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**THE DESIGN OF MODIFIED ATMOSPHERE
PERFORATED PLASTIC PACKAGING
FOR FRESH CHILLIES**

A thesis presented in partial fulfilment of the requirements for the degree of

Master of Technology in Packaging Technology

at Massey University, Palmerston North
New Zealand.

Weerawate Utto

2001

Errata

p. xxiii and p. 39:

Density, $\rho = \text{g cm}^{-3}$ not g cm^{-1}

p. 10:

673 kcal mol⁻¹ glucose not “kcal”

p. 41:

psychrometric, not psychometric

p. 54: Figure 4-2, vertical axis

Permeance: $\text{pmol.s}^{-1}.\text{m}^{-2}.\text{Pa}^{-1}$ not $\text{pmol.s}^{-1}.\text{m}^{-1}.\text{Pa}^{-1}$

p. 66: Figure 4-9 Legend:

“wet bulb temperature” not “skin temperature”

p. 73 and p. 138:

Analysis of variance tables do not have all the significant effects asterisk; the text is correct but the tables are not.

P. 103:

The diagram labels from k – o are wrong, they should be:

k) Evaporation of water vapour from the product to the air

l) Water vapour transport through packaging material by effective diffusion

m) Water vapour transport through the holes by diffusion, capillary action or both

n) Absorption or desorption of water vapour by the packaging material

o) Carbon loss from respiration.



“... to see what everyone has seen and think what no one has thought”

Albert Szent-Györgyi

(1893-1986)

ABSTRACT

The quality of fresh chillies changes rapidly and under the Thai ambient conditions (30 ± 5 °C and 75 ± 5 % RH), these products spoil in a short time frame. This rapid quality deterioration causes a direct loss in returns to growers and marketers. The objectives of this study were to design a modified atmosphere perforated plastic packaging system to extend shelf life and marketability of fresh chillies.

Physiological data about fresh green 'Cayenne' chillies was measured; respiration rate, internal partial pressure of O₂ ($p_{O_2}^i$) and CO₂ ($p_{CO_2}^i$), skin permeance to O₂ ($P_{O_2}^i$), CO₂ ($P_{CO_2}^i$) and water vapour ($P_{H_2O}^i$) as well as, water activity (a_w). The extent to which these attributes were affected by a range of temperatures 5, 10, 20 and 30°C was also characterised. Respiration dramatically increased as storage temperature was increased from 5 to 30°C, whilst $P_{O_2}^i$ and $P_{CO_2}^i$ slightly increased. The differing effects of temperature on these two variables were responsible for the depression of internal partial pressure of O₂ and elevation of CO₂ internal partial pressure.

The skin permeances to O₂ and CO₂ were very close (approximate ratio $P_{CO_2}^i : P_{O_2}^i$ as 1.06) and it was determined that the major pathway for gas exchange of green 'Cayenne' chillies was dominated by movement through pores (through the stem area), rather than the cuticle. Average value of skin permeance to water vapour of green 'Cayenne' chillies was $201.78 \text{ nmol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot\text{Pa}^{-1}$. Water vapour permeances were inconsistent over the 5-30°C temperature range due to errors from thermistor probes and environment around chillies. Surface area of green 'Cayenne' chillies provided the positive relationship with fresh weight, volume and the rate of water loss (measured at ambient temperature $\approx 20^\circ\text{C}$). Fresh weight and a_w of fresh chillies decreased as the storage temperature increased from 5 to 30°C.

Storage temperatures (5, 10, 20 and 30°C) and packaging types (perforated/nonperforated plastic bags and unpackaging) had significant impact on storage qualities (colour, firmness, weight and decay) of fresh green 'Cayenne' chillies

during a 2-week storage trial period. Refrigerated storage temperatures and perforated plastic bag showed promise in reducing quality attributes changes and eliminating condensation. At 5 and 10°C, no signs of chilling injury were detected on green 'Cayenne' in any packaging type used during the trial period. The atmospheres inside perforated plastic bag were similar to ambient air condition, thus ensuring that there were aerobic conditions inside.

The rate of weight loss of packaged chillies varied with storage temperature, perforation area and size of perforation. The optimum storage condition and package for a 100g retail pack of chillies during a 2-week storage period is 5°C and 152.40 × 228.60 mm plastic bag with 0.49% perforation area (2.5 mm perforation size). Chillies stored under this condition had low percentage of weight loss (less than 2.5%) with no signs of chilling injury and their quality attributes were within the marketable levels.

Bell peppers (*Capsicum annuum* L.) were used to study effects of postharvest disinfecting treatments (sodium hypochlorite (NaClO, 2%w/v) and hot water dip (HWD, 53°C 4 minutes)) on storage quality. Both disinfectants significantly reduced decay appearances on bell peppers particularly on those stored at high temperature (20 and 30°C), during a trial 2-week storage period. The application of these disinfecting treatments will be further researched on fresh chillies, for minimising decay appearance.

The 'Weight Loss Simulator' model developed by Tanner (1998) was tested by comparing predicted weight loss with experimental data. The model had general agreement with the experimentally observed trends. Lack of fit of model predictions to experimental data however, was obvious in some cases. Variations, e.g. storage temperature/relative humidity, packaging and dynamic changes in biological properties of stored chillies can deviate the predicting result of this model. Sensitivity analyses performed on the model showed that the observed lack of fit could largely be explained by estimated uncertainties in the respiration rate data. From this model testing, the accuracy of the 'Weight Loss Simulator' model appeared to be limited by assumptions, input data and uncertainties occurred during data collection rather than by shortcomings in the model itself.

ACKNOWLEDGEMENTS

I wish to express my appreciation to the following persons whose help and co-operation made this research possible.

Mr. Tom Robertson, Senior Lecturer, my supervisor, for his academic comments, support and encouragement, throughout my study and friendliness to me. Thanks also for introducing to Fresh Technologies, Institute of Food, Nutrition and Human Health, Massey University.

Dr. David Tanner, Director of Fresh Technologies and my supervisor, for his professional attitude, expertise and experience as well as friendliness and frankness to me.

Mr. John Wakenshaw and VSR Packaging Ltd., Te Atatu, Auckland, New Zealand for financial and experimental materials for this project as well as encouragement and friendliness.

My professional human and knowledge resources, named Fresh Technologies, Institute of Food, Nutrition and Human Health, Massey University. You guys are my lecturers and friends simultaneously:

Dr. Kate Maguire for her guidance and expertise in physiological properties of fresh produce, statistics and experimental designs, and professional skill in the laboratory, also thanks for your time for discussing, checking and shaping the physiological part of my thesis.

Maarten Hertog for his professional attitude, skill and guidance in physiological knowledge, statistic and simulation programme and laboratory. Also thanks for your time for discussing, checking and correcting my chapter on physiological properties of fresh chillies.

Sue Nicholson for her professional skills in lab guidance, advice and discussion, particularly on aspects of bell pepper as well as lending the humidifier during the experiment. Peter Jeffery for your computer expertise when I had problems with my computers, you usually came up with cool suggestions. Dr. Henry Sabarez for your professional thinking and advice on mass transfer. Melanie Sergent for her help in my project's financial details and administration as well as your friendliness. Andrew Nevins for his help in Origin graphical programme and the great time for discussions in several aspects. Nick Smale for introducing me to the golf tournament of Fresh Technologies group (the first time in my life on the green). Ringo Feng for several discussions and yummy kiwifruit.

Ms. Gabrielle Eustace for her concerns about my health and studying. She is my kiwi mom, one and only. Also, her family and other members of 7 Moerangi Street.

Members of Department of Agro-Industry, Faculty of Agriculture, Ubon Ratchathani University (Apinya, Jitra, Ekasit and Weera) for their great encouragement. Mr. Pitak Singthongla, a lecturer at Faculty of Agriculture, Ubon Ratchathani University, for initial idea in chilli postharvest problems and his suggestions.

Mrs. Arunee and Wisanu Srichantra for discussion, advises and parties throughout my study life.

My friends and their families (Jinghui, Shirlyn, Julie, Mark and Bair) in postgraduate room RC2.03, who always give me friendly and great time.

The NZODA study award scholarship for providing fund and chance to study at Massey University.

Finally, I would like to thank my 'Utto' family: my dad (Thongkum), my mom (Buppha), my great brother (Chakkrarith), my wonderful sister (Noppanporn), for their supports, mentally and physically, during long and lonely road.

Weerawate Utto

May, 2001

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LIST OF SYMBOLS AND ABBREVIATIONS

A	surface area of fruit	m ²
a _w	water activity	
C	constants in sorption isotherm	
CO ₂	carbon dioxide	
°C	celsius	
C*	chroma of fruit skin	
CA	controlled atmosphere	
cal	calories	
CI	chilling injury	
D	dried look in visual quality	
DM	dry matter	%
Ea	energy of activation	J·mol ⁻¹
$Ea_{r_{CO_2}^{max}}$	the energy of activation of $r_{CO_2,ref}^{max}$	J·mol ⁻¹
Ea_i'	the energy of activation of skin permeance to gas i	J·mol ⁻¹
ERH	equilibrium relative humidity	%
F	fresh look in visual quality	
g	gram	
GLM	general linear model	
h°	hue angle of fruit skin	
H ₂ O	water	
HDPE	high density polyethylene	
HWD	hot water dip	
K	constant in sorption isotherm	
K	kelvin	
K _i	parameter used for the respiration model proposed by (Lee <i>et al.</i> 1994)	%(CO ₂)

K_m	parameter used for the respiration model proposed by (Lee <i>et al.</i> 1994)	$\%(\text{O}_2)$
k_{ref}	rate at T_{ref}	
K_{pkg}	mass transfer coefficient of packaging	$\text{kg}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot\text{Pa}^{-1}$
K_{skin}	mass transfer coefficient of fruit skin	$\text{kg}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot\text{Pa}^{-1}$
l	litre	
L^*	brightness of fruit skin	
LDPE	low density polyethylene	
LLDPE	linear low density polyethylene	
LLDPE/LDPE	linear low density polyethylene blended with low density polyethylene	
M	fruit mass	kg
m	metre	
min	minute	
MA	modified atmosphere	
MAP	modified atmosphere packaging	
MDPE	medium density polyethylene	
MC	moisture content (dry basis)	
M_t	mass at determined time-t (fresh weight)	
M_0	mass at starting time-0 (wet basis)	
M_o	monolayer moisture content (dry basis)	
mol	mole	
N	no condensation in visual quality	
N/A	not available	
NaClO	sodium hypochlorite	
n	number of observations	
O_2	oxygen	

Pa	pascal	
PP	polypropylene	
$P_{\text{CO}_2}^{\text{final}}$	CO ₂ in jar at the end of time t	%
$P_{\text{CO}_2}^{\text{initial}}$	initial CO ₂ in jar	%
P^{tot}	air pressure	Pa
$P'_{\text{H}_2\text{O}}$	water permeance of fruit surface	$\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot\text{Pa}^{-1}$
P_j^{fruit}	skin permeance to gas j	$\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot\text{Pa}^{-1}$
P'_{CO_2}	skin permeance to CO ₂	$\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot\text{Pa}^{-1}$
P'_{O_2}	skin permeance to O ₂	$\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot\text{Pa}^{-1}$
$P'_{i,\text{ref}}$	skin permeance to gas i , (O ₂ and CO ₂), at T_{ref}	$\text{pmol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot\text{Pa}^{-1}$
$P'_{\text{CO}_2,\text{ref}}$	skin permeance to CO ₂ at T_{ref}	$\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot\text{Pa}^{-1}$
$P'_{\text{O}_2,\text{ref}}$	skin permeance to O ₂ at T_{ref}	$\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot\text{Pa}^{-1}$
$P_{\text{H}_2\text{O}}^{\text{sat}}(T_f)$	saturated partial pressure of water vapour at T_f	Pa
$P_{\text{H}_2\text{O}}^{\text{sat}}(T_w)$	saturated partial pressure of water vapour at T_w	Pa
p_j^i	internal partial pressure of gas j	Pa
p_j^e	external partial pressure of gas j	Pa
$p_{\text{H}_2\text{O}}^f$	partial pressure of water vapour in fruit	Pa
$p_{\text{H}_2\text{O}}^e$	partial pressure of water vapour in air	Pa
$\Delta p_{\text{H}_2\text{O}}$	difference in partial pressure of water vapour between fruit and environment	Pa
Δp_j	partial pressure difference for diffusion of gas j	Pa
ρ_{fruit}	density of the fruit	$\text{g}\cdot\text{cm}^{-3}$
R	rotted appearance in visual quality	

R	gas constant (8.314)	$\text{m}^3 \cdot \text{Pa} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$
R^2	percentage variance accounted for	%
RC	resistance coefficient to water vapour transmission of perforated plastic films	
RH	relative humidity	%
r_{CO_2}	respiration rates	$\text{mol} \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$
$r_{\text{CO}_2, \text{ref}}^{\text{max}}$	the maximum CO_2 production rate at T_{ref}	$\text{mol} \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$
$r'_{\text{H}_2\text{O}}$	rate of water loss from product	$\text{mol} \cdot \text{s}^{-1}$
r_j	rate of transfer of gas j	$\text{mol} \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$
γ	psychometric constant (equals 67 $\text{Pa} \cdot ^\circ\text{C}^{-1}$)	$\text{Pa} \cdot ^\circ\text{C}^{-1}$
S	shrivelled or soft appearance in visual quality	
s	seconds	
SE	standard errors	
SED	standard error of the difference	s
t_0	time at beginning of the fruit of the first conditions	s
t_1	time at end of the fruit of the first conditions	s
T_e	temperature of air (dry bulb temperature)	$^\circ\text{C}$
T_f	temperature at fruit skin	$^\circ\text{C}$
THA	a type of perforation manually punctured, using cork bore with 5 mm diameter bore, to make 6 holes	
T_{ref}	reference temperature (288.15 K, (15°C))	$^\circ\text{C}$
T_w	dew point temperature (wet bulb temperature)	$^\circ\text{C}$

t	time for the reading	s
UNT	bell peppers untreated with postharvest disinfecting	
V_{jar}	volume of jar	ml
V_m	parameter used for the respiration model proposed by (Lee <i>et al.</i> 1994)	$\text{ml}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$
w/v	weight per volume	
Y	presence of condensation in visual quality	

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW OF THAILAND'S EXPORTED FRESH FRUIT AND VEGETABLES

In 2000, the amount and value of Thailand's exported fruit were 225,000 tons and 4,735 million bahts (1 \$NZ approximately equals 20 bahts). The amount of fresh vegetables exported and value were about 65,000 tons and 12,400 million bahts, respectively (Anon, 2000c; Anon, 2000d). The main fresh fruits and vegetables exported are available in Table 1-1 and Table 1-2.

Thailand also imported fresh fruits and vegetables, however, in small amounts and quantities. In 1999, the importing amounts and values of fruits were estimated to be 1,246 tons and 56,287,000 bahts, respectively, while for vegetables were 1,516 tons and 46,268,000 bahts, respectively (Anon, 2000a).

China, Hong Kong, Singapore, Japan, and Taiwan are the major buyers of fresh products, while the United States and Western Europe prefer frozen products (Anon, 1998b; Anon, 2000b). Taiwan is Thailand's principal competitor in the world's market for horticultural products and in the Japanese export market in particular (Hans, 1994; Anon, 2000b).

Table 1-1 Main exporting fresh vegetables of Thailand (Anon, 2000c; Anon, 2000e).

Vegetables		
Asparagus	Baby corn	Chillies
Egg plant	Ginger	Hot pepper
Lime	Long green bean	Okra
Onion	Pepper	Red Onion

Table 1-2 Main exporting fresh fruits of Thailand (Anon, 2000c; Anon, 2000e).

Fruits			
Banana	Durian	Honeydew	Jackfruit
Lychee	Longan	Mango	Mangosteen
Papaya	Pineapple	Pomelo	Rambutan
Spodilla	Strawberry	Young coconut	

1.2 POSTHARVEST LOSS OF FRESH FRUITS AND VEGETABLES IN THAILAND

Postharvest losses, e.g. water loss, mechanical damage and microbial deterioration, in Thailand is still high both in term of quality and quantity (Siripanich, 1999). The approximated percentage of postharvest losses of fresh fruits and vegetables through the marketing chain in Thailand might be up to 40% (Thompson, 1996). Inadequate packaging, a lack of cool storage and refrigerated transportation, non-existing legal standards as well as no regular inspection are identified as critical problems, which influence postharvest losses to horticultural produce in Thailand (Wivutvongvana *et al.*, 1987; Ketsa and Klaewkasetkorn, 1992; Anon, 1998b). According to such problems, Thai exporters strongly require the research and practices for upgrading packaging and preservation standard (Anon, 1998b).

1.3 POSTHARVEST LOSS OF FRESH CHILLIES IN THAILAND

Chilli is one of the most important vegetables economically in Thailand. According to the National Economic and Social Development Plan No.6 (1987-1991), chillies were proposed as a growth industry in the agricultural development plan for production, marketing, exporting and agro-industry (Anon, 1991). The varieties of chilli for production in Thailand are diverse across regions; however, the northeastern part of Thailand is the largest chilli producer (Nualplub, 1998).

Singthongla (1999, pers.com.) mentioned that fresh chillies are generally packaged 10-kg plastic bags. These are distributed to markets (Figure 1-1) under ambient conditions (30 ± 5 °C and 75 ± 5 % RH, Sornsrivichai *et al.* (1992) and Apivathananukul *et al.* (1996)). The largest market in Thailand is Bangkok, which is also the major export centre. The main trading partners for chilli are Taiwan, Malaysia and the Middle East

(Anon. 1998a). The selling price of fresh chillies is approximately 7-8 bahts/kg (\$NZ 0.35-0.40; \$NZ 1 equals 20 bahts). Exporting fresh chillies and peppers provided approximately 419.5 million bahts in 1998 (Anon., 1999).

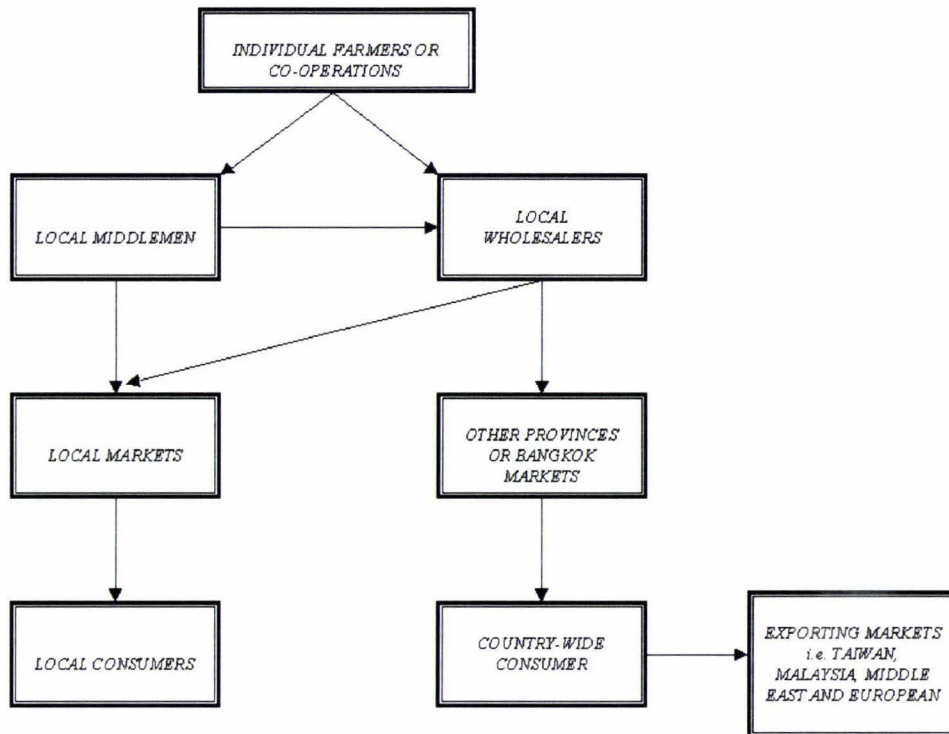


Figure 1-1 Marketing channels of fresh chillies in Thailand (Developed from Tepsomboon (1997) and Anon. (1998a))

As fresh chillies move through the marketing system, they quickly change weight and appearance e.g. colour and firmness. Postharvest losses of fresh chillies can be up to 30% (Anon., 1998a; Singthongla, 1999, pers.com). The study of Utto (2000) found that the high levels of condensation inside the plastic bag were acknowledged as the reason for the undesirable appearance of the packaged chillies. This condensation was blamed for hastening the physiological changes and reducing the shelf life of the fresh chillies, which in turn lowered the saleability of fresh chillies. To prevent condensation, most of plastic bags were perforated, in order to increase ventilation of the package.

A systematic approach to optimise postharvest water loss and storage quality of pepper by using perforated plastic film was developed by Lownds *et al.* (1994). As a result,

water-loss and colour change rates were reduced by 20 times or more among peppers in perforated polyethylene packages at 14 to 20°C. The application of perforated packaging for extending the shelf life of fresh chillies can be also found in Hans (1994). Perforated plastic bags have been used with other products and could be further found in Emond *et al.* (1995) or Tanner (1998).

However, there is no previous research completed on development of a perforated package for fresh chillies in Thailand, nor is there any extension work underway in Thailand. Therefore, this research will be conducted in order to design the suitable perforation area for plastic packages, which extends the shelf life of fresh chillies under the Thai ambient conditions.

1.4 RESEARCH STRUCTURE AND OBJECTIVES OF THE THESIS

1.4.1 RESEARCH STRUCTURE

In chapter 2, a review of relevant literature is presented, covering three aspects: changes during ripening and senescence; modified atmosphere packaging and mathematical modelling. Chapter 3 presents the materials and methods using for data collection and analysis in this experiment.

Chapter 4 present the results and discussions for physiological properties of fresh chillies under different storage temperatures. Chapter 5 investigates the effects of storage temperature and packages on the qualities attributes of chillies, with the results of weight loss. These results are further used in Chapter 7 for mathematical model simulation and testing.

Chapter 6 and 7 study mathematical modelling of weight loss of fresh chillies. The conceptual models of weight loss characteristics regarding chilli packages are developed. Chapter 7 presents the weight loss model testing of fresh chillies. This model was developed by Tanner (1998). The validity and sensitivity of the model regarding the input data from the weight loss experiments are also presented.

Chapter 8 presents the results of experiments developed as a result of data presented in chapter 5. In this chapter the postharvest disinfections (both chemical and non-chemical) are introduced to improve the quality of fresh bell pepper, which were used instead of fresh chillies, due to the unavailability of chillies as a result of off-season of chillies.

Chapter 9 presents conclusions and recommendations, providing summary of the information presented in this thesis. The last chapter is appendix, which presents the nomenclature of 'chillies' generally confuses with 'chile' or 'chilli'; examples of commercial varieties of fresh chillies; traditional postharvest practices: packaging and handling, of fresh chillies in Thailand, computer based pictorial scales for evaluating chilling injury, decay and wrinkle level of bell peppers and movie-file of colour changing of fresh chillies.

The research to design the modified atmosphere perforated plastic bags for the fresh chillies was funded by VSR NZ. Ltd. (Te Atatu, Auckland) and the design of the final plastic bags should be considered confidential.

1.4.1.1 AIM AND OBJECTIVES OF THESIS

The aim of this project is to use the applications of modified atmosphere perforated plastic bags to design the appropriate packages for fresh chillies and to extend the shelf life of packaged chillies under the Thai ambient condition (30 ± 5 °C and $75\pm 5\%$ RH).

The main objectives are:

- To study postharvest physiological changes of fresh chillies under prevailing storage conditions.
- To study the effects of storage temperatures and modified atmosphere packages on storage shelf life of fresh chillies.
- To study and implement using the data from first two objectives and a generalised computer-based dynamic simulation system, developed by Tanner (1998) for development of optimum perforated plastic bags for fresh chilli.

CHAPTER 2

LITERATURE REVIEW

2.1 POSTHARVEST PHYSIOLOGY OF CHILLIES DURING STORAGE

2.1.1 INTRODUCTION

Chillies and other fresh fruits, vegetables and ornamentals are living tissues subject to continuous change after harvest. Postharvest physiology changes in fresh produce during storage, handling and entering marketing, chains cannot be stopped, but they can be slowed within certain limits (Kader, 1992). There are several biological processes, i.e. respiration or water loss that lead to reduction in quality attributes, i.e. appearance, texture or flavour. The rapid changes in these processes can rapidly lower the marketability of fresh produce (Kay, 1991). To reduce such rapid changes of fresh chillies, the postharvest physiological changes and the influences of environmental condition during storage must be understood.

2.1.2 POSTHARVEST QUALITY ATTRIBUTES

2.1.2.1 COLOUR CHANGES

Chilli is characteristically green when it is mature, but unripe, and turns brown, red, orange, or yellow upon ripening, depending upon the cultivar (Nagle and Burns, 1979). The change in colour of the pepper surface takes places as a result of chlorophyll degradation and a considerable increase in its carotenoid content, which is influenced by the temperature and illumination to which fruit is exposed (Gomez and Pardo, 1996). The rate of colour loss of pepper (from green to red) generally increased with increasing storage temperature, and decreasing relative humidity (RH) (Lownds *et al.*, 1994; Gomez and Pardo, 1996; Varon *et al.*, 2000).

2.1.2.2 FIRMNESS CHANGES

Firmness changes or softening is one of the most significant quality alterations. Alterations in texture affect both the edibility of the fruit and the length of time the fruit

may be held. The texture of fleshy fruits is affected by the composition of their cell walls, cellular constituents, levels of enzymatically degradative changes in cell wall and their degrees of hydration (Kay, 1991).

Firmness or the degree of dehydration of chillies is the primary indication of chilli freshness (Wall and Bosland, 1993). Chilli becomes more rapidly flaccid, when the temperature is increased (Lownds *et al.*, 1994). Rapid loss in firmness during fruit ripening or under high storage temperature is associated with an increase in enzymic activity as well as with depolymerisation of cell wall pectins (Gross and Sams, 1984). Turner (1997) stated that under low relative humidity storage, tissues are easily dry and this can lower the firmness of fruits.

Packaging peppers in polymeric films has been reported to retard the softening occurring to the fruit. Ben-Yehoshua *et al.* (1983), Lownds *et al.* (1994) and Gonzalez *et al.* (1999) also reported that flaccidity development of pepper appears to be directly associated with water loss from fruit. Thus, if the water loss of peppers could be reduced, in turn the loss of firmness would also be minimised.

2.1.2.3 POSTHARVEST PATHOLOGY

Extended storage of fresh chillies can be limited by progressive increase in decay (Mohammed *et al.*, 1991). Postharvest diseases are prolific at high temperatures (>14°C) and humidity (common inside low water permeability film). The most prevalent postharvest diseases on chillies are bacterial soft rot (*Erwinia carotovora*), black mould (*Alternaria alternata*), Fusarium rot (*Fusarium oxysporum*), gray mould (*Botrytis cinerea*), Rhizopus rot (*R. stolonifer*) and Cladosporium rot (*C. herbarum*) (Wall and Bosland, 1993).

In Thailand, apart from those diseases, anthracnose (*Collectotrichum* spp.), or 'Khoong-Haeng' disease (indigenous pronunciation, meaning 'dried shrimp') is the most prevalent disease. This kind of disease prefers high humidity and high storage temperatures, especially under sunny conditions, to survive. Anthracnose can rapidly devalue Thai fresh chillies (Tepsomboon, 1997; Nualplub, 1998).

Spore germination and infection on stored peppers, which ultimately cause decay, obviously needs to be controlled. As well as controlling storage temperature and relative humidity control, chemical solutions, e.g. chlorinated water or benomyl, and non-chemical treatments, e.g. hot water dipping or chitosan or antiscent subsatance (e.g. Ascorbic acid) have been successfully used for sanitising chillies and peppers in order to reduce undesirable postharvest decay (Mohammed *et al.*, 1992; Lurie, 1998; Gonzalez *et al.*, 1999; Nunes and Emond, 1999).

However, in Thailand, the use of postharvest disinfecting treatment on chillies for fresh sale has not been reported, though sodium hypochlorite solution has been used on chillies to be dried (Tepsomboon, 1997).

2.1.2.4 CHANGES IN CHEMICAL COMPOSITION

Carbohydrate, protein, fat, fibre, ash, gum and essential oils are the major components, which increase rapidly as chillies advance from the green stage to the ripe stage. Of nutritional importance is the vitamin C content of chillies (Rahman *et al.*, 1978; Govindarajan and Sathyanarayana, 1985; Hirasa and Takemasa, 1998). Raw fresh chillies are among the richest known plant source of Vitamin C. A chilli can contain six times as much Vitamin C as an orange (Wall and Bosland, 1993).

The mount of Vitamin C content declines with maturity (Efiuvwevwere and Oyelade, 1991). This is in contrast to the report of Rahman *et al.* (1978) that vitamin C content of several chilli cultivars (i.e. Large green, Pacific Bell, Long Red Cayenne, College Gold or Hungarian Yellow) significantly increased as the result of transition from the immature to the fully ripe condition. The differences in quantitative determinations of ascorbic acid could differ due to variations in factors such as fruit variety, agronomic and environmental conditions and stage of maturity. Vitamin C also decreases with increasing storage temperature. The effects of raised temperatures might be associated with the higher activity of oxidizing enzymes, especially phenolases, leading to quinone-induced oxidation of ascorbic acid (Montes, 1966; Mohammed *et al.*, 1992).

Pungency, caused by the presence of capsaicinoids, which is a fat soluble, odorless, colourless compound (Huffman *et al.*, 1990) is one of the major quality-determining

factors in chilli (*Capsicum* spp.) (Zewdie and Bosland, 2000). Stages of maturity have been reported to influence capsaicin contents (Huffman *et al.*, 1990). Nisar *et al.* (1987) reported that capsaicin contents increased when fruit reaches red colour stage. However Krajayklang *et al.* (2000) found that different colour stages of fresh chillies have no effects on pungency. These contrast results could be due to other factors such as variety, geographic location, growing and processing condition and location within fruits, which have been reported influence in capsaicin contents (Huffman *et al.*, 1990).

2.1.2.5 CHILLING INJURY (CI)

Low temperatures (e.g. 0-5°C) are generally chosen for storage and distribution of most fruits and vegetables. At such temperatures, many biochemical activities involving ripening and senescence and growth of spoilage are lowered, which could prolong the shelf life of fresh produce (Day, 1993). However, crops of tropical origin are generally subject to chilling injury. Chillies and peppers are highly susceptible to chilling injury at temperatures lower than 7°C (Hardenburg *et al.*, 1986; Wall and Bosland, 1993; JunSoo and DongSun, 1997).

At this temperature, the tissues become weaken because they are unable to carry on normal metabolic processes. Respiration rates and other physiological and biochemical processes increases in response to chilling injury. The symptoms of chilling injury are softening, pitting and predisposition to decay. Most fresh chillies can be stored for 2-3 weeks, without chilling injury if kept cool at 7-8°C (Hardenburg *et al.*, 1986; Wall and Bosland, 1993; JunSoo and DongSun, 1997).

Meanwhile some researchers report that there are no signs of chilling injury in capsicum stored at 5 or 10°C (Gorini *et al.*, 1976; Mencarelli *et al.*, 1989; Mercado *et al.*, 1995). The variability of chilli and pepper cultivars, packaging types and storage conditions (e.g. relative humidity) could cause the differences in susceptibility to chilling injury (Kader *et al.*, 1989; Kay, 1991). The determination of optimum low temperature storage regimes for fresh chillies is thus an important research problem in order to find the compromise between extending the shelf life and preventing chillies from getting chilling injury in chillies.

2.1.2.6 WEIGHT LOSS

Weight loss results from both transpiration and respiration. However, weight loss by respiration is generally small. Water loss is the main cause of weight loss (Ben-Yehoshua, 1987; Kay, 1991; Lownds *et al.*, 1993). However, when the relative humidity of storage condition is increased, the weight loss contributed from respiration may become significant (Butchbaker *et al.*, 1973).

Chilli fruits are highly susceptible to water loss (and weight loss). Postharvest water loss is generally rapid, particularly without refrigeration (Wall and Bosland, 1993). This can result in direct losses in quantitative weight loss, appearance (wilting and shrivelling), textural quality (softening, loss of crispness and juiciness) and nutritional quality (Kader *et al.*, 1989; Efiuvwevwere and Oyelade, 1991; Kader, 1992; Wall and Bosland, 1993; Wall and Berghage, 1996). As chillies are marketed on a weight basis (Wall and Berghage, 1996), small losses in weight can substantially reduce return to growers. Only 5-7% weight loss can result in chillies losing marketability, which in turn can reduce the selling price (Ben-Yehoshua 1987).

2.1.3 RESPIRATION

Respiration is the oxidative breakdown of the more complex substrates normally present in the cells, such as starch, sugars, and organic acids, to simpler molecules (CO_2 and H_2O), with the concurrent production of energy and other molecules, which can be used by the cell for synthetic reactions. Such metabolic reactions are essential for maintenance of cellular organisation and membrane integrity in living cells. About 42% of the total energy produced (673 kcal) is biologically useful energy, and the remainder is dissipated as heat (Kader, 1987).

Respiration rate thus is an excellent indicator of potential storage life of horticultural products (Ballantyne, 1989; Robertson, 1993). For a given fruit species, a high respiration rate indicates the rate at which the fruit is deteriorating in both quality and food value and is commonly associated with a short storage life (Cheng, 1999).

Respiration can occur either under aerobic or anaerobic conditions, depending on the availability of oxygen (Figure 2-1) (Blanke, 1991). Under low oxygen condition, anaerobic respiration (fermentation) is initiated. This is a less efficient respiration process, involving the conversion of respiratory substrates into acetaldehyde and CO₂, with 21 kcal as total energy produced. The substantial accumulation of acetaldehyde can lead to build up of ethanol, both of which are toxic to the plant cell and cause development of off-flavours (Kader, 1987; Lee *et al.*, 1995).

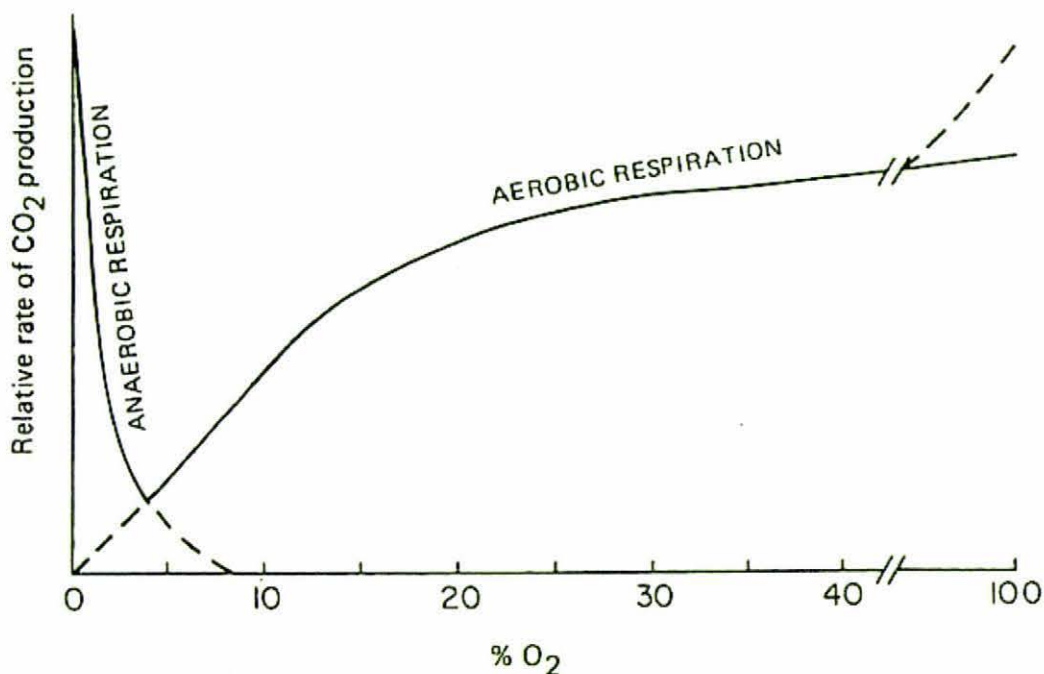


Figure 2-1 A schematic representation the effects of O₂ concentration on aerobic and anaerobic respiration rates of fresh vegetables (Kader, 1987).

2.1.3.1 PHYSIOLOGICAL STATE

Fruits are classified as 'climacteric' and 'non-climacteric' according to their respiratory and ethylene production profiles during maturation and ripening (Biale and Young, 1981; Cheng, 1999). Pepper is classified in the group of non-climacteric fruit with moderate respiratory intensity and low ethylene production rate (Kader, 1987; Kay, 1991; Krajayklang *et al.*, 2000). However the hot chilli cv. '*Choorahong*' (Gross *et al.*, 1986) and red bell pepper cv. '*Truhart Perfection*' (Batal and Granberry, 1982) have been

reported as exhibiting climacteric behaviour. There are no data in literature on climacteric characteristic of chilli varieties from Thailand.

2.1.3.2 FACTORS AFFECTING RESPIRATION

The postharvest respiratory responses of plant products can be strongly influenced by a number of commodity and environmental factors. Since elevated respiration rates are in many products closely correlated with shortened product life expectancy, proper management of the factors that affect respiration is imperative for maximising storage life (Kay, 1991).

2.1.3.2.1 EFFECTS OF TEMPERATURE ON RESPIRATION RATE

Rate of respiration is strongly temperature-dependent. As high rate of respiration can accelerate a commodity's natural process of ripening, maturity and senescence (Huffman *et al.*, 1990; Cheng, 1999), thus the increasing temperature, in its turn, can affect these processes (Kader, 1987; Kader *et al.*, 1989; Blanke, 1991; Cheng, 1999). Respiration rates of chillies or pepper fruit have been shown to be highly sensitive to temperature changes (Robinson *et al.*, 1975). Increasing temperature cause an exponential increase in respiration rate (Figure 2-2) (Kader *et al.*, 1989).

Many technologies for preserving fresh produce involve modifying respiration rate by lowering storage temperature. The benefits of lowering temperature management for reducing the respiration rate, in turn prolonging the shelf life, have been well documented in (Hayakawa *et al.*, 1975; Kader, 1987; Kay, 1991).

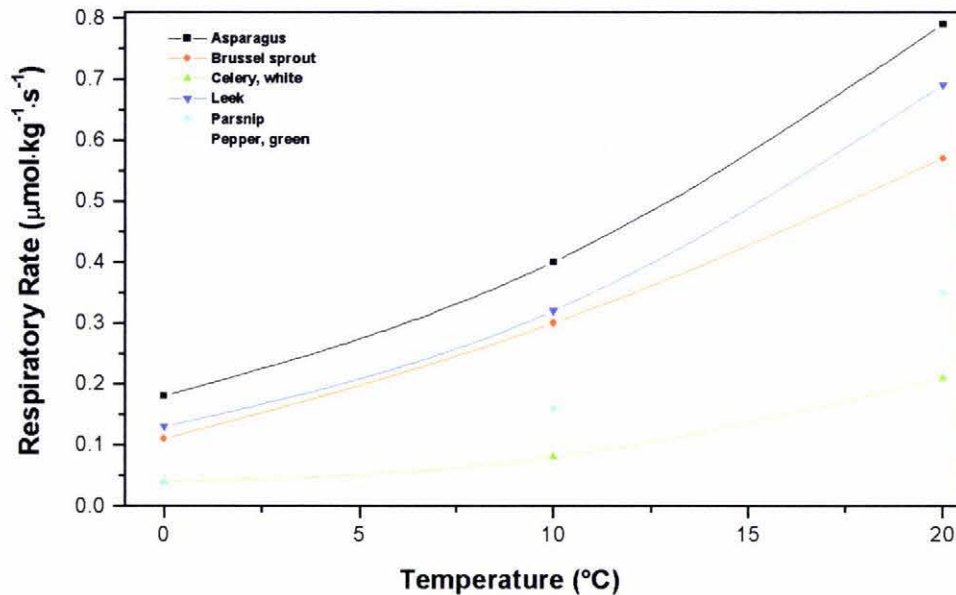


Figure 2-2 Effects of temperature on respiration rate of certain produce (adapted from Robinson *et al.* (1975)).

2.1.3.2.2 EFFECTS OF O₂ AND CO₂ ON RESPIRATION RATE

The composition of the gaseous atmosphere to which postharvest products are exposed can markedly influence both the respiration and metabolic rate of the commodity. Oxygen and carbon dioxide are the most important in influencing respiration (Kay 1991). Oxygen is closely tied to the rate of respiration of harvested products. As the internal concentration decreases, respiration decreases (Kader *et al.*, 1989). Robinson *et al.* (1975) reported that respiration rate of chillies and pepper fruit lowered by up to 40% under 3% oxygen condition. The respiratory rate of most stored products can be decreased by lowering the oxygen concentration to a concentration that is not below the lower oxygen limit (*LOLs*). Below the *LOLs*, anaerobic respiration occurs (Yearsley *et al.*, 1996). More details of *LOLs* on respiration rate will be discussed later.

Elevation of the ambient concentration of CO₂ can impede respiration rate. The degree to which respiration rate is retarded is related to the concentration of CO₂ in the atmosphere (Kay, 1991). However the CO₂ level should not be too high to induce

abnormal metabolism and cause disorders (Kader *et al.*, 1989). Hulme (1956) reported that high concentration of carbon dioxide (e.g. 15%) have been shown to result in toxic levels of succinate accumulating in apples, causing damage to tissues.

The minimum O₂ and the maximum CO₂ level tolerated (%) of stored fresh produce are varied among commodities. These levels for fresh chillies and peppers are 3%O₂ and 2-5%CO₂ (Kader *et al.*, 1989). Applications of low O₂ and high CO₂ of storage environment for reducing the respiration rate and extending shelf life of stored produce have been known as modified atmosphere storage (Robertson, 1993; Merts, 1996).

2.1.3.2.3 LOWER OXYGEN LIMITS (*LOLS*)

As the level of O₂ partial pressure is reduced there is a depression in the rate of respiration until the lower oxygen limits is reached (Figure 2-1) (Yearsley *et al.*, 1996). Lower oxygen limits can be expressed on the basis of gas internal partial pressure (internal *LOLS* or *LOLⁱ* s, Pa) or gas external partial pressure, e.g. in-package gases, (external *LOLS* or *LOL^e* s, Pa) (Yearsley *et al.*, 1997a; Yearsley *et al.*, 1997b). It is generally accepted that the optimal storage atmosphere for a given temperature is at an O₂ partial pressure above *LOLS*, in which below the *LOLS*, fermentation is initiated (Banks *et al.*, 1993).

As storage temperature increases, rate of O₂ uptake of stored product then increases. Consequently, partial pressure of O₂ in both products' internal ($p_{O_2}^i$, Pa) and external ($p_{O_2}^e$, Pa) atmosphere decrease, whilst those of CO₂ ($p_{CO_2}^i$ and $p_{CO_2}^e$, Pa) increase due to increasing respiration rate. Exposure to elevated temperatures can result in O₂ levels falling below the *LOLS*, at which fermentation is initiated and can result in rapid loss of stored product qualities i.e. off-flavour or softening (Yearsley *et al.*, 1996; Yearsley *et al.*, 1997b).

Approaches for determining *LOLS* and factors affecting *LOLS* of certain fruits e.g. apple and blueberry have been well documented and could be further found in (Beaudry and Gran, 1993; Yearsley *et al.*, 1996; Yearsley *et al.*, 1997b). However, lower oxygen limits (*LOLS*) of chillies or pepper fruit have not been reported.

2.1.3.2.4 OTHER FACTORS

There are still a numbers of both internal and external factors, which can affect the rate of respiration. These factors are, for examples, type of commodity and genotype, maturity stage at harvest, plant organ, stress during handling and storage (i.e. mechanical damage or dehydration) or stress from microbiological damage. The details on effects of such factors on respiration of fresh produce can be further found in Hardenburg *et al.* (1986), Kader (1987), Kay (1991) and Salisbury and Ross (1992).

2.1.4 GAS EXCHANGE

The O₂ required for respiration and the CO₂ produced, move to and from the fruit by a process of diffusion. Diffusion is a spontaneous process leading to the net movement of a material from one region to an adjacent one, from high concentration to low concentration (Kay, 1991).

The rate of gas diffusion depends on the properties of the gas molecules, the magnitude of the gradient (between fruit and environment), the physical properties of the intervening barriers such as the skin of the fruit and the temperature of immediate environment. The presence of barriers such as the fruit skin and the consumption of O₂ through respiration, creates a decrease in the concentration of O₂ within the plant organ, while the production of CO₂ creates an increase in CO₂ within the plant organ (Kader, 1987; Kay 1991).

2.1.4.1 SKIN PERMEANCE TO O₂ AND CO₂ (P'_{O_2} AND P'_{CO_2})

The resistance that the skin represents to gas exchange can be described as the permeance of a plant organ to a gas. This is the rate at which the gas can diffuse in or out of the organ per unit of surface for a given gradient of partial pressure (Banks *et al.*, 1995). Permeances to gas vary depending on the type of commodity, cultivar, part of the plant, severity of preparation, and stage of maturity. Permeance appears to be little affected by temperature (Cameron and Yang, 1982; Kader *et al.*, 1989; Day, 1993).

The magnitude of permeance to O₂ and CO₂ combined with the respiration rates, determine the internal O₂ ($p^i_{O_2}$) and CO₂ ($p^i_{CO_2}$) concentrations for any given postharvest condition. As increasing storage temperature increase respiration rate rapidly but skin permeance does not response as rapidly, this leads to a decline $p^i_{O_2}$ and an increase in $p^i_{CO_2}$. Internal O₂ of fruit with very low skin permeance can therefore decline rapidly at high storage temperatures and can lead to fermentation (Banks *et al.*, 1993).

Fruit skin permeance to gases comprises the combined permeance of pores (stem scars, cut end of peduncles, surface punctures and other discontinuities of out integument) and cuticle (interspersed with stomata and/or lenticels) (Kay, 1991). The total fruit skin permeance to CO₂ and O₂ depends on the dominant diffusion routes through the fruit surface. P'_{O_2} and P'_{CO_2} are similar when gas diffusion is dominated by pores, whilst if and P'_{CO_2} is much higher than P'_{O_2} , the major gas diffusion route is through cuticle of skin (Banks, 1983; Cheng *et al.*, 1998; Cheng, 1999).

Solanaceous fruits such as capsicum, tomatoes and eggplants lack stomata or lenticels that contribute greatly to gas exchange through cuticles of other fruits and vegetable, and cuticles of Solanaceous fruits are thus relatively impermeable to gases (Blanke and Holthe, 1997). The route of gas exchanges of pepper fruit have therefore been reported mainly occurring through the stem end (de Varies *et al.*, 1996; Bower *et al.*, 2000; Banks *et al.*, 2001).

Permeances to O₂ and CO₂ of bell pepper have been reported relatively similar and range from 580 pmol·s⁻¹·m⁻²·Pa⁻¹ (cv. Tasty, (Chen *et al.*, 2000)) to 790 pmol·s⁻¹·m⁻²·Pa⁻¹ (cv. Samanta, (Banks *et al.*, 2001)). However the skin permeances to O₂ and CO₂ of hot chilli peppers have not been reported.

2.1.5 WATER LOSS

Water loss is one of the major factors that limits marketable life of fresh produce. Water loss can cause undesirable changes in appearance such as wilting and shrivelling, softening of tissue, weight loss and changes in flavour. It also induces water stress, which can lead to accelerate senescence (Ben-Yehoshua, 1987). Chillies can develop an unattractive shriveled and wilted appearance after loosing 5-7% of fresh weights (Ben-Yehoshua, 1987). Knowledge of the water loss of the stored chillies is essential for a rational analysis of desired environmental conditions in cold storage in order to minimize water loss (Maguire, 1998).

2.1.5.1 FACTORS AFFECTING WATER LOSS

At steady state, water loss from horticultural products is governed by Fick's first law of diffusion (Nobel, 1991a) as shown in Eq. 2-1:

$$r'_{\text{H}_2\text{O}} = \Delta p_{\text{H}_2\text{O}} A P'_{\text{H}_2\text{O}} \quad (\text{Eq.2-1})$$

where:

$r'_{\text{H}_2\text{O}}$ = rate of water loss from product (mol·s⁻¹)

$\Delta p_{\text{H}_2\text{O}}$ = difference in partial pressure of water vapour between the environment and inside the fruit (Pa)

A = surface area of fruit (m²)

$P'_{\text{H}_2\text{O}}$ = effective permeance of the fruit surface to movement of water vapour under prevailing condition (mol·s⁻¹·m⁻²·Pa⁻¹)

From Eq. 2-1, rate of water loss is dependent on barrier properties of fruit surface ($P'_{\text{H}_2\text{O}}$), surface area of the fruit, and driving force ($\Delta p_{\text{H}_2\text{O}}$). The changes in rate of water loss are due to changes in one or more of these factors.

2.1.5.1.1 PERMEANCE TO WATER VAPOUR (P'_{H_2O})

Permeance to water vapour characterises the ease with which water vapour can escape from fruit. As fruit tissues do not present a uniform barrier to gas diffusion, permeance is likely to be a more appropriate measurement than permeability (Banks *et al.*, 1997), where permeability is calculated by multiplying permeance by the thickness of the diffusion barrier (Banks *et al.*, 1995).

There are great variations in permeance between commodities and/or within cultivars (Ben-Yehoshua, 1987). The variations in these values for individual fruit indicate that P'_{H_2O} is likely to be a key determination of relative rates of mass loss and which fruit within a given population are likely to develop wilting or shrivel symptoms (Maguire, 1998). Permeance to water vapour of several fruits and vegetables e.g. bell peppers, apples, pears, celery or tomatoes have been investigated by several researchers such as Sastry *et al.* (1978), Maguire (1998) and Banks *et al.* (2001). However P'_{H_2O} of hot chilli varieties have not been reported.

2.1.5.1.2 FACTOR AFFECTING PERMEANCE TO WATER VAPOUR

2.1.5.1.2.1 CUTICULAR STRUCTURE AND ROUTE FOR WATER EXCHANGE

Resistance to water vapour exchange is derived mainly from the cuticular layer. A cuticle is composed of biopolymer cutin and embedded wax with epicuticular waxes on the outer surface. This layer protects the plant from excessive loss of water by evaporation to its environment. Differences in surface morphology, cuticular thickness, cuticular composition and structure and development of cuticle could contribute to variations in the resistance to water vapour exchange among individual commodity (Sastry *et al.*, 1978; Ben-Yehoshua *et al.*, 1987; Kay, 1991).

The permeance of cuticle is also likely to vary as it may contain break, such as stem scar, lenticels, growth of cracks and/or mechanical damage e.g. bruises. These are likely to be particularly important in contributing to total fruit permeance (Maguire, 1998; Bower *et al.*, 2000). Further details of effects of cuticular structure on water vapour permeance were well documented by Maguire (1998).

In addition to water exchange through cuticle, Banks *et al.* (2001) reported that water exchange of bell peppers cv. 'Samanta' also occurs through stem area. The permeance of stem ($487 \text{ nmol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot\text{Pa}^{-1}$) is reasonably close to that of cuticle ($506 \text{ nmol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot\text{Pa}^{-1}$). Thus the additional route of water exchange between fruit and environment thus has to be taken into account when considering water loss of peppers.

2.1.5.1.2.2 MATURITY AND CHANGE IN PERMEANCE DURING STORAGE

The maturity of a fruit or vegetable could affect its rate of transpiration. Diaz-Perez (1997) reported that changes in skin permeance to water vapour of tomato occurred as a function of ripeness stage. Fruits harvested at turning stage have higher P'_{H_2O} than those harvested at mature green (MG) stage. The increasing in P'_{H_2O} as the fruit maturity changes were also found in eggplants (Diaz-Perez, 1997), apples (Pieniazek, 1943) and bell peppers (Lurie and Ben-Yehoshua, 1986; Lurie *et al.*, 1986). Changes in surface structure with maturity appear to be reasons for changes in transpiration rate (Sastry *et al.*, 1978). Diaz-Perez (1997) also found that reduction in skin permeance to water vapour of tomato occurred over storage period and this trend was also observed by Pieniazek (1943) in the decrease in water vapour permeance of apple during storage.

2.1.5.1.2.3 RELATIVE HUMIDITY

Several researchers have reported an increase in permeance to water vapour associated with increasing RH or decrease driving force (Δp_{H_2O}) (Smith, 1933; Lentz and Rooke, 1964; Fockens and Meffert, 1972; Sastry *et al.*, 1978; Shirazi and Cameron, 1993). Chamel *et al.* (1991) also found that isolated tomato, apple and pepper cuticles sorb increasing amounts of water with increasing atmospheric water vapour pressure. This trend also occurred to isolated cuticles from citrus leaves as observed by Schonherr and Schmidt (1979).

Schonherr and Lenzian (1981) stated that water and hydrophilic solutes move through the cuticle in polar water filled pores. Ambient relative humidity greatly affect the resistance of fruit to gas exchange by influencing the water conductance, fraction pore area and water content of separated cuticle as well as of detached whole fruits or

vegetable (Possingham *et al.*, 1967). However, permeance to water vapour of skin have been considered to be independent of environmental modification (Sastry and Buffington, 1982). A number of studies also have assumed that the permeance of skin to water vapour is not affected by the water vapour pressure it is exposed to (Chau *et al.*, 1988).

2.1.5.1.2.4 TEMPERATURE

Schönherr *et al.* (1979), Eckl and Gruler (1980) and Schreiber and Schönherr (1990) stated that increasing temperature (>45°C) caused structural changes in isolated cuticle of apples, which lead to an increase in water permeability. This increase in the permeability to water can result in an increase in the rate of water loss, which could rapidly limit the longevity and marketability of stored products.

2.1.5.1.2.5 WAXING

Waxing decreases the fruit's permeance to water vapour by adding a layer through which the water molecules must move (Banks *et al.*, 1997). In most cases, wax blocks pores or lenticels that allow O₂ and CO₂ exchange and can modify the internal gas atmosphere of the fruit. However, excessive modification of the skin barrier (by inappropriate wax or its concentration), coupled with elevated respiration at high temperatures may suffocate the fruit and cause them to ferment and development of off-flavour (Ben-Yehoshua, 1987; Hagenmaier and Shaw, 1992; Banks *et al.*, 1997).

For pepper fruit, the internal gases (O₂ and CO₂) can be affected when wax is applied to the stem area as the major route for gas exchanges is through stem area. Thus careful coating of peppers, where wax is not applied to the stem area, can reduce mass loss (dependent on the type of coating used) without substantial risk of excessive internal atmosphere modification (Banks *et al.*, 2001).

2.1.5.1.3 SURFACE AREA

Surface area, size and shape of a fruit or vegetable has a significant effect on its water loss (Sastry *et al.*, 1978). Lownds *et al.* (1993) found that postharvest water loss rates of 3 pepper cultivars are inversely related to surface area. The cultivars 'NuMex R Naky'

and 'Santa Fe Grande' having smaller surface area has higher rates of water loss than 'Keystone'. This contrasts to the relationship between rate of water loss and surface area (Eq. 2-1), where greater surface area should result in a higher water loss. As permeance to these cultivars has not reported (Lownds *et al.*, 1993), this relationship most likely stems from different water vapour permeance.

Smaller fruits possess a larger surface area to volume or mass ratio and will lose more moisture on a per unit mass basis. Therefore smaller fruits tend to shrivel faster than bigger ones (Sastry *et al.*, 1978; Ben-Yehoshua, 1987). Examples of surface/volume ratios of certain fruits and vegetables are shown in Table 2-1.

Woods (1990) stated that transpiration coefficient or water vapour permeance reported based on surface area of produce provides more accurate information use than that reported on a weight basis. It is particularly important in comparing the likely water loss of individual product. As water loss is controlled by surface structure and each commodity varies in size and shape, water vapour permeance based on surface area provides the most reliable comparison.

Table 2-1 Examples of Surface/Volume Ratios of Edible Plant Material (Ben-Yehoshua, 1987).

Surface/volume ratio ($m^2 \cdot m^{-3}$)	Commodity
5 - 10	Edible leaves (intercellular surface)
0.5 - 1	Individual edible leaves (exposed surface); very small grain (e.g. teff)
0.10 - 0.15	Most cereal grains
0.05 - 0.10	Leguminous seeds; small soft fruits (e.g. currants)
0.02 - 0.05	Leguminous fruits; nuts (except coconut); larger soft fruits (e.g. strawberry); rhubarb; shallot
0.005- 0.015	Tubers; tuberous roots (except e.g. large yams); tap-roots (except e.g. large Swede turnips); pomes, stone and citrus fruits; cucurbituous fruit (except e.g. large marrow); banana; onion
0.002 - 0.005	Densely packed cabbage (e.g. cv. Decema); large Swede turnips and yams; coconut

2.1.5.1.4 DRIVING FORCE (Δp_{H_2O})

The partial pressure of water vapour in the intercellular spaces can be assumed to be very close to saturation at the fruit temperature (Burton, 1982). The amount of water vapour of air in typical storage environments is generally less than this, and depends upon temperature and relative humidity of the air. Following the laws of diffusion, water vapour moves out of the fruit into the environment from high concentration to low concentration. The driving force (Δp_{H_2O} , Pa) for the loss of water is therefore the difference in the partial pressures between the fruit ($\Delta p_{H_2O}^f$) and the environment ($\Delta p_{H_2O}^e$) (Maguire, 1998). Thus, increasing driving force can directly enhance the water loss from fruit to environment.

2.1.5.1.5 FACTOR AFFECTING DRIVING FORCE

2.1.5.1.5.1 FRUIT TEMPERATURE AND WATER VAPOUR PARTIAL PRESSURE

Temperature of the product surface is a major determinant of the driving force for water loss (Nobel, 1991b) since it controls the saturation vapour pressure beneath the surface layer, which also controls the water vapour pressure difference between fruit and environment (Woods, 1990). Heat of respiration accumulates in the product and will raise the temperature of product (Gaffney *et al.*, 1985), which enhances water loss (Kay, 1991). The additional sources of heat transfer, which could alter the fruit temperature are evaporative cooling, convective and radiative heat flow.

When measuring driving force, it is common to assume that skin temperature is equal to air. However, the magnitudes of the additional sources of heat transfer can change fruit temperature, which can lead to significant errors when determining driving force. This in turn affects the P'_{H_2O} determination (Gaffney *et al.*, 1985).

2.1.5.1.5.2 DISSOLVED SOLUTES

The vapour pressure of fruits and vegetables at the evaporating surface depends on the temperature at the product surface. However the vapour pressure is not that of pure water at this temperature because in most fruits and vegetables, the water in the product

contains certain dissolved substance. A solution consisting of dissolved substances in water has a lower saturation vapour pressure than pure water. The water vapour pressure at the surface of fruits and vegetables is lower than that of pure water at the same temperature, this therefore lowers the driving force for water loss from fruit to environment (Gaffney *et al.*, 1985).

2.1.5.1.5.3 TEMPERATURE AND RELATIVE HUMIDITY OF THE ENVIRONMENT

As the vapour pressure at the evaporating surface positively relates to temperature at the product surface (Gaffney *et al.*, 1985), lowering the temperature of the environment reduces fruit temperature, which also lowers the partial pressure of water vapour at the fruit surface. This can in turn reduce the driving force for water loss (Amos, 1995). Increasing the relative humidity of the air by adding moisture raise the water vapour pressure in the atmosphere which can also reduces the driving force for water loss (Amos, 1995).

Reducing storage temperature (depending on the chilling injury tolerance of individual products) and increasing relative humidity is therefore very effective at minimising the driving force for water loss. This principle has been successfully used to reduce weight loss and prolong shelf life of stored produce by many researchers (Hardenburg *et al.*, 1986; Chau and Talasila, 1994; Emond *et al.*, 1995; Fisherman *et al.*, 1996).

2.1.5.1.5.4 PACKAGING EFFECTS

Gas molecules moving from the exterior to the interior of a product firstly pass through a boundary layer of air surrounding the product. The boundary layer is a localized area where the air is static and movement of individual molecules is by diffusion forces (Kay, 1991). Air movement over the surface of the commodity decreases the thickness of the boundary layer. The thickness of a boundary layer determines the resistance to exchange of water molecules between the product and its environment. The thickness of the boundary layer is inversely related to air velocity (Nobel, 1975). Packaging interferes with free air movement around product, increasing the thickness of the boundary layer (boundary layer shown in Figure 2-3), reducing the driving force for

water vapour around fruit. Packaging can therefore profoundly influence effective Δp_{H_2O} (Nobel, 1975).

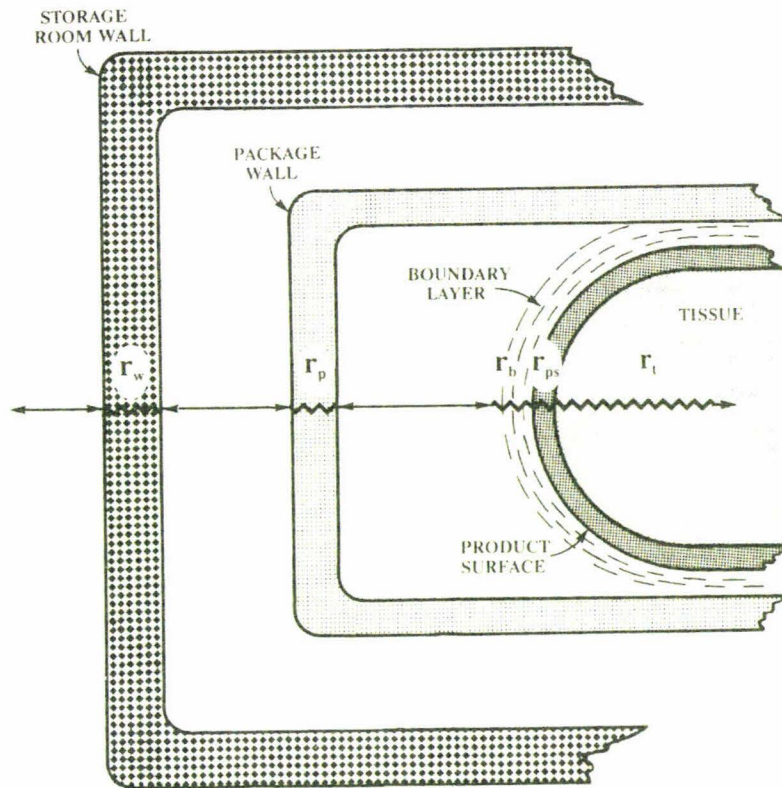


Figure 2-3 Resistance to gas exchange in a harvested product (Kay, 1991).

2.2 EXTENDING SHELF LIFE OF FRESH CHILLIES USING MODIFIED ATMOSPHERE PACKAGING (MAP) WITH PERFORATED PLASTIC BAGS

2.2.1 INTRODUCTION

Modification of the gaseous atmosphere surrounding the product is another method used to maintain quality of fresh produce and it is used to supplement the optimum temperature and humidity for fresh produce storage. Modified atmosphere (MA) storage refers to the storage of food products under atmospheric compositions that, due to the addition or removal of gases, differ from the normal composition of air either N_2 , O_2 , CO_2 or water vapour (Day, 1993). The techniques for modifying the atmosphere, which

have generally been used, are controlled atmosphere (CA) and modified atmosphere packaging (MAP) (Kader *et al.*, 1989; Chau and Talasila, 1994; Merts, 1996).

Controlled atmosphere (CA) technique controls the gas concentration (generally N_2 , O_2 and CO_2) to precisely a set level but there can be a significant cost for controlling and maintaining this process. Modified atmosphere packaging (MAP) is created by packing fresh produce in polymeric film bags or in the containers and allowing modified atmosphere to occur as a result of produce transpiration and respiration and restricted permeability of gases through the polymeric bag (Kader, 1987; Day, 1993; Chau and Talasila, 1994). Unlike CA storage, there is no direct control of levels of specific gases (Day, 1993; Merts, 1996). A conceptual model of the commodity and its environment showing the types of barriers, which can be used to establish a modified atmosphere, is shown in Figure 2-4.

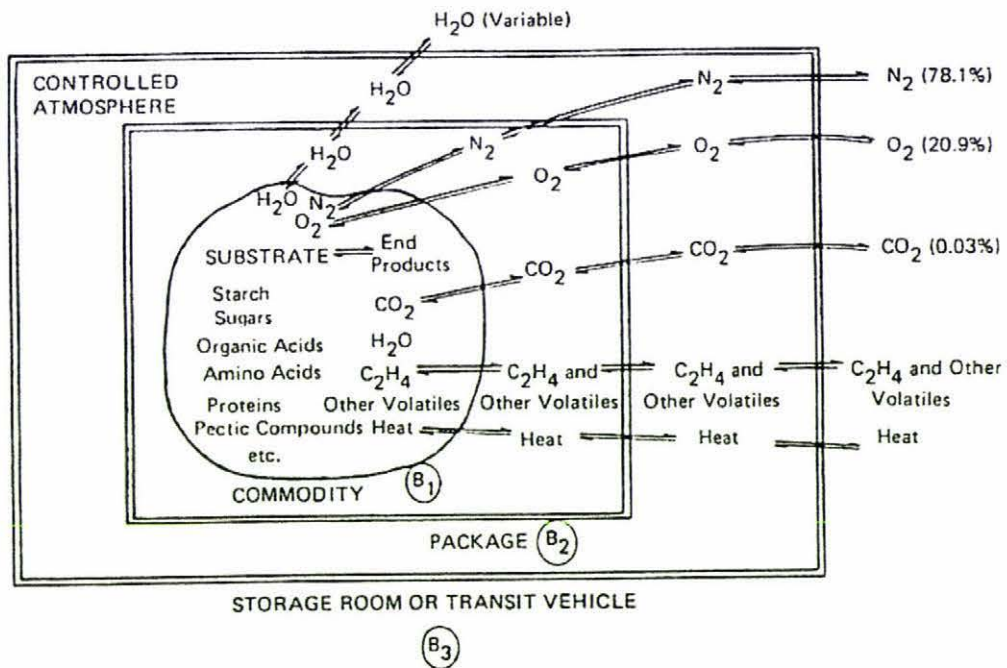


Figure 2-4 Schematic model of a commodity and its environment illustrating three levels of barriers to gas exchange (Kader, 1987).

Applications of modified atmosphere packaging for extending the shelf life of fresh fruit and vegetables have been reported and review many times by several researchers (Bussel and Kenigsberger, 1975; Ben-Yehoshua *et al.*, 1983; Ben-Yehoshua *et al.*,

1987; Cameron *et al.*, 1989; Kader *et al.*, 1989; Lee *et al.*, 1991; Beaudry *et al.*, 1992; Robertson, 1992; Aharoni *et al.*, 1993; Chau and Talasila, 1994; Lee *et al.*, 1994; Lee *et al.*, 1995; Merts, 1996; Fernandez-Trujillo *et al.*, 1998; Garcia *et al.*, 1998; Sanz *et al.*, 1999; Lee *et al.*, 2000).

The gaseous atmosphere changes continuously throughout the storage period and the optimum gas compositions over the storage period vary among individual produce. There are several factors, relating to the shelf life of modified atmosphere packaged product, which can be categorised into 3 main groups: packaged product, package and environment. Factors e.g. respiration rate, temperature, RH or film permeability, affecting these groups can therefore directly affect the quality and shelf life of modified atmosphere packaged produce (Kader *et al.*, 1989).

The advantage of MAP is that it does not incur the large capital costs involved with CA. Therefore modified atmosphere packaging have been widely used for handling and storage of fresh produce (Kader *et al.*, 1989; Robertson, 1993; Meir *et al.*, 1995; Merts 1996).

In this review, modified atmosphere packaging using plastic bags will be slightly broader to include the issue of how perforated bags affect the storage quality of fresh produce and particularly of chillies and peppers.

2.2.2 CREATION AND MAINTENANCES OF ATMOSPHERES

Creation and maintenance of atmospheres inside the plastic bags can be established via active or passive modifications or a combination of the two. For active modification, an atmospheric is established by replacing the existing atmosphere of the package with the desired gas mixture and/or using gas adsorbents/absorbents in the package to control the internal gas concentration (Chau and Talasila, 1994).

In the case of passive modification, modified atmosphere is attained through controlling the gas exchange across the package. The process relies on the natural process of respiration and diffusion of CO₂ and O₂ across the barrier (or package) to provide the desired environment (Day, 1993; Chau and Talasila, 1994).

Most available data in the literature of modified atmosphere packaging for chillies and peppers is about the passive type MAP, using both nonperforated and perforated plastic bags. As a key objective of this research relates to the use of perforated polymeric bags, the use of these bags to modified atmosphere will be further examined.

2.2.3 PERFORATED FILMS FOR MAP OF FRUITS AND VEGETABLE

Films used for a modified atmosphere pack must be machinable, capable of withstanding transport and handling, attractive to the prospective purchaser, capable of carrying information and be of acceptable cost. Films commonly used for MAP include polyvinylchloride (PVC), polypropylene (PP), polystyrene (PS), nylon and polyethylene (PE) (Day, 1993).

Low density polyethylene (LDPE) film has been widely used for fresh produce packaging, due to its properties e.g. low water vapour, but high oxygen transmission, which can reduce the weight loss and keep the atmosphere inside the bag aerobic, as well as its low cost (Day, 1993; Robertson, 1993). However, LDPE polymer has lower levels of stiffness, tensile strength and/or chemical resistance, compared to other polymers in the polyethylene group (medium density polyethylene (MDPE), high density polyethylene (HDPE) or linear low density polyethylene (LLDPE)) (Brown 1992). Thus, the LDPE bag is susceptible to mechanical damage during handling.

Combination of other films (via lamination, coextrusion or extrusion coating) with LDPE is an alternative to improve the LDPE duration's properties (Greengrass, 1993). LLDPE/LDPE film is an example of combination LDPE with LLDPE providing the required properties of higher tear resistance and clarity compared to LDPE. In addition, LDPE/LLDPE film is more commonly used for packaging fresh produce (Wakenshaw, 2000, pers.com.).

Using polymeric bags for modified atmosphere high relative humidity, low O₂ and high CO₂ conditions occur inside the bag. Such conditions can promote condensation and microbial growth and sometimes impede the normally physiological activity i.e. ripening or colour and texture development of certain fruits, e.g. mushroom or mango, which in turn limit their storage shelf life and marketability (Ben-Yehoshua *et al.*, 1993;

Lownds *et al.*, 1994; Lee *et al.*, 1996; Ben-Yehoshua *et al.*, 1998; Sornsrivichai *et al.*, 2000).

To optimise the relative humidity and levels of gases (O₂ and CO₂) inside the bags, several researchers have used perforated films, which have high O₂ and CO₂ and water vapour permeabilities (Geeson, 1990; Emond *et al.*, 1995).

The methods for perforating plastic bags vary between manufacturers or converters. There are 3 available commercial methods namely: (1) gas flamed perforating, (2) needle perforation systems and (3) pneumatic perforation systems (Anon, 1983; Castle, 1996; Mykytiuk, 1997).

2.2.4 EFFECTS OF PERFORATED FILMS ON IN-PACKAGE GASES (O₂, CO₂ AND WATER VAPOUR)

Ben-Yehoshua *et al.* (1998) studied the effects of perforation on in-package condition and they found that perforating the film greatly affected O₂ and CO₂ concentration and water condensation. This result is in contrast to some researchers, who reported that gas compositions inside the perforated bags are not modified, with O₂ and CO₂ levels close to ambient air levels (Geeson, 1990; Lownds *et al.*, 1994; Wang and Qi, 1997; Garcia *et al.*, 1998).

Different effects of perforated film on the in-package gas condition (O₂, CO₂ and water vapour) are related to the perforation area, diameter of perforation and the shape of hole (Geeson, 1990; Emond *et al.*, 1995; Garcia *et al.*, 1998; Sanz *et al.*, 1999). Examples of effects of degree of perforation (hence including perforated area and shape/size of perforation) on permeabilities of water vapour and gases (O₂ and CO₂) are shown in Table 2-2 to Table 2-3.

Variation in degrees of perforation (area and size/shape of hole) can affect properties of perforated film, which in turn affect the quality attributes of packaged product e.g. weight loss and firmness (Chau and Talasila, 1994) stated that one disadvantage of perforations is the lack of selective permeabilities for CO₂ and O₂. If perforations are used for modified atmosphere packages that are kept in ambient conditions (21%O₂ and

0.03% CO₂), these packages will provide modified atmospheres within a certain range of values only.

An optimum degree of perforation (including area and size/shape of hole) for maintaining the desired levels of O₂ and CO₂ and relative humidity, is required to extending the shelf life of modified atmosphere packaged produce (Geeson, 1990; Emond *et al.*, 1995; Sanz *et al.*, 1999).

Table 2-2 Table Resistance coefficient (RC) to water vapour transmission of perforated plastic films (developed from the results of Emond *et al.*, (1995)).

Diameter of Perforation (mm)	Number (holes/m ²)	Openings (%)	Resistance coefficient
0.40	251,100	3.20	2.49
0.40	54,250	0.70	7.04
0.40	12,400	0.20	17.74
1.00	40,000	2.90	4.18
1.10	89,900	8.50	2.70
1.10	7,500	0.70	13.55
1.20	10,000	2.00	7.83
2.90	20,000	13.40	1.94
3.70	16,250	17.50	1.81
5.5 x 2.0	26,250	23.30	1.82

Table 2-3 Gas concentration inside perforated films.

Diameter of Perforation (mm)	Perforation Area ^a	Film Type		O ₂ (%)	CO ₂ (%)	References
		Macroperforated	Microperforated			
1	8 holes/pack		+	20	^{b?}	Lownds <i>et al.</i> (1994)
8	3% of total surface	+		21	0.2	Garcia <i>et al.</i> (1998)
8	18-20 holes/pack	+		21	0	Sanz <i>et al.</i> (1999)
1	1.57 mm ²		+	4.84	23.38	
	3.14 mm ²		+	6.72	17.39	
	4.71 mm ²		+	8.08	15.91	
0.4	2-3 holes/250cm ²		+	4-6	5-6	Geeson (1990)
0.4	highly perforated		+	20.8	1.6	
7	8 pinholes/pack		+	8.91-10.72	12.38-14.94	Koolpluksee <i>et al.</i> (1993)
?	?		+	15.5-16.5	4.5-5.5	Rai <i>et al.</i> (2000)
?	0.0018% of total area		+	10	5	Pesis <i>et al.</i> (2000)
2	33 holes/dm ²	+		21	0	Fernandez <i>et al.</i> (1998)
0.4	2-3 holes/pack		+	6-7	5-6	Everson <i>et al.</i> (1992)
0.4	highly perforated		+	>18%	<2%	

^aperforation areas were presented as appeared in references.

^{b?} data was not reported

2.2.5 EFFECTS OF PERFORATED FILMS ON STORAGE QUALITIES OF MODIFIED ATMOSPHERE PACKAGED PRODUCE

2.2.5.1 RESPIRATION RATE

Respiration rate directly varies in response to the surrounding O₂ and CO₂ concentration. Modified atmosphere using nonperforated plastic bags can change the levels of these gases. Generally, O₂ concentration becomes lower and CO₂ concentration is higher compared to air, with a resulting decreased respiration rate (Kader, 1987; Kader *et al.*, 1989).

Unlike nonperforated plastic bags, the modification of gas atmosphere compositions inside the perforated bags varies with degree of perforation, where microperforated film can modify the gas compositions, while atmosphere inside macroperforated films are close to air (Fisherman *et al.*, 1996; Fernandez-Trujillo *et al.*, 1998; Garcia *et al.*, 1998; Sanz *et al.*, 1999).

Whilst the atmospheres inside packages made from microperforated film are modified, the effects of this modification on lowering the respiration rate of fresh produce have not been reported.

2.2.5.2 WEIGHT/FIRMNESS LOSS AND CONDENSATION

Perforated film is effective in reducing condensation formation inside the fruit and vegetable packages but it increases water loss in comparison with the nonperforated film. However, perforated film is still significant in minimising the weight loss when compared to unpackaged produce (Ben-Yehoshua *et al.*, 1998). As fruit firmness positively correlates to weight loss, attempts to minimise the weight loss also reduce the loss of firmness (Lownds *et al.*, 1994; Ben-Yehoshua *et al.*, 1998; Peretz *et al.*, 1998). Fruits and vegetables tend to lose their weight and firmness faster when the perforation area and perforation diameter are increased (Emond *et al.*, 1995; Garcia *et al.*, 1998; Sanz *et al.*, 1999).

Due to its practical properties in reduction of condensation and weight/firmness loss, perforated films have been used for weight loss control in several fresh produce,

including chillies and peppers (Geeson, 1990; Aharoni *et al.*, 1993; Ben-Yehoshua *et al.*, 1993; Lownds *et al.*, 1993; Meir *et al.*, 1995; Ben-Yehoshua *et al.*, 1998; Sornsrivichai *et al.*, 2000).

2.2.5.3 COLOUR CHANGE

Effects of perforated film on colour retentions of fresh produce are not obvious. The rates of colour loss in cucumbers or tomatoes or broccoli wrapped in perforated film were similar to those in nonperforated film (Otma, 1988; Garcia *et al.*, 1998). Lownds *et al.* (1994) found that packaging peppers or strawberry with perforated plastic bag can reduce the colour development. However Sanz *et al.* (1999) reported that colour change of strawberries packaged in microperforated films are not significantly different from those packaged with macroperforated films.

Whilst some researchers have used perforated film to retain the colour of packaged produce, others have successfully used perforated film to develop colours in certain types of fruits e.g. mango, since perforated film allows enough oxygen level for normal ripening activity and colour development (Ben-Yehoshua *et al.*, 1998).

2.2.5.4 FLAVOUR CHANGE

Effects of perforated film on flavour change of fresh produce are not apparent. Rosenfeld and Sundell (1995) reported that there was no significant difference in flavour of lettuce packaged into either nonperforated or perforated bags. This report is in contrast to Mohammed (1993) and Soylemezoglu and Agaoglu (1994), who reported that Thompson Seedless berries and passion fruit wrapped with perforated polyethylene had better flavour than those wrapped with nonperforated film.

Whilst there are no clear effects of perforated film on flavour of packaged products, perforated films have been used to avoid or reduce off-flavour or alcoholic scents, which develops under high CO₂ concentrations with sealed plastic (Otma, 1988; Koolpluksee *et al.*, 1993; Yantarasri *et al.*, 1995; Ratti *et al.*, 1996; Morkkila *et al.*, 1999).

Effects of modified atmosphere using either nonperforated or perforated plastic films on the flavour (or pungency) aspects of fresh chillies or bell peppers have not been reported.

2.2.5.5 NUTRITIONAL CHANGE

Changes in nutritional contents of packaged produce due to the effects of perforated film are not apparent. Garcia *et al.* (1998) reported that strawberries packaged with macro-perforated package have significantly lower in citric acid than unwrapped fruit. However, Sanz *et al.* (1999) reported that there were no significant differences in level of ascorbic acid and sucrose between strawberries packaged with micro-perforated and macro-perforated plastic package.

There are however no other available data in effects of perforated film on nutritional values of other fresh produce (including chillies or peppers).

2.2.5.6 MICROBIOLOGICAL SPOILAGE

Perforation can minimise the condensation inside the bag, which could possibly delay microbiological growth or secondary contamination of packaged fruit (Day, 1993). Hans (1994), Meir *et al.* (1995) and Ben-Yehoshua *et al.* (1998) reported that perforated film minimised condensation inside the packages of bell pepper and significantly reduced decay on the fruit. However, Efiuvwevwere and Oyelade (1991) reported that oranges packaged with perforated polyethylene bag have much more off-odour from fermentation than fruit packaged in nonperforated bag. Mercado *et al.* (1995), Wang and Qi (1997) and Peretz *et al.* (1998) also reported that sealing with the perforated film did not reduce decay development on mandarin and cucumber.

The effects of perforated film on the retarding microbiological spoilage of fresh produce thus could be considered still unproven. There could be several factors e.g. production practices or postharvest disinfecting treatment or storage environment, which might affect the levels of spoilage on packaged fruit and vegetables (Lurie, 1998; Noel *et al.*, 1999).

2.3 MATHEMATICAL MODELS OF MODIFIED ATMOSPHERE PACKAGING (MAP)

The development and application of predictive models in horticultural refrigeration has increased markedly in the past decade. By applying appropriate mathematical tools to the packaging design process, quantitative prediction of important variables can be made. This will allow designs to be screened prior to any prototype testing, reducing the need to perform “trial and error” testing which is both time consuming and can be expensive (Tanner, 1998).

Models for modified atmosphere packaging of fresh produce have been developed in order to predict the equilibrium atmosphere (O_2 and CO_2 level) within a package given the commodity mass and respiration rate and the film size and permeability to O_2 and CO_2 . The limitations and applications of mathematical models for design the appropriate gas compositions inside the modified atmosphere packaging for fresh (including fresh chillies and peppers) or minimally processed produce have been extensively reviewed and implemented by several researchers i.e. Robertson (1992), Lee *et al.* (1994) and Ratti *et al.* (1996).

Lee *et al.* (1994) successfully used mathematical models proposed by Lee *et al.* (1991) and Hayakawa *et al.* (1975) to design modified atmosphere using nonperforated packages for fresh green chillies, where during 2 week storage, the levels of O_2 and CO_2 were in the range of recommendation (3% O_2 and 5% CO_2), proposed by Watada *et al.* (1987), for retarding ripening and senescence. However they did not provide the results on condensation and microbiological deterioration that can question the effectiveness of modified atmosphere with sealed packages on prolonging the shelf life of fresh chillies.

As previously mentioned, perforated films have been used for minimising condensation, in turn reducing the deteriorating rate. Attempts to use mathematical models to predict the dynamic of gases (O_2 , CO_2 and water vapour) inside the perforated plastic film and shelf life of packaged produce have been reported by a number of researchers (Renault *et al.*, 1994; Fisherman *et al.*, 1995; Fisherman *et al.*, 1996; Ben-Yehoshua *et al.*, 1998). The modification of atmosphere inside the bag however can be questioned (section 2.2.4). Nonetheless, the applications of perforated films in weight loss and condensation

reduction are obvious. For this study, only mathematical models for predicting weight loss of fresh chillies packaged in either nonperforated or perforated plastic bags under prevailed conditions will be examined.

The mathematical model and the computer simulation 'Weight Loss Simulator' developed by Tanner (1998) will be used for this purpose. This programme has been used for design packaging for minimising weight losses for a wide range of horticultural products i.e. apples, pears and tomatoes. Solutions and validation of this model using assumptions and experimentally obtained data in weight loss of fresh chillies will be studied and discussed in detail.

2.4 CONCLUDING REMARKS

This chapter has outlined the information for the design of modified atmosphere perforated plastic packaging of fresh chillies. Following chapters will present experimental methodologies and results.

CHAPTER 3

GENERAL MATERIALS AND METHODS

3.1 MATERIALS AND EXPERIMENTAL DESIGN

3.1.1 INTRODUCTION

In this chapter, the materials and methods, which applied to more than one chapter of the thesis, are presented. Other methods, which are specific to an individual chapter, are included in those chapters.

3.1.2 PLANT MATERIAL

For all experiments freshly harvested, mature field-grown green chillies (*Capsicum annuum* L. cv. Cayenne) were obtained directly from local growers (Feilding, New Zealand). Chillies were washed with tap water, and allowed to dry at room temperature ($\approx 20^{\circ}\text{C}$) for 1 hour. They were then dried with a paper kitchen towel to remove any residual surface water (Figure 3-1) before being separated, at random into two groups.



Figure 3-1 Fresh green chillies (*Capsicum annuum* L. cv. Cayenne)

The first group was used to study physiological aspects including respiration rate, surface area, volume and water vapour and/or gas permeances. The other group was used to study the effects of modified atmosphere packaging (MAP) on product quality.

3.2 PHYSIOLOGICAL ATTRIBUTES MEASUREMENT

3.2.1 WEIGHT, VOLUME AND SURFACE AREA DETERMINATION

A balance (0.001g Mettler Toledo PR1203, Switzerland) protected by a wind shield was used to measure the weight (g) of individual chilli. To determine fruit volume, the entire fruit (including stem plate area) was immersed in a known volume of water and the displacement measured (Lownds *et al.*, 1993).

The same fruits were carefully covered with fabric and glue. Once dry, the fabric covering was cut into sections and then carefully removed from the surface of the fruit. The fabric was mounted on an acetate sheet and area determined using a leaf area meter (Model L1-3100, Li-Cor, Lincoln, USA) (Figure 3-2) (Clayton *et al.*, 1995).

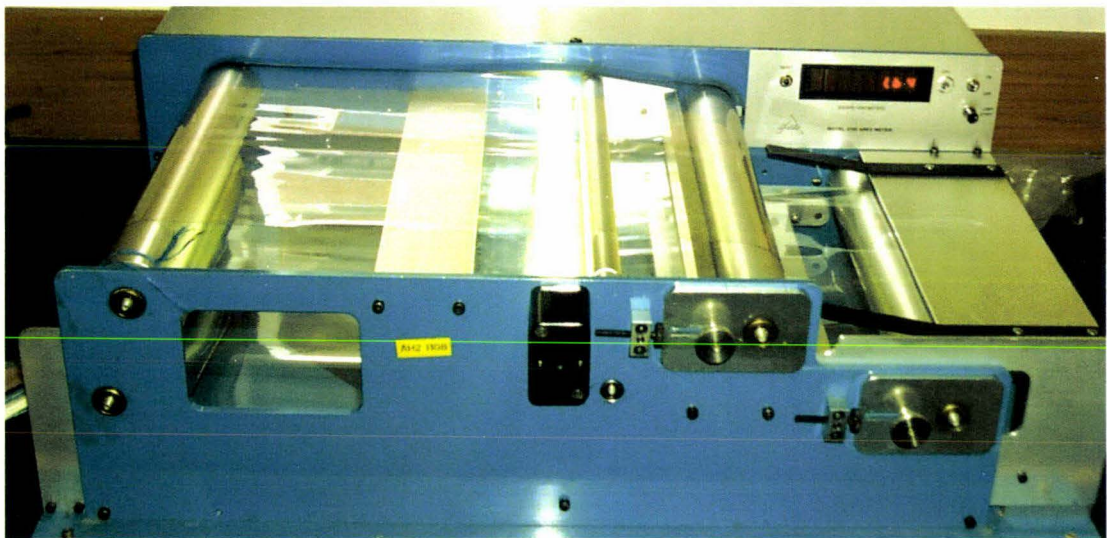


Figure 3-2 Leaf area meter

3.2.2 RESPIRATION RATE MEASUREMENTS

Respiration rates (r_{CO_2} , mol · kg⁻¹ · s⁻¹) of individual fruit were determined at 4 different storage temperatures, 5 °C, 10 °C, 20 °C and 30 °C, by measuring the accumulation of CO₂ in 500-ml opaque airtight plastic containers (30 replicates per storage temperature).

After placing the fruits in the respiration chambers and closing, a sample headspace gas was withdrawn from each container, using a syringe (1ml size), through a septum in the top of the container. The syringe is then immediately sealed by a rubber bung (Figure 3-3). Simultaneously a timer was started with the initial time recorded as t_0 (Banks *et al.*, 1997).

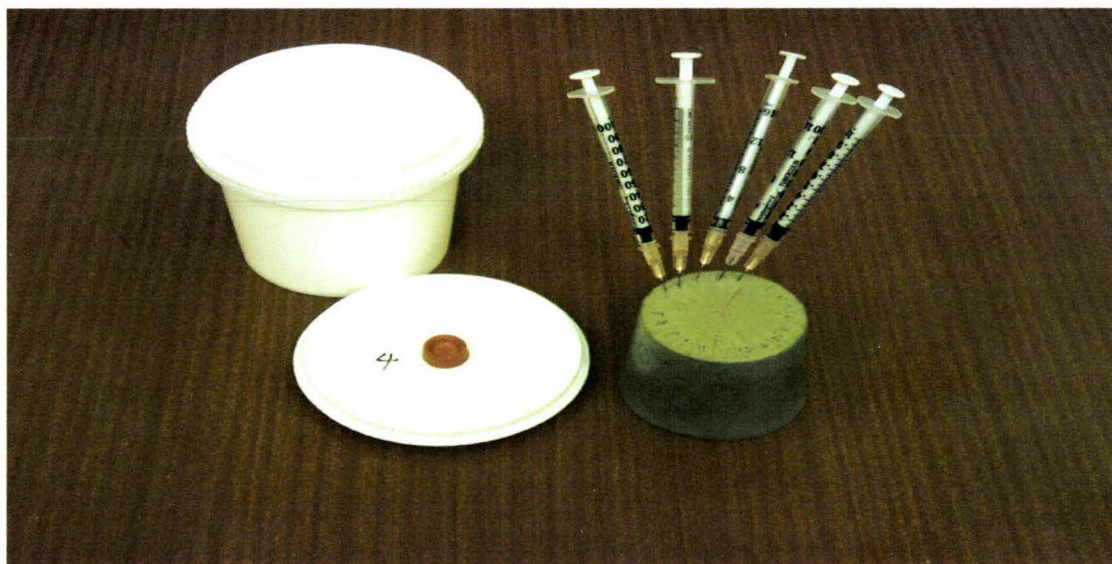


Figure 3-3 Respiration chamber and 1ml syringes

Subsequently, samples were injected into a gas chromatograph fitted with an O_2 electrode (Citicell C/S type, City Technology Ltd., London, UK) in series with a miniature infrared CO_2 transducer (Analytical Development Company, Hoddesdon, UK) with O_2 -free N_2 as the carrier gas (flow rate $580 \text{ mm}^3 \cdot \text{s}^{-1}$) (Figure 3-4). Output signals were analysed by using integrators (Hewlett Packard, Model 3394A) (Figure 3-4).

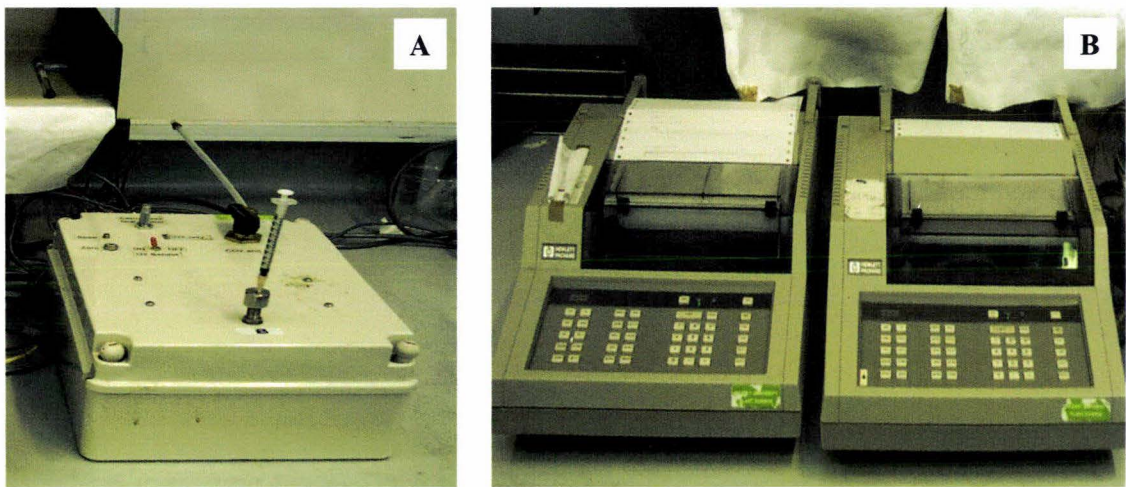


Figure 3-4 A) Gas Chromatograph and B) Integrators.

Commercially prepared standards (BOC Special Gases, Wellington, NZ) were used for calibration of the gas analyser ($0.49 \pm 0.01\%$ O₂ and $20.00 \pm 0.2\%$ CO₂ in nitrogen). Ambient pressure data were collected with a pressure transducer (Barigo Electronic Altimeter, Barigo Barometerfabrik GMBH, D-7730 Villingen Schwenningen).

The appropriate time (recorded as t_1), after the initial time (t_0), for repeatedly taking and measuring the concentration of CO₂ has to be determined. Banks *et al.* (1997) suggested that this appropriate time should contribute to a change in CO₂ concentration of between 0.1 and 0.3%. The appropriate time between sampling will vary with studied tissues, temperature and volume of container used. For this study, the t_1 was different among storage temperatures. For treatments at 5 and 10°C, the appropriate sampling time was approximately 10 hours while for 20 and 30°C sampling time was about 3 hours.

After the appropriate time (at t_1), the same 1 ml syringes (previously used for taking samples at t_0) were inserted into the jars and a gas sample removed. These samples were then injected into the gas chromatograph and the results were read by the integrator. The data were subsequently calculated by using the Eq. 3-1.

$$r_{CO_2} = \frac{\left((V_{jar} - \frac{M_{fruit}}{\rho_{fruit}})(P_{CO_2}^{final} - P_{CO_2}^{initial})P^{tot} 1E^{-8} \right)}{8.3143(T_f + 273.15)M_{fruit}t} \quad (\text{Eq. 3-1})$$

where:

- r_{CO_2} = respiration rate ($\text{mol} \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$)
 V_{jar} = volume of jar (ml)
 ρ_{fruit} = density of the fruit ($\text{g} \cdot \text{cm}^{-3}$)
 $P_{CO_2}^{final}$ = CO_2 in jar at the end of time t_1 (%)
 $P_{CO_2}^{initial}$ = initial CO_2 in jar of t_0 (%)
 T_f = temperature of fruit ($^{\circ}\text{C}$)
 M_{fruit} = fresh weight of fruit (g)
 P^{tot} = air pressure (Pa)
 t = time for reading (s)

3.2.3 SKIN PERMEANCE TO WATER VAPOUR MEASUREMENTS

Skin permeances to water vapour of fresh chillies were determined under 5, 10, 20 and 30°C (30 replicates per storage temperature). Chillies were placed in airflow of $\approx 3 \text{ m} \cdot \text{s}^{-1}$ and the mass loss from each fruit was determined over a 12-hour period using a balance (0.001g Model PM1203; Metler Toledo, Switzerland). An average dew point temperature and air temperature were determined by wet and dry bulb temperature reading (thermistor probes CM type, U bead, $\pm 0.2^{\circ}\text{C}$; Grant Instruments, Cambridge, U.K.).

Skin temperature was logged by Grant 1200 series Squirrel meter/logger (Grant Instruments, England) during the period of measurement by recording the output of thermistor probes (FF type, U bead, $\pm 0.2^{\circ}\text{C}$; Grant Instruments, Cambridge, U.K.) inserted under the skin of several additional sample fruit (Figure 3-5) (Banks *et al.* 2000). Effective permeance of the fruit surface to water vapour, P'_{H_2O} ($\text{mol} \cdot \text{s}^{-1} \cdot \text{m}^{-2} \cdot \text{Pa}^{-1}$) was then calculated using Eq. 3-2 to Eq. 3-6 (Maguire, 1998).

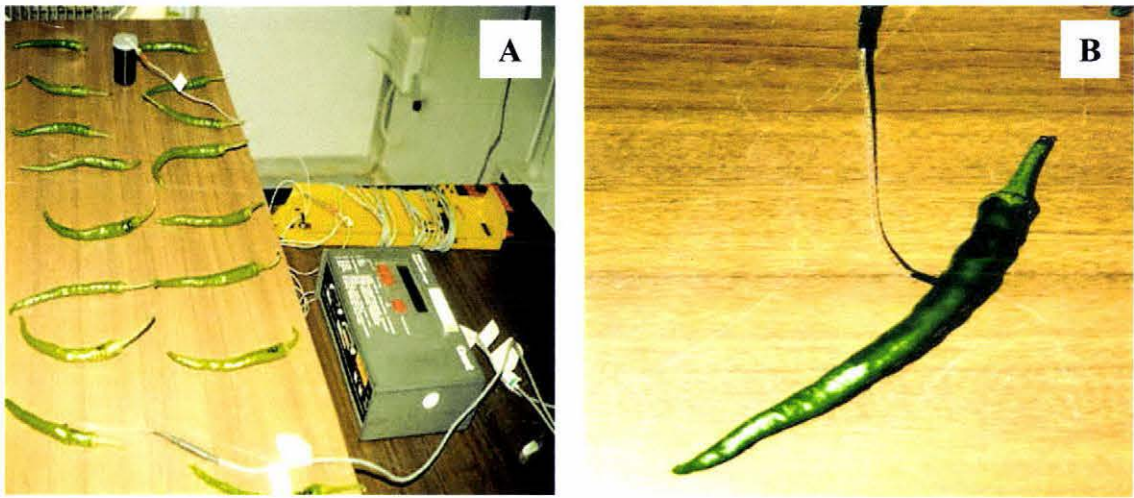


Figure 3-5 A) Wet/Dry bulb, data logger and probe and B) Skin temperature measurement.

$$P'_{\text{H}_2\text{O}} = \frac{r'_{\text{H}_2\text{O}}}{\Delta p_{\text{H}_2\text{O}} A} \quad (\text{Eq. 3-2})$$

where:

$P'_{\text{H}_2\text{O}}$ = effective permeance of the fruit surface to movement of water vapour under prevailing conditions ($\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot\text{Pa}^{-1}$)

$r'_{\text{H}_2\text{O}}$ = rate of water loss from product ($\text{mol}\cdot\text{s}^{-1}$)

A = surface area of fruit (m^2)

$\Delta p_{\text{H}_2\text{O}}$ = difference in partial pressure of water vapour between the environment ($p_{\text{H}_2\text{O}}^e$) and inside the fruit ($p_{\text{H}_2\text{O}}^f$) (Pa) and this value is calculated by Eq. 3-3

$$\Delta p_{\text{H}_2\text{O}} = p_{\text{H}_2\text{O}}^f - p_{\text{H}_2\text{O}}^e \quad (\text{Eq. 3-3})$$

Where:

$p_{\text{H}_2\text{O}}^f$ = the partial pressure of water vapour in the fruit and this value is calculated by Eq. 3-4

$$p_{\text{H}_2\text{O}}^f = p_{\text{H}_2\text{O}}^{\text{sat}}(T_f) = \left[611 \exp \left(17.27 \left(\frac{T_f}{T_f + 237.3} \right) \right) \right] \times a_w \quad (\text{Eq. 3-4})$$

Where: T_f = temperature at fruit skin ($^{\circ}\text{C}$)

a_w = water activity (fixed as 0.995)

$p_{H_2O}^e$ = the partial pressure of water vapour in the environment and this value is calculated by Eq. 3-5 and Eq. 3-6

$$p_{H_2O}^e = p_{H_2O}^{sat}(T_w) - \gamma(T_e - T_w) \quad (\text{Eq. 3-5})$$

$$p_{H_2O}^{sat}(T_w) = 611 \exp\left(17.27 \left(\frac{T_w}{T_w + 237.3}\right)\right) \quad (\text{Eq. 3-6})$$

Where: T_e = temperature of environment (dry bulb temperature) ($^{\circ}\text{C}$)

T_w = dew point temperature (wet bulb temperature) ($^{\circ}\text{C}$)

γ = psychometric constant (a value of $67 \text{ Pa}\cdot^{\circ}\text{C}^{-1}$)

3.2.4 SKIN PERMEANCE TO CO_2 AND O_2 GASES

Eighty chillies were used to determine internal atmosphere and skin permeances to O_2 and CO_2 under 5, 10, 20 and 30°C (20 replicates per storage temperature). Cannulae (14 gauge stainless steel needles, cut down to 2-cm length) were inserted through the fruit wall into the cavity of the fruit (Figure 3-6). The connection between cannula and skin was sealed gas-tight using epoxy adhesive (5 min cure; Arelidite[®], Ciba-Geigy, Auckland, New Zealand).

Once the cannulae were attached, fruit were separated into 4 groups (20 fruits each) and then equilibrated for 24 hr overnight in 4 different temperatures (5, 10, 20 and 30°C). Afterward, steady state internal gas (CO_2 , $p_{\text{CO}_2}^i$ and O_2 , $p_{\text{O}_2}^i$) at each storage temperature were determined by sampling 100 μl from the fruit cavities through the cannulae (Banks 1983). Values for permeance of the fruit's skin to CO_2 and O_2 ($p_{\text{O}_2}^i$ and $p_{\text{CO}_2}^i$) were then calculated using (Eq.3) (Cheng, 1999).

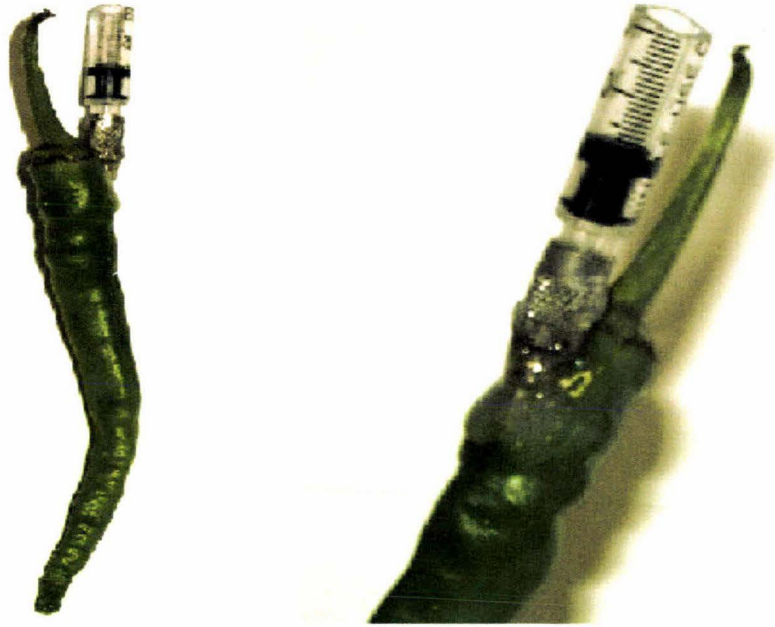


Figure 3-6 Cannulated fruit for internal atmosphere sampling.

$$P_{CO_2}^{fruit} = \frac{r_j}{\Delta p_j} \cdot \frac{M}{A} \quad (\text{Eq. 3-7})$$

where:

- P_j^{fruit} = skin permeance to gas j ($\text{mol} \cdot \text{s}^{-1} \cdot \text{m}^{-2} \cdot \text{Pa}^{-1}$)
- A = surface area of fruit (m^2)
- Δp_j = partial pressure difference for diffusion of gas j between internal (p_j^i) and external (p_j^e) atmosphere (Pa)
- M = fruit mass (kg)
- r_j = rate of transfer of gas j ($\text{mol} \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$)

3.2.5 WATER ACTIVITY (a_w) MEASUREMENT

To measure water activity (a_w) of fresh chillies, the a_w meter, model (a_w -Wert-Messer) was used (Figure 3-7).

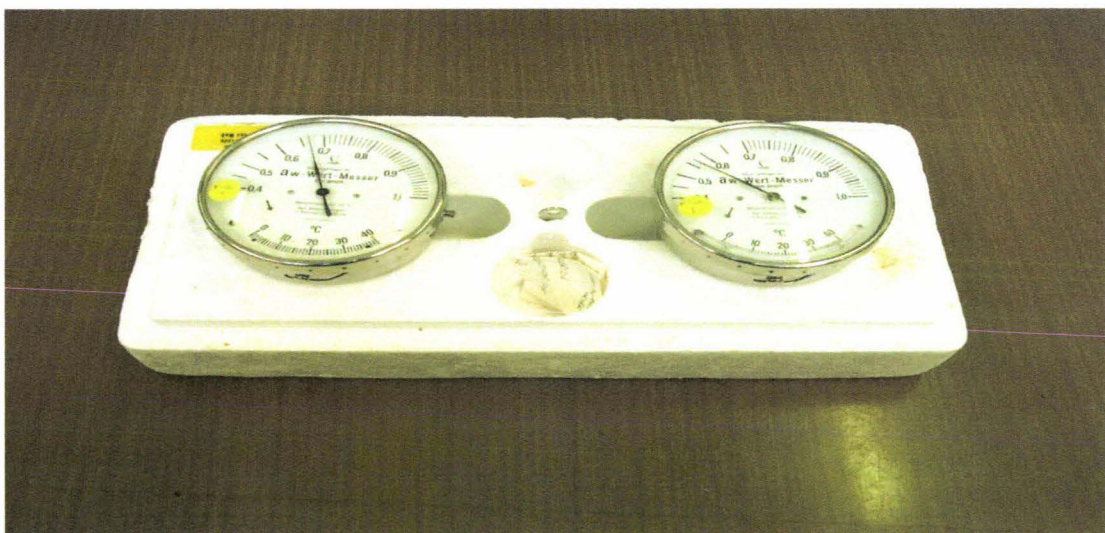


Figure 3-7 Water activity (a_w) meter.

Before measuring chilli water activity, the meter had to be calibrated by using saturated barium chloride (BaCl_2) solution, at controlled room temperature condition ($\approx 20^\circ\text{C}$). The approximate calibrating time is 3 hours. The water activity (showed on a dial) of this solution theoretically equals 0.90. Next, after meter being cleaned, one fresh chilli was carefully put inside. The meter was left 3 hours before the a_w value was read. 2 replicates of chillies were measured per measurement (due to limitation in instrument).

In addition to measuring water activity (a_w) of individual fresh chilli, the correlations of water activity (a_w) and dynamic weight loss over a 2-week storage period, of chillies at 4 different temperatures (5, 10, 20 and 30°C) were studied. To measure the weight of a fruit, a balance (0.001g Mettler Toledo PR1203, Switzerland) protected by a windshield was used. 2 experiments were carried out during May-June 2000.

3.2.6 GAS COMPOSITION INSIDE PLASTIC BAGS

A sample headspace gas was withdrawn from each bag in every treatment, using a syringe (through the septum attached to plastic bag, which was sealed using 100- μl size, at 5, 10 and 14 days during the storage period. Subsequently, these samples were injected into a gas chromatograph for analysis.

The commercially prepared standards (BOC Special Gases, Wellington, NZ) used for calibration of the gas analyser in the study of this section were as same as used in the study of skin permeance to gases. Consequently, the gas levels and their dynamics, during 2 weeks, of oxygen (O₂) and carbon dioxide (CO₂) were reported.

3.2.7 MAP PACKAGE TESTING

Chillies were packaged in 6 different types of plastic bags, which were separately stored at 4 different temperatures. Clear (with one side printed) plastic bags used for this experiment were obtained from VSR Packaging Ltd (Te Atatu, Auckland, New Zealand). These were made from 0.05mm thick Linear Low Density Polyethylene blended with Low Density Polyethylene (LLDPE/LDPE) and were perforated with the following levels of perforation: **0.00%** (nonperforation), **0.49%** (25mm x 40mm x 2.5 mm), **0.98%** (25mm x 20mm x 2.5 mm) and **1.96%** (25mm x 10mm x 2.5 mm).

All plastic bags, used as chilli packages for the experiment, were sized to 152.40 x 228.60 mm using a heat sealer (Thornton Ratcliffe Ltd, New Zealand). This size of plastic bag is generally used for retail chilli packaging in Thailand (Utto, 2000).

In addition, nonperforated plastic bags were manually punctured, using a 5 mm diameter cork bore to make 6 holes (giving rise to the **0.17%** perforated area, denoted as **THA**). This was a simulation of the typical Thai style perforating method for ventilating packages. In Thailand, the sharp point of a knife is often used to create this ventilation (Utto, 2000). Four storage temperatures, 5°C, 10°C, 20°C and 30°C were used in this study, and each plastic bag, contained approximately 100g of fresh-green chillies. To seal the plastic bag, a rubber band was used (Figure 3-8).



Figure 3-8 Chillies in plastic bags.

3.2.8 EXPERIMENTAL DESIGN

A general full factorial design was used to design the experimental treatments with 4 temperatures (5, 10, 20, and 30°C), and 6 types of packages (0.00%, 0.49%, 0.98%, 1.96%, THA and unbagged (called control)). For each temperature × package treatment, there were 5 replications (bags). The shelf life simulation period was 14 days since this period is generally used for storing chillies for retailing and household applications, in Thailand (Utto, 2000).

During the 2-week storage period, chilli quality attributes and appearances (see section 3.3) were assessed every 5 days. Among these 5 replications (bags), 1 bag was randomly chosen in order to measure quality attributes at each of storage day 5 and 10, respectively. Chillies in these bags were then discarded after measuring. Whist the rest of replications (3. bags) was all measured for their quality attributes at the end of simulation period. Three experiments were conducted from May until July 2000.

3.3 MEASUREMENT OF QUALITY ATTRIBUTES

To determine and design the modified atmosphere packaging (MAP) for prolonging the shelf life of green chillies, some quality parameters were developed. These parameters were weight loss, skin colour, firmness, postharvest decay, condensation, visual quality and in-bag gas composition.

3.3.1 WEIGHT LOSS

A balance (0.001g Mettler Toledo PR1203, Switzerland) protected by a wind shield was used to measure weight (g) of packages contained fresh chillies. The weight loss was then calculated in grams per day and expressed in percentage of the initial weight.

3.3.2 COLOUR AND FIRMNESS MEASUREMENTS

From each treatment, five fruits were taken from 1 replication (bag) to analyse changes in skin colours, at day 5 and 10. At the end of the simulating period (14 days), five fruits were also taken from every available replication (bag) to measure their colours. Three locations along the length of the fruit (excluding calyx and the stem) were measured, using a Minolta CR200 Chromameter (Minolta Camera Co. Osaka, Japan) (Figure 3-9).

The colour spacing system used was $L^* C^* h^\circ$, where L^* for skin brightness ranges from 0 = black to 100 = white; C^* , for chroma, represents colour saturation which varies from dull (low value) to vivid colour (high value); and h° (hue angle) is defined as a colour wheel with red-purple at an angle of 0° , yellow at 90° , bluish-green at 180° , and blue at 270° (McGuire, 1992; Maguire, 2000 pers. com.).



Figure 3-9 Minolta CR200 Chromameter.

The same fruits were used for measuring fruit firmness using the KIWIFIRM equipment (Figure 3-10) (Industrial Research Limited, New Zealand) (Jeffrey, 2000 pers. com.). Data were expressed in one unitless digit scale from 0.0 to 9.9. Firmness was also determined on the following scale (1-5); 1 = flaccid, 2 = slightly firm, 3 = moderately firm, 4 = firm, and 5 (and more than 5) = very firm (Miller and Rise, 1986).

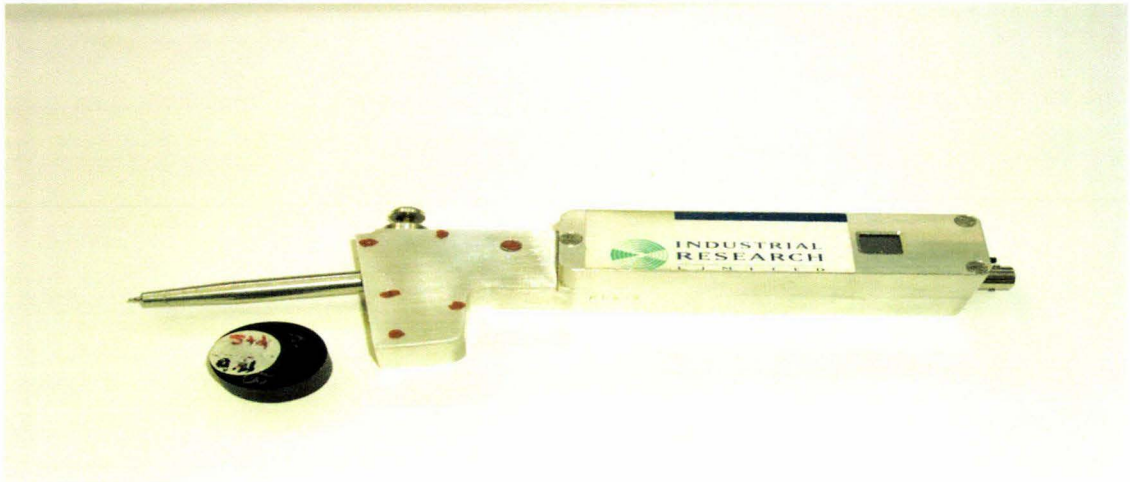


Figure 3-10 The KIWIFIRM (Industrial Research Limited, New Zealand).

3.3.3 POSTHARVEST DECAY AND VISUAL QUALITIES

The incidence of postharvest decay (fruits with visible mycelial growth) was monitored at the same times as for colour and firmness measurements. Data were expressed as a percentage of decayed fruits (Garcia *et al.*, 1998). At the same time, any off-odours from packaged products were monitored. To detect the off-odours, the sense of smell was used (Emond *et al.*, 1995).

To determine visual quality, the external appearance of chillies among the different treatments was examined on a daily basis. The quality parameters were categorised into 2 parts: Condensation and Visual Quality. A grade was also given to each package. The following grades were used: **Y** for presence of condensation, **N** for no condensation, **D** for dried look, **F** for fresh look, **R** for rotted appearance and **S** for shrivelled or soft appearances. These quality parameters and techniques for examining external appearance were applied from (Emond *et al.*, 1995).

3.4 DATA ANALYSIS

All data from this experiment were processed using Microsoft Excel 97 (Microsoft Corp.). All analyses were applied directly without transformation to data. In Chapter 4 physiological property of fresh chillies, all collected data were analysed and expressed according to the units proposed by Banks *et al.* (1995).

The data on gas exchange, respiration, skin permeances to O₂ and CO₂ were analysed using the temperature dependence according Arrhenius's law from Eq. 3-8. The reference temperature for Arrhenius's law was in all cases fixed at 15°C (288.15 K). The non-linear equations were applied directly, using SAS (Statistical Analysis System), without transformation to data or equations.

$$k = k_{\text{ref}} \cdot e^{\frac{Ea}{R} \left[\frac{1}{T_{\text{ref}}} - \frac{1}{T} \right]} \quad (\text{Eq. 3-8})$$

Where:

- R = gas constant (8.314 J mol⁻¹ · K⁻¹)
- Ea = energy of activation (J·mol⁻¹) expresses the dependence of given rate k (exact unit depends on the rate) on temperature T (K)
- k_{ref} = the rate at arbitrarily chosen reference T_{ref} (K)
- T_{ref} = reference temperature (288.15 K, (15°C))
- T = measured temperature (K)

For Chapter 5, effects of storage temperature and packages on chilli qualities, the average of data from 3 experiments were analysed using the General Linear Model (GLM) analysis of variance and Tukey multiple range test (p<0.05) for comparison of means using MINITAB version 12.1 (Minitab Inc.).

CHAPTER 4

PHYSIOLOGICAL PROPERTIES OF GREEN 'CAYENNE' CHILLIES

4.1 INTRODUCTION

Fresh chillies generally have a short shelf life after harvesting. Their physiological and biochemical activities are continuing at a rapid rate, particular at ambient conditions. This can accelerate weight loss, deterioration, senescence and the rate of growth of pathogens (Wall and Bosland, 1993), which could rapidly reduce produce quality and sales revenues.

The most appropriate handling practices and storage conditions must be determined, in order to prolong the shelf life of fresh chillies. This requires an understanding of the physiological characteristics of fresh chillies, e.g. respiration rate, skin permeance to water vapour (P'_{H_2O}) as well as skin permeance to CO₂ and O₂ (P'_{CO_2} , P'_{O_2}). Therefore, the objectives of this chapter were to study the postharvest physiological attributes of green 'Cayenne' chillies under prevailing conditions, in order to facilitate design and development of strategies for management of quality losses of fresh chillies.

4.2 RESPIRATION RATE (r_{CO_2})

Respiration rates, r_{CO_2} , of green 'Cayenne' chillies were studied at four different temperatures (5, 10, 20 and 30°C). The respiration rate increased exponentially with increasing temperature (Figure 4-1). Values for respiration rate increased about 20 fold from 0.07 $\mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{s}^{-1}$ to 1.34 $\mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{s}^{-1}$ as temperature increased from 5 to 30°C. The estimates for activation energy ($Ea_{r_{CO_2}}^{\max}$) and respiration rate at reference temperature ($r_{CO_2, \text{ref}}^{\max}$) are given in Table 4-1. The variation in respiration rate of fresh chillies increased with increasing storage temperatures (Figure 4-1).

Table 4-1 Parameter estimates and standard errors (SE) resulting from non-linear regression analysis of the data on the effects of temperature on respiration^a

$r_{\text{CO}_2, \text{ref}}^{\text{max}}$ ^b (SE)	$Ea_{r_{\text{CO}_2}^{\text{max}}}$ (SE)	R^2 ^c	n ^d
0.32 (4.06)	69813 (3.11)	95.90	111

^a The standard errors (SE) are expressed as a percentage, relative to the estimated values.

^b $r_{\text{CO}_2, \text{ref}}^{\text{max}}$ is the maximum CO₂ production rate ($\mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{s}^{-1}$) at reference temperature T_{ref} ($= 15^\circ\text{C}$);

$Ea_{r_{\text{CO}_2}^{\text{max}}}$ is the energy of activation ($\text{J}\cdot\text{mol}^{-1}$) of the maximum CO₂ production rate ($r_{\text{CO}_2, \text{ref}}^{\text{max}}$)

^c R^2 is the percentage variance accounted for by regression

^d n is the number of observations

4.2.1 DISCUSSION OF RESPIRATION RATE

The exponential relationship between temperature and respiration rate for fresh green chillies confirmed that r_{CO_2} is governed by temperature (Hardenburg *et al.*, 1986). The results observed in the current experiment coincide very well with literature data available in Table 4-2, which gives an overview of published values of respiration rates for fresh green chillies.

There is no literature data on $Ea_{r_{\text{CO}_2}^{\text{max}}}$ of green 'Cayenne' chillies and/or other types of hot peppers. However, as the $Ea_{r_{\text{CO}_2}^{\text{max}}}$ of bell peppers (Chen *et al.*, 2000) is less than that of chillies, the respiration rate of bell peppers are less sensitive to temperature than that of hot chillies.

Furthermore, the respiration rate of bell peppers ($\approx 0.01 \mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{s}^{-1}$, at 15°C (Chen *et al.* 2000) is significantly lower than that of hot chillies ($\approx 0.32 \mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{s}^{-1}$). Considering both $Ea_{r_{\text{CO}_2}^{\text{max}}}$ and respiration rate, the biological properties of hot peppers might be expected to be more sensitive to temperature difference. This result is consistent with the report of Lownds *et al.* (1994) and Wall and Berghage (1996) in that

fresh green chilli peppers (*Capsicum annuum L.*, New Mexican Type) are more perishable than bell peppers.

Table 4-2 Estimates of respiration rate of fresh green chillies from previously published works.

Cultivar	Temperature (°C)	Respiration Rate ($\mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{s}^{-1}$)	Source
Anaheim	5	0.04	Kader <i>et al.</i> 1989
	10	0.06	
	12.5	0.15	
Capsicum annuum L.	5	0.06	JunSoo and DongSun 1997
	10	0.08	
Caysan SPS705	22	0.47	Krajayklang <i>et al.</i> 2000
Changjiao	22	0.63	Lu <i>et al.</i> 1990
Choorahong	20	0.95	Gross <i>et al.</i> 1986
New Mexico 6-4	not reported	0.92	Biles <i>et al.</i> 1993
Nogkwang variety	10	0.06	Lee <i>et al.</i> 1994

Chen *et al.* (2000) reported that, as the energy of activation for bell peppers respiration was very close to the energies of activation for film permeabilities to the respiratory gases, the gas conditions inside the package were almost insensitive to temperatures between 0 and 30°C. This could be beneficial for maintaining the appropriate atmospheric gas composition of modified atmosphere packaging of chillies, as in Thailand, much of the time chillies are subjected to varying conditions and are often stored and transported under high temperatures.

Keeping fresh green chillies at 5°C could minimise the respiration rate (Figure 4-1). Low temperature storage can be used for prolonging the shelf life of green 'Cayenne' chillies. However, some studies reported that the pepper fruit is relatively susceptible to chilling injury at temperatures below 7°C thereby increasing the respiration rate and limiting the shelf life (Burzo *et al.*, 1994). In this experiment, there was no rise in respiration rate observed at 5°C, nor any chilling injury symptoms.

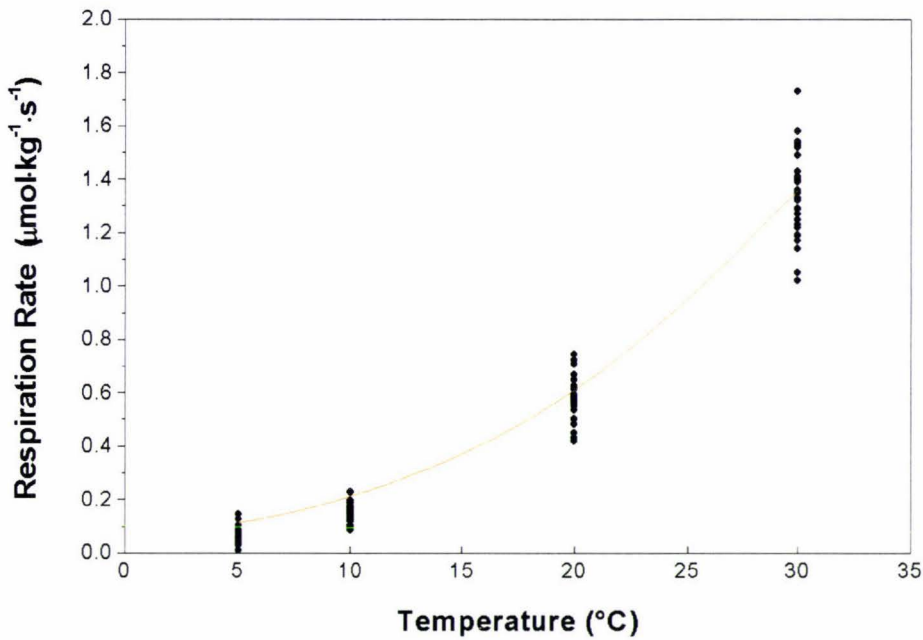


Figure 4-1 Temperature effect on respiration of green 'Cayenne' chillies for temperatures ranging from 5 to 30°C.

(Solid line was fitted using Eq. 3-8)

4.3 SKIN PERMEANCES TO CO₂ AND O₂ (P'_{CO_2} , P'_{O_2})

The skin permeance to CO₂ and O₂ (P'_{CO_2} , P'_{O_2}) of chillies increased exponentially with increasing temperature (Figure 4-2). However, values for P'_{CO_2} and P'_{O_2} increased only 2 folds as temperature increased from 5 to 30°C. The largest variations in P'_{CO_2} and P'_{O_2} were found in fruits stored at 10°C.

The estimates for activation energy and skin permeance to both CO₂ and O₂ at the reference temperature ($P'_{CO_2,ref}$ and $P'_{O_2,ref}$) are given in Table 4-3. The activation energy of the permeance for these two gases appeared to be similar. The skin permeance at reference temperatures were also very close. The approximate ratio between $P'_{CO_2,ref}$ and $P'_{O_2,ref}$ was 1.06.

Table 4-3 Parameter estimates and standard errors (SE) resulting from non-linear regression analysis of the data on the effects of temperature on chilli skin permeance to O₂ and CO₂^a.

Gas (i)	$P'_{i,ref}$ (SE) ^b	Ea'_i (SE) ^c	R^2 ^d	n ^e
O ₂	185 (0.96)	19948 (3.07)	93.70	80
CO ₂	197 (0.80)	18798 (2.74)	94.89	80

^a The standard errors (SE) are expressed as a percentage, relative to the estimated values.

^b $P'_{i,ref}$ is the skin permeance to gas i, (O₂ and CO₂), (pmol·s⁻¹·m⁻²·Pa⁻¹) at reference temperature T_{ref} (= 15°C).

^c Ea'_i is the energy of activation (J·mol⁻¹) of skin permeance to gas i

^d R^2 is the percentage variance accounted for by regression

^e n is the number of observations.

4.3.1 DISCUSSION OF GAS PERMEANCE

P'_{CO_2} and P'_{O_2} of fresh chillies increased just 2 fold with increasing temperature (5 to 30°C), as compared to the 20 fold increase in respiration rate (section 4.2). This can be explained by the fact that the energies of activation for skin permeance were comparably lower than the energy of activation for respiration (Table 4-1 and Table 4-3).

Chen *et al.* (2000) found that the permeability of capsicum was relatively temperature independent as most of the diffusion takes place in air through gaps underneath the stem plate (de Varies *et al.*, 1996). Banks *et al.* (2001) also reported that the majority of the gas exchange of CO₂ and O₂ occurs through the stem end of bell peppers. Our measured ratio of P'_{CO_2} to P'_{O_2} of 1.06 was relatively consistent with the same ratio for whole bell pepper (of 0.99) measured by Banks *et al.* (2001).

Therefore, it could be suggested that the major pathway of gas exchange of green 'Cayenne' chillies occurs through the stem end, and as a consequence their skin permeances to CO₂ and O₂ are considered reasonably temperature independent.

Compared to certain varieties of bell peppers, P'_{CO_2} and P'_{O_2} of 'Cayenne' chillies are lower than those of bell peppers cultivar 'Tasty' (Chen *et al.*, 2000) and 'Samanta' (Banks *et al.*, 2001).

Beaudry *et al.* (1992), Cameron *et al.* (1995) and Chen *et al.* (2000) reported the average energy of activation for LDPE film to be about 31100 to 39720 J·mol⁻¹. Cameron *et al.* (1995) also provided values for polypropylene (PP), polyvinylchloride (PVC) and cellulose acetate, which are approximately 46900, 56300 and 21000 J·mol⁻¹, respectively. Meanwhile from this study, the activation energy of chilli skin permeance to gas (CO₂ and O₂) was approximately 19000 J·mol⁻¹. Hence plastic films are more sensitive to any temperature changes than gas permeances of skin.

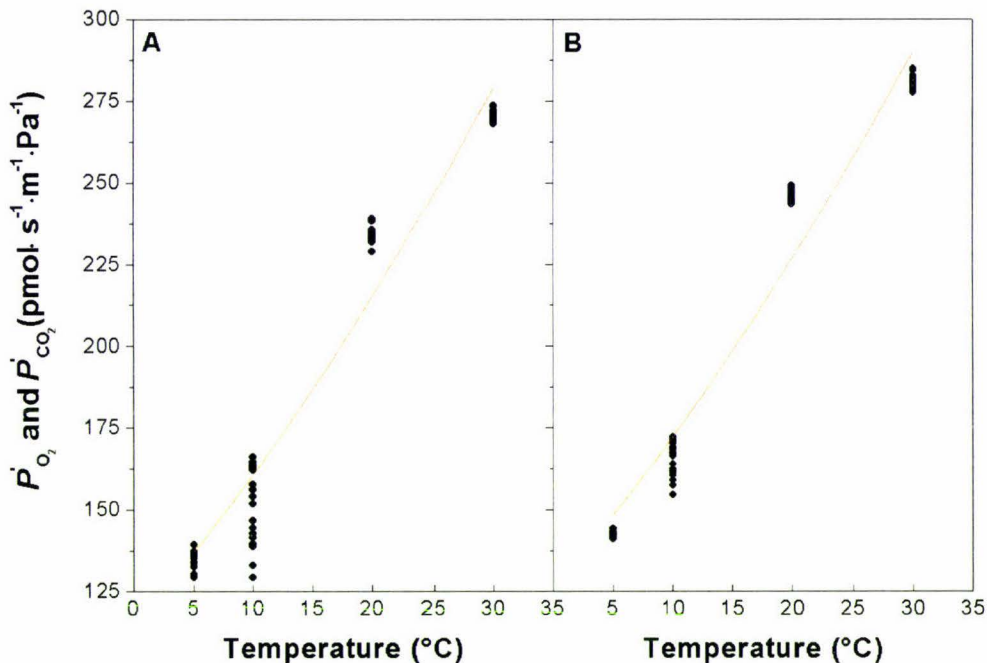


Figure 4-2 Temperature affects on skin permeance to A) O₂ (P'_{O_2} , pmol·s⁻¹·m⁻²·Pa⁻¹); and B) CO₂ (P'_{CO_2} , pmol·s⁻¹·m⁻²·Pa⁻¹), of green 'Cayenne' chillies held at temperatures between 5 and 30°C.

(Solid lines were fitted using Eq. 3-8)

4.4 PARTIAL PRESSURE OF INTERNAL O₂ AND CO₂ ($p_{\text{CO}_2}^i$ AND $p_{\text{O}_2}^i$)

The internal partial pressure of O₂ ($p_{\text{O}_2}^i$, kPa) declined to half its value, with temperature increasing from 5 to 30°C. Meanwhile, the internal partial pressure of CO₂ ($p_{\text{CO}_2}^i$, kPa) increased approximately 9 times (Figure 4-3). The total internal partial pressure for O₂ and CO₂ ($p_{\text{CO}_2}^i$ plus $p_{\text{O}_2}^i$) was approximately 21.57 ± 0.30 kPa.

4.4.1 DISCUSSION OF INTERNAL GASES

As storage temperature is increased, $p_{\text{O}_2}^i$ declines and $p_{\text{CO}_2}^i$ increases in chillies. This could be explained by the different degrees in which rate of respiration and skin permeances responds to the changes of temperatures (section 4.2 and section 4.3). As the energy of activation of respiration is larger than that of skin permeance in response to an increasing in temperature, respiration rate will increase faster than skin permeance. As a results, the level of internal oxygen partial pressure progressively decreased, whilst the internal CO₂ partial pressure continuously accumulate with increasing temperature.

Similar relationship between the changes in $p_{\text{O}_2}^i$ and $p_{\text{CO}_2}^i$ and increasing temperature has been found in apples, which is reported by Beaudry *et al.* (1992), Cheng *et al.* (1998) and Cheng (1999). When the sum of internal partial pressure of O₂ and CO₂ was close to 21, it could be concluded that the route of gas exchange was through air (Beaudry *et al.*, 1992; Cheng *et al.*, 1998; Cheng, 1999; Banks *et al.*, 2001). This is consistent to the result of this study (≈ 21.57 kPa) and it also supports the results in section 4.3, in that the route of gas exchange of chillies is mainly occurring though the stem end.

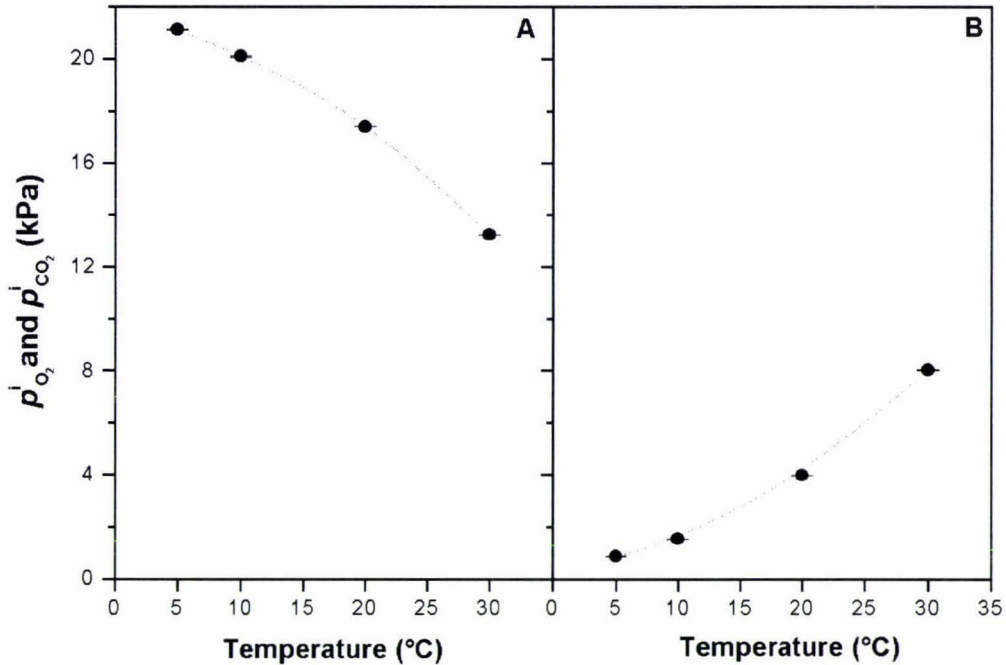


Figure 4-3 Variation in A) internal partial pressure of O₂ ($p_{O_2}^i$, kPa), and B) internal partial pressure of CO₂ ($p_{CO_2}^i$, kPa), of green 'Cayenne' chillies held at 5 and 30°C.

(Data are means of 20 replicates, error bars represent SE of the mean)

4.5 SURFACE AREA MEASUREMENT

The approximate length of single green 'Cayenne' chilli (including its stem area) for this study is 13.10 ± 1.13 cm. The diameter (measured at the centre of the fruit) is about 1.07 ± 0.11 cm. The average volume of a fruit is 8.75 ± 1.60 ml. The approximate fresh weight of single chilli is 5.68 ± 0.85 g.

The estimated surface area of an averaged chilli is 0.0034 ± 0.0004 m². The relation of surface area with fresh weight (Figure 4-4A) and volume (Figure 4-4B) of individual fruit were linear and explained more than 85% of the total variation in the data (Eq. 4-1 and Eq. 4-2). The relationship between rate of water loss ($\mu\text{mol}\cdot\text{s}^{-1}$) and surface area at ambient temperature ($\approx 20^\circ\text{C}$) was linear and explained 78% of the total variation in the data (Figure 4-5; Eq. 4-3).

4.5.1 DISCUSSION OF CHILLI SURFACE AREAS

The total variation in the relationship (40 replicates) between surface area and volume ($R^2 = 0.95$) could be explained better than those in surface area with weight ($R^2 = 0.87$). The results were similar to the report on the characterisation of surface area of apples, in which the surface area had a higher correlation to volume than to fresh weight (Clayton *et al.*, 1995).

The good R^2 found in this data will enable the determination of surface area of 'Cayenne' peppers in future experiments by determining fresh weight or volume. Similar relationships have been developed for green bell pepper (Mittal and Osunde-Macfoy, 1984; Mittal and Osunde-Macfoy, 1987) and apples (Clayton *et al.*, 1995).

Postharvest water loss (weight loss) of green 'Cayenne' chillies at room temperature ($\approx 20^\circ\text{C}$) was significantly and positively correlated with surface area (SA). As the rate of water loss from fresh chillies is governed by Fick's law of diffusion (Eq. 3-2), thus based on the skin permeance, which is expressed per unit of skin area, the rate of water loss is directly related to surface area (26 replicates). However, the scatter in this relationship (Figure 4-5) could be related to the variation in water permeances among these fruit (Maguire, 1998).

Considering Eq. 4-3., constant offset value in this relationship (≈ 0.356). It could be interpreted that even when the surface area of chilli is totally covered, i.e. by wax coating, (presumably surface area equals to 0), water loss still occurs.

The surface area of a chilli was determined without taking the area of the stem end into account, since this area was assumed to be relatively small, compared to the whole fruit. However, the route of gas exchange between internal and external atmospheres of chillies occurs through the stem end (section 4.3 and section 4.4, Dadzie *et al.* (1996) and Chen *et al.* (2000)). Thus, this part of a chilli can be an additional route for exchanging water vapour as well. In contrast to Lownds *et al.* (1993) who state that the skin is the main route for water loss of peppers, results from green 'Cayenne' chillies study indicate that 89% of the total water loss is going through the stem end. This could be due to the differences in fruit cultivar and difference in experimental techniques, which might contribute to difference in water loss characteristics.

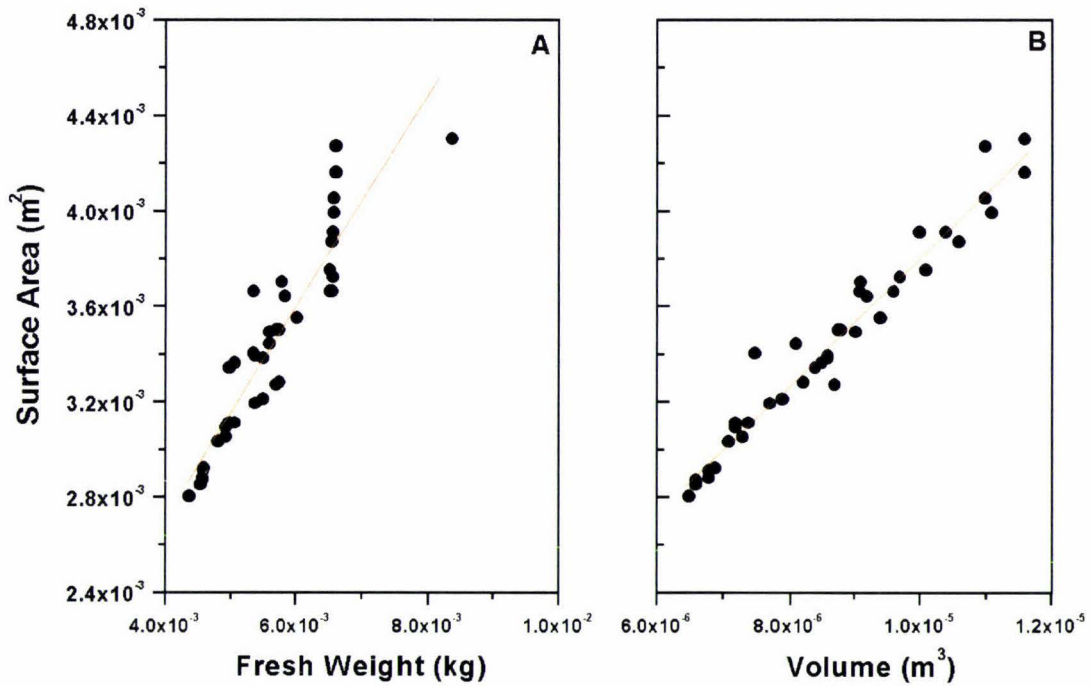


Figure 4-4 Relations between surface area and A) fresh weight and B) volume of green 'Cayenne' chillies.

$$\text{A: } SA = (9.304\text{E-}4 \pm 1.723\text{E-}4) + (0.444 \pm 0.030) \cdot \text{Wt} \quad (\text{Eq. 4-1})$$

$$R^2 = 85\%$$

$$\text{B: } SA = (0.001 \pm 8.366\text{E-}5) + (268.955 \pm 9.474) \cdot V \quad (\text{Eq. 4-2})$$

$$R^2 = 95\%$$

Where;

SA = Surface area (m²)

Wt = Fresh weight (kg)

V = Volume (m³)

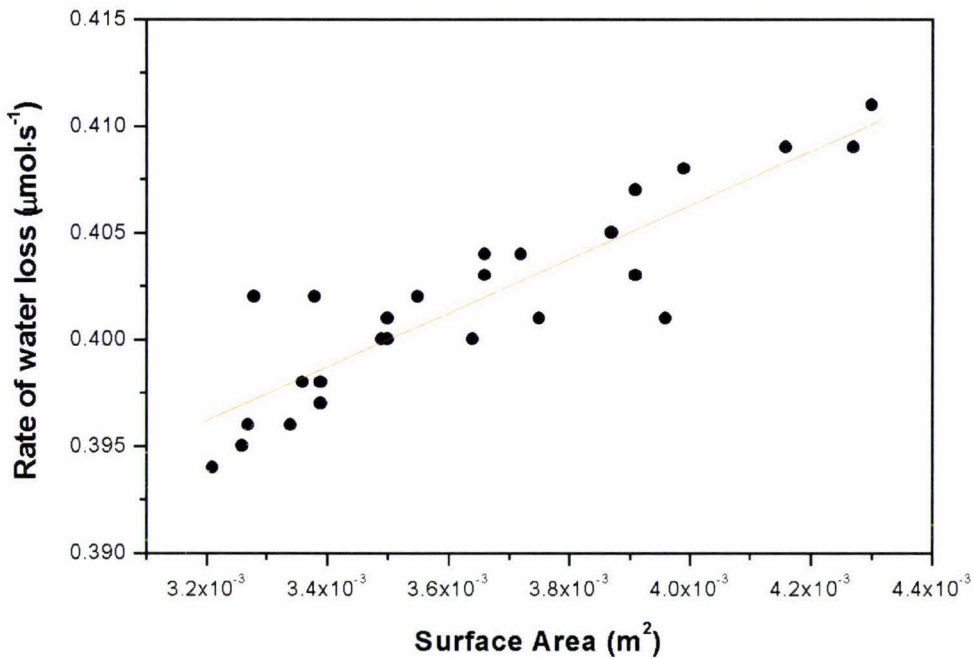


Figure 4-5 Relationship between rate of water loss and surface area, at temperature (20°C).

$$r'_{H_2O} = (0.356 \pm 0.005) + (12.610 \pm 1.290) \cdot SA \quad (\text{Eq.4-3})$$

$$R^2 = 78\%$$

Where;

r'_{H_2O} = Rate of water loss (calculated with rates of mass loss correcting for respiration rate) ($\mu\text{mol s}^{-1}$)

SA = Surface area (m^2)

4.6 SKIN PERMEANCE TO WATER VAPOUR (P'_{H_2O})

The skin permeance to water vapour, P'_{H_2O} , of fresh chillies increased when the temperature was elevated from 5 to 10°C. However, the skin permeance to water vapour of chillies decreased sharply when the temperature was raised beyond 10°C (Figure 4-6). There was an approximate 2.5 times decrease in P'_{H_2O} value when the temperature

was moved up from 10 to 30°C. The overall average $P'_{\text{H}_2\text{O}}$ for green 'Cayenne' chillies was $201.78 \text{ nmol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot\text{Pa}^{-1}$.

Skin permeance to water vapour is calculated from Eq. 3-2. To allow this calculation an estimate of the driving force is required ($\Delta p_{\text{H}_2\text{O}}$, Pa). The driving force describes the gradient in water vapour between the fruit and the environment. The magnitude of this gradient ($\Delta p_{\text{H}_2\text{O}}$) is dependent on both temperature and relative humidity (measured by wet bulb thermometer in this instance) of the surrounding air and temperature and water activity of the product.

In this experiment the driving force at each temperature was different. Water vapour permeance when plotted against driving force shows an exponential decline as driving force is increased (Figure 4-7). However, measurements taken at 5°C are not consistent with this trend.

4.6.1 DISCUSSION OF SKIN PERMEANCE TO WATER VAPOUR

Estimation of the driving force for water loss is an area where errors are easily introduced (Gaffney *et al.*, 1985). All temperature probes and relative humidity sensors have errors associated with them. For example, the measurement of fruit temperature is dependent on the temperature probe being used and the placement of that probe. Water activity of intact horticultural products is very difficult to measure and in most cases, an estimation is used.

The extent of these errors on the subsequent calculation of water vapour permeance depends on the magnitude of the driving force. A 0.20 kPa error in $\Delta p_{\text{H}_2\text{O}}$ when the driving force is 2 kPa leads to a 1% error in water vapour permeance, however the same error at 0.05 kPa driving force leads to a 66% error in water vapour permeance (calculation not shown). As the driving force at each temperature was different in this experiment, the magnitudes of the possible errors were also different.

The error level from thermistor probes used for measuring temperatures (skin and wet/dry bulb temperature) during Δp_{H_2O} determination was $\pm 0.2^\circ\text{C}$ (Eq. 3-3). Skin temperature and wet bulb temperature were hypothesised as the main contributors causing the errors during estimating Δp_{H_2O} . Percentages of errors in P'_{H_2O} compared to the overall average P'_{H_2O} were calculated when skin temperature or wet bulb temperature showed errors (assuming no error in other temperatures), Figure 4-8 and Figure 4-9, respectively.

The percentages of errors in P'_{H_2O} (Figure 4-8) were calculated by calculating at rate of water loss for each model environment (Table 4-4) assuming same P'_{H_2O} in each temperature. Then Δp_{H_2O} was calculated by increasing and decreasing the existing skin temperatures at a constant either side of the experimental value of wet bulb temperature. The skin temperatures with errors were used to calculate Δp_{H_2O} . The Δp_{H_2O} with errors were then use to calculate P'_{H_2O} based on the rate of water loss in that environment (Table 4-4, Eq. 3-2). This was repeated for wet bulb temperature (Figure 4-9).

The percentages of errors at 5°C were highest; approximately 30 and 940%, when considering regarding 0.15°C errors caused by skin temperature and wet bulb temperature, respectively (Figure 4-10). Percentages of errors reduced as storage temperatures were increased (Figure 4-10) as would be expected because of the increase in Δp_{H_2O} .

Maximum errors assuming a $\pm 0.2^\circ\text{C}$ error in both skin temperature and wet bulb temperature were calculated as limits on the data (Figure 4-11). This highlights that the highest errors in P'_{H_2O} estimation occurred at 5°C and the errors were decreased when the temperature was increased (Figure 4-11).

Table 4-4 Experimental values of dry/wet bulb temperature (°C) and rates of water loss (nmol·s⁻¹)

Temperature (°C)	Dry Bulb Temperature (°C)	Wet Bulb Temperature (°C)	Rate of Water Loss (nmol·s ⁻¹)
5	5.07	4.80	25.78
10	9.64	9.06	89.72
20	19.71	15.96	401.68
30	29.88	20.80	894.05

The effects of temperature observed by other researchers i.e. Schonherr *et al.* (1979) were not seen in our data (Figure 4-6). The skin permeance to water vapour (P'_{H_2O}) of fresh chillies tended to decrease with increasing temperature and Δp_{H_2O} . The data between 5 and 10°C however appears not to follow these trends but the levels of errors likely at 5°C conditions (Figure 4-11) questions the validity of the data at 5°C.

The effect of temperature was confounded by the different driving forces the chillies were subjected to (Figure 4-7). From this data, it would appear that the effects of driving force or relative humidity may be larger than those of temperature effects in the case of chillies. However further work will be required to try and separate the effect of temperature from relative humidity on water vapour permeance of chillies.

P'_{H_2O} increased when driving force was reduced, for fresh chillies (Figure 4-7). This is consistent with observations by previous researchers who found increases in skin permeance to water vapour of apples with a decrease in driving force (Δp_{H_2O}) (Smith, 1933; Lentz and Rooke, 1964; Fockens and Meffert, 1972). These changes are likely to occur because the cuticle of intact fruit, can also respond to the relative humidity or driving force. The intact (isolated) cuticle of pepper fruit can sorb the increasing amounts of water with increasing atmospheric water vapour pressure (Chamel *et al.*, 1991). The responsive ability to the relative humidity of intact cuticle is dependent on the soluble cuticular lipids, their physical arrangement and resultant transport properties based upon the existence of polar pores through the hydrophobic materials (Schonherr

and Schmidt, 1979). Temperature and RH in the immediate environment and temperature of fruit, water activity (a_w) also affect the driving force (Gaffney *et al.*, 1985; Maguire 1998). Dissolved solutes can affect the level of water vapour partial pressure of fruit skin (Gaffney *et al.*, 1985). This can be expressed as water activity (a_w), the ratio of partial pressure of water vapour in steady state with solution ($p_{H_2O}^{soln.}$) to that of the saturated water vapour partial pressure of pure water ($p_{H_2O}^{sat.}$).

For this experiment, a_w of chillies was fixed as 0.995, which is generally determined as a_w of fresh produce (Maguire and Tanner, 2000 pers.com). The expected error from a 1% change in water activity would lead to only a 3.5% error in water vapour permeance at 20°C (calculation not shown). The extent of this error could be expected to increase at lower temperatures but is negligible compared to the likely errors from other components of driving force (Figure 4-8 and Figure 4-9).

In this experiment the contribution of weight loss due to carbon loss during respiration was considered negligible. The expected level of this error could contribute was 0.7% (calculations not shown), again considerably less than those calculated for skin or wet-bulb temperature (Figure 4-8 and Figure 4-9).

Recommendations for minimising water loss often include the reduction of temperature and the increase in humidity around the chillies (reduced driving force), which would hold true, when assuming a constant skin permeance to water vapour in different driving force environments. However, the evidence presented here suggests that minimising driving force may increase the water vapour permeance, which could have a detrimental effect on the overall rates of water loss. However, the rates of water loss were decreased significantly by reducing the driving force despite any change in skin permeance to water vapour (Figure 4-12). The increases in permeance caused by decreased driving force as observed in this experiment would not be sufficient to nullify the benefits of increased relative humidity.

Considerably more work is required to separate the effects of temperature and relative humidity on skin permeance to water vapour. The extent of possible errors at low temperature and driving force environment will mean greater care and precision will be

taken to obtain valid results in these environments. Understanding of how temperature and relative humidity influence water vapour permeance will lead to better management of water loss in fresh chillies.

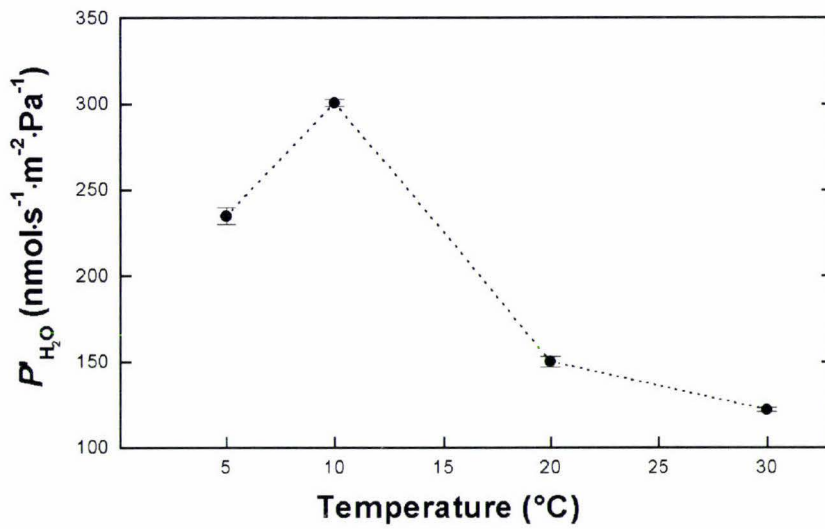


Figure 4-6 Variation in skin water vapour permeance (P_{H_2O}) of green 'Cayenne' chillies held at between 5 and 30°C.

(Data are means of 29 replicates, error bars represent SE of the mean)

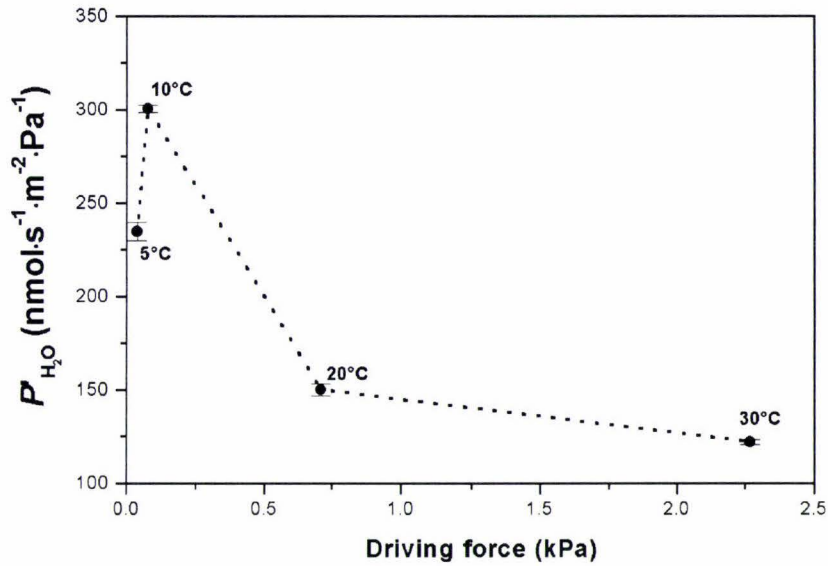


Figure 4-7 The relationship between P_{H_2O} and driving force (Δp_{H_2O}) of green 'Cayenne' chillies held between 5 and 30°C.

(Data are means of 29 replicates, error bars represent SE of the mean)

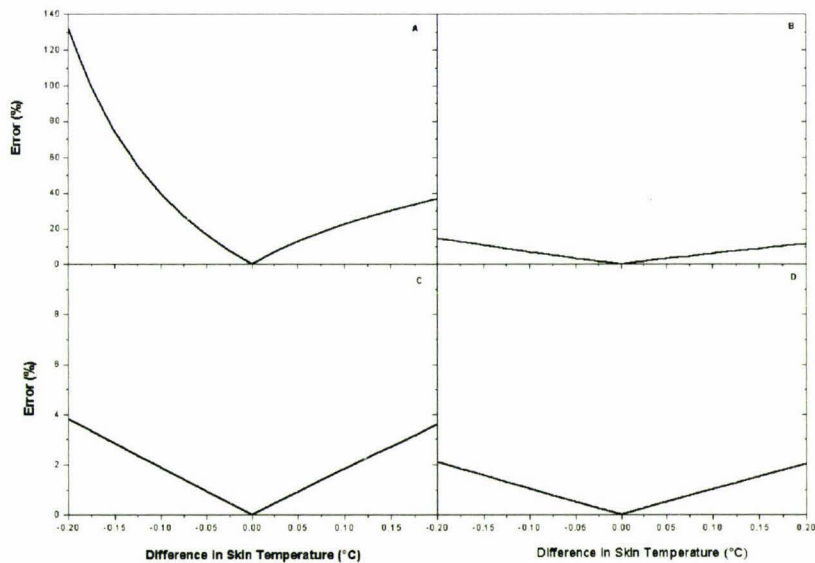


Figure 4-8 Percentage error in water vapour permeance of green 'Cayenne' chillies assuming small errors in skin temperature measurement, at A) 5 °C, B) 10°C, C) 20 °C and D) 30 °C (also see Table 4-4).

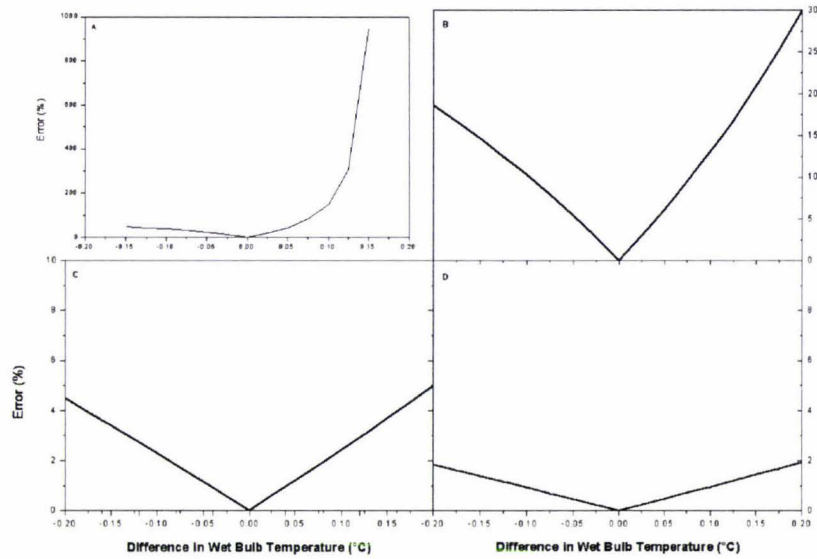


Figure 4-9 Percentage error in water vapour permeance of green 'Cayenne' chillies assuming small errors in skin temperature measurement, at A) 5 °C, B) 10°C, C) 20 °C and D) 30 °C (also see Table 4-4).

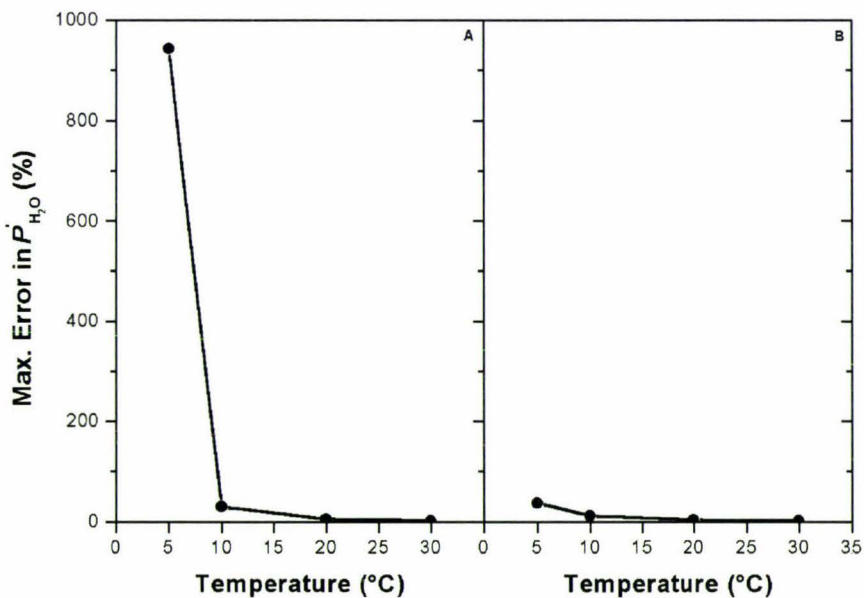


Figure 4-10 Maximum percentage of errors in P'_{H_2O} of green 'Cayenne' chillies assuming an error of +0.2 °C in A) wet bulb temperature and B) skin temperature held between 5 and 30 °C (also see Table 4-4).

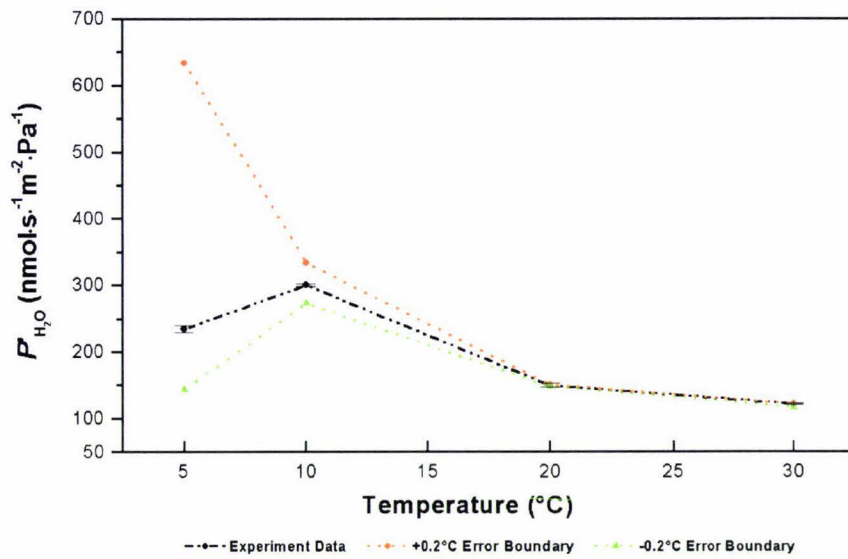


Figure 4-11 Boundary assuming $\pm 0.2^\circ\text{C}$ error on skin and wet bulb temperature, with the experimental values for water vapour permeance ($P'_{\text{H}_2\text{O}}$) of green 'Cayenne' chillies held between 5 and 30 °C.

(Data are means of 29 replicates, error bars represent SE of the mean)

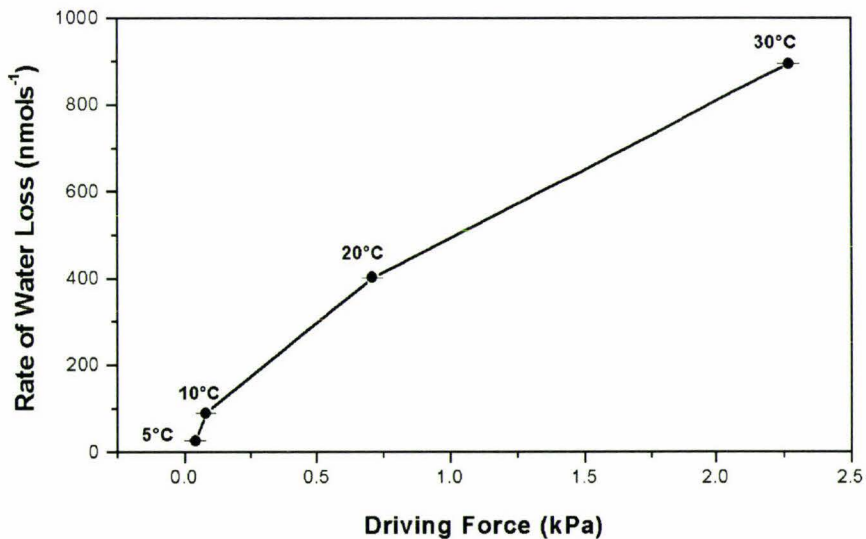


Figure 4-12 Relationship between rate of water loss and driving force ($\Delta p_{\text{H}_2\text{O}}$) of green 'Cayenne' chillies held between 5 and 30°C

(Data are means of 29 replicates, error bars represent SE of the mean)

4.7 RELATIONSHIP OF WATER ACTIVITY (A_w) AND WEIGHT LOSS

The water activity of fresh chillies (approximately 1-2 hours after harvesting) was about 0.95. Over a 14-day storage period, green chillies lost weight and their a_w decreased. The higher the temperature, the more dramatic the changes of weight and a_w were (Figure 4-13). Further, water activity was negatively related weight loss.

The Guggenheim-Anderson de Boer (GAB) sorption model was used to explain water activity in terms of the actual fresh weight during storage (Eq. 4-4). According (Kiranoudis *et al.*, 1993; Adamicki, 1997), the GAB sorption model gave a close fit to their experimental data for adsorption and desorption of green and red peppers. The GAB model also has been considered as a relatively simple model with a small number of parameters and can be applied to a high range of water activities.

Normally, the GAB-model is used to relate a_w to moisture content (MC). MC can be described in terms of fresh weight (Mt) assuming the total dry matter (DM · M0) doesn't change during time (Eq. 4-5). Combining Eq. 4-4 and Eq. 4-5 and solving for a_w resulted in an expression for a_w in function of fruit weight Mt (Eq. 4-6).

$$MC = \frac{M_0 \cdot C \cdot K \cdot a_w}{[(1 - K \cdot a_w) \cdot (1 - K \cdot a_w + C \cdot K \cdot a_w)]} \quad (\text{Eq. 4-4})$$

$$MC = \frac{Mt - DM \cdot M_0}{Mt} \quad (\text{Eq. 4-5})$$

where:

- MC = Moisture content (dry basis)
- Mt = Mass at determined time-t (fresh weight)
- DM = Dry Matter (approximately 15%)
- M_0 = Mass at starting time-0 (wet basis)
- M_o = Monolayer moisture content (dry basis)
- C, K = Constants in sorption isotherm
- a_w = Water activity

$$a_w = -\frac{1}{2} \left[\frac{\left[\begin{aligned} &(-C + 2 + Mo \cdot C) \cdot Mt + DM \cdot M0 \cdot C - 2DM \cdot M0 - \\ &(C \cdot (-C + 4Mo - 2Mo \cdot C + Mo^2 \cdot C) \cdot Mt^2 + \\ &2C \cdot DM \cdot M0 \cdot (-C + Mo - 2Mo) \cdot Mt + DM^2 \cdot Mo^2 \cdot C^2 \end{aligned} \right]^{\frac{1}{2}}}{[(C-1) \cdot Mt + DM \cdot M0 - DM \cdot M0 \cdot C] \cdot K} \right]$$

(Eq. 4-6)

The weight loss data was analysed with Eq. 4-6 using nonlinear regression analysis in SAS (Statistical Analysis System). Attempts to fit the three parameters of Eq. 4-6 (C , K and Mo), proposed by (Kaymak-Ertekin and Sultanoglu, 2001) resulted in failure of the model to converge. By fixing the value for parameter Mo to the value of 0.5 (chosen subjectively), reasonable values for the three parameters were obtained. The results were shown in Table 4-5. Consequently, the GAB model was used, in this study, to relate the water activity (a_w) to the percentage of weight loss (fresh weight) with satisfactory results (Figure 4-13). The predicted a_w s using the GAB-based model explained more than 99% of the total variation in the data. (Figure 4-13).

Table 4-5 Estimated GAB sorption model for green 'Cayenne' pepper in desorption

C^a	K^a	Mo^b	R^2^c (%)
2.0031	0.6158	0.5	99.92

^a Constants in GAB sorption model

^b The monolayer moisture content (arbitrarily fixed as 0.5, during nonlinear regression)

^c Percentage variance accounted for by regression

4.8 DISCUSSION OF RELATIONSHIP OF WATER ACTIVITY (A_w) AND WEIGHT LOSS

The experimental values of water activity (a_w) of fresh chillies, approximately 0.95, from this study were considerably lower than those estimated values of peppers (0.992-0.997) and other vegetables (0.990) proposed by (Chirife and Ferro Fontan, 1982). This could be due to the differences in methods of a_w measurement. (Chirife and Ferro Fontan, 1982) used freezing point temperatures of fruits and vegetables to derive the a_w ,

where this method is accurate measure of high water activity solute system. Meanwhile in this experiment the a_w was directly determined by the water activity meter (section 3.2.5).

Prior *et al.* (1977) and Chirife and Ferro Fontan (1982) stated that the direct measurement of a_w at very high water activities (i.e. >0.98) presents several difficulties when using the a_w -measurement device, most used in the food area. Errors in a_w measured by device can also arise from moisture loss during manipulation of sample (Prior *et al.*, 1977). Further the water activity meter does not take into account the loss of mass from respiring products during the measurement, which could also deviate measured water activity values (Maguire, 2001, pers.com). Thus variations from direct measurement could contribute errors to values of water activity, in this experiment. The GAB constants (C and K and M_0) from this study were considerably different from Kiranoudis *et al.* (1993) and Kaymak-Ertekin and Sultanoglu (2001). This could be due to the differences in chilli cultivars and their hygroscopic properties (Kiranoudis *et al.*, 1993).

Ben-Yehoshua (1987) and Kay (1991) mentioned that chillies have maximum permissible weight loss around 5-7%. Considering a_w -GAB-based model, in this study, the levels of water activity when chillies lost 5-7% of their weights were approximately 0.92, thus the ERH around chillies is estimated as 92%. As such, to minimise the weight loss of fresh chillies (to be less than 5-7%), the relative humidity around the products has to be higher than 92%. This is consistent to the relative humidity levels for lowering weight loss of capsicum recommended by Hardenburg *et al.* (1986). In addition, the water activity (also weight loss) rapidly changes when the temperature is increased. Therefore the low storage temperature (5-10°C) should be applied to storage condition of fresh chillies coinciding with the high relative humidity.

For future research, the moisture sorption isotherm characteristic of 'Cayenne' peppers should be defined for describing the relationship between the water activity (a_w) and the equilibrium moisture content at constant pressure and temperature in order to optimise the drying process, design packaging-storage condition and/or predict the shelf life of ground chilli products. This is important as ground chillies, particularly made from

‘Cayenne’ cultivar, and other related products (e.g. oleoresins) have been strong in demands according to the global spice market (Smith, 1982).

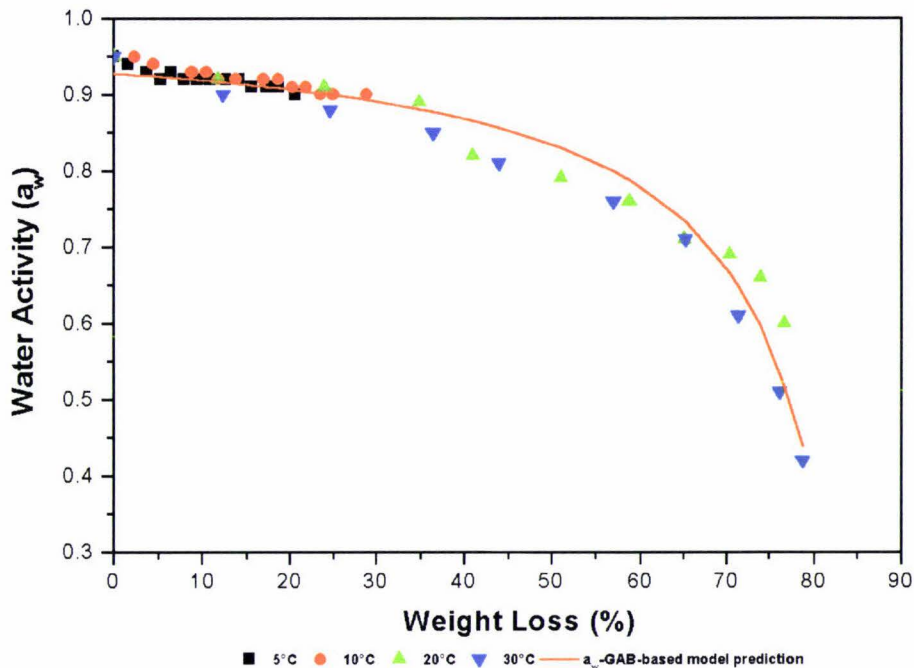


Figure 4-13 Water activity and prediction of GAB-based model for green ‘Cayenne’ chillies between 5 and 30°C.

4.9 CONCLUSION

Respiration was shown to increase much more dramatically than skin permeance to O_2 (P_{O_2}) and CO_2 (P_{CO_2}) as storage temperature was increased. This caused a decline in O_2 and increase in CO_2 levels in the chilli’s internal atmosphere. It would be recommended that reducing the storage temperature could minimise the respiration rate, then reduction in losses of postharvest qualities could be expected.

The major routes of O_2 , CO_2 and water vapour exchanges of green chillies found in this study was through the stem area. This supports that gas exchange characteristics of green ‘Cayenne’ chillies like those of other members of *Solanaceae* fruits (e.g. tomato or bell peppers), in which predominantly occur through the stem area.

A relationship between surface area and fresh weight or volume of green 'Cayenne' chillies was developed. This relationship will assist in future work in physiological or packaging modelling for 'Cayenne' and other cultivars. The positive relationship between rate of water loss and surface area confirms the theoretical relationships outlined by Fick's law (Eq. 3-2).

Water vapour permeance of chillies in this experiment was dependent on the driving force (temperature and RH) of the environment surrounding the fruit. Errors occurred during measurement, particularly at 5°C caused inconsistent trend of P'_{H_2O} regarding different storage temperatures. Despite this relationship, reducing the driving force (by reducing storage temperature or by elevating RH) was still effective at minimising water loss, which is the main contributor to weight loss.

Chillies stored at high temperatures (20 and 30°C) lost their weight (and marketability, in which percentage of weight loss are high than 7%) and water activity much more rapid by than those stored at lower temperatures (5 and 10°C). From this study, temperature between 5 and 10°C have the potential for minimising weight loss of stored fresh chillies. It can also be suggested that increasing the relative humidity of storage environment could reduce weight loss of stored fresh chillies.

Overall this study has characterised certain physiological properties of fresh green 'Cayenne' chillies, which should provide valuable information for future research in order to develop suitable packages and storage conditions for prolonging shelf life and saleability of fresh chillies.

CHAPTER 5

EFFECTS OF STORAGE TEMPERATURE AND MODIFIED ATMOSPHERE PACKAGING ON QUALITY ATTRIBUTES OF FRESH CHILLIES

5.1 INTRODUCTION

Quality attributes of fresh chillies: chilling injury (CI), colour change, firmness, decay appearance, weight loss and O₂-CO₂ composition inside bags, as well as visual qualities (e.g. condensation and shrivelling signs) are analysed and discussed in the following sections.

The analysis of variance probability values for the effects of storage temperature and packages on the quality attributes: hue angle (h°), firmness, percentage of decay and percentage of weight loss of fresh chillies during a 14 day storage period are shown in Table 5-1. The results from this table will be taken into account, when the quality attributes are discussed in this chapter.

Table 5-1 The analysis of variance probability values for the effects of storage temperature and packages on the quality attributes of bell peppers during 14 day storage period.

Source of Variation	Hue Angle (h°)	Firmness	Decay	Weight Loss
Temperature	0.000*	0.000*	0.000*	0.000*
Packages	0.405	0.000*	0.000*	0.000*
Temperature x Packages	0.150	0.504	0.007	0.000*

* p<0.05

The optimum storage temperature(s) and package(s) required to maintaining marketable qualities of chillies during a 14-day storage period will be proposed and discussed.

5.2 CHILLING INJURY (CI)

5.2.1 RESULT OF CHILLING INJURY

During the 14-day storage period, no chilling injury appeared on chillies stored at either 5 or 10°C, regardless of the type of packaging. Based on this preliminary experiment, this variety of chillies grown in the Feilding-Palmerston North region could be stored up to 14 days without signs of chilling injury at storage temperatures of 5 and 10°C.

5.2.2 DISCUSSION OF CHILLING INJURY (CI)

While many researchers, e.g. Hardenburg *et al.* (1986), Wall and Bosland (1993) and Lee *et al.* (1994) have reported that chilling injury can occur in chillies or peppers at temperatures lower than 7°C, this was not seen in this study. Mercado *et al.* (1995) reported that no chilling injury occurred with green capsicum (cvs. Jupiter and Capistrano) stored at 5 or 10°C and Mencarelli *et al.* (1989) reported that peppers (*Capsicum frutescens* L.) packaged with low water transmission rate film were not affected by the chilling injury, when they were stored at 5°C. Likewise Gorini *et al.* (1976) found some cultivars of peppers (cvs. Wandertop and Voghera) packaged with polyethylene bags and stored at 5 or 6°C show no incidence of chilling injury.

The differences in cultivars and packaging types used in this study may provide the contrast to the recommended storage temperature, which is between 7 and 10°C (Hardenburg *et al.*, 1986; Kader *et al.*, 1989; Wall and Bosland, 1993; Lee *et al.*, 1994). However Yao *et al.* (1986) noted that chillies harvested during the summer were more sensitive to C.I. than those harvested in autumn. This may explain why chillies in this study did not manifest C.I. as they were harvested in autumn. Our study also showed green 'Cayenne' chillies could tolerate lower temperature (5°C) without CI.

5.3 COLOUR CHANGES

5.3.1 RESULT OF COLOUR CHANGES

The initial colour of fresh chillies were $L = 41.10 \pm 3.35$, $C = 28.54 \pm 3.47$, $H = 123.61 \pm 2.03$. The changes in L and C values of fresh chillies during the 14 day storage period were very small with values of L and C at the end of this period being 43.05 ± 3.95 and 29.47 ± 5.12 , respectively. Only the hue angle (h°) values changed significantly over storage period.

McGuire (1992) reported that hue angle (h°) represents the changes in fruit ripening and maturity. Wall and Berghage (1996) and Gonzalez *et al.* (1999) also used the hue angle (h°) value to trace the colour changes of peppers during shelf life tests. Therefore, the following will concentrate on changes in hue angle (h°) values.

This experiment showed similar results in that hue angle values (h°) of fresh chillies were changed significantly when the storage temperature was raised from 5 to 30°C (Figure 5-1).

Fruits stored at the lower temperatures, 5 and 10°C, had no significant differences in h° values, after 14 day storage period, compared to the values at harvest day. Most of chillies stored at these temperatures were still relatively green. In contrast, chillies stored at both 20 and 30°C had obviously changed colour, from green to orange, yellowish-red or fully red.

At the end of storage period, all chillies stored at 20 and 30°C became badly spoiled and considered unmarketable, and could not be used to measure h° values. Statistical analysis showed that the storage temperature was the only factor ($p < 0.05$) affecting the changes of h° values (Table 5-1).

The 8 stages of chilli colour development (from green to red) are shown in Figure 5-2 and the time-lapse photography of colour development of fresh chillies is also available in Appendix 4.

5.3.2 DISCUSSION OF COLOUR CHANGES

Reduced green colour of the chillies became apparent as the storage temperature was raised (from 5 to 30°C) as shown by the changes of hue angle (h°) values (Figure 5-1). Most of fruits stored at 20 and 30°C were yellowish-red or fully red meanwhile those stored at 5 and 10°C remained green. This result was similar to that reported by Mohammed *et al.* (1992) and Lownds *et al.* (1994).

Krajayklang *et al.* (2000) explained peel colour changes (in particular turning from green to red) during ripening as the result of chlorophyll loss. Likewise, Lee *et al.* (1994) found that chlorophyll content of hot chillies were reduced significantly over the initial 7 days of storage period. However, the changes were negligible for the subsequent 7 days.

From this study, temperature was the only significant factor ($p < 0.05$) affecting the changes in hue angle (h°) values. Packaging had no significant effect on colour change, which was in contrast to the report of Ben-Yehoshua *et al.* (1983) and Lownds *et al.* (1994) who state packaging with low water vapour permeability (i.e. polyethylene), reduced rates of colour change in fruit.

Wang (1977) reported that peppers stored in a modified atmosphere of 3% O₂ and 5% CO₂ showed reduced chlorophyll degradation compared with air control. Similarly, Wall and Berghage (1996) mentioned that 480g modified atmosphere package of peppers ripened at a slower rate and remained green longer than fruit packaged in 120 or 240g units. This could result from decreasing O₂ level (and increasing CO₂ concentration) inside the packages with greater fruit weights, thus indicating that the changes in packaging atmosphere delayed chlorophyll degradation.

The effects of increasing CO₂ level on lowering the colour development of chillies were in contrast to the report of Watada *et al.* (1987) in which nearly the same level of chlorophyll retention for packaged and unpackaged peppers were observed. Moreover, the chlorophyll content of stored vegetables can be increased by biosynthesis (Lee *et al.*, 1994). Therefore, the influence of modified atmosphere storage conditions as well as the cultivars on colour development and chlorophyll degradation will require further study.

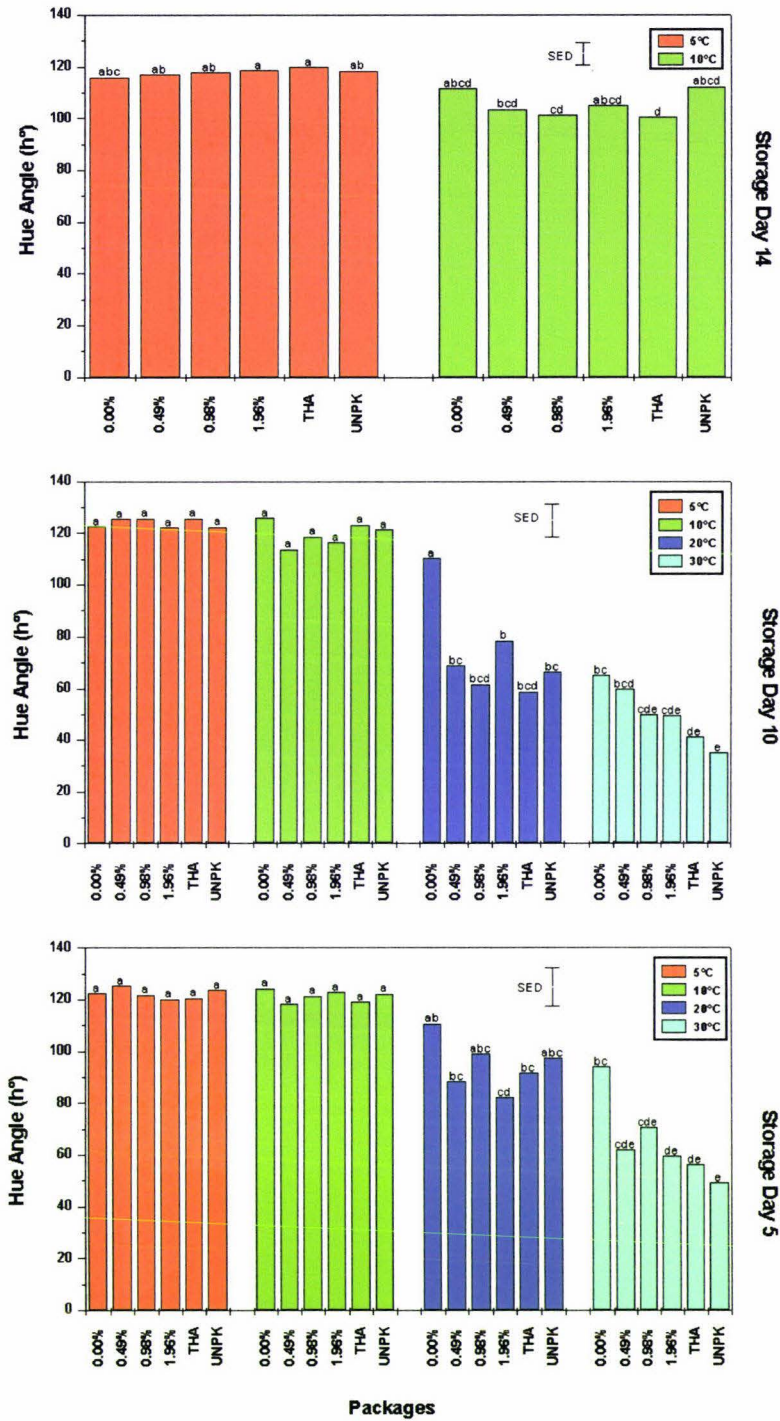


Figure 5-1 Effects of storage temperatures and modified atmosphere packaging (MAP) on changes in hue angle (h°) of fresh chillies¹.

¹ The data is the average of 3 experiments. Data are means of 15 replicates, SED = standard error of differences. Means within each storage day followed by the same letter are not significant different according to Tukey range test ($p < 0.05$), 0.00%-THA representing perforated area of plastic bags, UNPK = unpacking treatment



Figure 5-2 8 stages of chilli colour development (from green to red).

5.4 FIRMNESS

5.4.1 RESULT OF FIRMNESS

The initial firmness of chillies measured at harvest was 4.9 ± 0.8 . The firmness of fruits decreased over the storage period, particularly among chillies stored at 20 and 30°C (Figure 5-3). Unpackaged chillies tended to lose their firmness quicker than packaged fruits. Both storage temperature and packaging were main factors ($p < 0.05$) affecting the

changes in firmness of fresh chillies. However, the interactions of these two factors on the levels of firmness were not apparent (Table 5-1).

At the end of storage period, all peppers stored at 20 and 30°C became spoiled (covered with mycelia) and unmarketable, thus firmness could not be measured. Only firmness of chillies stored at 5 and 10°C can be measured. Using a 1-5 scale as proposed by Miller and Rise (1986) (section 3.3.2), firmness levels of packaged chillies at 5°C were regarded as 'firm', and firmness of unpackaged chillies were 'moderate'. At storage temperature 10°C, the firmness of fruits was in the range of moderate to firm.

5.4.2 DISCUSSION OF FIRMNESS

Firmness of fresh chillies declined during the storage period. Similar to colour development, the changes of firmness became obvious when the storage temperature was raised (Figure 5-3). Packaging also had the major effect on firmness characteristics of chillies over storage time. Unpackaged chillies generally lost firmness faster than packaged chillies. This trend was particularly apparently with chillies stored at high temperatures (20 and 30°C).

However, at 5 and 10°C, the differences in the firmness between packaged and unpackaged chillies were not significantly different. This may have contributed to the non-significant interaction of temperatures and packaging on levels of firmness (Table 5-1). As such, it could be the effects of storage temperature, particularly at chilling temperatures (between 5 and 10°C), which might minimise the changes in skin firmness of fruits during storage (Kay, 1991).

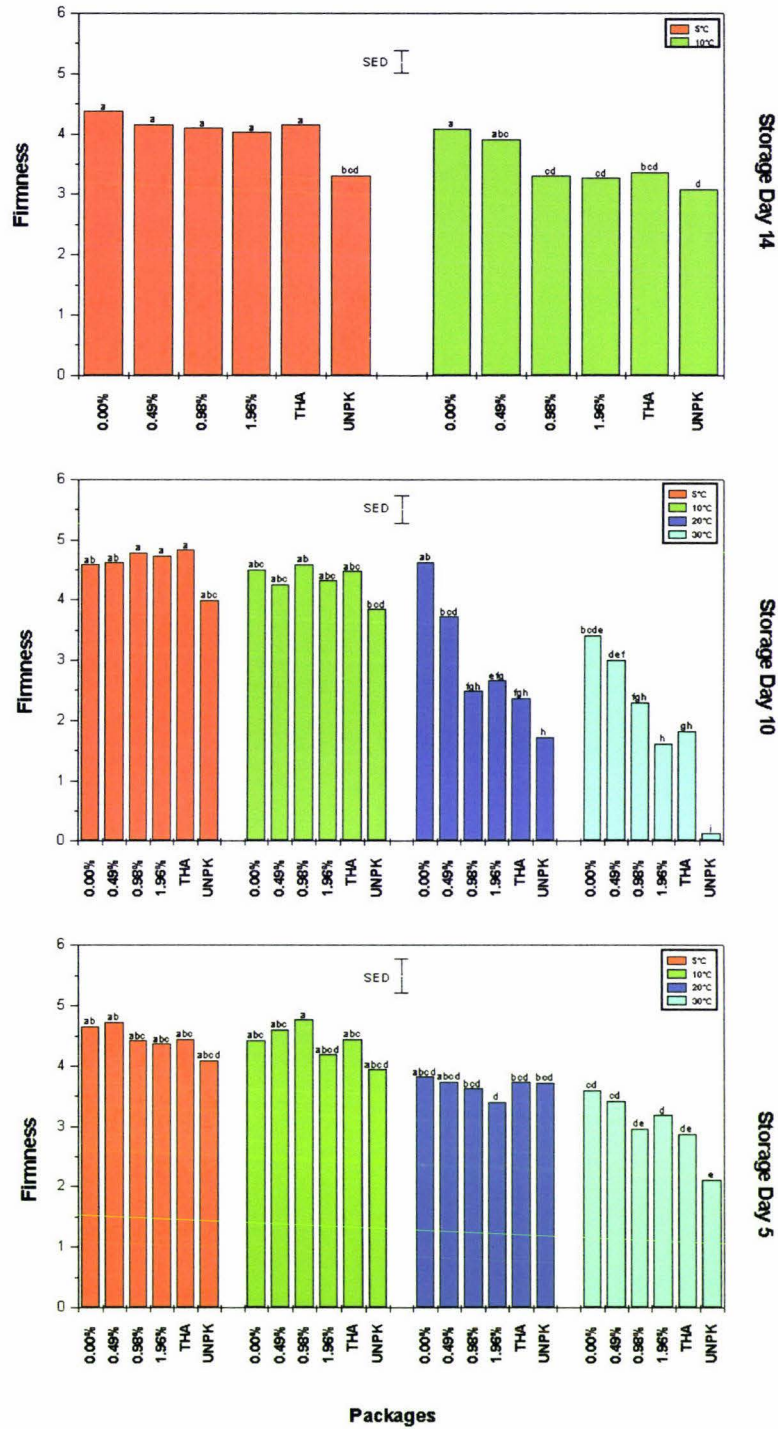


Figure 5-3 Effects of storage temperatures and modified atmosphere packaging (MAP) on changes in firmness of fresh chillies¹.

¹ The data is the average of 3 experiments. Data are means of 15 replicates, SED = standard error of differences. Means within each storage day followed by the same letter are not significant different according to Tukey range test ($p < 0.05$), 0.00%-THA representing perforated area of plastic bags, UNPK = unpacking treatment

5.5 DECAy

5.5.1 RESULTS OF DECAy

After 5 days of storage, chillies stored at 30°C had signs of decays (Figure 5-10). Peppers packaged with 0.00% perforation plastic bags had the highest decay while unpackaged chillies had the lowest percentage ($p < 0.05$). Among the chillies with perforated bags, there were not significant differences in their decay levels.

After 10 days of storage, decayed chillies could be detected at storage temperatures of 10, 20 and 30°C. The chillies stored at 20 and 30°C showing the highest levels of decays. The most prevalent decay pathogens observed in this experiment were *Alternaria*, *Rhizopus*, and *Erwinia* species (Figure 5-4 to Figure 5-7).



Figure 5-4 Alternaria rot (*Alternaria* spp.).



Figure 5-5 Rhizopus rot (*Rhizopus* spp.).



Figure 5-6 Gray mould (*Botrytis* spp.).



Figure 5-7 Bacterial soft rot (*Erwinia* spp.).

At the end of storage period, chillies at 20 and 30°C were unmarketable since they were covered with mycelia (Figure 5-8). The fruits packaged in nonperforated bags (0.00%) had badly rotted, probably due to condensation drips inside the bags (Figure 5-9). Both temperature and package type are significant factors ($p < 0.05$) affecting decay levels of fresh chillies (Table 5-1) as is the interaction of temperature and package type.

At day 14 of storage period, chillies stored at 10°C generally had higher ($p < 0.05$) levels of decay than fruits stored at 5°C, except for the nonperforated package stored at 5°C. There were no significant differences in decay levels of chillies stored at 10°C (Figure 5-10). At 5 or 10°C, there were not significant differences in decay level between chillies in perforated packages and unpackaged fruits. Similarly, the effects of perforation area and diameter of hole on levels of decay at either 5 or 10°C were not significant.



Figure 5-8 Rotten chillies.



Figure 5-9 Rotten chillies with condensation drips.

5.5.2 DISCUSSION OF DECAY

There were high incidences of decay appearance when the storage temperature was raised (from 5 to 30°C), as the high temperatures promote growth of postharvest pathogens of chillies (Wall and Bosland, 1993). Chillies packaged with nonperforated plastic bags had the highest levels of rotten fruits. Inside the nonperforated bag, there was condensation, which could lead to proliferation of pathogen as reported by (Mohammed *et al.*, 1992). However, anthracnose (*Colletotrichum* spp), which is the main chilli pathogen in Thailand (Tepsomboon, 1997; Nualplub, 1998), was not found during experimental periods. This pathogen not being present could be due to the different growing conditions and practices between Thailand and New Zealand.

There were no obvious differences in levels of decay appearance on chillies, between perforated bags and the unpackaging treatment. To improve the storage quality of chillies, a postharvest disinfecting treatment could be applied to chillies. The applications of disinfecting treatment for minimising the levels of decay of fresh chillies and peppers have been reported by Gonzalez *et al.* (1999).

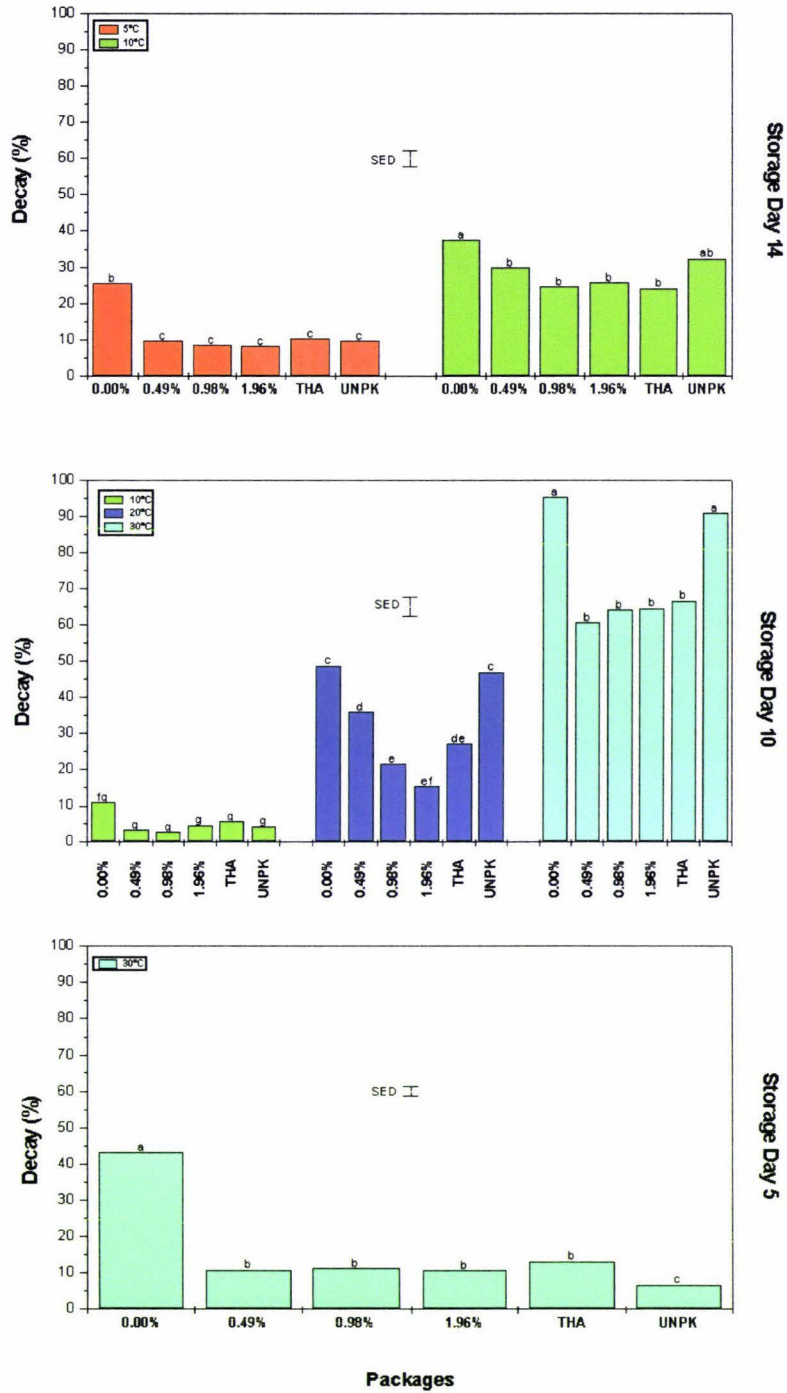


Figure 5-10 Effects of storage temperatures and modified atmosphere packaging (MAP) on percentage of decay of fresh chillies¹.

¹ The data is the average of 3 experiments. Data are means of 15 replicates, SED = standard error of differences. Means within each storage day followed by the same letter are not significant different according to Tukey range test ($p < 0.05$), 0.00%-THA representing perforated area of plastic bags, UNPK = unpackaging treatment

5.6 WEIGHT LOSS

5.6.1 RESULTS OF WEIGHT LOSS

The dynamic weight loss of chillies during storage at the 4 temperatures is shown in Figure 5-12. Weight loss of fresh chillies is significantly affected ($p < 0.05$) by storage temperature and packaging and the temperature: package interaction (Table 5-1).

Chillies stored at high temperatures (20 and 30°C) had higher percentage of weight loss than fruits stored at cooler temperatures (5 and 10°C) (Figure 5-11). Unpackaged chillies stored at 20 and 30°C lost weight up to 6 times faster than unpackaged fruits at 5 and 10°C.

Chillies packaged in 0.00% showed the lowest percentage of weight loss over the 14 day storage period, at all storage temperatures. However, at each storage temperature, there was condensation inside the nonperforated plastic bags and this was not taken into account (as the entire package was weighed).

The weight loss of chillies stored in perforated bags changed with temperature. At the end of the simulating period, chillies within THA treatments, at 10°C had the highest weight loss ($p < 0.05$).

5.6.2 DISCUSSION OF WEIGHT LOSS

Storage temperature and packaging types greatly influenced percentage of weight loss of chillies. Fruits stored at high temperatures, especially 30°C, quickly lost weight, compared to those stored at chilling temperatures. Packaging could significantly reduce the weight loss. In particular chillies packaged in nonperforated bag showed negligible weight loss during the 2-week storage period. This result is similar to the report of Lee *et al.* (1994). The effects and applications of chilling temperatures and packaging on diminishing weight loss of chillies are similar to those of other researchers, e.g. Hardenburg *et al.* (1986) with other types of fresh produces.

Bussel and Kenigsberger (1975), Robinson *et al.* (1975) and Ben-Yehoshua *et al.* (1987) reported chillies or peppers are considerably unmarketable after they have lost about 5-7% of their weight. Fruits, except those stored in the nonperforated bag, stored at temperatures above 5°C lost greater percentages of weight and this would therefore reduce their marketability.

In this experiment, at 5°C, unpackaged chillies tended to lose their saleability after the 2-week storage period. Although chillies packaged in the nonperforated plastic bag lost less than 5% weight, condensation inside the plastic bag would limit their commercial acceptability (Wall and Berghage, 1996). Chillies packaged with perforated plastic bags showed promising weight loss reduction and minimal condensation development. Among these perforated bags, weight loss increased according to perforation area and diameter of hole. Though the THA treatment had lower perforation areas, compared to other perforated treatments, the individual perforations were larger. This could contribute to the high percentage of weight loss, even with small overall perforation area. This trend of weight loss characteristics, being related to perforation area and hole diameter, is consistent with that reported by Geeson (1990), Emond *et al.* (1995), Sanz *et al.* (1999) and Sabarez and Tanner (2001).

Based on this study, the 0.49% and/or 0.98% perforated plastic bags stored at 5°C, were considered the optimum for storing green chillies for a 2-week storage period, since the packaged chillies still looked hydrated and had lost only 2.5% of weight (which is within the marketable limit). From a commercial point of view, Wall and Berghage (1996) mentioned that green chillies are marketed on a price per unit weight basis, therefore the reduction in weight loss translates directly into lost revenue. This optimisation could be profitable to the chilli industries in either New Zealand or Thailand.

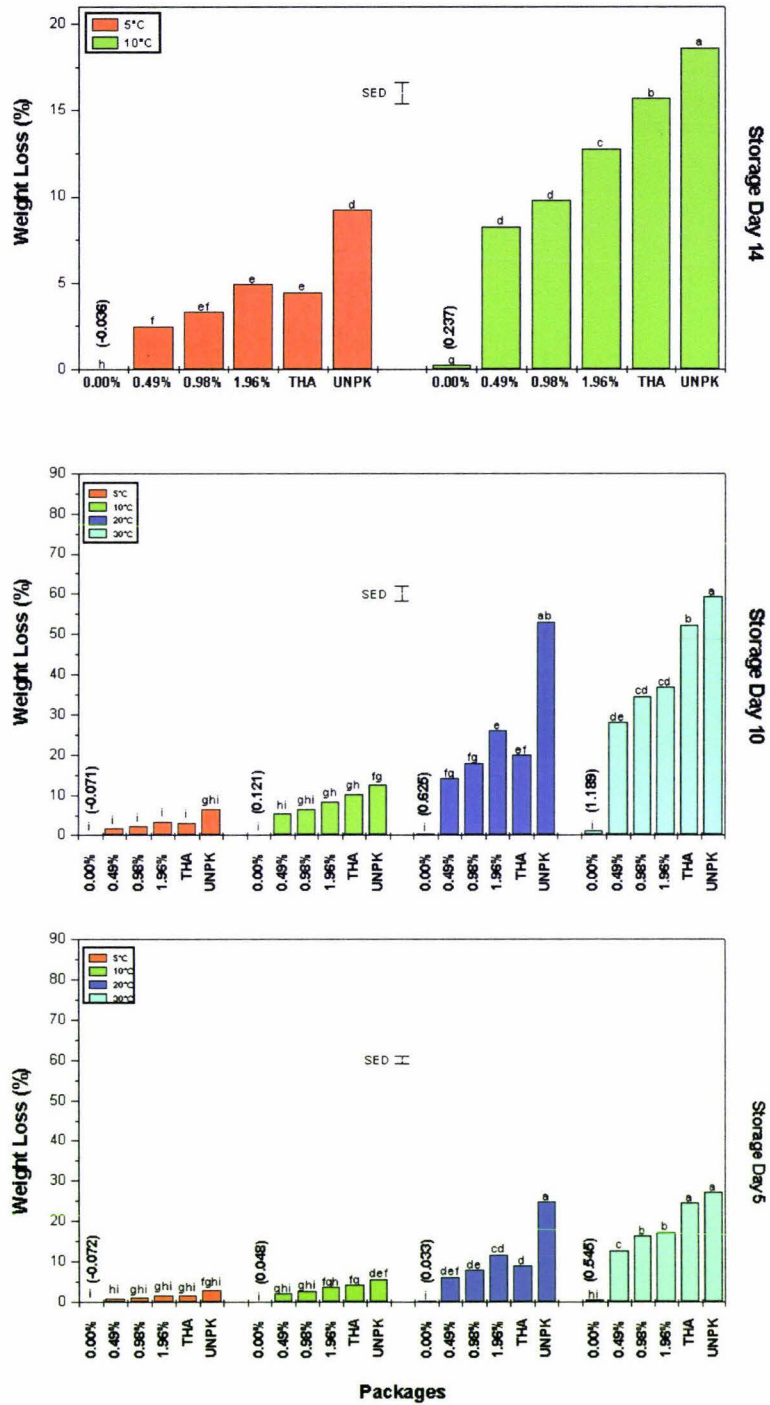


Figure 5-11 Effects of storage temperatures and modified atmosphere packaging (MAP) on percentage of weight loss of fresh chillies¹.

¹ The data is the average of 3 experiments. Data are means of 15 replicates, SED = standard error of differences, Means within each storage day followed by the same letter are not significant different according to Tukey range test (p<0.05), 0.00%-THA representing perforated area of plastic bags, UNPK = unpackaging treatment

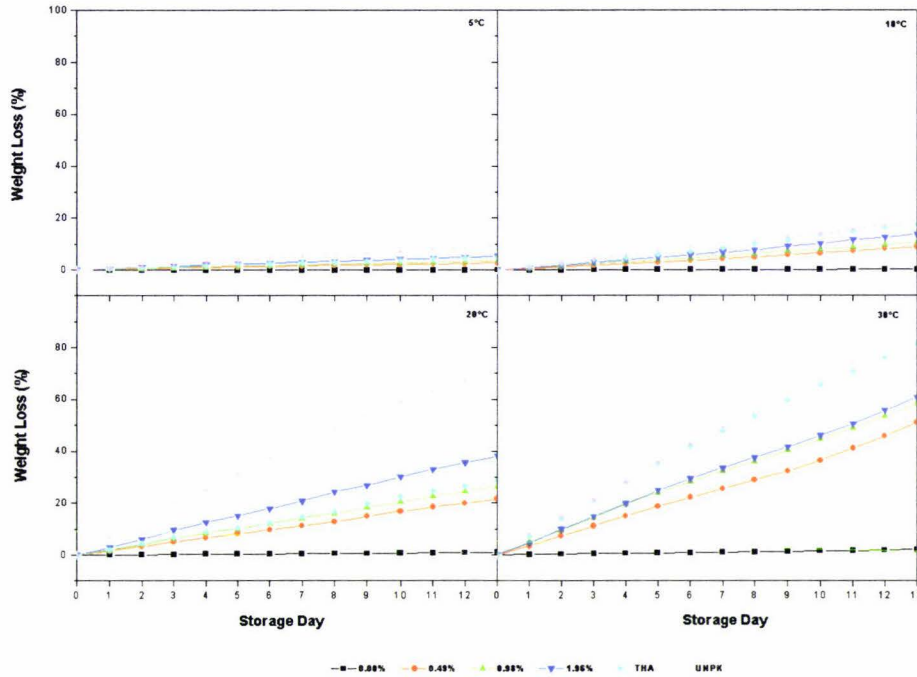


Figure 5-12 Dynamic weight loss of fresh chillies stored between 5 and 30°C, during 14 day storage period.

(0.00%-THA representing perforated area of plastic bags, UNPK = unpackaging treatment).

5.7 GAS COMPOSITIONS INSIDE PLASTIC BAGS

5.7.1 RESULT OF O₂ AND CO₂ COMPOSITION INSIDE PLASTIC BAGS

The gas compositions (O₂ and CO₂) inside the different packages stored at different temperatures are shown in Figure 5-13 to Figure 5-16. Only atmospheres inside the nonperforated plastic bags were modified, where the oxygen concentrations declined and the carbon dioxide concentrations were increased, over the storage period. Dramatic changes in gas concentrations were found at 20 and 30°C.

5.7.2 DISCUSSION OF O₂ AND CO₂ COMPOSITION INSIDE PLASTIC BAGS

The atmospheres inside the different types of perforated plastic bags were not modified, regardless of storage temperatures. Their O₂ and CO₂ concentrations were close to the ambient air condition. These results are consistent with the report of Chau and Talasila

(1994) in that highly perforated plastic film or increasing degrees of perforation would result in less or no modification of package atmospheres.

However, the atmospheres inside the nonperforated plastic bags were modified compared to the gas concentration in air and storage temperatures affected the O₂ and CO₂ concentrations. The gas levels were dramatically changed at high temperatures (20 and 30°C), a result similar to Wall and Berghage (1996) in which chillies were packaged into sealed bags and stored at 24°C.

At 20 and 30°C, O₂ concentration was lower than 2%, at which level anaerobic respiration and fermentation, creating off-flavours and rotting stimulation can be expected (Kader *et al.*, 1989; Wall and Berghage, 1996). The CO₂ levels were above 10%. Wang (1977) reported CO₂ concentration at this level or above might cause calyx injury on peppers. This further indicates that 20 and 30°C are not suitable storage temperature for fresh chillies.

The levels of O₂ and CO₂, in the nonperforated bags stored at 5 and 10°C, were approximately 15-17%O₂ and 5-7%CO₂. These levels are higher than the general recommend levels of O₂ and CO₂ inside modified atmosphere packaging used for fresh chilli storage, which are 3-5% O₂ and 5%CO₂ (Kader *et al.*, 1989).

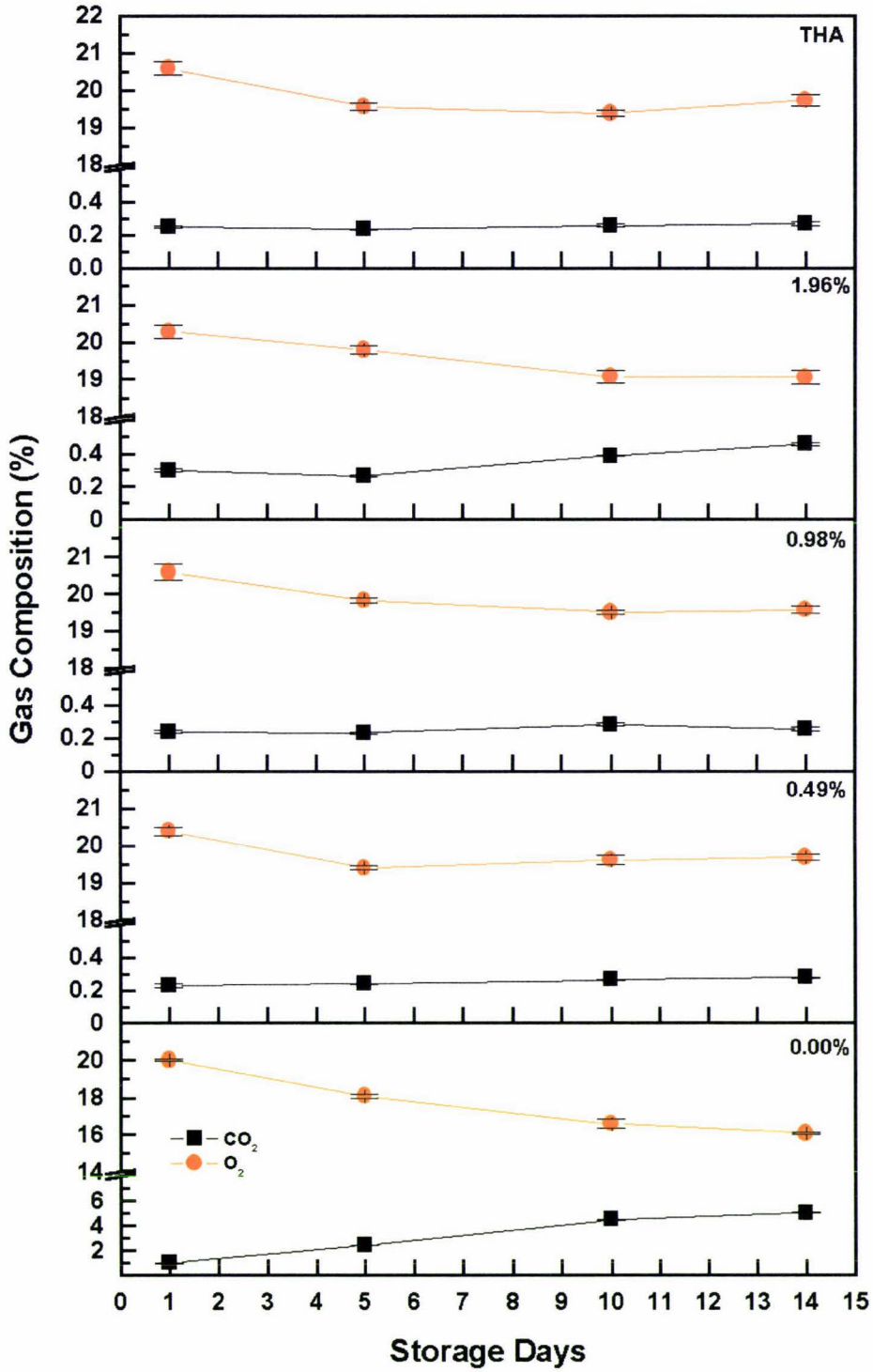


Figure 5-13 O_2 and CO_2 concentrations inside plastic bags at 5°C during the 2-week storage period.

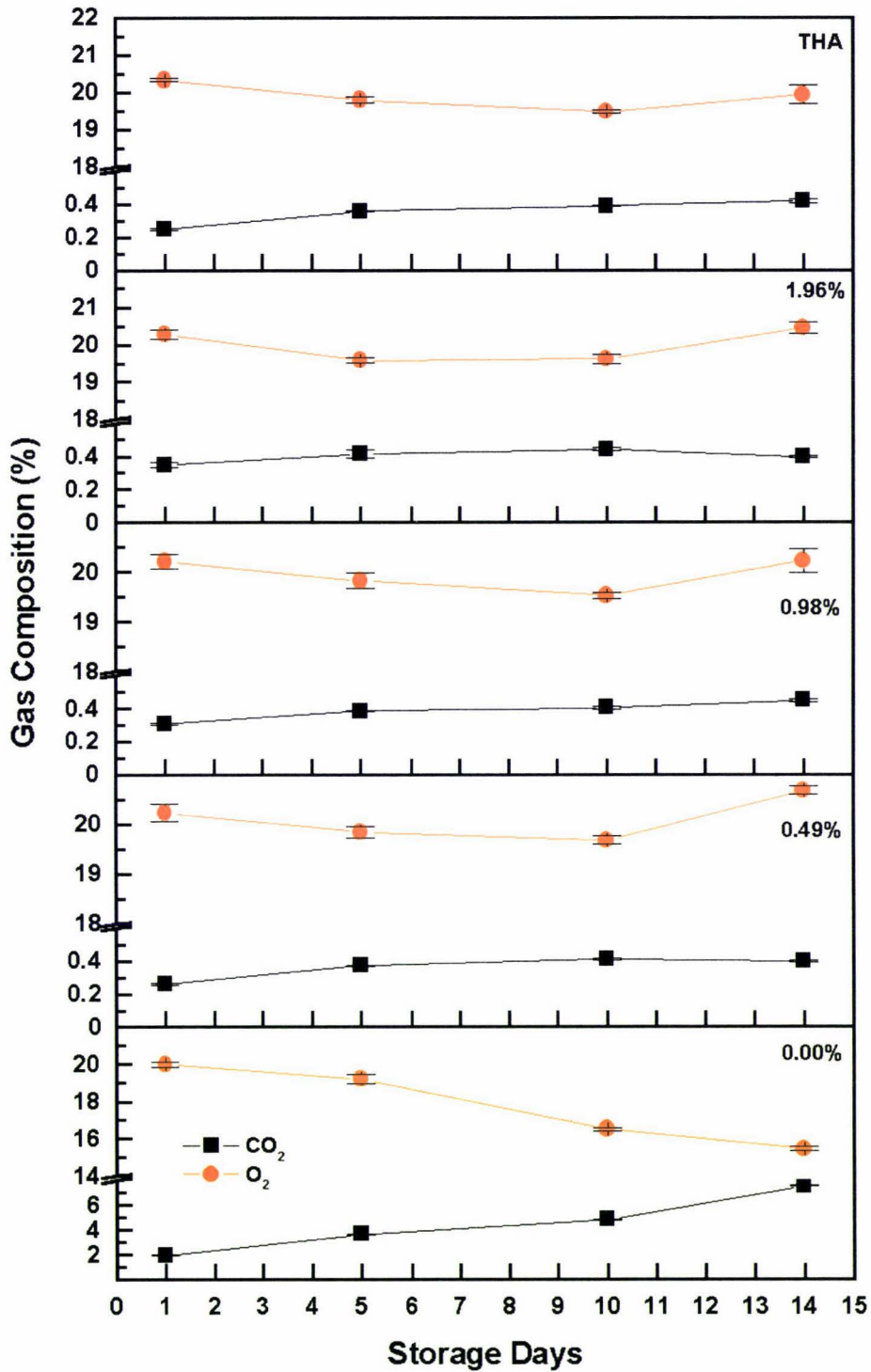


Figure 5-14 O₂ and CO₂ concentrations inside plastic bags at 10°C during the 2-week storage period.

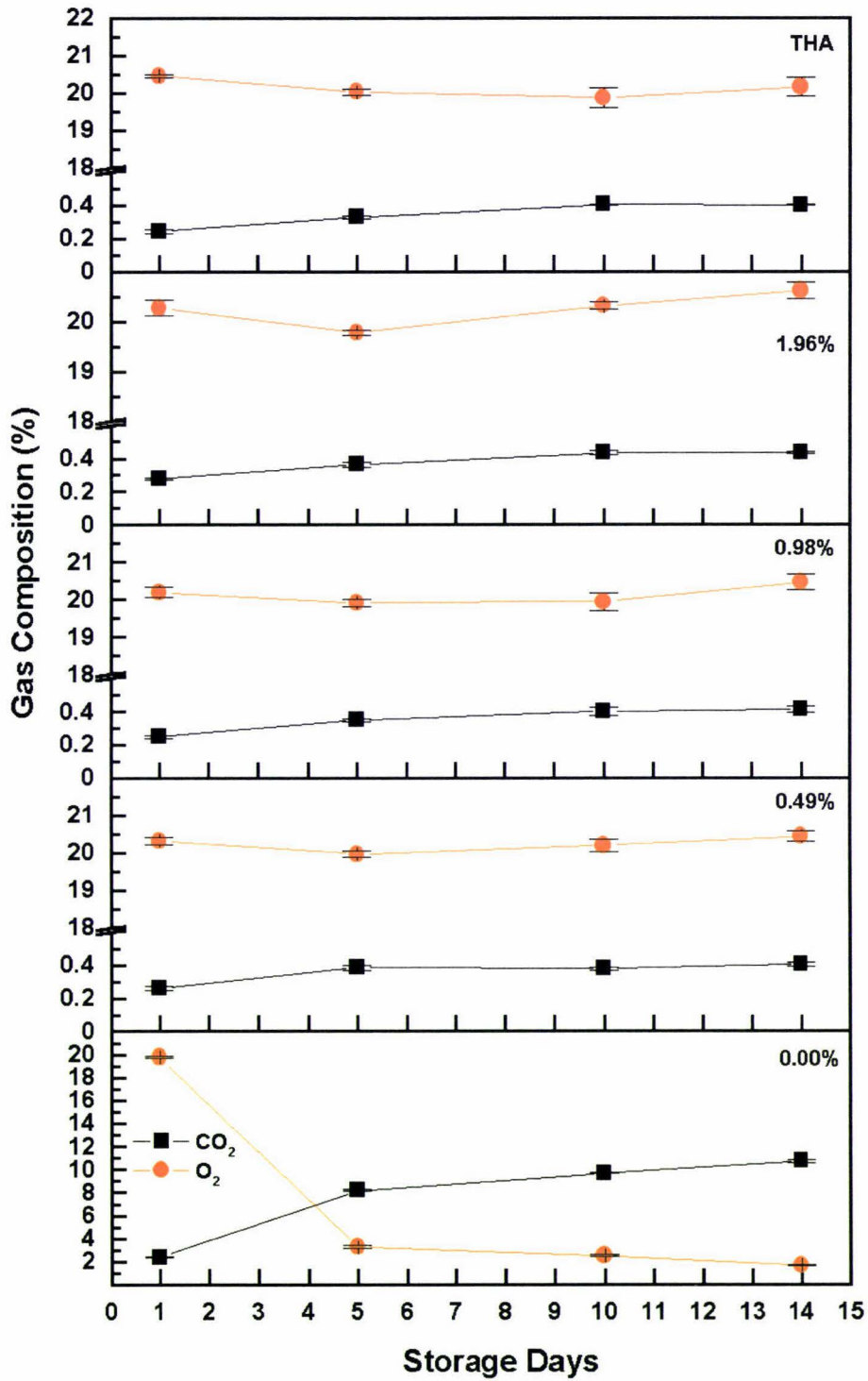


Figure 5-15 O₂ and CO₂ concentrations inside plastic bags at 20°C during the 2-week storage period.

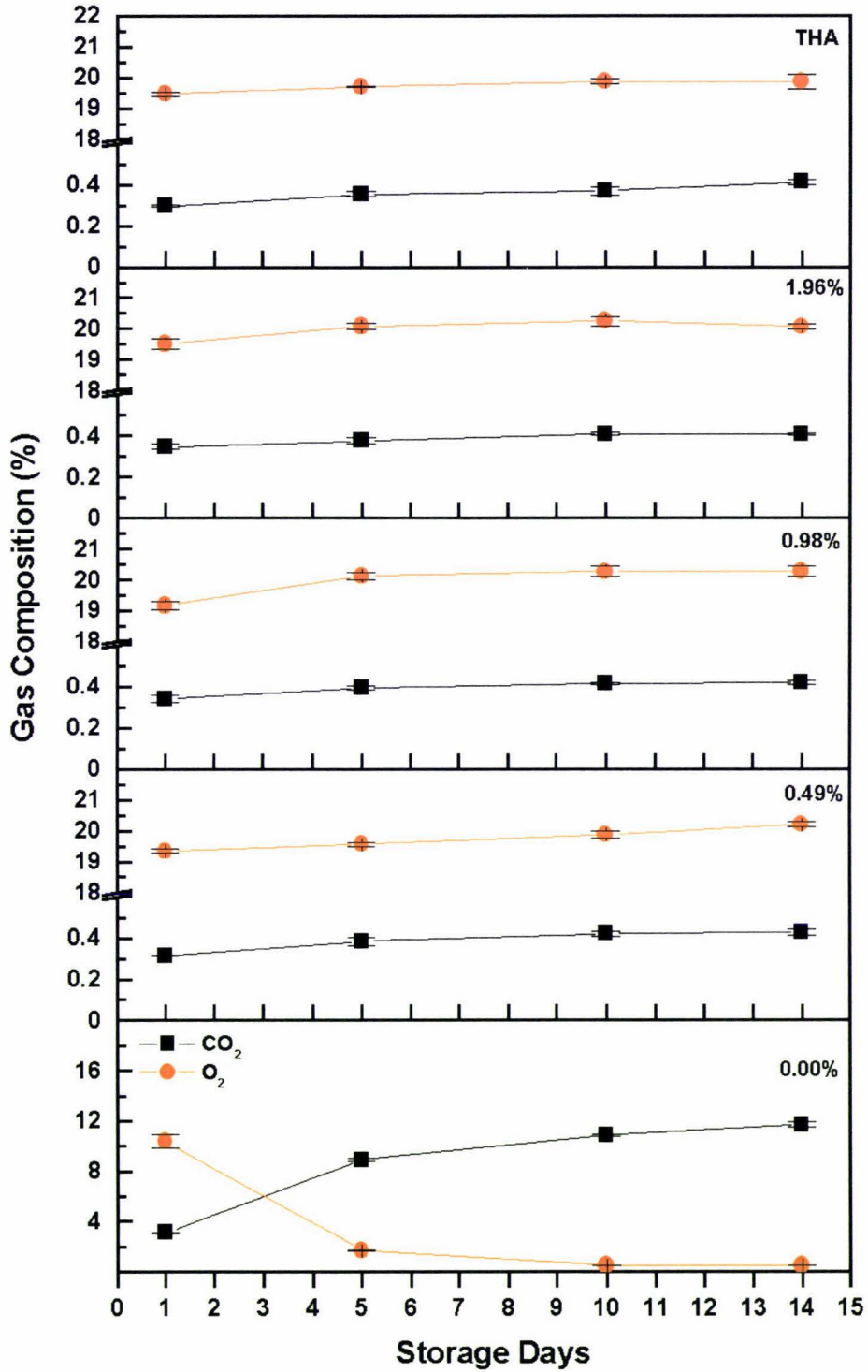


Figure 5-16 O_2 and CO_2 concentrations inside plastic bags at 30°C during the 2-week storage period.

5.8 VISUAL QUALITY

5.8.1 RESULTS OF VISUAL QUALITY

The visual qualities of fresh chillies, according to storage temperatures and packages, during 2-week storage period are shown in Table 5-2 to Table 5-5. Chillies stored at 5 and 10°C still appeared fresh and had lower decay appearances when compared with those stored at 20 and 30°C.

Condensation was observed inside only the nonperforated plastic bags (Figure 5-17) and fresh chillies stored within this kind of plastic bag spoiled faster than fruits stored in the other types of packages. Unpackaged chillies stored at the high temperatures (20 and 30°C) were more dehydrated and shrivelled (or wilted) compared to other treatments (Figure 5-18).



Figure 5-17 Condensation inside the nonperforated plastic bag.



Figure 5-18 Dehydrated and shrivelled chillies.

Table 5-2 Visual quality of chillies stored at 5°C during the 2-week storage period.

Storage Day	Unpackaging (UNPK)		Nonperforated Bag (0.00%)		1.96%		0.98%		0.49%		THA	
	Condensation	Visual Quality	Condensation	Visual Quality	Condensation	Visual Quality	Condensation	Visual Quality	Condensation	Visual Quality	Condensation	Visual Quality
Day 1	N	F	Y	F	N	F	N	F	N	F	N	F
Day 2	N	F	Y	F	N	F	N	F	N	F	N	F
Day 3	N	F	Y	F	N	F	N	F	N	F	N	F
Day 4	N	F	Y	F	N	F	N	F	N	F	N	F
Day 5	N	F	Y	F/S	N	F	N	F	N	F	N	F
Day 6	N	F	Y	F/S	N	F	N	F	N	F	N	F
Day 7	N	F	Y	F/S	N	F	N	F	N	F	N	F
Day 8	N	F/S	Y	F/S	N	F/S	N	F	N	F	N	F
Day 9	N	F/S	Y	F/S	N	F/S	N	F	N	F	N	F/S
Day 10	N	F/S	Y	F/S	N	F/S	N	F/S	N	F/S	N	F/S
Day 11	N	F/S	Y	F/SR	N	F/S	N	F/S	N	F/S	N	F/S
Day 12	N	F/S	Y	F/SR	N	F/S	N	F/S	N	F/S	N	F/S
Day 13	N	F/SR	Y	F/SR	N	F/SR	N	F/SR	N	F/SR	N	F/SR
Day 14	N	F/SR	Y	F/SR	N	F/SR	N	F/SR	N	F/SR	N	F/SR

Condensation: Y = presence of condensation; N = no condensation

Visual Quality: D = dried; F = fresh look; R = rotten; S = shrivelled or soft

Table 5-3 Visual quality of chillies stored at 10°C during the 2-week storage period.

Storage Day	Unpackaging (UNPK)		Nonperforated Bag (0.00%)		1.96%		0.98%		0.49%		THA	
	Condensation	Visual Quality	Condensation	Visual Quality	Condensation	Visual Quality	Condensation	Visual Quality	Condensation	Visual Quality	Condensation	Visual Quality
Day 1	N	F	Y	F	N	F	N	F	N	F	N	F
Day 2	N	F	Y	F	N	F	N	F	N	F	N	F
Day 3	N	F	Y	F	N	F	N	F	N	F	N	F
Day 4	N	F	Y	F	N	F	N	F	N	F	N	F
Day 5	N	F/S	Y	F	N	F/S	N	F	N	F	N	F/S
Day 6	N	F/S	Y	F/S	N	F/S	N	F	N	F	N	F/S
Day 7	N	F/S	Y	F/S	N	F/S	N	F/S	N	F	N	F/S
Day 8	N	F/S	Y	F/SR	N	F/S	N	F/S	N	F	N	F/S
Day 9	N	F/SR	Y	F/SR	N	F/SR	N	F/S	N	F	N	F/SR
Day 10	N	F/SR	Y	F/SR	N	F/SR	N	F/S	N	F/SR	N	F/SR
Day 11	N	F/SR	Y	F/SR	N	F/SR	N	F/S	N	F/SR	N	F/SR
Day 12	N	F/SR	Y	F/SR	N	F/SR	N	F/SR	N	F/SR	N	F/SR
Day 13	N	F/SR	Y	F/SR	N	F/SR	N	F/SR	N	F/SR	N	F/SR
Day 14	N	F/SR	Y	F/SR	N	F/SR	N	F/SR	N	F/SR	N	F/SR

Condensation: Y = presence of condensation; N = no condensation

Visual Quality: D = dried; F = fresh look; R = rotten; S = shrivelled or soft

Table 5-4 Visual quality of chillies stored at 20°C during the 2-week storage period.

Storage Day	Unpackaging (UNPK)		Nonperforated Bag (0.00%)		1.96%		0.98%		0.49%		THA	
	Condensation	Visual Quality	Condensation	Visual Quality	Condensation	Visual Quality	Condensation	Visual Quality	Condensation	Visual Quality	Condensation	Visual Quality
Day 1	N	F	Y	F	N	F	N	F	N	F	N	F
Day 2	N	F	Y	F	N	F	N	F	N	F	N	F
Day 3	N	F/S	Y	F	N	F	N	F	N	F	N	F
Day 4	N	F/S	Y	F	N	F/S	N	F	N	F	N	F/S
Day 5	N	F/S/D	Y	F	N	F/S	N	F/S	N	F/S	N	F/S
Day 6	N	F/S/D	Y	FR	N	F/S	N	F/S	N	F/SR	N	F/S/D
Day 7	N	F/SDR	Y	FR	N	F/SD	N	F/S	N	F/SR	N	F/SD
Day 8	N	F/SDR	Y	FR	N	F/SDR	N	F/SDR	N	F/SDR	N	F/SDR
Day 9	N	F/SDR	Y	F/SR	N	F/SDR	N	F/SDR	N	F/SDR	N	F/SDR
Day 10	N	F/SDR	Y	F/SR	N	F/SDR	N	F/SDR	N	F/SDR	N	F/SDR
Day 11	N	F/SDR	Y	F/SR	N	F/SDR	N	F/SDR	N	F/SDR	N	F/SDR
Day 12	N	F/SDR	Y	F/SR	N	F/SDR	N	F/SDR	N	F/SDR	N	F/SDR
Day 13	N	F/SDR	Y	F/SR	N	F/SDR	N	F/SDR	N	F/SDR	N	F/SDR
Day 14	N	F/SDR	Y	F/SR	N	F/SDR	N	F/SDR	N	F/SDR	N	F/SDR

Condensation: Y = presence of condensation; N = no condensation

Visual Quality: D = dried; F = fresh look; R = rotten; S = shrivelled or soft

Table 5-5 Visual quality of chillies stored at 30°C during the 2-week storage period.

Storage Day	Unpackaging (UNPK)		Nonperforated Bag (0.00%)		1.96%		0.98%		0.49%		THA	
	Condensation	Visual Quality	Condensation	Visual Quality	Condensation	Visual Quality	Condensation	Visual Quality	Condensation	Visual Quality	Condensation	Visual Quality
Day 1	N	F	Y	F	N	F	N	F	N	F	N	F
Day 2	N	F/S	Y	F	N	F	N	F	N	F	N	F/S
Day 3	N	F/S	Y	F	N	F/S	N	F	N	F	N	F/SD
Day 4	N	F/S/D	Y	FR	N	F/S	N	F/S	N	F/S	N	F/SDR
Day 5	N	F/S/D	Y	FR	N	F/SD	N	F/SDR	N	F/SDR	N	F/SDR
Day 6	N	F/SDR	Y	FR	N	F/SD	N	F/SDR	N	F/SDR	N	F/SDR
Day 7	N	F/SDR	Y	FR/S	N	F/SDR	N	F/SDR	N	F/SDR	N	F/SDR
Day 8	N	F/SDR	Y	FR/S	N	F/SDR	N	F/SDR	N	F/SDR	N	F/SDR
Day 9	N	F/SDR	Y	FR/S	N	F/SDR	N	F/SDR	N	F/SDR	N	F/SDR
Day 10	N	F/SDR	Y	FR/S	N	F/SDR	N	F/SDR	N	F/SDR	N	F/SDR
Day 11	N	F/SDR	Y	FR/S	N	F/SDR	N	F/SDR	N	F/SDR	N	F/SDR
Day 12	N	F/SDR	Y	FR/S	N	F/SDR	N	F/SDR	N	F/SDR	N	F/SDR
Day 13	N	F/SDR	Y	FR/S	N	F/SDR	N	F/SDR	N	F/SDR	N	F/SDR
Day 14	N	F/SDR	Y	FR/S	N	F/SDR	N	F/SDR	N	F/SDR	N	F/SDR

Condensation: Y = presence of condensation; N = no condensation

Visual Quality: D = dried; F = fresh look; R = rotten; S = shrivelled or soft

5.8.2 DISCUSSION OF VISUAL QUALITY

Chillies stored at high temperatures (20 and 30°C) generally had poor visual qualities, which could be seen as: dehydrated/shrivelling (wilting), faster colour development and high appearance of rotten fruits. At all storage temperatures, chillies packaged with nonperforated plastic bags sweated and there was condensation inside the bags. Overall, chillies packaged with perforated plastic and stored at 5 and 10°C had good visual quality (less decay, no condensation and a fresh appearance).

5.9 CONCLUSION

The postharvest quality attributes of fresh chillies were affected by storage temperature and packaging. Chilling or refrigerated storage temperatures and plastic bags could be

used for maintaining or extending the quality of fresh chillies. In addition, at 5 and 10°C, chillies could be stored without the signs of chilling injury and fruits looked fresh, green and hydrated.

Storage temperature, in particular, had the greatest influence on all quality attributes. Extreme increases in the storage temperature contribute to seriously low visual appearance and quality of stored fruits e.g. rapid colour change, flaccidity development or pathogenic proliferation.

Condensation occurring inside nonperforated plastic bags renders this kind of plastic bag impractical to be used for chilli storage, although chillies within this bag had lowest loss in weight or firmness. Thus perforated plastic bags could be used to diminish condensation inside plastic bags. Perforation area and diameter of hole are the main factors affecting the properties of perforated plastic bags. Furthermore, the atmospheres inside perforated plastic bags were similar to ambient air condition, ensuring aerobic respiration conditions inside the bags.

Refrigerated storage temperatures and perforated plastic bags also reduce weight loss of fresh chillies. Chillies stored at 5°C and packaged with 0.49% perforated plastic bags had low weight loss while maintaining other qualities attributes within marketable levels. This technology could be used for commercial benefit in chilli retailing supply chains.

Because rapid postharvest weight loss causes the main economic problems to chillies industry, a conceptual model for generalising and understanding the characteristics of chilli weight loss was developed and is discussed in Chapter 6. Furthermore, in Chapter 7 the computer-based weight loss simulation model developed by Tanner (1998) will be used to predict the weight loss of chillies with respect to different storage temperatures and packaging.

In addition to optimum storage temperature and package, use of a postharvest disinfecting treatment is recommended for added quality assurance, in term of controlling pathogenic proliferation or secondary contamination, which may occur

during the postharvest storage period. In Chapter 8 postharvest disinfecting treatments affecting storage shelf life of peppers will be further discussed.

CHAPTER 6

CONCEPTUALISATION AND MATHEMATICAL MODELLING OF WEIGHT LOSS OF FRESH CHILLIES

6.1 INTRODUCTION

Tanner (1998) developed a mathematical model and computer-based simulation programme to predict product mass loss for a wide range of horticultural commodities. The results from his research were used to design packages and assess storage conditions relating to the commercial handling of fresh produce. This weight loss simulation package also contributed to sound solutions to water loss problems in the fresh produce industry.

To enhance fresh chilli shelf life and marketability, a mathematical model based on fresh chilli attributes could be used. A number of other researchers have reported successful applications of mathematical models to simulate and design appropriate packages for shelf life extension of fresh fruits and vegetables including chilli peppers (Lee *et al.*, 1994). One such model developed by Tanner (1998) was adapted to provide a conceptualisation to model for determining and controlling weight loss of fresh chillies.

The purpose of this chapter is to describe the overall factors affecting the weight loss of fresh chillies. The conceptual models, related to current chilli packaging systems used in Thailand, were also proposed in order to understand the complexity of weight loss characteristics.

6.2 CONCEPTUAL MODELS: CHILLI PACKAGING SYSTEMS

Conceptual models provide a sound basis for both intuitive and creative development and rational assessment of new ideas. Several aspects of the conceptual model used to drive a recent programme that investigated ways to reduce weight loss from apples. Most importantly, strong conceptualisation and characterisation of the system under study also enhances the likelihood of developing innovative solutions and management

tools suited to industry application (Banks *et al.*, 2000). The practical applications of conceptual models in weight loss optimisation of fresh horticultural products can be further found in Maguire (1998) and Tanner (1998).

Accordingly, to understand the weight loss characteristics of fresh chillies, conceptual models regarding the commercial packages and storage conditions, in Thailand, were developed. These conceptual models were linked to pathways for heat and mass transfer in the product-package environment since these factors are generally regarded as the main contributors to weight loss in fresh produce.

6.3 EXAMPLE PACKAGING SYSTEM FOR FRESH CHILLIES IN THAILAND

6.3.1 EXAMPLE 1- PERFORATED PLASTIC BAGS OF FRESH CHILLIES (FIGURE 6-1)

The total system is an individual perforated plastic bag of fresh chillies. These fruits are usually stored under shade (together with other fresh produce) for sale or transport at ambient conditions in Thailand (at about 30°C and 75%RH).



Figure 6-1 Physical model of the system described in Example 1.

(The blue circles showed the position of the holes)

For this example, a number of heat and mass transfer pathways exist as shown in Figure 6-2.

Heat transfer pathways

- a) Heat and mass flow of the external medium (air) through the packages
- b) Heat conduction within the product (chillies)
- c) Heat convection from the product to the air
- d) Radiation from the product to other surfaces
- e) Heat conduction between items of product
- f) Heat conduction within packaging material
- g) Heat convection between the air and packaging material
- h) Heat conduction between the product and the package
- i) Convection between the internal air and the package
- j) Convection between the external air and the package

Mass transfer pathways

Evaporation of water vapour from the product to the air

- k) Water vapour transport through packaging material by effective diffusion
- l) Water vapour transport through the holes by diffusion, capillary action or both.
- m) Absorption or desorption of water vapour by the packaging material.
- n) Carbon loss from respiration

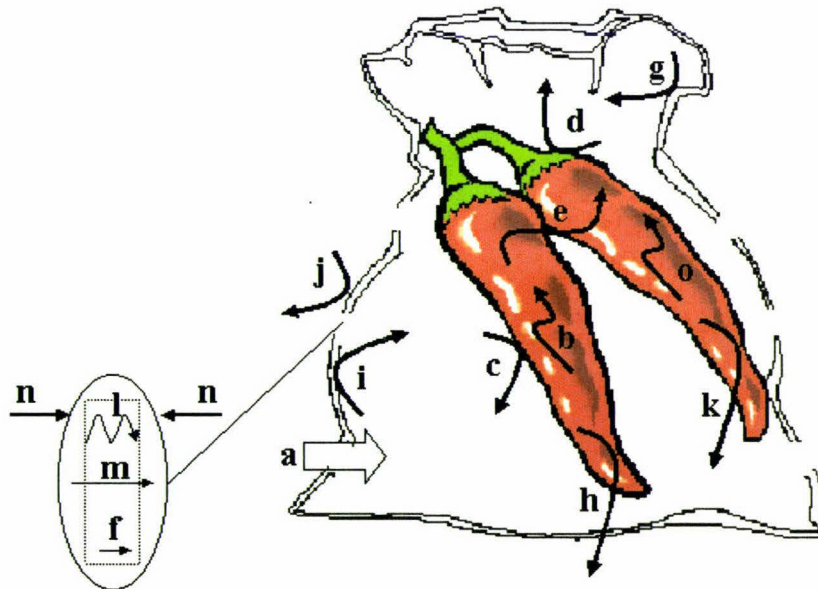


Figure 6-2 Conceptualisation of the main pathways existing for heat and mass transfer in Example 1.

6.3.2 EXAMPLE 2- NONPERFORATED PLASTIC BAGS OF FRESH CHILLIES (FIGURE 6-3)

The total system is an individual nonperforated plastic bag of fresh chillies. These fruits are also usually stored under shade (together with other fresh produce) for sale or to transport at ambient conditions in Thailand (at about 30°C and 75%RH).



Figure 6-3 Physical model of the system described in Example 2.

For this example, a number of heat and mass transfer pathways exist as shown in Figure 6-4.

Heat transfer pathways

- a) Heat and mass flow of the external medium (air) through the packages, but outside the package
- b) Heat conduction within the product (chillies)
- c) Heat convection from the product to the air
- d) Radiation from the product to other surfaces
- e) Heat conduction between items of product
- f) Heat conduction within packaging material
- g) Heat convection between the air and packaging material
- h) Heat conduction between the product and the package
- i) Convection between the internal air and the package

j) Convection between the external air and the package

Mass transfer pathways

k) Evaporation of water vapour from the product to the air

l) Water vapour transport through packaging material by diffusion, capillary action or both

m) Absorption or desorption of water vapour by the packaging material

n) Carbon loss from respiration

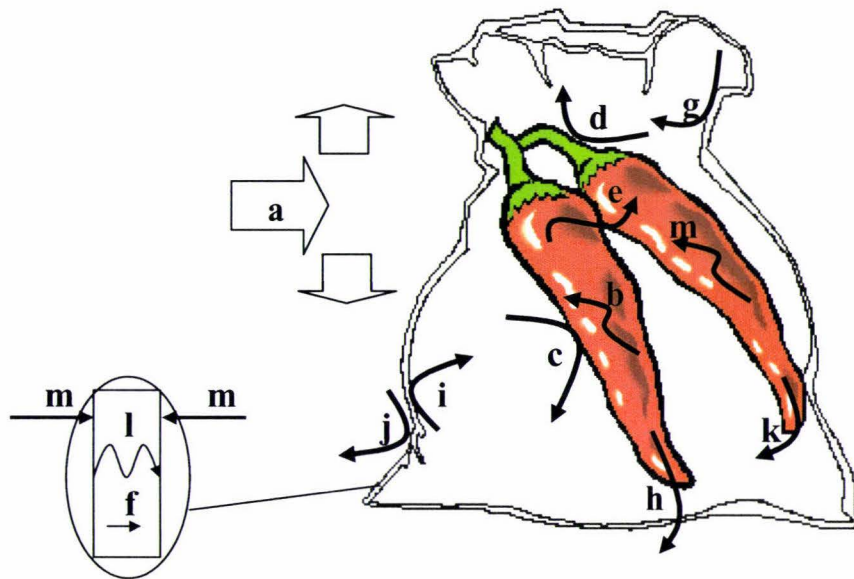


Figure 6-4 Conceptualisation of the main pathways existing for heat and mass transfer in Example 2.

6.3.3 EXAMPLE 3- UNBAGGED FRESH CHILLIES (FIGURE 6-5)

The total system is a bulk pile of fresh chilli. These fruits are usually placed on the floor under shade (together with other fresh produce) for sale or to transport at the ambient condition of Thailand (at about 30°C and 75%RH). These fruits are usually placed in a forced draft air to cool the product from high temperature during the daytime. Therefore, the air flow rate and temperature of forced air have to be taken into account when calculating the weight loss of these unbagged chillies.



Figure 6-5 Physical model of the system described in Example 3.

For this example, a number of heat and mass transfer pathways exist as shown in Figure 6-6.

Heat transfer pathways

- a) Energy and mass flow due to flow of the air through the product (chillies).
- b) Heat conduction within items of product.
- c) Heat conduction between items of product.
- d) Heat convection from the product to the air.
- e) Radiation from the product to other surfaces

Mass transfer pathways

- f) Evaporation of water vapour from the product to the air
- g) Carbon loss from respiration

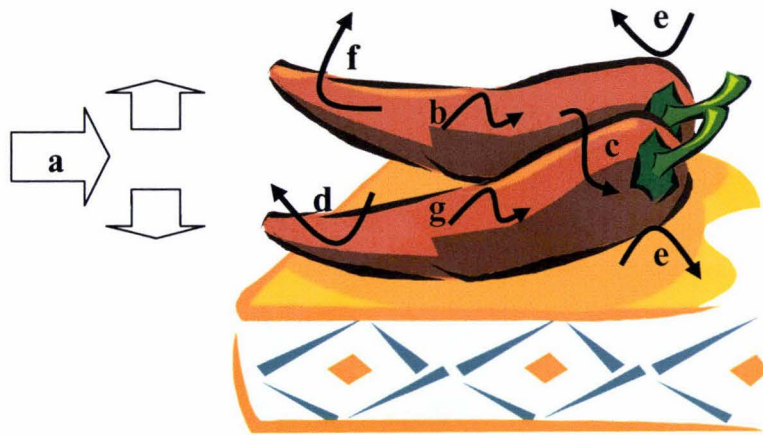


Figure 6-6 Conceptualisation of the main pathways existing for heat and mass transfer in Example 3.

6.4 CONCLUSION

Regarding developed conceptual models of fresh chilli packaging systems in this chapter, the extrinsic factors affecting weight loss were outlined. Equally important, apart from those external factors (i.e. air or types of packages), the fruit attributes, for example respiration rate or water vapour permeance of skin, have to be taken into account. These intrinsic factors could vary the weight loss and other quality attributes of fresh produce (Robertson, 1993).

The overall conceptual model, which summarises relationships between fruit attributes, environmental conditions and processes that contribute to overall mass loss of fresh chillies, is shown in Figure 6-7. These factors were used in the study of mathematical models and simulation, which are presented in the following chapter (Chapter 7).

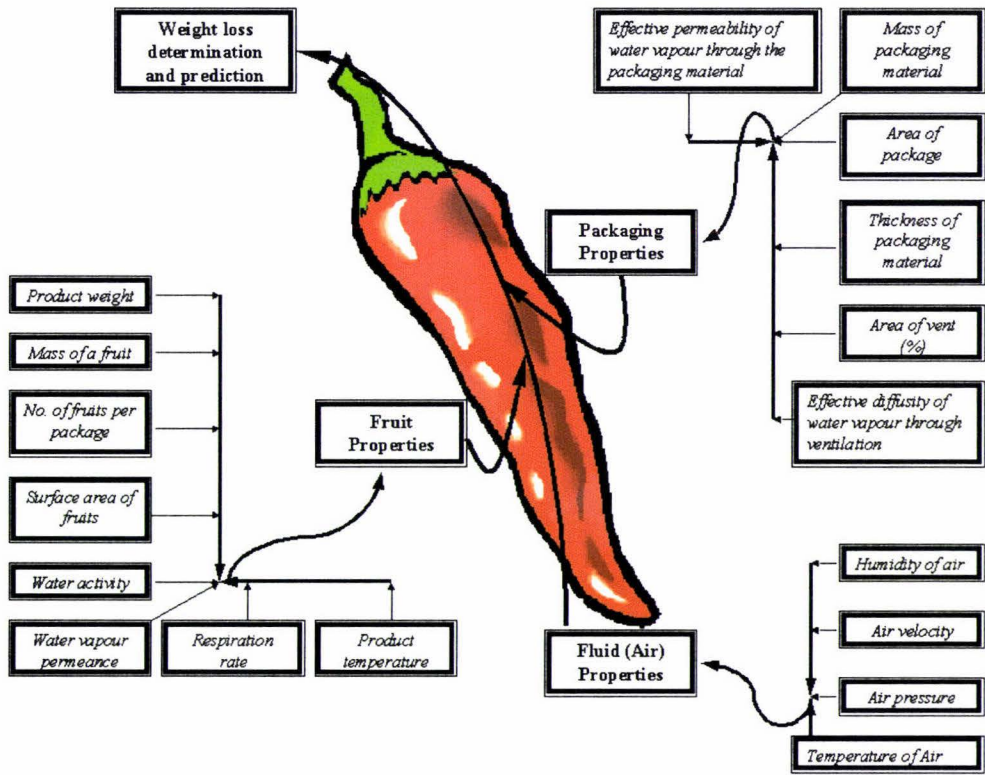


Figure 6-7 Conceptual model of factors affecting weight loss of packaged chillies.

CHAPTER 7

WEIGHT LOSS MODEL TESTING: CHILLI PACKAGING SYSTEMS

7.1 INTRODUCTION

This chapter details the approach taken to test and validate the mass transfer component of the computer-based 'Weight Loss Simulator' model (a steady-state model), developed by Tanner (1998). An experimental programme for measurement of chilli weight loss characteristics was conducted to provide model-testing data. Results of chilli weight loss were used for comparison with the model predictions. Applications of this model will assist the chilli industry of Thailand in assessing packaging regimes designed to improve the postharvest quality and shelf life of fresh chillies.

7.2 CHILLI MASS LOSS DATA COLLECTION

This experiment was designed to quantify the influence of packaging type and storage temperature on chilli mass loss. The materials and methods used in this data collection are covered in Chapter 3. Data used for testing the model were obtained from Chapter 4 and Chapter 5.

7.3 'WEIGHT LOSS SIMULATOR' MODEL TESTING

The results of predicted chilli mass loss compared with the measured data will be presented as the percentage of weight loss (on an initial basis) at the end of simulating period, with respect to types of packages and storage temperatures. The 95% confidence bounds for the experimental data are also shown in each model test. The internal air relative humidity (inside plastic bags) had not been measured during the mass loss data collection, thus only predicted values will be presented and discussed. This variable is the one that is calculated.

The assumptions in 'Weight Loss Simulator' model testing were devised in order to reduce the complexities of modelling the physical system. These assumptions are:

1. Steady state conditions exist for weight loss characteristics of fresh chillies
2. The mass transfer coefficient of a chilli is constant at individual storage temperatures and over the period of experiment.
3. The respiration rate of a chilli is constant at a single storage temperature
4. Temperature inside the plastic bag is equal to the skin temperature of a fresh chilli
5. Temperature and humidity of the storage room are constant
6. Air velocity inside the storage room has no effect on weight loss characteristics of chillies
7. Effective diffusivity of water vapour through a plastic bag are determined based on the relationship between percentage of perforation (per bag) and values of effective diffusivity (Sabarez and Tanner, 2001).
8. Water vapour transfer only exists through the ventilation area
9. Plastic bag dimensions and surface area are constant
10. There is no moisture uptake by plastic bags
11. Water activity of a chilli is constant
12. Gas conditions (O₂ and CO₂) within the bags are constant

The major data for the development of the mass transfer simulation model data file both for unpackaged and packaged chillies are shown in Table 7-1 and Table 7-2.

Table 7-1 Major data used for development of the mass transfer simulation model datafile for unpackaged chillies. These data were sourced from Chapter 4.

Variable	Value	Unit	Variable	Value	Unit
Product Data			Fluid Data		
Mass transfer coefficient at:			External fluid relative humidity at:		
5°C	2.87E-10	kg.s ⁻¹ .m ⁻² .Pa ⁻¹	5°C	56	%
10°C	1.24E-09	kg.s ⁻¹ .m ⁻² .Pa ⁻¹	10°C	80	%
20°C	5.93E-10	kg.s ⁻¹ .m ⁻² .Pa ⁻¹	20°C	20	%
30°C	2.43E-10	kg.s ⁻¹ .m ⁻² .Pa ⁻¹	30°C	76	%
Mass of individual product	0.005	kg	External fluid temperature at:		
Total mass of products	0.100	kg	5°C	5.07	°C
Surface area of individual product	0.003	m ²	10°C	9.64	°C
Product water activity	0.995	fraction	20°C	19.71	°C
Product skin temperature at:			30°C	29.88	°C
5°C	5.18	°C	Atmospheric pressure	101325	Pa
10°C	9.70	°C			
20°C	19.60	°C			
30°C	29.58	°C			
Product Respiration Rate at:					
5°C	2.95E-09	kg / s			
10°C	6.46E-09	kg / s			
20°C	2.59E-08	kg / s			
30°C	5.92E-08	kg / s			

Table 7-2 Major data used for development of the mass transfer simulation model datafile for packaged chillies. These data were source from Chapter 4 and Chapter 5.

Variable	Value	Unit	Variable	Value	Unit
Product Data			External Environmental Data		
Mass transfer coefficient at:			External fluid relative humidity at:		
5°C	2.87E-10	kg.s ⁻¹ .m ⁻² .Pa ⁻¹	5°C	56	%
10°C	1.24E-09	kg.s ⁻¹ .m ⁻² .Pa ⁻¹	10°C	80	%
20°C	5.93E-10	kg.s ⁻¹ .m ⁻² .Pa ⁻¹	20°C	28	%
30°C	2.43E-10	kg.s ⁻¹ .m ⁻² .Pa ⁻¹	30°C	76	%
Mass of individual product	0.005	kg	External fluid temperature at:		
Total mass of products	0.100	kg	5°C	5.07	°C
Surface area of individual product	0.003	m ²	10°C	9.64	°C
Product water activity	0.995	fraction	20°C	19.71	°C
Product skin temperature at:			30°C	29.88	°C
5°C	5.18	°C	Atmospheric pressure	101325	Pa
10°C	9.70	°C			
20°C	19.60	°C			
30°C	29.58	°C			
Product Respiration Rate at:					
5°C	2.95E-09	kg / s			
10°C	6.46E-09	kg / s			
20°C	2.59E-08	kg / s			
30°C	5.92E-08	kg / s			
Fluid Data			Packaging Material Data		
Internal fluid temperature at:			Width	0.15	m
5°C	5.18	°C	Length	0.23	m
10°C	9.70	°C	Surface area	0.069	m ²
20°C	19.60	°C	Effective Diffusivity according		
30°C	29.58	°C	percentage of perforation		
			0.00	0.00	kg.s ⁻¹ .m ⁻² .Pa ⁻¹
			0.17 ^a	6.40E-14	kg.s ⁻¹ .m ⁻² .Pa ⁻¹
			0.49 ^b	1.28E-13	kg.s ⁻¹ .m ⁻² .Pa ⁻¹
			0.98 ^b	2.26E-13	kg.s ⁻¹ .m ⁻² .Pa ⁻¹
			1.96 ^b	4.22E-13	kg.s ⁻¹ .m ⁻² .Pa ⁻¹
			100 ^c	N/A	

^a Manually perforated bag, there are 6 holes per bag and the diameter of hole is approximately 5mm

^b Commercially perforated plastic bags, the diameter of hole is approximately 2.5mm

^c Unpackaged chillies

It should be noted that the skin permeance to water vapour (to calculated mass transfer coefficient) used for model prediction were different from those presented in section 4.6. The recalculated permeances at 4 storage temperatures were obtained and then the 'mass transfer coefficient' ($\text{kg}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot\text{Pa}^{-1}$) was calculated (calculation not shown). Using these coefficients to predict the weight loss of unpackaged fruit, predicted results were satisfactorily consistent with researched data.

7.4 RESULTS AND DISCUSSIONS OF MODEL TESTING

The measured data for chillies were predicted by the 'Weight Loss Simulator' model with general agreement (Figure 7-1). The magnitudes of predicting deviation and lacks of agreement were varied with respect to the storage condition (temperature and relative humidity) and packaging types (perforation area and size of hole) and dynamic changes in biological properties (i.e. rapid dehydration or microbiological contamination). The influences of these factors on weight loss of fresh chillies obtained from the model simulation were also consistent with the results discussed in section 5.6.

The predicted relative humidity values inside the plastic bags were relatively high. This resulted from low water vapour permeability of LDPE and LLDPE film (Day, 1993) and moisture mainly moving through the perforated regions (Tanner, 1998). Therefore, the effects of perforation areas and the diameter of hole (Figure 7-1) contribute to the differences in weight loss of packaged products (Emond *et al.*, 1995; Sanz *et al.*, 1999). In particular the 0.17% perforated bag, with 5 mm of hole-diameter, although the area of perforation is smaller than other perforated bags, the percentage of weight loss is relatively higher. The effects of hole dimension could be used to explain this deviation (Sabarez and Tanner, 2001).

The high levels of relative humidity inside the plastic bags (Table 7-3) would minimise the water vapour pressure difference between inside fruits and environment (inside bags). This suppresses water loss, which is the major source of weight loss, from fruit. Subsequently, the weight loss due to respiration (or carbon loss) becomes a significant proportion (Maguire, 1998).

Butchbaker *et al.* (1973) reported that respiration could contribute to 100% of weight loss among potatoes, stored under high relative humidity (100% RH). As such, this could be used to explain the result of this experiment, in which the respiration was the major source (more than 99%) contributing to weight loss of fresh chillies, packaged in plastic bags in all storage temperature (Table 7-3). Hence, the predicted lines for weight loss of packaged chillies are all similar.

According to Table 7-3, the weight loss of unpackaged chillies stored at 30°C from the model was dominated by the respiration. This is in contrast to the results in section 4.6 that transpiration (water) loss is the main contributor to weight loss of fresh chillies.

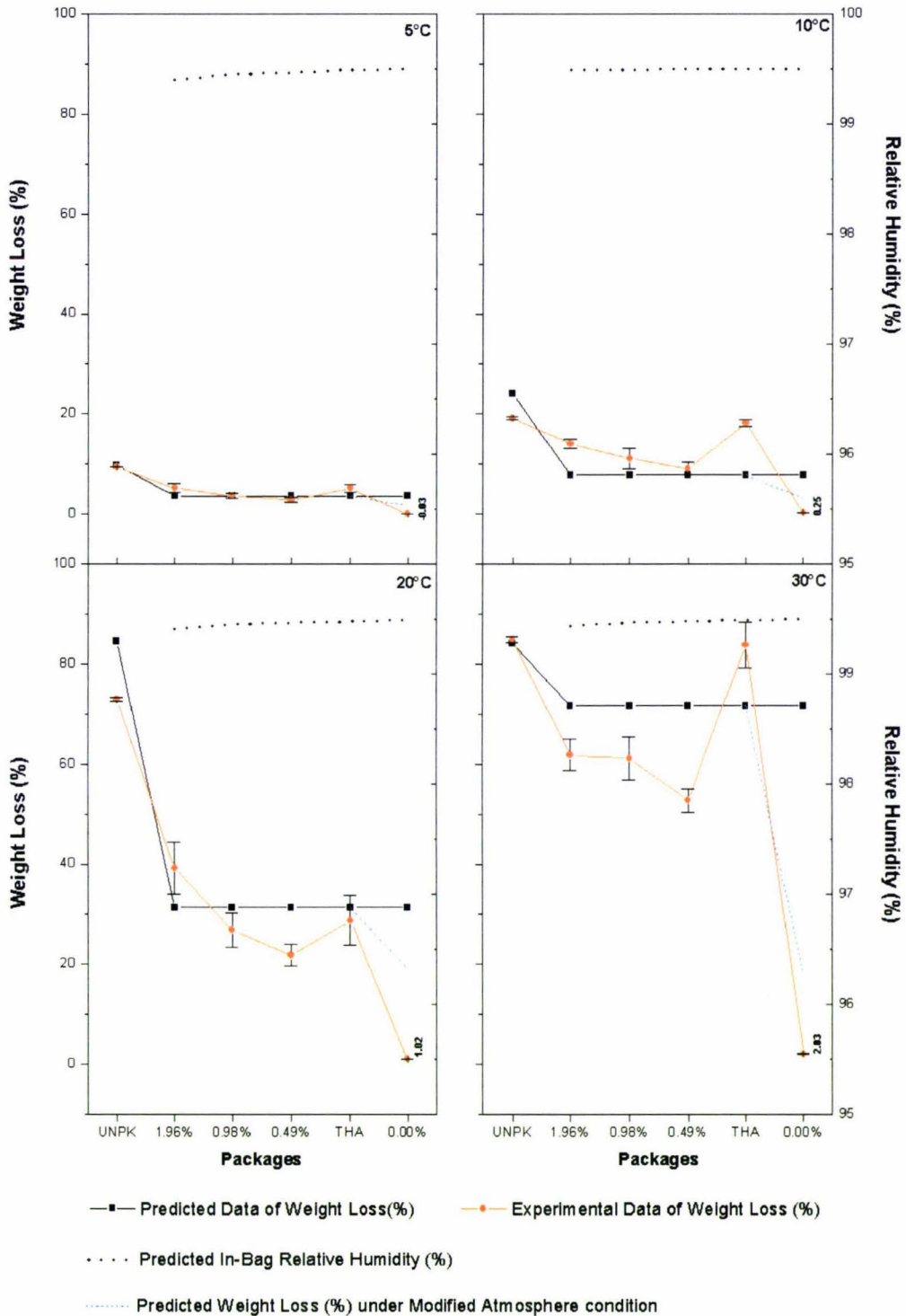


Figure 7-1 Results of ‘Weight Loss Simulator’ model testing. The dashed lines are the predicted internal relative humidity. Blue-colour dotted line represents the effects of MAP lowering the weight loss of chillies packaged with nonperforated bag (0.00%)

Table 7-3 Summation of proportions contributed to weight loss of fresh chillies

Temperatures (°C)	Packages	Predicted water loss contributed to total weight loss (%)	Predicted respiration loss contributed to total weight loss (%)
5	UNPK	63.14	36.86
	1.96%	0.38	99.62
	0.98%	0.20	99.80
	0.49%	0.12	99.88
	0.17%	0.06	99.94
	0.00%	0.00	100.00
10	UNPK	67.72	32.28
	1.96%	0.11	99.89
	0.98%	0.06	99.94
	0.49%	0.03	99.97
	0.17%	0.02	99.98
	0.00%	0.00	100.00
20	UNPK	62.96	37.04
	1.96%	0.18	99.82
	0.98%	0.10	99.90
	0.49%	0.06	99.94
	0.17%	0.03	99.97
	0.00%	0.00	100.00
30	UNPK	14.92	85.08
	1.96%	0.05	99.95
	0.98%	0.02	99.98
	0.49%	0.01	99.99
	0.17%	0.01	99.99
	0.00%	0.00	100.00

Condensation inside the plastic bags also could be another variation contributing to lacks of agreement, in this simulation. Gaffney *et al.* (1985) stated that under this condition, the heat of condensation, in combination with respiratory heat generation, causes the product surface temperature to rise above the air temperature. This could contribute to the error in mass transfer coefficient of packaged fruit, which, in turn, causes deviation from the weight loss prediction.

Another variation in the simulations might occur from the atmospheric modification inside the plastic bags. Due to analysis of the in-bag gas composition (section 5.7), the atmosphere inside nonperforated bags (0.00%) was modified (11-17%O₂ and 1-7% CO₂). Specific to internal gas composition at 20 and 30°C, Day (1993) suggested that such gas levels could cause anaerobic conditions inside the plastic bags. However the atmospheres inside perforated bags were similar to the air condition (section 5.7).

Consequently, the respiration rate of chillies under modified atmosphere condition was recalculated based on the respiration model and parameters for fresh chillies (V_m , K_m

and K_i) proposed by Lee *et al.* (1994). As a result of the new respiration data, the predicted values of weight loss of chillies packaged in nonperforated bag could be up to 48% lower than the existing value (Figure 7-1), which supported the variation in model testing.

From this study, there seem several potential factors, which might affect the accuracy of model prediction. In the following section (section 7.5), the sensitivity of 'Weight Loss Simulator' to changes of certain system-input parameters, i.e. mass transfer coefficient or external relative humidity, therefore, will be studied and discussed.

7.5 SENSITIVITY ANALYSIS

A sensitivity analysis was performed to assess the sensitivity of predictions to variation (or inaccuracy) in key individual data needed for simulation of mass transfer. There were two main packaging configurations: Unpackaging and packaging system and they are under 4 different storage conditions (Table 7-1 and Table 7-2), which were used in this weight loss model simulation.

Product mass transfer coefficient, respiration rate, product water activity as well as initial coolstore relative humidity-temperature were altered to establish the effect of data variability on the reliability of product mass and fluid relative humidity predictions.

7.5.1 SENSITIVITY TO VARIATION IN PRODUCT MASS TRANSFER COEFFICIENT (K_{skin})

Tanner (1998) mentioned that the sensitivity of predictions to possible variability/inaccuracy in the mass transfer coefficient was assessed both to cover error that may have been introduced during measurement, and to establish the strength of the need to measure this product property accurately. Variations of $\pm 10\%$ of the measured value were chosen following the guidelines of Tanner (1998). The results of the test are shown in Figure 7-2.

With 10% changing in K_{skin} , only unpackaged chillies changed their product mass losses apparently and changes approximately varied from ± 2 to $\pm 7\%$, over 4 storage

temperatures. In contrast, there were not obvious changes in weight loss of chillies from the packaged group. The internal relative humidities did not change.

This variation in prediction highlights a moderate need for accurate measurement (or prediction method) for product mass transfer coefficient, especially for predicting weight loss of unpackaged chillies. However, neither inaccurate data nor variation in product mass transfer coefficient has a significant effect on product mass loss and relative humidity modification of packaged chillies.

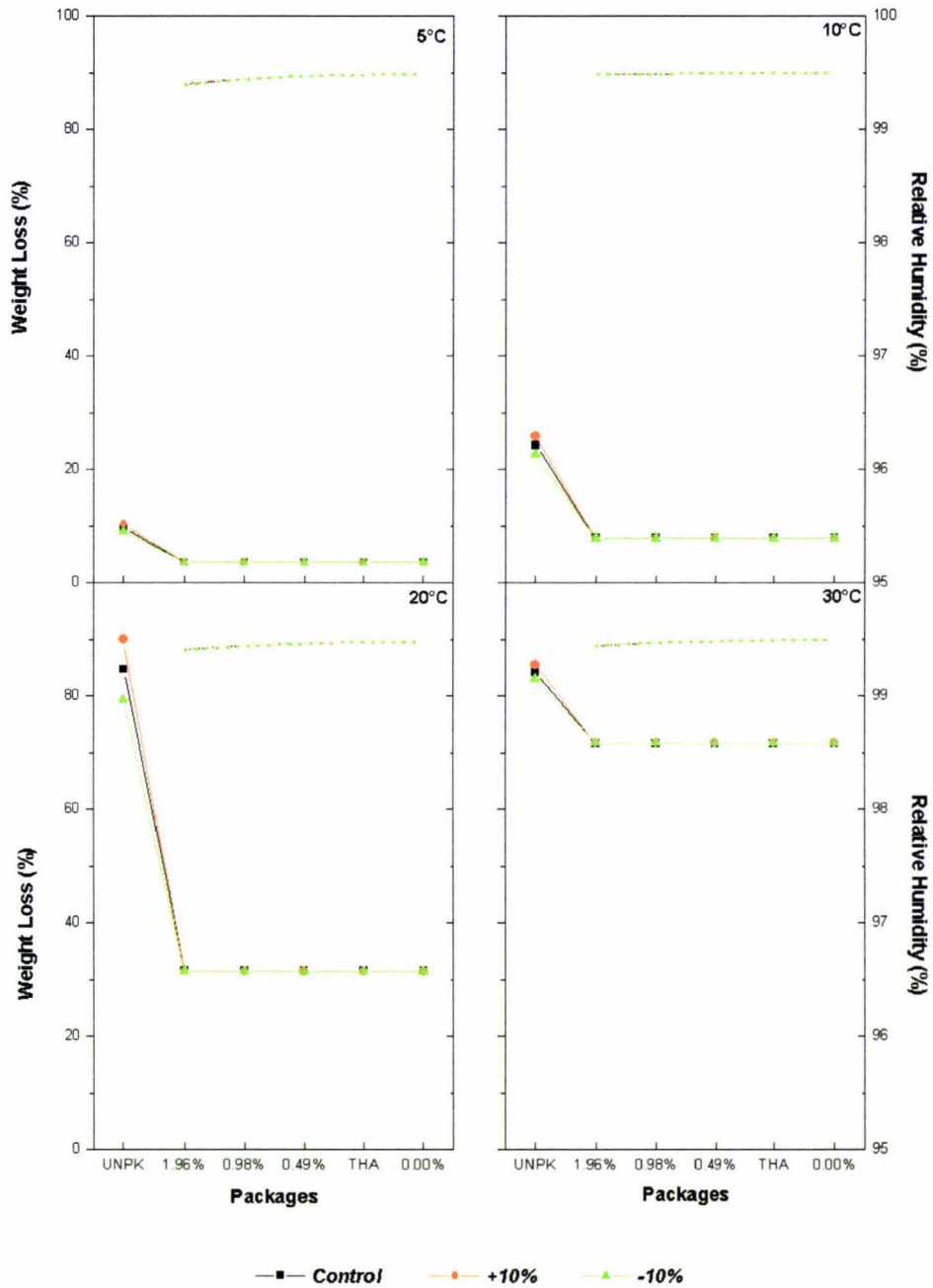


Figure 7-2 Assessment of the effect of variation/inaccuracy in the chilli mass transfer coefficient on predictions of product mass loss and packaging internal air relative humidity, at 4 different storage temperatures. The dashed lines are the relative humidity predictions whilst the solid lines predict mass loss.

7.5.2 SENSITIVITY TO VARIATION IN PRODUCT RESPIRATION RATE

The sensitivity to variation/inaccuracy was assessed using $\pm 10\%$ variation (Figure 7-3). The predictions of sensitivity to changes in respiration rate are moderately. The changed could be varied from $\pm 3.2\%$ to $\pm 10.1\%$, however the internal relative humidity did not change. In this study, mass loss of packaged chillies was dominated by respiration since the internal relative humidity was so high. This was supported by the report of Butchbaker *et al.* (1973).

In addition, the effects of CO_2/O_2 level atmospheric modification to respiratory or carbon loss rate, particularly in the nonperforated bag, were not taken into account. The result of this test highlights the need for accurate measurement for this system input-parameter.

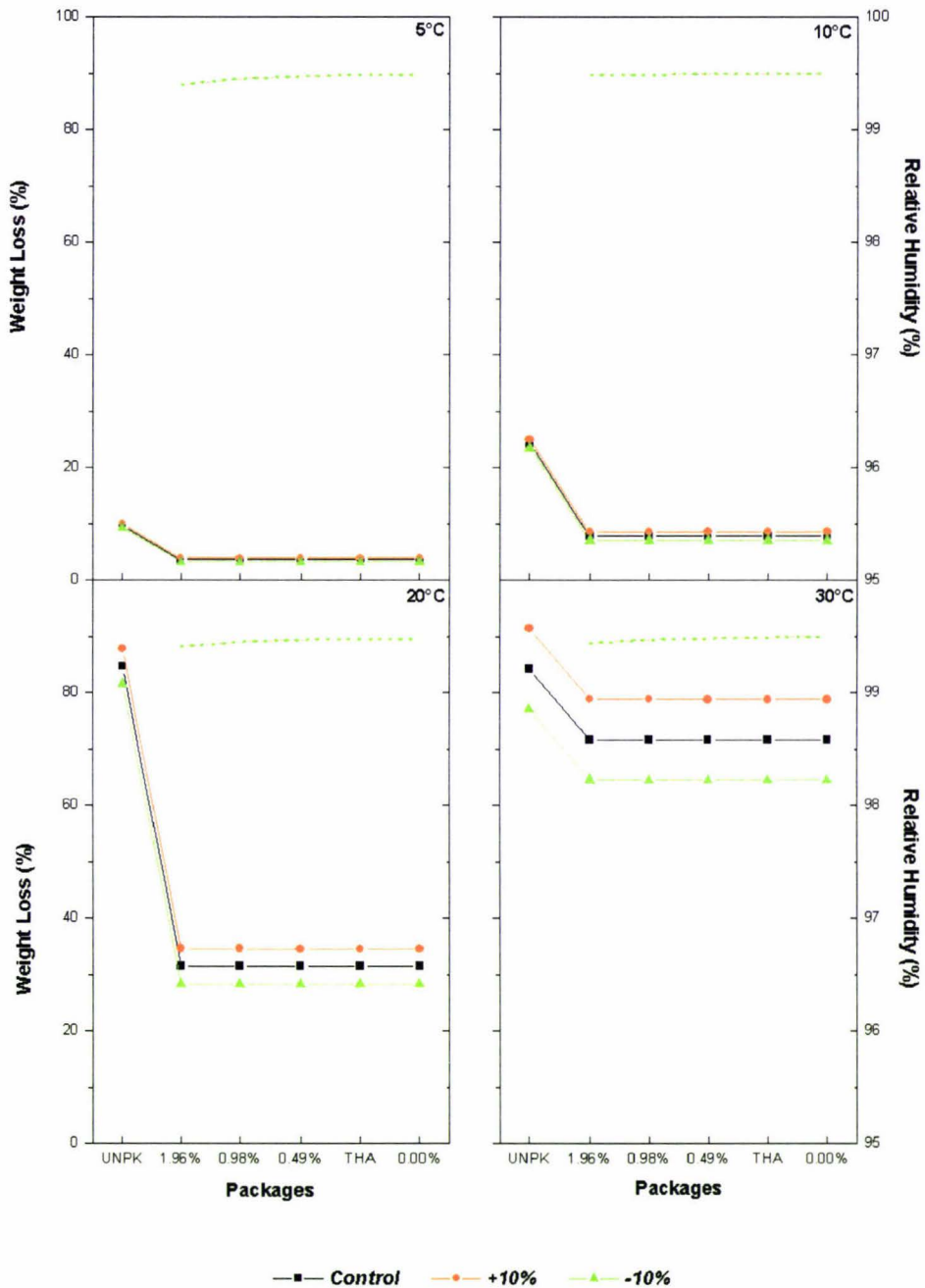


Figure 7-3 Assessment of the effect of variation/inaccuracy in the chilli respiration rate on predictions of product mass loss and packaging internal air relative humidity, at 4 different storage temperatures. The dashed lines are the relative humidity predictions whilst the solid lines predict mass loss.

7.5.3 SENSITIVITY TO VARIATION IN THE DIFFERENCE OF FRUIT TEMPERATURE AND PACKAGE AIR TEMPERATURE

In the base modelling data, the product to internal package air temperature difference was assumed to be equal. Sensitivity of predictions to variation/accuracy in this parameter was assessed by assuming the difference both increased and decreased 0.1°C. This also assumed a change in the partial pressure driving force between the product and the air (the dominant driving force for product mass loss). The results are shown in Figure 7-4.

The predictions of sensitivity to changes in the product-package air temperature difference are not sensitive to inaccuracy/variation, while the internal relative humidity (RH) changed slightly. However, the changes of internal relative humidity have no effects on weight loss. This could be due to the relatively high RH (>99%) inside the plastic bags and the weight loss is mainly due to respiration (carbon loss). This highlights that neither inaccurate data nor variation in difference of fruit temperature and package air temperature had a significant effect on product mass loss and relative humidity modification of packaged chillies in this case.

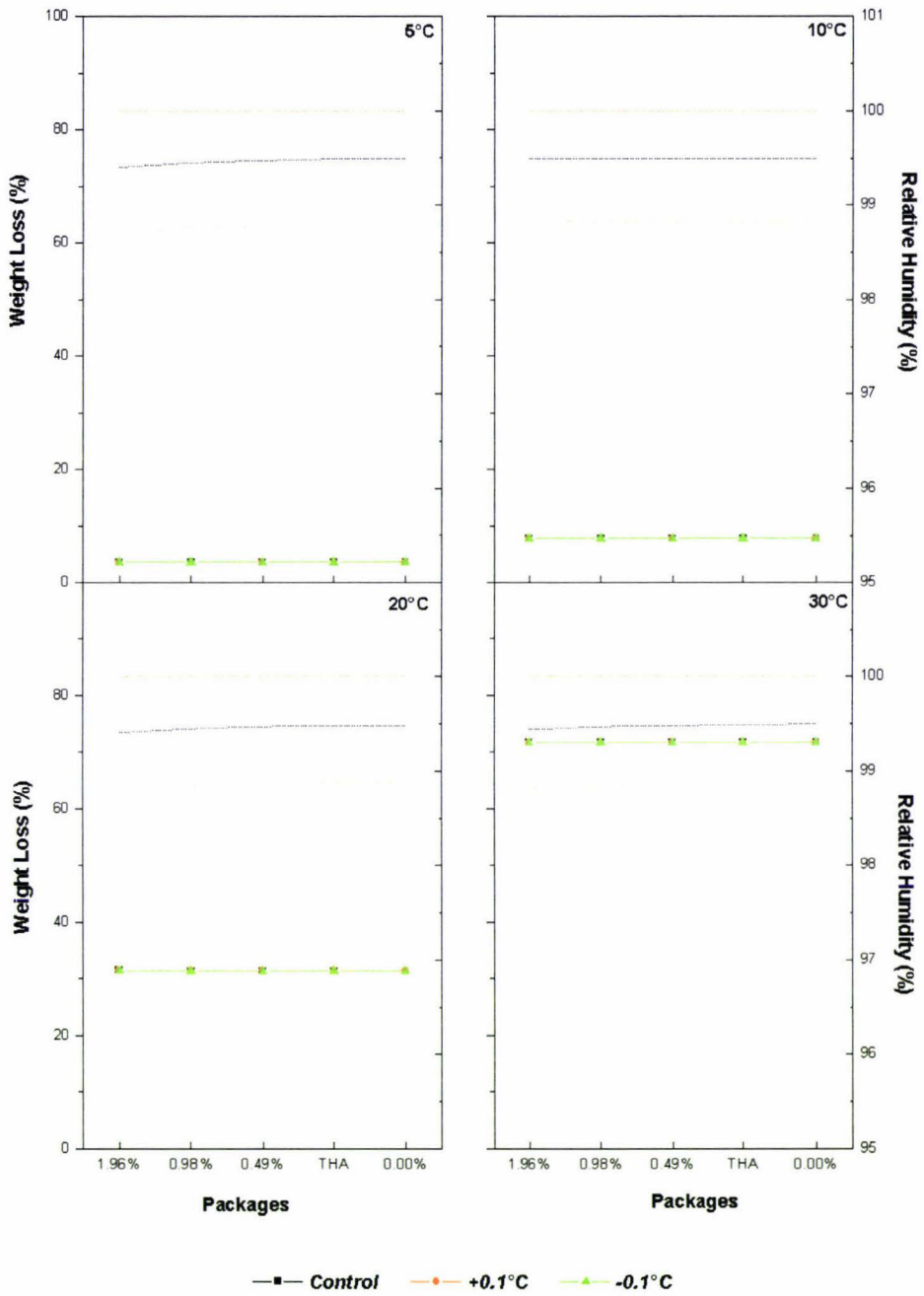


Figure 7-4 Assessment of the effect of variation/inaccuracy in the product-package air temperature difference on predictions of product mass loss and packaging internal air relative humidity, at 4 different storage temperatures. The dashed lines are the relative humidity predictions whilst the solid lines predict mass loss.

7.5.4 SENSITIVITY TO VARIATION IN PRODUCT WATER ACTIVITY

The chilli water activity was assumed to be 0.995. However, in section 4.7, the water activity was measured to be approximately 0.95. Sensitivity to imprecision in this parameter was assessed by using 0.95 as value of water activity in weight loss prediction. Tanner (1998) mentioned this could cause a major change in the partial pressure driving force between the product and the air (a dominant driver in product mass loss prediction).

Mass loss of unpackaged chillies ($\pm 3-15\%$) and internal relative humidities (4.5%) were moderately sensitive to variation/inaccuracy (Figure 7-5), whilst, there were no changes in mass loss of packaged chillies. Although the internal relative humidity (RH) apparently changed, there were no changes in weight loss. However, it can be questioned in the weight loss characteristics of packaged chillies since the RH significantly drop to 95%. From this simulation, it could be said that weight loss caused by water loss was relatively smaller than that caused by respiration.

This highlights that neither inaccurate data nor variation in water activity has a significant effect on product mass loss and relative humidity modification of packaged chillies.

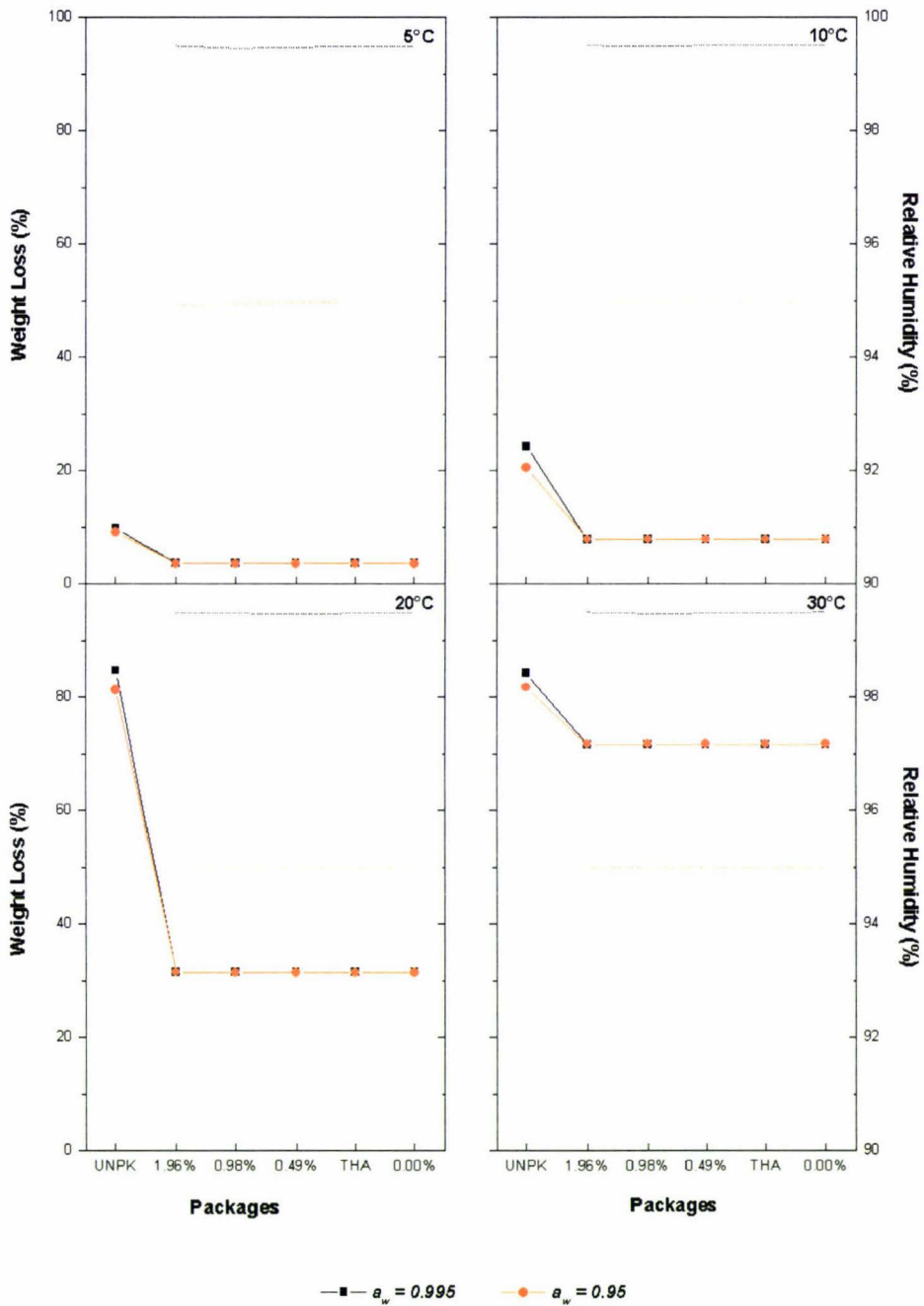


Figure 7-5 Assessment of the effect of variation/inaccuracy in the chilli water activity on predictions of product mass loss and packaging internal air relative humidity, at 4 different storage temperatures. The dashed lines are the relative humidity predictions whilst the solid lines predict mass loss.

7.5.5 SENSITIVITY TO VARIATION IN EFFECTIVE PACKAGING MATERIAL MASS TRANSFER COEFFICIENT ($K_{eff, pk}$)

Tanner (1998) mentioned the mass transfer coefficient was used to describe the rate of water vapour across the packaging material. The transmission rate was both increased to twice the control rate, and decreased to half the control rate, because such changes are realistically achievable by packaging design. The sensitivity of predictions is shown in (Figure 7-6).

While the mass losses were not sensitive to the doubling or halving the rate of water vapour across the plastic films, internal relative humidities of packaged chillies were slightly sensitive to the inaccuracy. There were no major differences in changing mass loss of chillies with perforated (regardless diameter of hole) or nonperforated film system.

This test highlights that neither inaccurate data nor variation in effective packaging material mass transfer coefficient has a significant effect on product mass loss of packaged chillies.

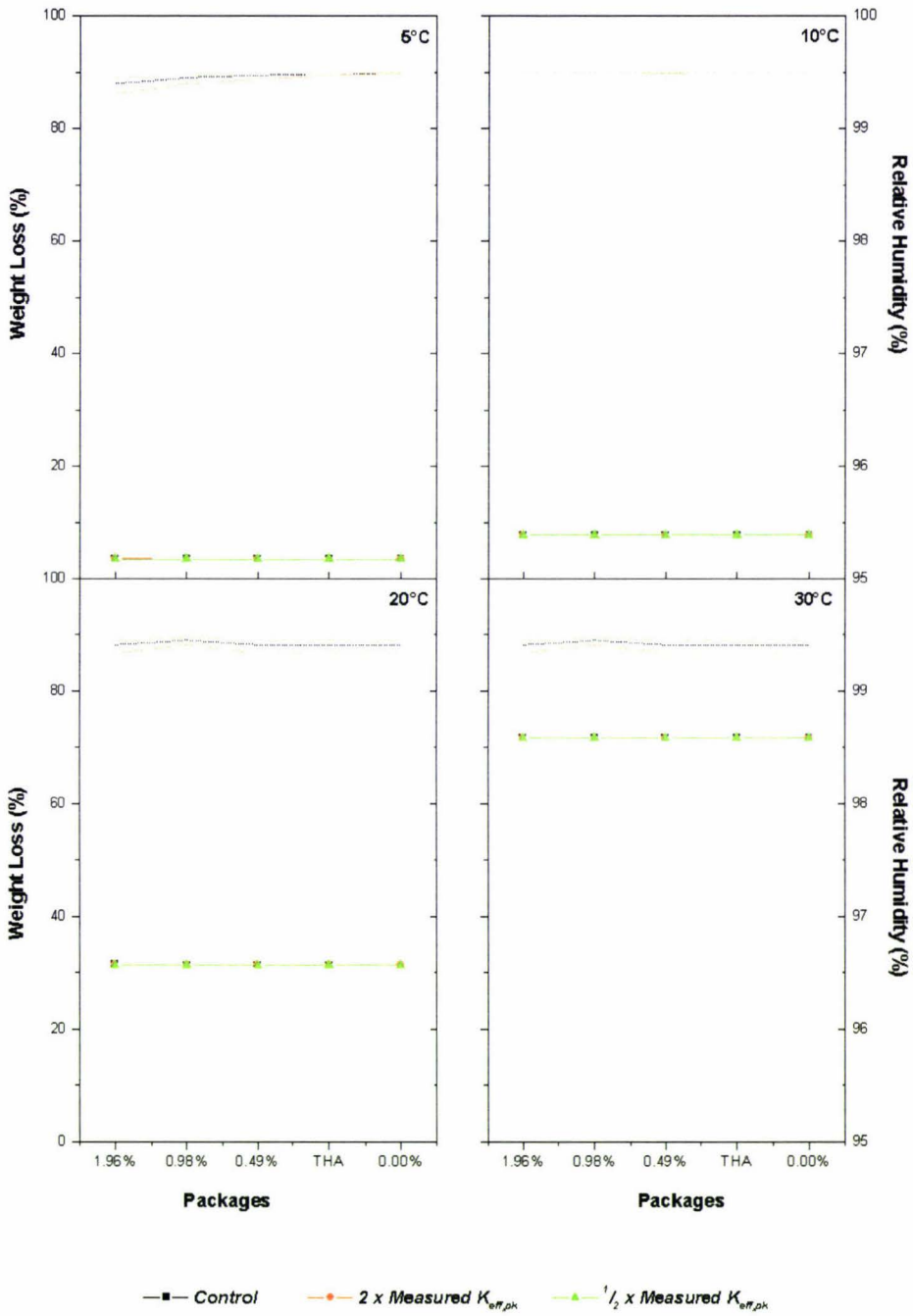


Figure 7-6 Assessment of the effect of variation/inaccuracy in the effective packaging material mass transfer coefficient on predictions of product mass loss and packaging internal air relative humidity, at 4 different storage temperatures. The dashed lines are the relative humidity predictions whilst the solid lines predict mass loss.

7.5.6 SENSITIVITY TO VARIATION IN THE EXTERNAL FLUID RELATIVE HUMIDITY

The accuracy of the equipment for measuring the external relative humidity level could contribute to the variation in predicting mass loss of fresh produce. By changing $\pm 1\%$ of this parameter, mass loss was changed $\pm 9.2\%$ (Tanner, 1998).

For this study, with changing the external relative humidity $\pm 1\%$, only unpackaged chillies were apparently sensitive (Figure 7-7). The mass loss changes among this system were up to $\pm 13.60\%$. There were not changes in mass loss of chillies with plastic bag, however the internal relative humidity was slightly sensitive to the variation.

This highlights that neither inaccurate data nor variation in this system-input parameter, has a significant effect on product mass loss and relative humidity modification of packaged chillies.

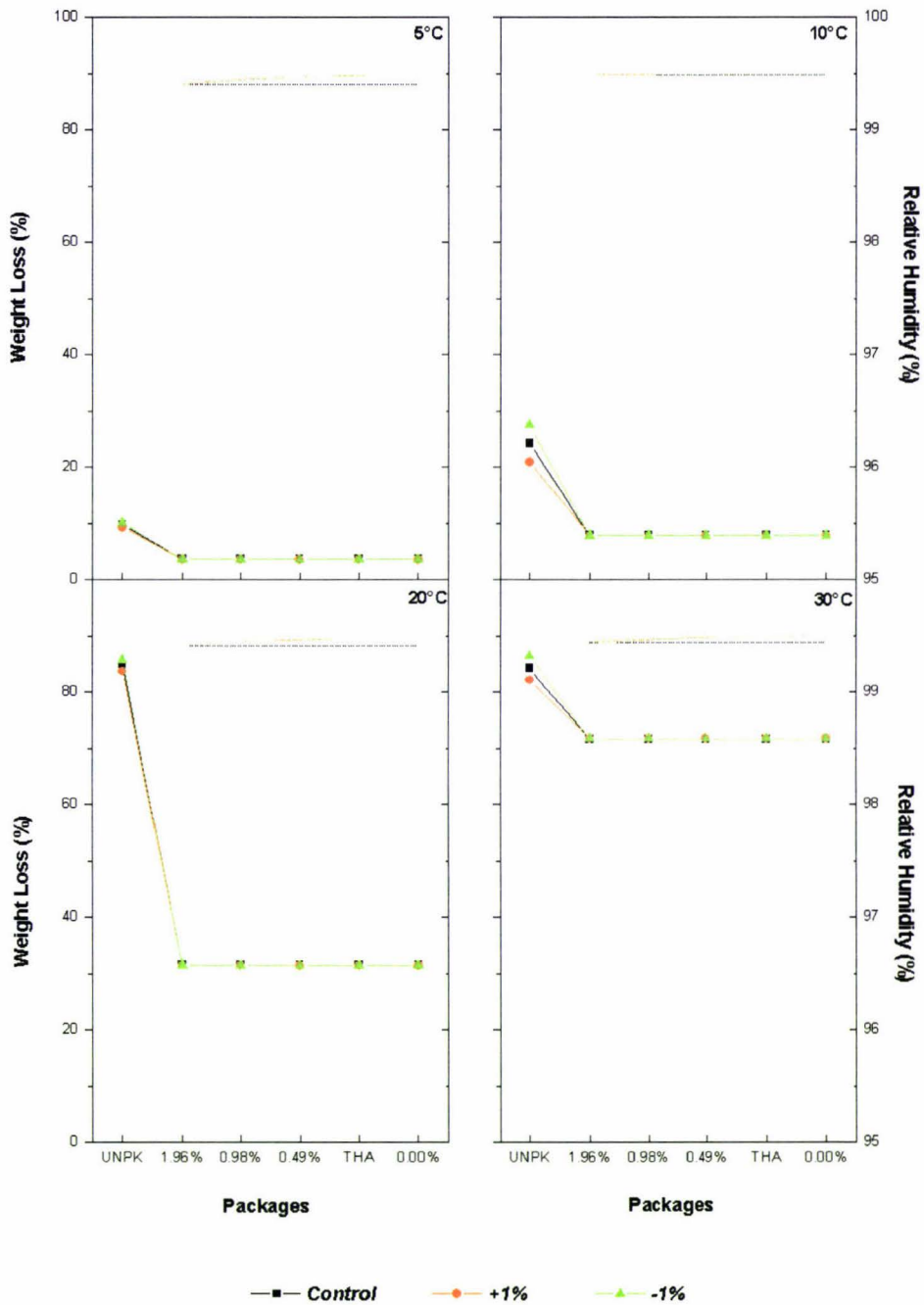


Figure 7-7 Assessment of the effect of variation/inaccuracy in the external fluid relative humidity on predictions of product mass loss and packaging internal air relative humidity, at 4 different storage temperatures. The dashed lines are the relative humidity predictions whilst the solid lines predict mass loss.

7.5.7 SENSITIVITY TO VARIATION IN THE IN-PACKAGE AIR AND COOLSTORE AIR TEMPERATURE DIFFERENCE

Inadequate pre-cooling, which could increase the temperature difference between in-package air and Coolstore, results in excessive heat (also heat generation) within the package (Tanner, 1998). The sensitivity of predictions to variation/inaccuracy in this parameter is shown in Figure 7-8.

The predictions in mass loss and internal relative humidity were not sensitive to the increasing of the product-coolstore air temperature difference by 0.1 and 0.2°C. This test highlights that neither inaccurate data nor variation in differences between in-package air and coolstore air temperature has effects on product mass loss and relative humidity modification of packaged chillies.

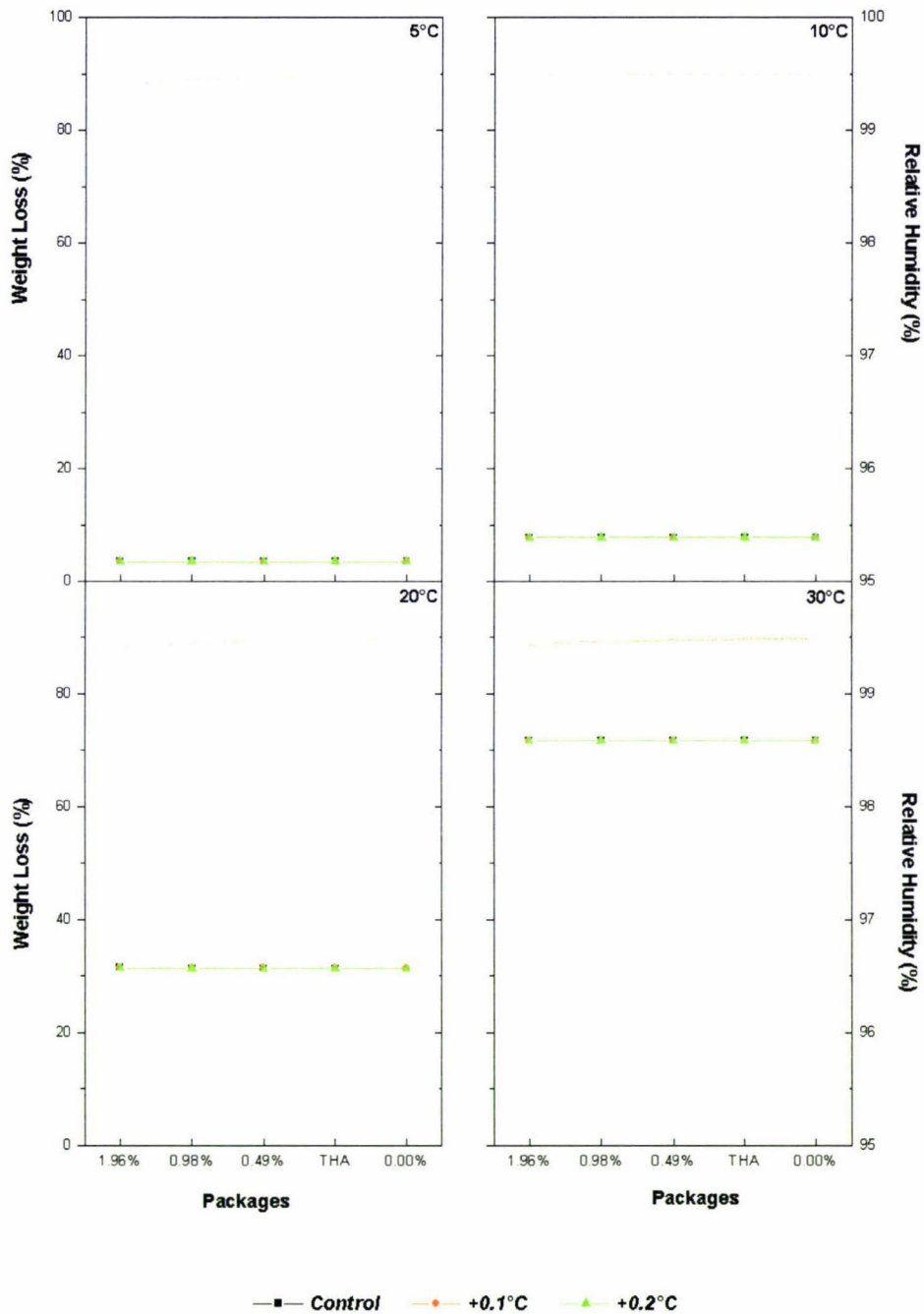


Figure 7-8 Assessment of the effect of variation/inaccuracy in the package-coolstore air temperature difference on predictions of product mass loss and packaging internal air relative humidity, at 4 different storage temperatures. The dashed lines are the relative humidity predictions whilst the solid lines predict mass loss.

7.6 DISCUSSION OF MODEL PERFORMANCE

Analysis of the accuracy of weight loss predictions was undertaken using graphical comparison, which showed there were uncertain results. Sensitivity analysis confirmed the uncertainties in that some variations could significantly affect the mass loss prediction. System-input parameters could be regarded as the main factors affecting the accuracy of model simulation. From this sensitivity analysis, 'Weight Loss Simulator' model is sensitive only to small changes in respiration rate, which could contribute to significant change in weight loss of chillies (either unpackaged or packaged chillies).

Specific to the effect of plastic bags (both perforated and nonperforated bags) on the mass loss, it was not apparent from this simulation. This could be due to high levels of in-bag relative humidity (more than 99%), regardless of the types of plastic bags. Under this condition, weight losses of packaged products were mainly dominated by respiration or carbon loss (Butchbaker *et al.*, 1973; Maguire, 1998). Subsequently, even though changes were made to the area of perforation and/or perforation diameter, the product mass losses remained constant. However, the trends of predicted weight loss and storage temperatures were consistent with experimental data, with the rate of weight loss increasing with increasing temperature.

Fisherman *et al.* (1996) stated the perforations did not significantly change the in-bag relative humidity, compared to that of nonperforated bag, which were both saturated. In contrast, Pesis *et al.* (2000) reported that perforated plastic film can lower relative humidity inside the plastic bags, which in turn reduces condensation. The differences in effectiveness of perforated film in reducing in-package relative humidity are likely due to area of perforation, perforation diameter and/or storage environment.

Overall, the model used for mass loss simulation in this work provides practical data and information, in particular for product-package integration concepts, for packaging design of fresh chillies and other horticultural products. From this study, it could be seen that additional data e.g. air velocity are importantly required in order to develop the model further, which will be suitable for the traditional products and storage/handling conditions of Thailand.

7.7 RECOMMENDATIONS FOR FUTURE WORK

Further investigation of the effects of biological aging, the dynamic characteristic of water vapour passing through ventilation area as well as reduction of input-data inaccuracy is to be justified. The effects of atmospheric modification inside the plastic bag, on loss of mass and quality of fresh chillies, will be further modelled.

In addition to suggestions, I would like to add the potential damages during handling/transportation i.e. stacking or vibration damages, into the model development since these could rapidly lower the marketability of fresh produce. The simulated results of models taking these hazards into accounts would expect to stimulate the attention of people involving in Thai horticultural industry, to consistently invest and develop sound packaging and transportation for the high quality of their products.

CHAPTER 8

POSTHARVEST TREATMENTS TO IMPROVE THE STORAGE QUALITY OF GREEN BELL PEPPERS

8.1 BACKGROUND

In Chapter 5, the effects of packages and temperatures on the postharvest qualities of fresh green chillies were studied. However, the effects of postharvest disinfecting treatment on the storage quality of chillies have not been discussed. This element of the study has not been included to-date since in Ubon Ratchathani province, Thailand, farmers use naturally available water supplies (i.e. small canals in the gardens) to clean the dirt residues off the fruits before and packaging them in plastic bags ready to sell or transport (Utto, 2000). The chilli shelf life simulation experiments were based on the traditional procedures of Thai farmers.

However, to improve the overall postharvest and marketing quality of fresh chillies in Thailand under high temperature conditions ($30\pm 5^{\circ}\text{C}$), which are suitable for parasitic infection (Wall and Bosland, 1993), a chilli postharvest disinfecting requirement was studied (Tanner, 2000, pers.com.). Therefore, this part of the masterate-study was developed.

Due to the season, chillies were not locally available for this experiment. However as, chillies and bell peppers are in the same genus *Capsicum* and Family *Solanaceae* (Smith, 1982) and their postharvest pest and disease management are systematically similar (Noel *et al.*, 1999). Green bell peppers then were used for this postharvest disinfecting treatment study. The results of this study will be applied to the further study using fresh chillies.

8.2 INTRODUCTION

Sweet bell pepper (*Capsicum annuum* L.) is stored for moderately long periods at temperatures between 7 and 13°C depending upon the variety and the stage of maturity.

However, these temperatures do not completely inhibit decay development, caused mainly by *Botrytis cinerea* and *Alternaria alternata* during prolonged storage (Meir *et al.*, 1995). Additionally, because of their large surface to weight ratio, peppers are also prone to water loss and shrivelling (Gonzalez-Aguilar *et al.*, 1999). Rapid cooling and low temperature storage with a high relative humidity is considered as the most effective method for maintaining the quality of bell peppers (Hardenburg *et al.*, 1986). Still, pepper fruits harvested at the mature-green stage are sensitive to temperature below 6°C and develop chilling injury (CI) (Meir *et al.*, 1995) and *Alternaria* rot often follows CI (Miller and Rise, 1986).

The benefits of a modified atmosphere package (MAP) and storage at low temperature has been reported to inhibit physical and physiological changes, including chilling injury, and improve the quality retention of bell peppers during storage (Ben-Yehoshua *et al.*, 1983; Meir *et al.*, 1995; Gonzalez *et al.*, 1999). However, disadvantages of MAP include the possibility of condensation inside packages, the growth of pathogens, and potential of anaerobic states to occur. The use of LDPE films with microperforations could eliminate the excessively low O₂ levels, while maintaining high humidity (Exama *et al.*, 1993; Wall and Berghage, 1996).

Spore germination and infection, which ultimately cause decay, obviously need to be controlled. Chemical dips, e.g. sodium hypochloride or benomyl, have been used in the treatment of several postharvest pathogens of fruits and vegetables (Mohammed *et al.*, 1991). Chlorinated water is also currently used in packing-houses for the purpose of sanitising fruits and vegetables in order to reduce postharvest decay (Nunes and Emond, 1999). Alternatively, postharvest heat treatments are being used for disinfestation and disinfection of an increasing variety of crops since there is a growing demand to decrease the postharvest use of chemicals against pathogens and insects (Lurie, 1998). Hot water dips are one of such techniques that have been successfully used to prevent decay in various crops (Gonzalez *et al.*, 1999).

Postharvest disinfecting treatments of hot chillies or bell peppers, using either chemical or nonchemical methods, in conjunction with film packaging have been studied (Mohammed *et al.*, 1992; Meir *et al.*, 1995; Gonzalez *et al.*, 1999).

However, the studies of combined effects of differences in storage temperatures and perforation areas of plastic films on postharvest qualities of treated bell pepper have not been reported.

The purpose of the present work was to examine the effectiveness of postharvest disease and decay treatments (both chemical and non-chemical), perforated plastic films and storage temperatures, in maintaining the quality of bell peppers during a 2-week storage period.

8.3 MATERIAL AND METHODS

8.3.1 PLANT MATERIAL

Freshly harvested green bell peppers (*Capsicum annuum* L.) were obtained from a local produce distribution centre. Fruits were delivered to the laboratory (Postharvest Laboratory, Massey University) immediately and 288 peppers (medium size, 80-100 mm in diameter) free of blemish or defects were selected for this study. All selected peppers were initially measured for skin colour, weight and firmness. Fruits were then separated into 3 equally sized groups, which were treated with different postharvest treatments: chlorine solution (NaClO), hot water dip (HWD) and no treatment.

8.3.2 CHLORINE SOLUTION AND HOT WATER TREATMENTS

2% (w/v) chlorine solution (NaClO) was prepared by diluting standard commercial household disinfectant (4.2% sodium hypochlorite, NaClO, Janola[®], Reckitt&Colman, Australia) with tap water (Woolley, 2000, pers.com.). Fruits were dipped and left in chlorine solution for approximately 15 minutes (Mohammed *et al.*, 1991). For heat treatment, water was heated to 53°C in a water bath (which was continuously monitored to keep the fluctuation within $\pm 1^\circ\text{C}$). Bell peppers were dipped in the heated water for 4 minutes (Gonzalez *et al.*, 1999). After peppers were treated, they were then dried at room temperature ($\approx 20^\circ\text{C}$) on kitchen paper towels for 1 hour, to remove any residual surface water.

8.3.3 PACKAGING AND STORAGE TEMPERATURES

Clear plastic bags used for this experiment were obtained from VSR Packaging Ltd (Te Atatu, Auckland, New Zealand). These were made from 50 μ m, Linear Low-Density Polyethylene blended with Low-Density Polyethylene (LLDPE/LDPE) and were perforated with the following perforation area: 0.08% (6 holes, 5 mm in diameter, manually puncturing), 0.49% (2.5 mm in diameter) and 0.98% (2.5 mm in diameter). All plastic bags were 230 x 320 mm. Four storage temperatures, 5, 10, 20 and 30°C, were used.

8.3.4 EXPERIMENTAL DESIGN

A full factorial design was used with 4 temperatures (5, 10, 20, and 30°C), 3 postharvest treatments (NaClO, HWD and Untreated) and 4 types of packages (0.08%, 0.49%, 0.98% and unbagged). The treatment with untreated and unbagged bell peppers was designated the control.

In each treatment, there were 3 replicates (bags), in which a single replicate (bag) contained 2 pepper fruits (totally weighing between 215 to 230 grams). The shelf life simulation period was 14 days. Green bell peppers' quality attributes and appearances were checked at 5, 10 and 14 days. Among these 3 replications (bags), one bag was randomly chosen for measuring the quality attributes on each checking day. The experiment was conducted during September and October 2000.

8.3.5 QUALITY ATTRIBUTES

On the checking dates, peppers were assessed for percentage weight loss, colour, firmness, quality, decay and chilling injury (CI) (Gonzalez *et al.*, 1999). Peppers were weighed daily (Mettler Toledo PR1203, Switzerland) to calculate percentage fresh weight loss. Skin colour (three locations around the equator of the fruit) were measured in the equatorial zone, using a Minolta CR200 Chromameter (Minolta Camera Co. Osaka, Japan) and employing the L*C*H* colour spacing system (L* for skin brightness, C* for chroma and H* for Hue angle). L* ranges from 0 = black to 100 = white. C* represents colour saturation which varies from dull (low value) to vivid

colour (high value), and H^* is defined as a colour wheel with red-purple at an angle of 0° , yellow at 90° , bluish-green at 180° , and blue at 270° (McGuire, 1992).

The same fruit was used for measuring fruit firmness using the non-destructive KIWIFIRM (Industrial Research Limited, New Zealand). Data were expressed in one digit, from 9 unitless scale from 0.0 to 9.9. Firmness was determined by scoring (1-5); 1=flaccid, 2=slightly firm, 3=moderately firm, 4=firm, and 5=very firm (Miller and Rise, 1986; Gonzalez *et al.*, 1999).

Quality was evaluated subjectively according the following scale: 1= unusable, 3= poor, 5= fair, 7= good, 9= excellent. Extent of decay was assessed based on the area of decay and amount of microorganisms growing on it. Decay was examined by scoring (1-5) where; 1= none, 2= slight, 3= moderate, 4= severe, 5= extreme. Chilling injury (CI) was rated on the scale of 1-3 where; 0= no injury, 1= slightly, 2=moderate, 3=severe (Gonzalez *et al.*, 1999).

8.3.6 MEASUREMENT OF SKIN PERMEANCE TO WATER VAPOUR (P'_{H_2O}) OF BELL PEPPERS AFTER POSTHARVEST DISINFECTING TREATMENT

A second batch of freshly harvested, green bell peppers (*Capsicum annum* L.) was obtained from the same grower in Palmerston North, New Zealand. Skin permeances to water vapour (P'_{H_2O}) of 45 fresh fruit were determined at $\approx 20^\circ\text{C}$ as described in Chapter 3. Subsequently, fruit were divided into three groups of 15 fruit each and applied with 3 postharvest disinfecting treatments. The three treatments were untreated (control), 2%(w/v) sodium hyperchlorite (NaClO), and a hot water dip (53°C , 4 minutes). After applying the selected disinfectants, skin permeances to water vapour of peppers were re-measured. The water vapour permeances of skins were then measured 4 times over a 2-week storage period.

8.3.7 DATA ANALYSIS

All data from this experiment were processed using Microsoft Excel 97 (Microsoft Corp.). Data analysed using the General Linear Model (GLM) analysis of variance and

Tukey multiple range test ($p < 0.05$) for comparison of means were performed using MINITAB version 12.1 (Minitab Inc.).

8.4 RESULTS

The analysis of variance probability values for the effects of storage temperatures, package and postharvest disinfecting treatment on the quality attributes: chilling injury (CI), firmness, hue angle (h°), percentage of weight loss, percentage of decay and overall quality, of bell peppers during 2-week storing period are shown in Table 8-1. Only significant sources of variation ($p < 0.05$) of each quality attributes (in Tale 8-1) will be analysed and discussed as following sections.

Table 8-1 The analysis of variance probability values for the effects of storage temperature, package and postharvest disinfecting treatment on the quality attributes of bell peppers during the 2-week storage period

Source of Variation	Chilling Injury	Firmness	Hue Angle (h°)	Decay	Weight Loss	Quality
Temperature	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*
Postharvest Disinfecting Treatment	0.006*	0.613	0.122	0.017*	0.074*	0.046*
Packages	0.002*	0.145	0.128	0.684	0.000*	0.012*
Temperature x Disinfecting Treatment	0.433	0.136	0.283	0.075	0.125	0.128
Temperature x Packages	0.227	0.301	0.217	0.551	0.009	0.352
Disinfecting Treatment x Packages	0.531	0.339	0.387	0.609	0.442	0.271
Temperature x Disinfecting Treatment x Packages	0.619	0.659	0.154	0.801	0.160	0.422

* $p < 0.05$

8.4.1 CHILLING INJURY

8.4.1.1 RESULT OF CHILLING INJURY

For the 2-week storing period, storage temperature, packages and postharvest disinfecting treatment were the main factors ($p < 0.05$) affecting the severity of chilling injury of bell peppers (Table 8-1.) However, none of the interactions of these factors were statistically significant. At 5-day storage period, there were no evidence of chilling injury on fruits, both in 5 and 10°C, regardless either packaging types or postharvest disinfecting treatments.

However, at day 10, the signs of chilling injury were detected only on peppers stored at 5°C. Nonpostharvest disinfecting treatment group apparently had higher levels of chilling injury ($p < 0.05$) than other groups of peppers (Figure 8-1). Within non-disinfecting group, the level of CI of peppers with 0.49% plastic bags is apparently lower than others ($p < 0.05$). Meanwhile, fruits applied with either NaClO or hot water were not statistically different in severity of CI from each other, regardless types of packages.

At the end of shelf life simulation, chilling injury had only occurred in fruits stored at 5°C. The level of CI of bell peppers with no packaging and/or no disinfecting treatment had higher level of chilling injury than disinfected fruits packaged into 0.08% and/or 0.98% bags. Meanwhile the CI levels of the rest were different in varied extents.

8.4.1.2 DISCUSSION OF CHILLING INJURY

Chilling injury only occurred in peppers stored at 5°C during the 2-week storage period. The severity of chilling injury among each treatment varied according to packages and postharvest disinfecting treatment. Still, the disinfected peppers packaged into the plastic bags showed the general trend of a reduced in level of chilling injury. It is recommended that a further study with an increased shelf life simulation period, in order to see the apparent effect of packages and disinfecting treatment on chilling injury of bell peppers.

The result from this study was contrary to the report of (Gorini *et al.*, 1976) where some cultivars of peppers that stored at 5 and 6°C in polyethylene bags did not get CI. This could be due to the cultivars chosen for this trial and/or the perforations in the bag used.

In this study, chilling injury (CI) appearances were evaluated based on 0 to 3-scale proposed by Gonzalez *et al.* (1999). The severity of chilling injury was determined by the amount of pitting and/or wrinkle or shrivelling. However, the CI evaluation was arbitrary and subjective. To improve accuracy during chilling injury rating, a pictorial scale (based on 0-3 scale) was proposed and available in (see Appendix 4).

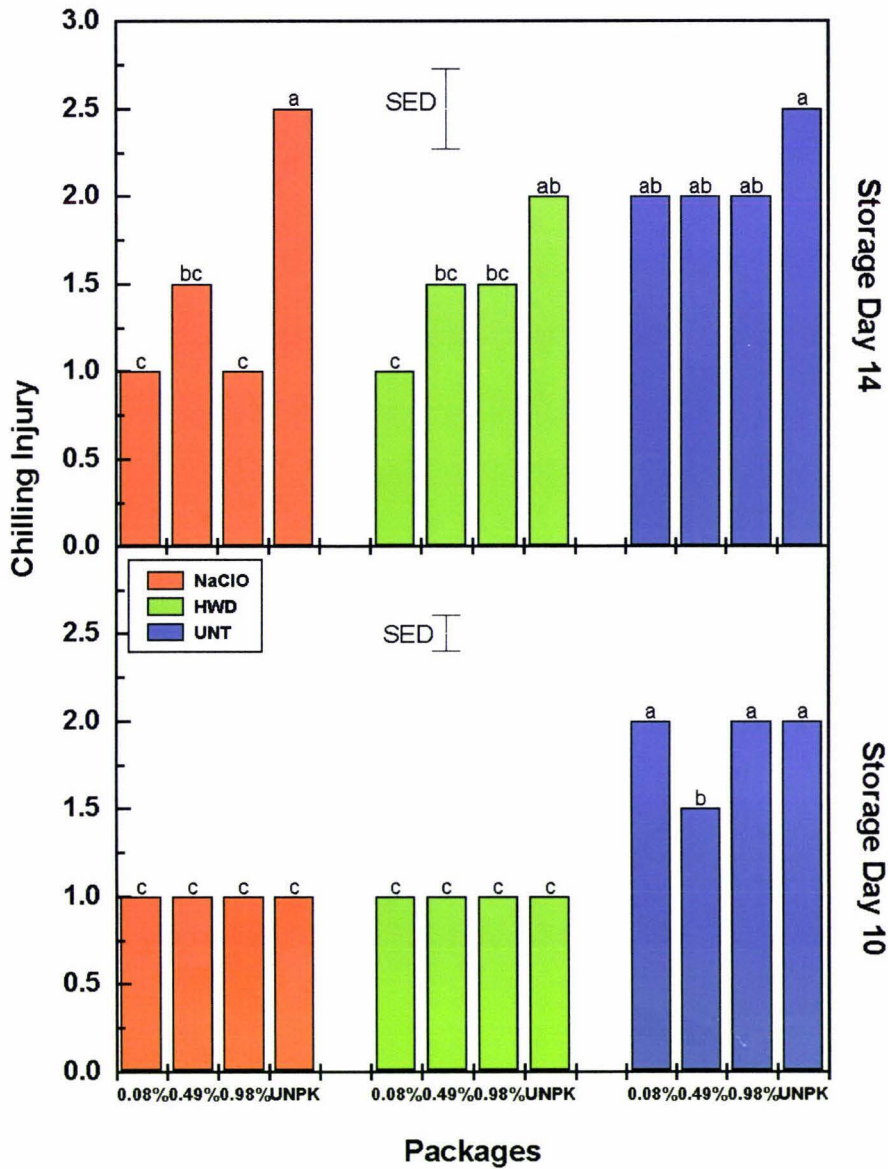


Figure 8-1 Effects of postharvest treatments on chilling injury of bells peppers at 5°C.

Data are means of 6 replicates; SED = standard error of difference

Chilling injury was evaluated according the following scale: 0 = no injury, 1 = slightly, 2 = moderate, 3 = severe

Means within each storage day followed by the same letter are not significant different according to Tukey multiple range test ($p < 0.05$)

NaClO = Sodium Hypochlorite, **HWD** = Hot Water Dipping, and **UNT** = Untreated with postharvest disinfecting 0.08%-0.98% representing perforated area of plastic bags

8.4.2 FIRMNESS

8.4.2.1 RESULT OF FIRMNESS

The initial firmness of fruits (measured on the harvesting day) was 5.9 ± 0.55 . The firmness of the stored peppers decreased over the storage period. Only temperature was the main factor ($p < 0.05$) affecting on the changes of firmness of bell pepper (Table 8-1). The effect of storage temperature on the loss of firmness in the fruit was significant (Figure 8-2).

Fruits stored at 30°C became badly spoiled after 10-day storage period regardless postharvest disinfecting treatment or packages. At the end of simulation period, bell peppers stored at 5°C had the highest firmness (approximately 4.8 ± 0.29) and the firmness of fruits stored at 10 and 20°C were 4.56 ± 0.24 and 3.2 ± 0.33 , respectively.

8.4.2.2 DISCUSSION OF FIRMNESS

The firmness of the stored peppers decreased over the storage period from an average initial firmness. This decrease in firmness was so extreme at 30°C that the fruit firmness could not be measured after the 14-day storage period. Generally, stored fruits at 5 and 10°C were firmer than those at higher temperatures.

In this study, temperature was the only factor that had a significant effect on firmness of bell peppers, while packages and postharvest disinfecting treatment did not contributed to the loss of firmness. These results are in contrast to other studies (Ben-Yehoshua *et al.*, 1983; Gonzalez *et al.*, 1999) where the main benefit of film packaging of peppers was a reduction in loss of fruit firmness. The difference in types of plastic films however could be used to explain this contrary result.

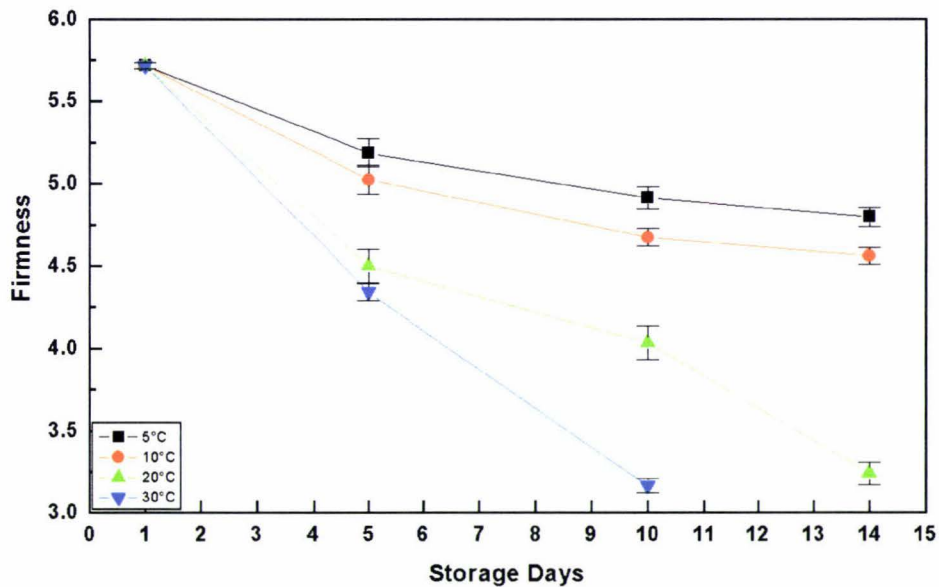


Figure 8-2 Effects of storage temperatures on firmness of bell peppers

Data are means of 24 replicates; error bars represent SE of the mean

Firmness was evaluated according the following scale; 1 = flaccid, 2 = slightly firm, 3 = moderately firm, 4 = firm, and 5 = very firm

8.4.3 COLOUR CHANGES

8.4.3.1 RESULTS OF COLOUR CHANGES

The initial colour of the peppers were $L = 34.81 \pm 3.23$, $C = 16.43 \pm 4.20$, $H = 128.26 \pm 3.48$. The changes in L and C values of peppers during the 2 week storage period did not change significantly (approximate values of L and C at the end of simulating period were 38.32 ± 2.53 and 20.83 ± 5.56 , respectively). Only hue angle (h°) was apparently change over the storage period and as hue angle (h°) represents best the changes in fruit ripening (Gonzalez *et al.*, 1999), the following results will concentrate on this change.

The characteristics of changes in hue angle (h°) (from green to red colour) were similar to firmness. Only temperature had a significant effect ($p < 0.05$) on the changes of hue angle (h°) of bell pepper (Table 8-1). These changes were occurring when the storage

temperature was raised (from 5 to 30°C). Note that the fruits stored at 30°C became seriously spoiled after 10-day storage period regardless postharvest disinfecting treatment or packages (Figure 8-3).

The bell peppers stored at 5 and 10°C for 14 days, still had green skin colours and their hue angles were as same as at the beginning of storage period. The skin colour of most of the fruit stored at 20°C changed dramatically, becoming orange or yellowish-red. However, some fruits were still green with average hue angles were higher than 90.

8.4.3.2 DISCUSSION OF COLOUR CHANGES

Hue angle (h°) values of stored peppers stored at 5 and 10°C were relatively close to the initial value. It could be said that fruits stored at chilling temperatures were still green over storage period. Colours of most fruits stored at 20 and 30°C became orange, yellowish red and red with some green peppers, which contributed to high deviation of colour changes. Variation in maturity stage and postharvest behaviour of individual fruit might explain this variation (Wall and Berghage, 1996; Krajayklang *et al.*, 2000).

In this study, the storage temperature was the only major factor affecting changes in hue angle (h°) and the influences of packaging and postharvest disinfecting treatments were not apparent. This result is consistent with Nunes and Emond (1999) that postharvest treatments had not affected changes in colour of bell peppers. On the contrary, Gonzalez *et al.* (1999) reported that a hot water dip and plastic film substantially influenced colour changes during storage period. The further research is required, in order to clarify the influence of packaging and postharvest disinfecting treatment on colour changes of bell peppers.

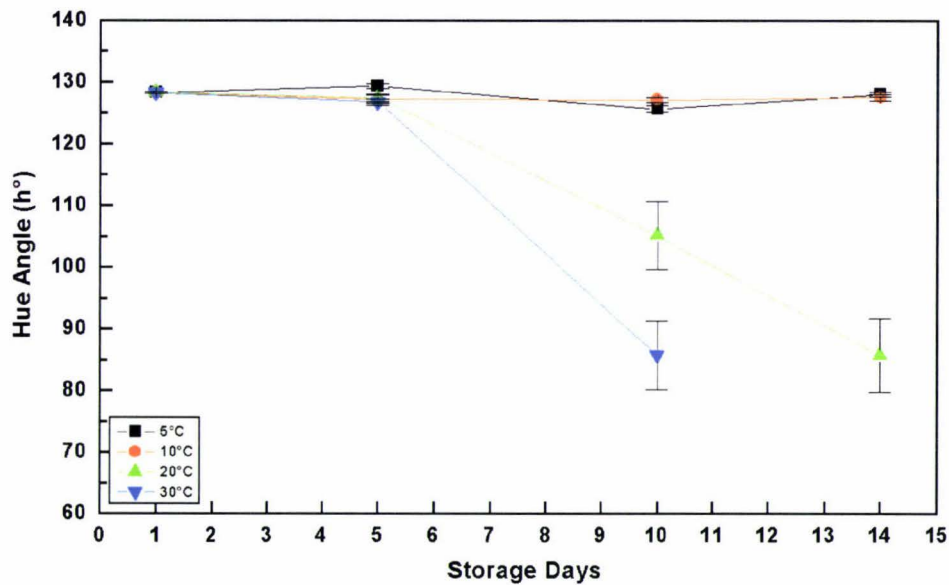


Figure 8-3 Effects of storage temperatures on hue angle (h°) of bell peppers

Data are means of 24 replicates; error bars represent SE of the mean

8.4.4 WEIGHT LOSS

8.4.4.1 RESULT OF WEIGHT LOSS

Storage temperature and packages were the main factors ($p < 0.05$) affecting the percentage of weight loss of bell peppers (Table 8-1). The interaction of these factors also apparently affected on this attributes. The trend of weight loss was increased as the storage temperature was raised from 5 to 30°C (Figure 8-4) and the pattern of statistical differences in weight loss among treatments was constant from storage day 10 to day 14.

For the 2-week storage period, peppers without packaging stored at 20 and 30°C had the highest percentage of weight loss ($p < 0.05$). Particularly, fruits stored at 30°C lost their weight nearly 40% on the last day of simulating period. Peppers with packaging stored at 20 and 30°C had a lower weight loss than the unpackaging ones.

Peppers stored at 5 and 10°C had an approximate percentage of weight loss of less than 7.2% by the end of storage period. At these lower temperatures, unpackaged peppers at 10°C had a significantly higher in weight loss than peppers stored at 5°C. However, the effects of packaging on weight loss of other treatments were not apparently.

8.4.4.2 DISCUSSION OF WEIGHT LOSS

The highest percentage of weight loss rate was found in peppers stored at 30°C, while the lowest percentage was observed at 5°C. At 20 and 30°C, percentage weight loss of peppers packaged in perforated plastic bags, regardless of disinfecting methods, were significantly less ($p < 0.05$) than the unbagged groups. This was agreement with other studies (Ben-Yehoshua *et al.*, 1983; Watada *et al.*, 1987; Meir *et al.*, 1995; Gonzalez *et al.*, 1999) in which the reduction in fruit weight loss is likely to be the main benefit of film packaging of peppers. At these high temperatures, peppers lost 6-7% of their weight, which were considered unmarketable (Ben-Yehoshua *et al.*, 1987; Kay, 1991).

However, at cooler temperatures (5 and 10°C) the differences in the effects of perforated plastic bag and unpackaging on the weight loss were not apparent in some extents. This could be effects of individual properties of fruits e.g. the thickness of wax layers, which could contribute to the different in changes of fruit characteristics (Salisbury and Ross, 1992). Additionally, the storage conditions, i.e. relative humidity level or air velocity, could also be taken into account (Gaffney *et al.*, 1985). For all that, the percentage of weight loss of peppers stored at 5 and 10°C were less than 7%, which are still considered marketable (Ben-Yehoshua, 1987; Kay, 1991). There were not significant weight losses according to the diameter of hole and perforation area of perforated bags. This is in contrast to the study of Sanz *et al.* (1999) who found strawberry packed in macro-perforated plastic film exhibited higher weight losses than in micro-perforated films. The effect of the sizes of hole and perforation area on weight loss reduction requires more study.

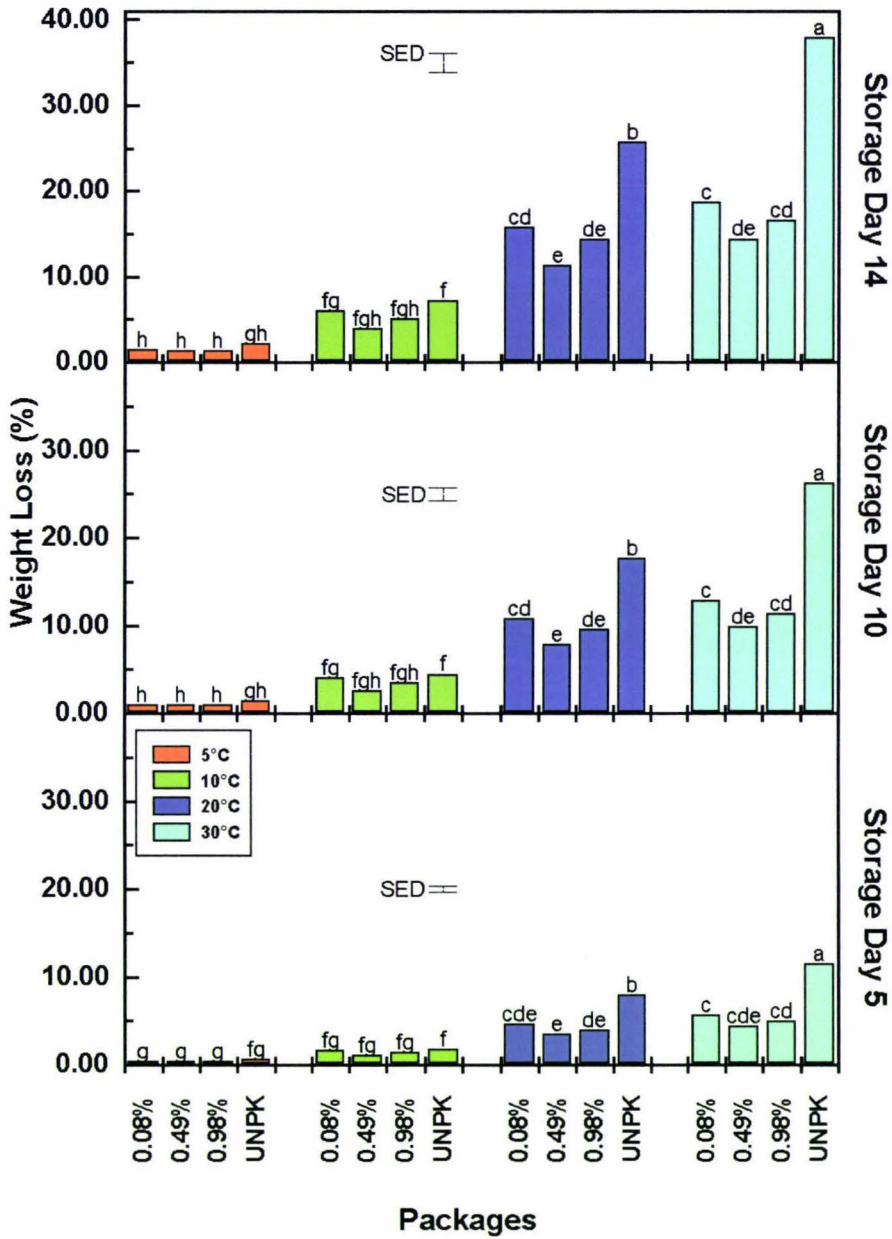


Figure 8-4 Effects of packages and storage temperatures on weight loss of bell peppers

Data are means of 6 replicates; SED = standard error of difference

Means within each storage day followed by the same letter are not significant different according to Tukey multiple range test (p<0.05)

0.08%-0.98% representing perforated area of plastic bags

8.4.5 DECAY

8.4.5.1 RESULT OF DECAY

Condensation inside plastic bags or on fruits' skin was not detected in this study. Still, the decay pathogen could be observed. *Alternaria alternata* (Fr.) Keissler (Alternaria rot), *Erwinia carotovora* spp. (Bacterial soft rot), *Botryotinia fuckeliana* (de Bary) Whetzel (grey mould rot) and Fusarium rot (*Fusarium* spp.) were mostly found (Figure 8-5).



Figure 8-5 A) *Alternaria alternata* (Fr.) Keissler (Alternaria rot); B) *Erwinia carotovora* spp. (Bacterial soft rot); C) *Botryotinia fuckeliana* (de Bary) Whetzel (Grey mould rot, after Snowden (1991)); D) *Fusarium* spp. (Fusarium rot).

Storage temperature and postharvest disinfecting treatment are the main factors ($p < 0.05$) affecting the levels of decay on bell peppers (Table 8-1). The levels of decay on fruits were increased as the storage temperature was raised from 5 to 30°C (Figure

8-6). Peppers stored at 30°C showed a high incidence of decay during the storage period, and by the end of this period, all peppers at this temperature were badly spoiled regardless packaging and disinfecting treatment.

The trend of measuring decay levels at 20°C was higher than at 5 and 10°C, particularly in the non-disinfecting treatment. On day 14 of the storage period, peppers without postharvest disinfecting treatment at 20°C had the highest level ($p < 0.05$) of decay. The level of decaying level of other treatments deviated from each other in varied extents.

8.4.5.2 DISCUSSION OF DECAY

Condensation inside plastic bags or on fruits' skins was not detected in this study. Perforation would be expected to minimise free moisture and prevent secondary infection (Bussel and Kenigsberger, 1975; Emond *et al.*, 1995). However, decay appearances caused by *Botrytis* spp., *Alternaria* spp., *Fusarium* spp. and/or *Erwinia* spp., were generally observed.

At the end of the shelf life storage period, all peppers stored at 30°C were badly spoiled and unmarketable (rated '5' on the decay scale), regardless types of disinfecting treatments. Peppers, particularly treated with disinfecting treatments, stored at chilling temperatures (5 and 10°C) showed lower level of decay than non-disinfected fruits at 20°C. These results confirmed that the applications of low temperature storage and disinfecting treatment, which are used to retard decay and spoilage in bell peppers, which are similar to reports of Ben-Yehoshua *et al.* (1983), Watada *et al.* (1987), Meir *et al.* (1995) and Gonzalez *et al.* (1999).

In this study, the pictorial scale for decay rating (based on 1-5 scale proposed by Gonzalez *et al.* (1999) was developed and proposed (see Appendix 4).

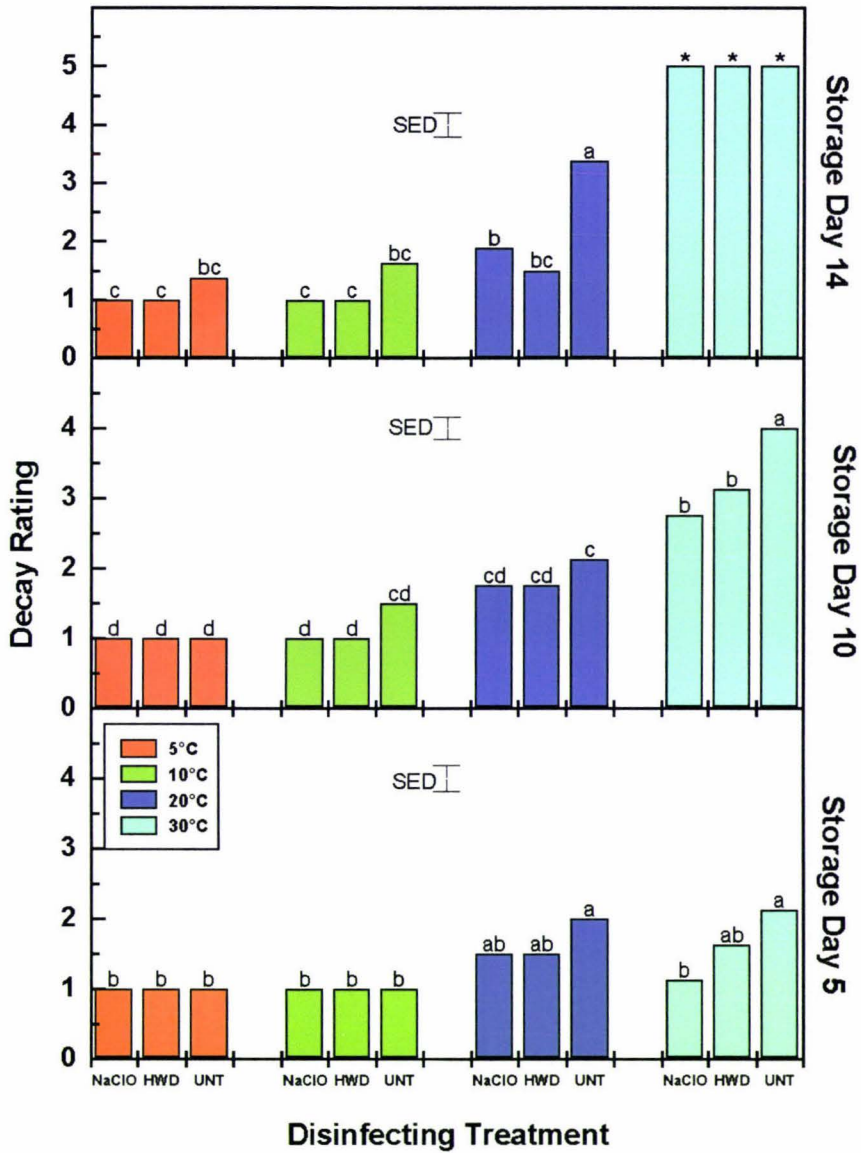


Figure 8-6 Effects of disinfecting treatment and storage temperatures on decay appearances of bell peppers

Data are means of 8 replicates; SED = standard error of difference

Means within each storage day followed by the same letter are not significant different according to Tukey multiple range test ($p < 0.05$)

* representing badly spoiled peppers

Level of decay was rated on 1-5 scale; 1=none, 2= slight, 3=moderate, 4=severe, and 5=extreme

NaClO = Sodium Hypochlorite, **HWD** = Hot Water Dipping, and **UNT** = Untreated with postharvest disinfecting

8.4.6 OVERALL QUALITY

8.4.6.1 RESULT OF OVERALL QUALITY

The overall quality of fruit was affected by storage temperatures, packages and postharvest disinfecting treatments during 2-week storage period (Table 8-1). In general, overall qualities of bell peppers stored at 5 and 10°C were considerably better than fruits at 20 and 30°C (data not shown).

At high storage temperatures (20 and 30°C), the qualities of the fruits were affected by poor appearance (e.g. shriveling, colour changes and/or decay appearance). Peppers stored at 5°C were affected by chilling injury, which resulted in lowering the overall quality of fruits at this storage temperature.

8.4.6.2 DISCUSSION OF OVERALL QUALITY

At the end of the shelf life simulation period, bell peppers stored at 30°C were badly spoiled and unusable (rated '1' on the quality scale). Quality of peppers stored at 20°C, become poor (dull colour and shrivelling) and some of them were unmarketable. The quality and appearance of peppers stored at 5°C were affected by chilling injury, with the wrinkles and pitting obviously (Noel *et al.*, 1999). Overall quality of bell peppers stored at 10°C was also affected by a low level of decay. However fruits stored at these chilling temperatures (5 and 10°C) generally remained hydrated and considerably good in quality.

In this study, the pictorial scale for wrinkle rating (based on 1-9 scale proposed by Gonzalez *et al.* (1999), which contributes to overall quality rating, was developed and proposed (see Appendix 4).

8.4.7 SKIN PERMEANCE TO WATER VAPOUR (P'_{H_2O}) AFTER POSTHARVEST DISINFECTING TREATMENT

8.4.7.1 RESULT OF SKIN PERMEANCE TO WATER VAPOUR (P'_{H_2O}) OF BELL PEPPERS

Skin permeance to water vapour (P'_{H_2O}) of peppers continuously decreased over the storage period (Figure 8-7). Whilst the P'_{H_2O} of NaClO treated fruit were not apparently different from the control group, the P'_{H_2O} of peppers dipped in hot water were higher than those groups. The weight loss rate of peppers from hot water dipped group was also the highest (data not shown).

8.4.7.2 DISCUSSION OF SKIN PERMEANCE TO WATER VAPOUR (P'_{H_2O}) OF BELL PEPPERS

Skin permeance to water vapour of bell peppers decreased over the storage period, because of the biological aging of the fruit (Maguire, 1998). P'_{H_2O} of peppers treated with hot water was higher than NaClO treated and/or controlled fruits and the rate of weight loss (water loss) from hot water dipped fruits was also highest. According to Eq. 3-2, the skin permeance to water vapour is determined by Fick's law of diffusion. In this study, surface area and the driving force were considered to be reasonably constant. The P'_{H_2O} was varied respective to the changes of rate of water loss. At this stage, the hot water treatment was presumed to have the effects on skin permeance to water vapour of green bell peppers, which in turn effect on the water loss.

Salisbury and Ross (1985) mentioned that water loss mainly occurs by diffusion through the fruit cuticle and also through the stem end (Cameron and Yang, 1982). However, Lownds *et al.* (1993) reported the water loss through stem end of pepper had no significant effect on the rate of water loss. Additionally, as pepper fruit have no stomata, postharvest water-loss rate was significantly correlated with the surface area and amount of epicuticular wax. Since the average surface areas of fruits from our study were uniform ($0.02 \pm 0.002 \text{ m}^2$), the amounts of epicuticular wax seem to result in the marked effects on the differences in P'_{H_2O} , in this study.

Lownds *et al.* (1993) found that the rate of water loss of peppers was related with the thickness of cuticle, particularly at high storage temperature (20°C). At such storage condition, they reported the thickness of cuticle was decreased, whilst rate of water loss of fruit increased. They suggested that resistance to water movement was decreased. From such water loss pattern, it might be used to explain our result of increased P'_{H_2O} within the hot water group.

Once peppers were immersed into the hot water (53°C) for 4 minutes, the melting effects of hot water on the amount and structures of epicuticular wax could be expected. The thickness of wax might be lessened or removed by the heat of hot water; thus reducing resistance to water movement, which increased the skin permeance to water vapour and in turn the rate of water loss become higher.

This result is consistent to the reports of Schirra and D'hallewin (1997), Silva and Vieites (1998) and Gonzalez *et al.* (1999) and our experimental results in 8.4.4, that peppers, mandarins and tomatoes treated with hot water (>50°C), lost weight more rapidly than untreated and/or chemically treated fruits. Consequently, the plastic bags are recommended to be used with these fruits after hot water treatment, in order to minimise the weight (water) loss.

However, Banaras *et al.* (1988), Lownds *et al.* (1993), Lownds *et al.* (1994) and Maguire (1998) suggested there are numbers of factors e.g. cuticle thickness, presences of cracks, epicuticular wax quantity/distribution or chemistry, which also vary between individual fruit, cultivars and/or stages of maturities, affecting on skin permeance to water vapour, P'_{H_2O} , or the water loss through the cuticle. Therefore, further study of the effects of hot water treatment on cuticular structures and characteristics including the P'_{H_2O} is required, in order to develop a proper heat disinfecting treatment, which compromises between strategies of weight loss and disinfecting management.

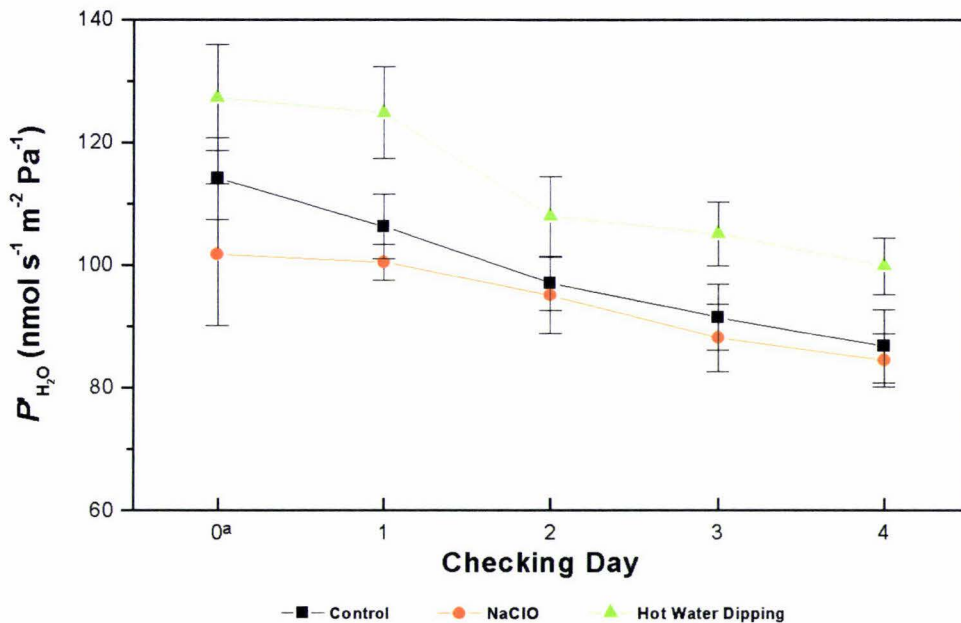


Figure 8-7 Changes of skin permeances to water vapour of postharvest disinfected peppers during 2-week storage period

Data are means of 15 replicates, error bars represent SE of the mean

^a The approximate P'_{H_2O} of all freshly harvested peppers (before treating) is shown in the control group at day 0.

8.5 COMPUTER BASED PICTORIAL SCALES

According to the literature search, quality and appearance determinations of bell peppers are generally available in subjective methods. Researchers, who lack skills and experiences, may face difficulties making decisions to discriminate the levels of qualities and appearances. To ease those hurdles, a computer based pictorial scales for evaluating chilling injury, decay and wrinkle level were devised. These were created with Microsoft Excel 2000 (Microsoft Corp.). The programme is compatible with desktop or notebook computers, which are IBM or IBM compatible personal computer running Windows 95 (a Pentium is recommended) and have CD-ROM drive. Researchers can easily simulate and compare severities of bell peppers' quality attributes with this programme (Appendix 4).

8.6 CONCLUDING REMARKS

Storage temperature between 5 and 10°C could be designated as the commonly optimum condition for storing green bell peppers for 14 days. At 5°C storage temperature or below, bell peppers are highly susceptible to chilling injury and at high temperature, 20 or 30°C, fruits quickly lost green colour and fresh weight as well as they become unmarketable and/or spoiling with relatively high rate.

The effects of packaging and postharvest disinfecting treatments on quality attributes of bell peppers stored at 5 and 10°C were not apparent. The increasing in the shelf life storage period and the number of replicates (combination of chilling temperatures, packages and disinfecting treatments) is recommended, in order to see the obvious effects of these main factors.

8.7 CONCEPTUAL MODEL FOR IMPROVING STORAGE QUALITY OF GREEN BELL PEPPERS

Banks *et al.* (2000) states that conceptual models are considered as the promising tools to solve postharvest problems of fresh produce. Innovative solutions for industrial applications have been likely resulted from simple and strong conceptualisation and characterisation of the studied system.

To attack and ease postharvest problems of bell peppers, the conceptual models for this requirement was developed and shown in (Figure 8-8). Factors and treatments affecting postharvest quality of peppers were defined. Solutions for improving quality of bell peppers could be clearly seen from this model.

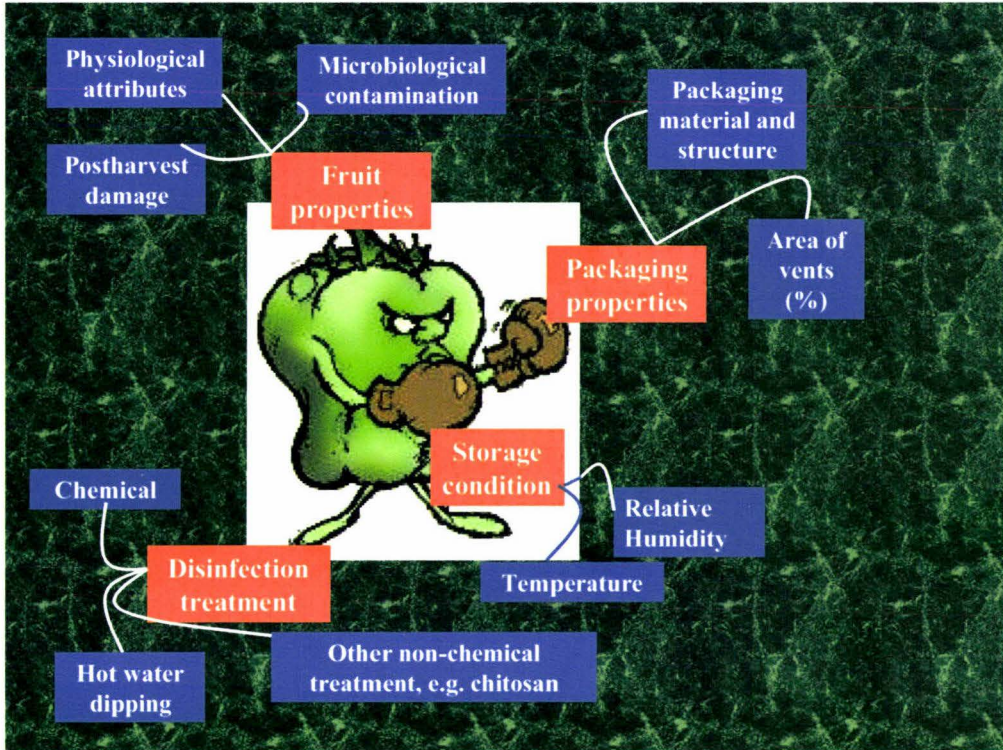


Figure 8-8 Conceptual model for improving storage quality of green bell peppers

CHAPTER 9

CONCLUSION

The results of this study of postharvest physiological attributes of green 'Cayenne' chillies under a range of conditions provides practical knowledge for package design and managing storage to maximise shelf life and marketability of fresh chillies. The chilli skin permeance to O_2 , CO_2 (P'_{O_2} and P'_{CO_2}) and water vapour, (P'_{H_2O}) from this study will contribute to the availability of this type of information since these skin permeance data have not been previously reported for chilli cultivars.

Shelf life storage trials confirmed that storage temperature and packaging have significant effects on storage quality, shelf life and marketability of fresh green 'Cayenne' chillies. Increasing the storage temperature led to a rapid loss quality attributes (colour, firmness, weight) and high levels of decay from growth of spoilage organisms. After a 2-week storage period, all chillies stored at high temperatures (20 and 30°C) were unmarketability due to excessive spoilage. In addition, condensation occurred inside the nonperforated plastic bags, which lowered the visual quality of packaged chillies. The high relative humidity presented in these bags of chillies enhances development of pathogens.

Refrigerated storage temperatures (5-10°C) and perforated plastic bags reduced the rate of change of quality attributes and eliminated condensation. Chilling injury was not detected in any of the shelf life trials conducted with green 'Cayenne' chillies. The atmospheres inside perforated plastic bags were similar to ambient air conditions, thus ensuring aerobic conditions inside the bags.

Percentages of weight loss of the packaged chillies varied with storage temperature, perforation area and size of perforations. Unpackaged chillies had highest percentage of weight loss in any storage temperature compared to those packaged into either perforated or nonperforated plastic bags. Whilst, nonperforated bag had the lowest percentage of weight loss, at every storage temperature (5, 10, 20 and 30°C), these bags had high percentage of decay and the highest appearances of condensation. Thus the

nonperforated bags were considered not suitable to use for chilli packaging. Chillies packaged into commercially perforated plastic bag (0.49%-1.96% perforation area with 2.5mm perforation size) basically had lower rates of weight loss than those packaged into manually perforated plastic bags, which have bigger size of perforation (5mm perforation size), even though lower in perforation area (0.17% perforation area).

100g packs of chillies stored at 5°C and packaged with 152.40 × 228.60 mm perforated bags with 0.49% perforation area (2.5 mm perforation size) had the lowest percentage of weight loss (approximately less than 2.5%) with no signs of chilling injury and their quality attributes were within the marketable levels during a 2-week storage period. This packaging system could be further investigated for commercial optimisation in chilli industry.

In an attempt to reduce postharvest spoilage, disinfecting treatments, sodium hypochlorite (2%) and hot water (53°C for 4 minutes) were evaluated. Both treatments significantly reduced decay appearances on bell peppers (*Capsicum annuum* L.) particularly at high storage temperatures (20 and 30°C), during a 2-week storage period. Application of a postharvest disinfecting treatment could be applied to chillies in Thailand, which are generally sold and transported under high temperature. Bell peppers disinfected with hot water however tended to loose weight faster than those treated with sodium hypochlorite, possibly due to hot water treatment increasing skin permeance to water vapour since the thickness of wax might be lessened or removed by the heat of hot water, thus reducing resistance to water movement, and this increases rate of weight loss of fruit. Use hot water disinfecting treatment to reduce microbiological contamination could be combined with the use of the perforated plastic bags to minimise this weight loss.

The 'Weight Loss Simulator' model developed by Tanner (1998) was tested by comparing predicted weight loss with experimental data collected during the shelf life trials of fresh chillies. The comparisons showed that the model has general agreement with observed weight loss trend. However, in some areas the model prediction did not fit the data from the experiments. This could be due to a number of variations, including storage conditions (temperature and relative humidity), packaging (perforation area and

size of hole) and dynamic changes in biological properties of stored chillies (e.g. changes in skin permeance to water vapour and respiration) through storage period.

Sensitivity analyses performed on the model showed that the observed lack of fit could largely be explained by uncertainties in the respiration rate data. These uncertainties in respiration data arose mainly from dynamic changes in respiration during storage period. The accuracy of the 'Weight Loss Simulator' model appeared to be limited by the accuracy of the input data and uncertainties that occurred during data collection rather than by shortcoming in the model itself. Therefore further investigation and resolving these uncertainties is to be justified.

9.1 RECOMMENDATION FOR FURTHER WORK

The studies reported in this thesis have provided a greater understanding of postharvest physiological properties, storage quality attributes and weight loss simulation under a range of conditions for green 'Cayenne' chillies. Based on the overall results obtained in this study, the following areas of further research are suggested:

- further investigation of a wide range of hot chilli cultivars
- increasing shelf life simulation to optimise storage conditions and packages for longer term chilli storage
- increasing weight of chillies per package (up to 10kg/bag as general weight per package for transportation in Thailand) and plastic bag dimension as well as its perforation area and then investigating storage shelf life quality attributes and optimising storage conditions and packages
- further investigation mechanical damage occurred during transportation and its effect on chilli quality attributes
- further study effects of perforated films on changes in chemical compositions (e.g. flavour, pungency or Vitamin C) of fresh chillies during storage
- further study the weight loss simulation for different chilli packaging systems the development of a model for predicting changes in chillies quality attributes

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APPENDIX

APPENDIX 1: NOMENCLATURE: CAPSICUM AND/OR CHILE AND/OR CHILLI

The genus of peppers, *Capsicum*, includes sweet variety called 'bell peppers', and hot varieties usually known as chile peppers. As for spelling, chile means the hot pepper, chilli refers to the spicy meat and bean dish, and chilli is the ground spice containing chiles. However, Webster allows all three spellings for the hot pepper.

Another source of confusion is mistaking a whole species or types of chile pepper for a single cultivar. The five domesticated species in the pepper genus, *C. annuum*, *C. frutescens*, *C. chinense*, *C. pubescens*, and *C. baccatum*, contain dozens of pod types and hundreds of cultivars. Except for the tabasco chile pepper in the *C. frutescens* species and the habanero in *C. chinense*, most chile peppers are in the *C. annuum* species (Buzzanell and Gray, 1995).

APPENDIX 2: SUMMATIONS OF CERTAIN CHILLI CULTIVARS

BELL PEPPER

It is the most common variety. Bell apparently refers to the fruit's blocky shape, with four lobes preferred in several countries (Wall and Bosland, 1993).

CHINENSE

It likes all *Capsicum* species, originated in the New World. Habanero (Scotch Bonnet) is the best-known cultivar of this species (Wall and Bosland, 1993). Available dark green, yellow and red when fully ripe, this lantern shaped chili is used extensively in Caribbean and South American salsas, chutneys and marinades (Meredith, 1999). A habanero cultivar from the Yucatan Peninsula of Mexico, has the distinct of being the world's hottest chillies (Wall and Bosland, 1993). The habanero has a distinctive sweet flavour with tropical fruit tones (Meredith, 1999).

CAYENNE

It has been named for the city in French Guiana, has red mature fruit and is characteristically wrinkled. It is highly pungent and is used to make hot sauces or dried powder, commonly known in United States households as “red pepper”. Cayenne pods are made into a mash with salt for the popular Louisiana hot sauce industry (Wall and Bosland, 1993).

D'ARBOL

Long, skinny and bright red, tiny dried d'arbols are closely related to cayenne chillies, and feature a smoky, tannic, grassy flavour with a searing, acidic burn. Primarily used in a powdered form to make sauces, soups and stews (Meredith, 1999).

GUAJILLO

This dried, medium-hot chilli is grown in northern and central Mexico and used in salsas, sauces and soups. The shiny, deep orange-red-brown pod imparts a green tea, piney flavour with a sweet, berry heat. The tough skin may require longer rehydration (Meredith, 1999).

JALAPENOS

They derived their name from Jalapa, Mexico (Wall and Bosland, 1993). This ubiquitous dark green chilli is commonly found in Southwestern, Mexican and Tex-Mex cuisines (Meredith, 1999). The majority of the jalapenos crop is preserved by canning or pickling, while a small amount is dehydrated in either the green or red stage (particularly red, known as chipotles (Wall and Bosland, 1993; Meredith, 1999).

NEW MEXICAN TYPE

It is also called long green or ‘Anaheim’. Actually, the varietal type is New Mexican, and ‘New Mexico No.6’ and ‘Anaheim’ are cultivars within this type. Green and red chillies generally represent two developmental states of the same fruit. If pods are left on the plant to be harvested at the red stage, they usually are dried and ground into chilli powder (called *paprika* if non-pungent) (Wall and Bosland, 1993).

PIMIENTO

It is sometimes spelled pimento, is characterised by a heart-shaped, thick-walled fruit that is green when immature and red at maturity. Pimiento is used in processed foods, such as pimiento cheese and stuffed olives, but can be eaten fresh. All spice, *Pimenta dioica*, usually known as pimento or Jamaican pepper outside the United States, is not related to *Capsicum* (Wall and Bosland, 1993).

POBLANO

Colored dark green to purple when fresh, poblanos are most popular roasted, imparting a fuller, smoky, earthy flavour. Less fiery than the jalapeno, the fleshy poblano is favoured for making stuffed chilli dishes (like rellenos), rajas and mole and pipian sauces. Dried poblanos are known as anchos, a sweet, woody chillies with mild fruit, coffee and licorice tones (Meredith, 1999).

TABASCO

It is the most common cultivar of *C. frutescens*. 'Tabasco' fruits are 2.5 to 5 cm long by 0.5 cm wide, yellow or yellow-green (turning red at maturity), and highly pungent. The red fruit is the ingredient in Tabasco sauce (Wall and Bosland, 1993).

THAI

Hotter than jalapenos, milder than habaneros, the Thai chili is indispensable in Southeast Asian cooking. The thin, long, pointed green to red pods impart a lingering heat (Meredith, 1999).

APPENDIX 3: TRADITIONAL POSTHARVEST PRACTICES AT LOCAL MARKETS**TRADITIONAL HANDLING PRACTICE AT THE WHOLESALING CENTRE**

After chillies are transported from garden to wholesaling centre, they are stored in the open air, with other fresh commodities, i.e. cucumbers. Chillies are then arranged into the daily orders of local retailers. Chillies are distributed by using a trolley and a motor-

tricycle (Figure A- 1). The trolley is generally used for shifting the product in the warehouse or distributing chillies to the close retailers, while the motor-tricycle is used for loading many packages and transporting to more distance customers (Utto, 2000, pers.com.).



Figure A- 1 Traditional handling practice at the wholesaling centre

STORING AND SELLING PRACTICES OF FRESH CHILLIES AT RETAILING PLACES

At the retail outlet area or market, chillies are generally repackaged into 2 different kinds of packages; a bulk container and/or plastic bag (Figure A- 2). The bulk containers are bamboo baskets and/or injection-moulded plastic containers, while the types of plastic bags are varied. Most of the commercial plastic bags for chillies are manufactured from low- and high- density polyethylene (LDPE and HDPE) and polypropylene (PP). The general size of plastic bag is 6'' x 9'' (152.40 mm x 228.60 mm) and 6'' x 11'' inches (152.40 mm x 279.40 mm).

Chillies stored in bulk container allow the buyers themselves to select and place the chillies into the plastic bags, and allowing sale of different quantities of chillies as

required. Chillies are pre-packaged into a plastic bag and generally weighing up to 100g. The selling and storing condition is under ambient condition ($30\pm 5^{\circ}\text{C}$ and $75\pm 5\%$ RH).

At the end of a day, the chillies are usually covered by a plastic sheet to prevent dust and rain from affecting them and kept at the retailing places. Dried or defect or flaccid chillies are sorted out and dried by solar power and either processed for ground chillies or sold as dried chillies.



Figure A- 2 Storing and selling conditions of fresh chillies at retailing places

Traditionally, the plastic bag is perforated in order to ventilate and reduce the condensation, which occurs inside the plastic bags giving an undesirable appearance (Utto, 2000).

The usual methods of perforation in local markets of Thailand (Figure A- 3 and Figure A- 4) are a knife or a cork borer making up to 9 holes per plastic bag. The diameter of the hole is varied from about 0.5 to 1.5 cm (Utto, 2000, pers. com).

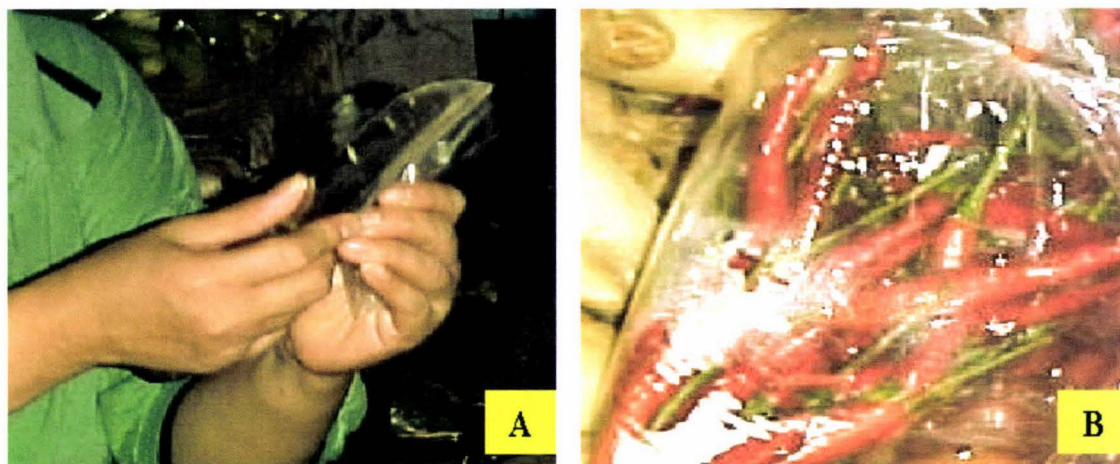


Figure A- 3 The perforating method by using a knife



Figure A- 4 The perforating method by using a cork bore

APPENDIX 4: COMPUTER BASED PICTORIAL SCALES OF BELL PEPPERS

The Microsoft Excel file named 'bell_scale' is available in CD-ROM (found attached to the inside back cover of this thesis). Practical guides and computer programme requirements for operating this file is available in section 8.5.

APPENDIX 5: TIME-LAPSE PHOTOGRAPHY OF COLOUR CHANGING OF FRESH CHILLIES

The images for file named 'chilli-timelapse.avi' (available in CD-ROM attached to the inside back cover of this thesis) were taken with a Kodak DC290 digital camera over 4 days at 30°C storage temperature and were processed with Corel PhotoPaint programme into a video file. The programme is compatible with desktop or notebook computers, which are IBM or IBM compatible personal computer running Windows 95 (a Pentium is recommended) having CD-ROM drive and to run the file avi media player (e.g. Microsoft media player) is required.