated limes with 52-53°C HWD condition dipped for 2 min, with and without C ₂ H ₄ absorbent and the same HWD condition plus IW condition (5°C for 12 days and 15°C for 2 days) with and without C ₂ H ₄ absorbent then stored under RA at 5°C from 2, 4, 6, 8, 10 and 12 weeks of storage, H3 (A) and limes stored under RA at 5°C and pre-treated limes with several HWD conditions, H5 (B).	134

Figure 5.30 Incidence of heat injury after 1 day (A) and 2 weeks of storage (B) of lime pre-treated with HWD at 52-53°C with and without C ₂ H ₄ or lime pre-treated with HWD at 52-53°C with and without C ₂ H ₄ and stored under IW condition (5°C for 12 days and 15°C for 2 days), H3.	135
Figure 5.31 Incidence of pitting and chilling injury after 8 (left) and 10 (right) weeks of storage of lime stored under RA at 5°C or limes pre-treated with HWD at 52-53°C with and without C ₂ H ₄ or lime pre-treated with HWD at 52-53°C with and without C ₂ H ₄ and stored under IW condition (5°C for 12 days and 15°C for 2 days), H3.	135
Figure 5.32 Incidence of chilling injury after 8 (A) and 10 (B) weeks of storage of lime stored under RA at 5°C or pre-treated limes with different HWD conditions (47°C or 52°C for 2, 4 or 6 min, respectively) with fungicide or pre-treated limes with HWD at 42°C for 2 min, 47 and 52°C for 4 min without fungicide and 57°C for 6 min with fungicide then all treatments were stored under RA at 5°C, H5	136
Figure 5.33 Incidence of rots after 10 (left) and 12 (right) weeks of storage for limes stored under RA at 5°C or limes pre-treated with HWD at 52-53°C with and without C ₂ H ₄ or lime pre-treated with HWD at 52-53°C with and without C ₂ H ₄ and stored under IW condition (5°C for 12 days and 15°C for 2 days), H3.	137
Figure 5.34 Incidence of rots after 8 (left), 10 (middle) and 12 (right) weeks of storage for limes stored under RA at 5°C or pre-treated limes with different HWD conditions (47°C or 52°C for 2, 4 or 6 min, respectively) then stored at 5°C, H5.	138
Figure 5.35 Incidence of rots after 8 (left), 10 (middle) and 12 (right) weeks of storage for limes stored under RA at 5°C or pre-treated limes with HWD at 42°C for 2 min or 47 and 52°C for 4 min without fungicide then stored under RA at 5°C, H5.	138
Figure 5.36 CF for NZ limes stored under RA at 5°C and pre-treated limes with 52-53°C HWD stored under RA at 5°C with and without C ₂ H ₄ absorbent or IW condition (5°C for 12 days and 15°C for 2days) with and without C ₂ H ₄ absorbent, H3.	139

- Figure 5.37 Acceptability of limes after storage under RA at 5°C, H2, 4 and 5 compared with limes stored under CA (3% CO₂/10% O₂) at 5°C, H2, limes stored under the step-down treatment (10°C, 2 weeks then stored under 5°C plus C₂H₄ ethylene absorbent until the end of storage, H4, limes stored under IW conditions (5°C, 12 days and 15°C, 2 days) regimes plus C₂H₄ ethylene absorbent and different warming frequency (1, 2 and 6 cycles) ,H4 and limes pre-treated with HWD at 47°C for 2 and 4 min, respectively and then stored under RA at 5°C, H5. 140
- Figure 6.1 H° on the green side of 24 lime fruit from H5 stored under RA at 13°C: Individual hue profiles for 24 lime fruit (A) and the mean (Δ) and predicted (dashed lines) hue of this sample fitted with the logistic model, Eq. 6.1, (LSD_{0.05} = 1.5738, n = 24) (B). 160
- Figure 6.2 Ranking of H° of the 24 green fruit at initial day 0 compared with the final H° of the same fruit at 12 weeks of storage. 161
- Figure 6.3 Comparisons between the high (●) and low (▲) hue angle fruit sets with the average (◆) hue data of 24 fruit. 162
- Figure 6.4 H° of lime stored under RA at 2 (A), 5 (B) and 13°C (C) on the green (closed symbol) and yellow side (open symbol), H1. (average of 18 fruit, independent sampling at 8 and 10 weeks). The data were converted from CR-200 data to spectrophotometer data by the formula Eq. 3.1. 163
- Figure 6.5 H° of combined data sets of limes stored under RA at 2 and 13°C (A) and RA at 5°C and 13°C (B) on the green (closed symbol) and yellow side (open symbol) , H1. Comparisons between yellow sides of H1 limes stored under RA at 2 (□) and 13°C (Δ) (A) and yellow sides of limes stored under RA at 5°C (◇) and 13°C (Δ) (B) were overlaid on each of their green sides of lime stored under 2 (■), 5 (◆) and 13°C (▲), respectively. Predicted H° (dashed lines) for limes stored at 2, 5 and 13°C are also presented. 164
- Figure 6.6 H° and predicted H° (dashed lines) of lime stored under RA at 5 (A) and 15°C (B) on the green (closed symbol) and yellow side (open symbol), H3. (average of 60 fruit at 0 day, 80 fruit at 2-4 weeks, 60 fruit at 6-8 weeks and 40 fruit at 10-12 weeks). The data at 0 day was converted from CR-200 data to spectrophotometer data by the formula: $y = 0.9136x$, ($y = H^{\circ}_s$ and $x = H^{\circ}_c$). Comparisons between yellow sides of limes stored under 5 (◇) and

15°C (Δ) were overlaid on each of their green sides of lime stored under 5 (♦) and 15°C (▲) (C).....	165
Figure 6.7 H° and predicted H° (dashed lines) of pre-treated limes (dipped in 15°C water, 2 min) then stored under RA at 5 (A) and 13°C (B) on the green (closed symbol) and yellow side (open symbol), H5. (average of 24 fruit). Comparisons between yellow sides of limes stored under 5 (◇) and 13°C (Δ) were overlaid on each of their green sides of lime stored under 5 (♦) and 13°C (▲) (C).....	166
Figure 6.8 H° on the green side of H1 (A & B) or H5 (C) lime and predicted H° (dashed lines) of H1 lime stored under RA at 2 (♦) and 13°C (■) (A) or 5 (▲) and 13°C (■) (B) and H5 limes stored under RA at 5 (×) and 13°C (●) (C), fitted with the logistic model, Eq. 6.1.	167
Figure 6.9 Arrhenius plots of H° of lime (♦) for three individual harvests stored at different storage temperatures; H1 at 2, 5 and 13°C (A), H2 at 5, 7, 9 and 13°C (B) and H3 at 5, 7, 15 and 20°C (C).	168
Figure 6.10 Arrhenius plots of H° of lime (♦) for the combined data sets stored at different storage temperatures from 2, 5, 7, 9, 13, 15 and 20°C (note data measured at 20°C is illustrated in a dotted circle) (A) and without 20°C (B).....	168
Figure 6.11 Mean CS (symbols) and predicted CS (solid line) of H1-H5 lime fruit stored under RA at different storage temperatures from 2 to 20°C, fitted with the logistic model, Eq. 6.3.	171
Figure 6.12 Digitised data of colour development of dark lemons stored at different temperatures at 2, 5, 8 and 14°C in Fig. 1 of Cohen and Schiffmann-Nadel (1978) by Techdig software and the data were fitted by the logistic model Eq. 6.1.	172
Figure 6.13 Arrhenius plots of CS of lime (♦) for five harvests stored at different storage temperatures; H1 at 2, 5 and 13°C, H2 at 5, 7, 9 and 13°C, H3 at 5, 7, 15 and 20°C, H4 at 5 and 7°C and H5 at 5 and 13°C compared to Arrhenius plot of digitised data of colour development of dark lemons (□) stored at different temperatures at 2, 5, 8 and 14°C in Fig. 1 of Cohen and Schiffmann-Nadel (1978).	172

Figure 6.14 Comparison of H° of stored lime experimental & calculated under RA at 5 and 15°C with stored lime under IW at 5°C for 12 days and 15°C for 2 days (A) and H° of stored lime experimental & calculated under RA at 7 and 20°C with stored lime under IW at 7°C for 12 days and 20°C for 2 days (B) (H3).	174
Figure 6.15 Comparison of CS of stored lime experimental & calculated under RA at 5 and 15°C with stored lime under IW at 5°C for 12 days and 15°C for 2 days (A) and CS of stored lime experimental & calculated under RA at 7 and 20°C with stored lime under IW at 7°C for 12 days and 20°C for 2 days (B) (H3).	175
Figure 6.16 Relationship between H° on the green side and chlorophyll $a+b$ of lime stored at 13°C (A) and pigments on lime peel changes of stored lime at 13°C at 2, 4 and 8 weeks of storage compared to H° of stored lime at 13°C for 2, 4 and 8 weeks of storage (B).	178
Figure 6.17 Relationship between CS and chlorophyll $a+b$ of lime stored at 13°C (A) and pigments on lime peel changes of stored lime at 13°C at 2, 4 and 8 weeks of storage compared to CS of stored lime at 13°C for 2, 4 and 8 weeks of storage (B).	179
Figure 6.18 Average ($n=24$) reflectance spectra (%) of limes stored under RA at 13°C for 0, 2, 4, 8, 10 and 12 weeks of storage on the green and yellow side.	181
Figure 6.19 Average ($n=24$) hue angle changes of limes stored under RA at 13°C for 0, 2, 4, 8, 10 and 12 weeks of storage on the green (\diamond) and yellow side (Δ) (A) and increase in % reflectance at 680 nm from 0, 2, 4, 8, 10 and 12 weeks of storage on the green (\diamond) and yellow side (Δ) (B).	182
Figure 6.20 Examples of most green A; ($H^\circ_s = 105^\circ$) and most yellow fruit B; ($H^\circ_s = 101^\circ$) used to examine changes in spectral reflectance during storage at 13°C, H5.	182
Figure 6.21 Average reflectance spectra (%) of limes stored under RA at 13°C for 0 day and 12 weeks of storage on the green and yellow side of fruit for the high H° value set (A) and the low H° value set (B).	183

- Figure 6.22 Difference of reflectance spectral data of lime stored under RA at 13°C for the “at harvest fruit” at T = 0 day (◇) and the “degreened fruit” at T = 12 weeks (□) stored at 13°C of the high H° value set (A) and the “at harvest fruit” at T = 0 day (○) and the “degreened fruit” at T = 12 weeks (Δ) stored at 13°C of the low H° value set of lime (B) NB: (Yellow at 0 day – Green at 0 day = “at harvest fruit” @ T=0) and (Yellow at 12 weeks – Green at 0 day = “degreened fruit” @ T=12 weeks). 184
- Figure 6.23 Difference of spectral reflectance data of “at harvest fruit” at T = 0 day of the high (◇) and low H° set (○) (A) and “degreened fruit” at 12 weeks stored at 13°C of the high (□) and low H° set (Δ) (B). 185
- Figure 6.24 A-D Range of pigments changing of different spectra from 0 day until 12 weeks of storage of average of five high H° limes on the green (A) and yellow side (B) and average of five lowest H° limes on the green (C) and yellow side (D). 186
- Figure 6.25 Average of reflectance index (R800/R680,G) (A) and (R800/R700,G) (B) plotted vs. average of chlorophyll *a* content of lime stored under RA at 13°C for 2 (◇), 4 (□) and 8 (Δ) weeks of storage. Reflectance index (R800/R680) plotted vs. weeks of storage of lime stored at 13°C (C). The index R800/R680 (G ◇) is plotted on the left scale for the green side of lime and the index R800/R680 (Y □) is plotted on the right scale for the yellow side of lime. Reflectance index (R800/R680) plotted vs. hue angle of lime stored under RA at 13°C for 0, 2, 4, 8, 10 and 12 weeks of storage on the green (◇) and yellow side (□) (D). 189
- Figure 6.26 Average of reflectance index (R800/R520,G) (A) plotted vs. average of carotenoid content of lime stored under RA at 13°C for 2 (◇), 4 (□) and 8 (Δ) weeks of storage. Reflectance index (R800/R520) plotted vs. weeks of storage of lime stored at 13°C (B). The index R800/R520 (G ◇) is plotted on the left scale for the green side of lime and the index R800/R520 (Y □) is plotted on the right scale for the yellow side of lime. Reflectance index (R800/R520) plotted vs. hue angle of lime stored under RA at 13°C for 0, 2, 4, 8, 10 and 12 weeks of storage on the green (◇) and yellow side (□) (C). 191

Figure 6.27 Reflectance indices (R800/R680) (A) and (R800/R520) (B) plotted vs. hue angle of lime stored under RA at 13°C on the green (◇) and yellow side (◆), IW condition (5°C, 12 days and 15°C, 2 days) for 6 cycles plus C ₂ H ₄ absorbent, on the green (□) and yellow side (■) and HWD treatment by dipped the fruit at 47°C for 4 min then stored at 5°C, on the green (Δ) and yellow side (▲).	192
Figure 6.28 Difference of average reflectance spectra (%) at 12 week and 0 weeks of storage of limes stored under RA at 13°C (RA) (◇), IW condition (5°C, 12 days and 15°C, 2 days) for 6 cycles plus C ₂ H ₄ absorbent or IW fruit (IW) (□) and HWD treatment by dipped the fruit at 47°C for 4 min then stored at 5°C (Δ), on the green (A) and yellow side (B).	193
Figure 7.1 Retention of vitamin C in H3 fruit stored under RA at 5, 7, 15 and 20°C (A), IW conditions (5°C, 12 days and 15°C, 2days with and without fungicide; 7°C, 12days and 20°C, 2 days; 7°C, 3.5 weeks and 20°C, 3 days) (B) and HWD conditions (C) at 0, 4, 8 and 12 weeks of storage, respectively (LSD _{0.05} = 2.988, n=2).	201
Figure 7.2 Three standard chromatograms of 22 flavonoid peaks in a lime juice sample showing the characteristic patterns of elution observed at (A) 280 nm, (B) 313 nm and (C) 350 nm.	202
Figure 7.3 PCA of changes in composition of flavonoids after storage for 0 days to 3 months for limes stored under RA at 2, 5 and 13°C (with and without GA), limes stored under high CO ₂ (3% CO ₂ and 10% O ₂) at 2, 5 and 13°C, limes stored under low O ₂ (0% CO ₂ and 10% O ₂) at 2 and 13°C, and limes stored under IW condition (2°C, 3 weeks and 13°C, 1 week), H1.	204
Figure 7.4 Association between PC1 values and weighted sum of CI scores for lime fruit, H1.	206
Figure 7.5 Latent vector analysis of changes in flavonoid composition of 20 separate compounds, H1.	207
Figure 7.6 Characteristic changes in peak height for selected lime flavonoids in fruit stored under RA at 2 or 13°C, or IW at 2°C for 3 weeks and 13°C for 1 week: peak 7 (Apigenin-6,8-di-C-glucoside) (A), peak 9 (Eriodictyol-7-O-rutinoside) (B), peak 10 (Quercetin-3-O-rutinoside) (C) and peak 13 (Naringenin-7-O-rutinoside) (D), H1.	209

Figure 7.7 Characteristic changes in peak height for selected lime flavonoids in fruit stored under RA at 7 or 20°C, or IW at 7°C, 12 days and 20°C, 2 days: peak 7 (Apigenin-6,8-di-C-glucoside) (A), peak 9 (Eriodictyol-7-O-rutinoside) (B), peak 10 (Quercetin-3-O-rutinoside) (C) and peak 13 (Naringenin-7-O-rutinoside) (D), H3.....	210
Figure 7.8 Characteristic behaviour of Hesperetin-7-O-rutinoside (peak 16) in H1 limes stored under RA at 2, 5 and 13°C (with and without GA ₃). IW condition at 2°C, 3 weeks and 13°C, 1 week (A), or CA (0 or 3% CO ₂ with 10% O ₂) at 2, 5 and 13°C (B), and H3 limes stored under RA at 5, 7, 15 and 20°C (C), or IW conditions (5°C, 12 days and 15°C, 2 days with and without fungicide), (7°C, 12 days and 20°C, 2 days or 7°C, 3.5 weeks and 20°C, 3 days) (D).	211
Figure A1 Weight loss (%) for NZ limes stored under RA at 5°C and IW conditions (5°C for 3 weeks and 13°C for 1 week or 7°C for 3.5 weeks and 20°C for 3 days, H2. (A), weight loss (%) for NZ limes stored under RA at 5°C and IW conditions (5°C for 12 days and 15°C for 2 days or 7°C for 12 days and 20°C for 2 days and 7°C for 3.5 weeks and 20°C for 3 days, H3.(B)	255
Figure A2 Incidence of pitting after 2(A), 4(B), 8(C) and 10 (D) weeks of storage of lime stored under RA at 5°C or pre-treated limes with different HWD conditions (47°C or 52°C for 2, 4 or 6 min, respectively) with fungicide or pre-treated limes with HWD at 42°C for 2 min, 47 and 52°C for 4 min without fungicide and 57°C for 6 min with fungicide then all treatments were stored under RA at 5°C, H5 (severity: white bar = 1, cross-hatched = 2, grey = 3, black = 4). n.d. = no data.....	257
Figure A3 Incidence of heat injury after 2(A), 4(B), 8(C) and 10 (D) weeks of storage of lime stored under RA at 5°C or pre-treated limes with different HWD conditions (47°C or 52°C for 2, 4 or 6 min, respectively) with fungicide or pre-treated limes with HWD at 42°C for 2 min, 47 and 52°C for 4 min without fungicide and 57°C for 6 min with fungicide then all treatments were stored under RA at 5°C, H5.....	258

List of Tables

Table 2.1 Chemical composition in <i>Citrus</i> species.....	10
Table 2.2 Flavonoid compounds in <i>Citrus</i> species	15
Table 3.1 Orchard locations and fruit sizes for each harvest.....	43
Table 3.2 Summary of treatments used for each harvest.	44
Table 3.3 The summary of equations for correlating $H^{\circ}_{\text{Spectrophotometer}}$ (H°_{S}) and $H^{\circ}_{\text{Chromameter}}$ (H°_{C}).	57
Table 3.4 Solvent-gradient table for flavonoids analysis.....	64
Table 3.5 Solvent-gradient table for ascorbic acid analysis.	65
Table 4.1 The air storage temperatures tested for five harvests of limes between 2004 -2006.....	69
Table 4.2 Time to reach the limit of acceptable hue for fruit stored at 13°C, 15°C and 20°C (All H° data are expressed as H°_{S} values, applying Eq. 3.1 as required).....	74
Table 4.3 Comparisons of H° data from Kluge <i>et al.</i> , 2003b and H° data (in H°_{S}) from H1 and H4 at 8 weeks of storage plus 3 days shelf life at 20°C and H3* at 8 weeks of storage (no shelf life).	74
Table 4.4 The temperatures ranges and CA conditions for H1 and H2 used during the year 2004.....	91
Table 5.1 Application of the criteria of lime acceptability.....	140
Table 6.1 The coefficients (k value) of the combined data sets of H1 limes stored at 2, 5 and 13°C, respectively.....	164
Table 7.1 Retention times and maximum wavelength for 22 peaks based on data from all days of flavonoid analysis.....	203
Table A.1 Ranking of H° of the 24 green fruit at initial day 0 compared with the final H° of the same fruit at 12 weeks of storage.....	259
Table A.2 Absorbance maxima and mass spectral data (negative mode) of lime juice flavonoids.....	261

Abbreviations

a*	CIE Lab ‘a’ value measured by a colorimeter
ABA	abscisic acid
ACC	1-aminocyclopropane carboxylic acid
ANOVA	analysis of variance
APX	ascorbate peroxidase
b*	CIE Lab ‘b’ value measured by a colorimeter
°C	degrees Celsius
CAT	catalase
cm	centimetre
C ₂ H ₄	ethylene
C ₂₀ H ₃₉	phytol
C*	chroma
CA	controlled atmosphere
C _a	chlorophyll <i>a</i>
C _b	chlorophyll <i>b</i>
C _{x+c}	carotenoids
CF	compression firmness
d	day
PFR	Plant and Food Research
CI	chilling injury
CO ₂	carbon dioxide
CS	colour score
DNA	deoxyribonucleic acid
DSM	diosmin
<i>e</i>	exponential
E _a	activation energy
EB	extraction buffer
Eq.	equation
ERC	eriocitrin
°F	degrees Fahrenheit

FC	fluorescent compound
FW	fresh weight
GA ₃	gibberellic acid
GAs	gibberellins
GC	gas chromatography
GR	glutathione reductase
hr	hour
H°	hue angle
H° _C	H° _{CR200} (hue angle measured by chromameter CR200)
H° _S	H° _{Spectrophotometer} (hue angle measured by spectrophotometer CM-2600d)
$H^{-\infty}$	maximum hue
$H^{+\infty}$	minimum hue
H1	Harvest 1
H2	Harvest 2
H3	Harvest 3
H4	Harvest 4
H5	Harvest 5
HI	heat injury
HPLC	high performance liquid chromatography
HSP	hesperidin
HWD	hot water dipping
HWRB	hot water rinsing and brushing
IRF	isorhoifolin
IW	intermittent warming
J	Joule
K	degrees Kelvin
k	reaction rate constant
k_0	preexponential Arrhenius constant (time ⁻¹)
kD	kiloDaltons
kg	kilogram
kJ	kiloJoule
KOAc	potassium acetate
L*	Lightness measured by a colorimeter

l	litre
LCMS	liquid chromatography mass spectrometry
LSD	least significant difference
MA	modified atmosphere
MAV	measurement area value
MeOH	methanol
MET	methionine
Mg ²⁺	magnesium ion
mm	millimetre
min	minute
mol	mole
µg	microgram
mg	milligram
µl	microlitre
ml	millilitre
n.d.	no data
nl	nanolitre
nm	nanometre
NPO	neoponcirin
NRG	naringin
NRT	narirutin
O ₂	oxygen
PAs	polyamines
PCA	principal components analysis
PC1	principal component 1
PC2	principal component 2
PGRs	plant growth regulators
ppm	parts per million
Put	putrescine
R	the universal gas constant
R ²	R-squared value
R800	reflectance at 800 nm
R700	reflectance at 700 nm

R680	reflectance at 680 nm
R520	reflectance at 520 nm
R480	reflectance at 480 nm
RA	regular air
RH	relative humidity
RNA	ribonucleic acid
ROS	reactive oxygen species
RP	rusty pigment
RTN	rutin
rpm	revolutions per minute
s	second
SAM	S-adenosylmethionine
SAM dec.	S-adenosylmethionine decarboxylase
SCE	spectral component excluded
SCI	spectral component included
SE	standard error
SOD	superoxide dismutase
Spd	spermidine
Spm	spermine
SSC	soluble solids content or Brix°
t	time
t_0	reference time at day 0
t_{ref}	reference time (d)
T	temperature (Kelvin)
TA	titratable acidity
TBZ	thiabendazole
TC	temperature conditioning
UV	ultra violet light