THE POSTHARVEST PHYSIOLOGY OF CHINESE CABBAGE CV. 'YUKI'

by

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ABSTRACT

Chinese cabbages are a leafy, head-forming Asian vegetable grown for both domestic and export markets. Limited information about the postharvest physiology of Chinese cabbage and incorrect postharvest practices often lead to poor quality heads. This study investigated the effects of various pre- and post-harvest factors on the postharvest life and sought to increase the knowledge of the postharvest physiology of Chinese cabbage.

Chinese cabbages cv. 'Yuki' was used for all experiments in the study. In 1999 the cabbages were grown in Ovens, Victoria, and transported to Adelaide in refrigerated road transport after harvest and overnight cooling. In 2000 and 2001 the cabbages were grown in Virginia, South Australia, and were transported to coolrooms at the Waite campus of the University of Adelaide within three hours of harvesting.

Various postharvest evaluations were used to assess the Chinese cabbage heads after harvest and during storage. They included weight loss, trimming loss, respiration rate, ethylene production, and quality score. Energy substrate levels and chlorophyll fluorescence were also measured in selected experiments.

Harvesting at five different times during the day and imposing a half-hour delay before cooling did not affect the postharvest behaviour of the Chinese cabbages. This was despite exposure of the heads to temperature differences of up to 15°C between harvest times throughout the day. The quality of cabbages harvested at dawn, mid-morning, midday, mid-afternoon, and dusk were similar before and after nine weeks storage at 0°C. The lack of effect is attributed to the protective function of wrapper leaves, which were removed at harvest.

Intermittent water stresses imposed on the Chinese cabbage plants during growth did not affect the postharvest performance of the stored heads. Relative water contents of leaves from the high, moderate and no stress treatments were 94.3%, 94.0% and 93.8%, respectively immediately after harvest. It is possible that the stress treatments applied were insufficient to elicit a response or that the cabbage plants were able to recover fully upon rewatering.

An investigation of three different storage temperatures showed that cabbages stored at 20°C had higher metabolic rates, weight loss and trimming loss and lower quality than cabbages stored at 0°C and 2°C. Respiration rates were 0.8, 1.1 and 23.6 mL $CO_2.kg^{-1}.hr^{-1}$ for cabbages stored at 0°, 2° and 20°C, respectively. No differences were found between the two low temperatures except in the occurrence and severity of symptoms of the disorder, Patchy

Papery Necrosis (PPN), which were worse in cabbages stored at 0°C. Lack of symptoms prior to storage and in cabbages stored at 20°C suggest that this disorder is a form of chilling injury.

Chinese cabbages were subjected to four wounding treatments: dropped, trimmed, compressed, or no wounding (control), designed to simulate injuries typically sustained during postharvest handling. Differences were found between the trimming treatment and the other three treatments for ethylene production, weight loss and trimming loss. No differences were found between treatments for respiration rate and quality, with quality scores of 3.1, 3.1, 3.7 and 3.3 (± 1.1) for control, trimmed, dropped and compressed treatments, respectively. Wounding treatments had no adverse effects on the postharvest life or length of storage of the cabbage heads.

Exposure of Chinese cabbages to 0.01 $\mu L.L^{-1}$, 0.1 $\mu L.L^{-1}$ or 1.0 $\mu L.L^{-1}$ 1-methylcyclopropene (1-MCP) for 12 hours prior to low temperature storage did not extend postharvest life nor affect quality. Increased respiration rate and ethylene production were detected directly after fumigation in cabbages treated with 0.1 $\mu L.L^{-1}$ and 1.0 $\mu L.L^{-1}$ 1-MCP suggesting a stress response, but decreased to levels similar to those of the control after cooling. Weight loss for control (0.0 $\mu L.L^{-1}$), 0.01, 0.1 and 1.0 $\mu L.L^{-1}$ 1-MCP treatments was 3.0%, 2.8%, 2.4% and 2.9%, respectively, after nine weeks storage.

Minimally processed Chinese cabbage leaves stored in sealed plastic barrier bags were used to investigate the effects of modified storage atmospheres containing high levels of carbon dioxide (CO_2) and/or oxygen (O_2). Atmospheres were monitored for changing gas levels and the minimally processed cabbage was assessed for visual quality over 14 days in 7°C storage. High O_2/low CO_2 initial atmospheres resulted in higher quality Chinese cabbage. Quality scores for 30:70, 0:70, 30:21 and 0:21 CO_2:O_2 atmospheres were 2.1, 4, 1.3 and 3.1, respectively after 14 days storage.

These results highlight the protective function of the wrapper leaves, the importance of low temperature storage, the value of careful handling, and the significance of production issues in postharvest quality. This study indicates the disorder, PPN, is a form of chilling injury, and that the use of 1-MCP is not recommended for Chinese cabbage. Both super-atmospheric O_2 storage and minimal processing of Chinese cabbage have potential but require further investigation. The results from this study will be useful to those involved in the Chinese cabbage industry.

DECLARATION

I, KERRY LOUISE PORTER, certify that this thesis does not incorporate without acknowledgement any material submitted for the award of any degree or diploma in any university or other tertiary institution, and that to the best of my knowledge, contains no material previously published or written by any other person, except where due reference is made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

Kerry Louise Porter

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ABBREVIATIONS

1-MCP	1-methylcyclopropene
A.D.	*Anno Domini*
Ag^+	silver ion
a.m.	*ante meridiem*
AUD	Australian dollars
AVG	aminoethoxyvinyl glycine
B.C.	before Christ
C_2H_4	ethylene
CA	controlled atmosphere
cm	centimetre
CO_2	carbon dioxide
cv.	cultivar
°C	degrees Celsius
D.W.	dry weight
et al.	*et alia*
EVA-PVDC	ethyl vinyl acetate – polyvinyl dichloride
Fm	maximum fluorescence level
Fo	level at which fluorescence begins to rise
Fv	variable component of fluorescence
Fv/Fm	ratio of variable to maximum fluorescence
g	gram

Ha/ha	hectare
$HClO_4$	perchloric acid
hr	hour
i.d.	internal diameter
kg	kilograms
kPa	kilo Pascals
KOH	potassium hydroxide
L	litres
Lour.	Loureiro, Joâo de
LSD	least significant difference
m	metre
MA	modified atmosphere
MAP	modified atmosphere packaging
mg	milligrams
min.	minute
mL	milliliters
mm	millimeters
mmol	millimoles
mol	moles
N_2	nitrogen
NADH	nicotinamide adenine dinucleotide (reduced)
NADPH	nicotinamide adenine dinucleotide phosphate (reduced)

nL	nanolitres
nm	nanometers
O_2	oxygen
p.	page
pers. comm.	personal communication
pH	symbol denoting the concentration of hydrogen ions in a solution
ppm	parts per million
PPN	Patchy Papery Necrosis
P=0.05	significance level of 5%
rpm	revolutions per minute
RQ	respiratory quotient
s	second
ssp.	subspecies
STS	silver thiosulphate
t	tonnes
UK	United Kingdom
var.	variety
Vic.	Victoria
µL	microlitres
µM	microMolar
µm	micrometres
µmol	micromoles

Chapter 1

1 INTRODUCTION

Fresh fruit and vegetables are an important and accessible source of vitamins, minerals and fibre in the human diet. It is estimated, however, that depending on location and commodity, anywhere between 5% and 50% of harvested produce perishes before it can be eaten (Kader, 1992b). For example, postharvest losses of Chinese cabbage, a popular Asian vegetable, during marketing in Taiwan are approximately 30% (Wills *et al.*, 1998).

Chinese cabbage is a Brassica species native to China and is the most consumed vegetable in that country (Daly and Tomkins, 1998). Production of Chinese cabbage in China during 2002 was approximately 27 million tonnes (FAO, 2003) but postharvest losses can be high, up to 61% in some areas (Wang and Bagshaw, 2001). The Chinese cabbage industry in Australia is small compared to China, producing approximately 16000 tonnes in 1999 (Australian Bureau of Statistics, 2000) for both domestic and export markets. Despite a greater emphasis on postharvest technology in Australia than in China, postharvest losses still occur.

Postharvest storage life depends to some extent on the quality of the produce at harvest, and this is affected by factors such as cultivar, field temperature, water

status, and nutrition (Thompson, 1996; Weston and Barth, 1997). Different Chinese cabbage cultivars can vary in their tolerance of high field temperatures (Kuo *et al.*, 1988) and in their susceptibility to the disorders, such as gomasho (Phillips, 1988) and tipburn (Rogers *et al.*, 1989).

Harvested Chinese cabbages are still metabolically active and begin to deteriorate as energy is used and moisture is lost. There are many factors that affect the rate of deterioration, including storage conditions, handling, and the development of diseases or disorders (Thompson, 1996; Wills *et al.*, 1998). The correct choice of storage conditions, careful handling, and the use of treatments designed to slow deterioration can maximise the postharvest life of Chinese cabbage. One of the most important factors is to reduce the temperature of produce immediately after harvest and maintain low temperatures during storage (Kader, 1992b; Wills *et al.*, 1998).

The use of controlled atmospheres (CA), such as those with high carbon dioxide and low oxygen levels compared to air, in the storage of some vegetables is reported to reduce the rate of respiration and ethylene production, thus slowing deterioration (Kader, 1992a; Wills *et al.*, 1998). CA can also suppress the growth of postharvest pathogens (Brecht, 1980). Protective packaging and careful handling can prevent injuries that can otherwise increase respiration, ethylene production, and the risk of microbial infection.

Research into Chinese cabbage in Australia has, until recently, concentrated mainly on production (Lomman *et al.*, 1987; McKay, 1988; Phillips, 1988; Hill, 1990) but is now focusing on postharvest issues. The main aims of the research reported in this thesis were to determine the effects of various pre- and postharvest factors on the storage life of Chinese cabbage, and to expand the general knowledge of the physiology that occurs during this period. The effects of water stress during growth, and of harvesting at different times during the day, on postharvest behaviour were investigated, as were modified atmosphere packaging and treatment with an ethylene-inhibiting agent. Various storage temperatures were tested to determine the most appropriate for the Chinese cabbage cultivar used in this research, and a variety of wound treatments were applied to simulate the effects of poor handling practices. The results of this study will be used to improve the growing, handling, and postharvest storage of Chinese cabbage in Australia, and will have important benefits for the industry in Asian countries where this vegetable is a major part of the diet.

Chapter 2

2 LITERATURE REVIEW

2.1 Chinese cabbage

2.1.1 Origins, varieties and uses

Chinese cabbage, *Brassica campestris* L. ssp. *pekinensis* (Lour.) Olsson synonym *Brassica rapa* ssp *pekinensis* (Lour.) Olsson, is first mentioned in Chinese literature in the 10th century A.D., although the cultivation of other brassica species (turnip and mustard) had been recorded much earlier in the 5th century B.C. (Li, 1981). Chinese cabbage is believed to have arisen from hybridisation between turnip (ssp. *rapifera*) and pak choi (ssp. *chinensis*) (Li, 1981; Ren *et al.*, 1995).

Over many centuries, selection for desirable characteristics resulted in many different forms of Chinese cabbage. The early forms were loose-leafed and did not produce heads. By the 17th century A.D., heading types that formed solid heads with close or overlapping leaves had been developed (Li, 1981). A wide range of forms is cultivated today, including the early loose-leafed and semi-heading types, and modern cultivars are adapted to many different climates and growing seasons (Lee, 1982).

Chinese cabbage is an important vegetable crop in China where it makes up a large proportion of vegetables consumed, especially in areas where other vegetables are scarce during winter and spring (Li, 1981). It is also widely cultivated in other Asian countries, such as Japan and Korea, and is grown in many countries around the world. Chinese cabbage is a useful source of vitamin C, calcium, and dietary fibre (Wills *et al.*, 1984). The leaves are eaten fresh, both raw and cooked, and are a common ingredient in salads, stir-fries, and hot-pot dishes. Chinese cabbage is also eaten pickled or fermented and is the main ingredient in the Korean food kimchi, a fermented side dish (Chun, 1981).

2.1.2 Production

Chinese cabbage is generally considered to be a cool-season crop (Li, 1981; Lee, 1982; Lomman *et al.*, 1987; Kuo *et al.*, 1988), traditionally sown in late summer and harvested in autumn in temperate climates. However, selection and breeding have produced a range of different genotypes adapted to various climates and temperature requirements. Heat tolerant cultivars are grown in tropical and sub-tropical countries such as the Philippines (Magallona, 1981), Taiwan (Yoshizawa *et al.*, 1981) and Bangladesh (Shinohara, 1981). In the Netherlands during spring, Chinese cabbage is often grown in greenhouses to protect against the cold weather (van Berkel, 1988). In Japan, the use of different varieties adapted to various climatic regions allows for cultivation almost all year round (Matsumura, 1981; Watanabe, 1981).

It is estimated that, in 2002, China produced almost 27 million tonnes of Chinese cabbages (FAO, 2003). By comparison, the Chinese cabbage industry in Australia is small, with production in 1999 (Table 2.1) of nearly 16000 tonnes (Australian Bureau of Statistics, 2000). Eighty-eight percent of the crop in Australia is grown in Queensland and Western Australia, and approximately 16% is exported, mostly to south-east Asian countries (Anonymous, 2003).

Table 2.1. Chinese cabbage production in Australia in 1999, including area and value, by State.

State	Production (t)	Area (Ha)	Value ($000s)
Queensland	12256	304	7419
Western Australia	2559	90	2599
New South Wales	669	67	581
Victoria	251	84	248
South Australia	52	47	43
Northern Territory	-	-	-
Tasmania	-	-	-
Total	15767	592	10690

(Source: Australian Bureau of Statistics, 2000.)

2.2 Maximising the storage life of Chinese cabbage

Fruit and vegetables continue to be metabolically active after they have been harvested and during storage. As harvested produce is no longer attached to

a plant or root system, it is unable to replenish water lost during transpiration and the energy used during respiration, and begins to deteriorate. This deterioration, along with other postharvest responses, such as an increase in the level of ethylene and the breakdown of cell components, leads to the aging and death of the produce, known as senescence (Wills *et al.*, 1998).

There are many factors that affect the rate of deterioration and the types of processes that occur during senescence. They include the quality of the crop at harvest, storage temperature and atmosphere, injury during harvest or storage, and the presence of diseases or disorders (Kader, 1992b; Thompson, 1996; Wills *et al.*, 1998).

2.2.1 Preharvest factors

The postharvest life of produce can be affected by the quality of the crop at harvest. This is influenced by numerous factors during the production of the crop and at the time of harvest, such as cultivar, water status, nutrition, temperature, and harvest maturity (Thompson, 1996; Weston and Barth, 1997).

2.2.1.1 Cultivars

Different cultivars of the same horticultural crop may differ in composition and in their susceptibility to diseases and disorders, leading to differences in

their rates of senescence, length of storage life, and postharvest quality. Differences in glucosinolate concentration between cabbage cultivars has been shown to influence the rate of senescence, with cultivars containing relatively high concentrations of glucosinolates senescing at a slower rate than cultivars with lower levels (Lipton, 1987). Chinese cabbage cultivars differ in their ability to tolerate high field temperatures, and this affects both leaf turgidity and head formation (Kuo *et al.*, 1988). They also differ in their susceptibility to bacterial soft rot (McKay, 1988), and in their tolerance of the disorders gomasho (Phillips, 1988) and tipburn (Rogers *et al.*, 1989). These disorders are further described below. (Phillips and Gersbach, 1989) found that the cultivars 'China Pride', 'WR Green 60', and 'Treasure Island' were tolerant to gomasho and that 'Kasumi II' and 'Hong Kong' were highly susceptible. The cultivar 'Hong Kong' was shown to be less susceptible to tipburn, as were 'Ming Emperor' and 'Jade Pagoda', than the cultivars 'Orient Express' and 'BF 060' (Rogers *et al.*, 1989).

2.2.1.2 Water status

In leafy vegetables, the progress of senescence is influenced by the water status of the leaves (Lipton, 1987). Fritz and Weichmann (1981) concluded that a completely turgid state was favourable for Chinese cabbage being placed into storage as this resulted in lower weight loss during storage. A turgid state is not, however, considered desirable at harvest as the leaves become brittle and are more likely to be damaged when handled (Kader *et al.*,

1974; Thompson, 1996). Water stress during growth can affect some quality characteristics of Chinese cabbage at harvest. The development and severity of tipburn is associated with adverse growing conditions including water stress (Saure, 1998), and Aloni *et al.* (1986) noted that tipburn develops quickly in Chinese cabbage plants that receive insufficient irrigation. Kuo *et al.* (1988) suggest that Chinese cabbage plants need to be provided with sufficient water during the heading stage to ensure leaf turgidity, which is linked to head formation. The effect of irrigation is most often measured by differences in yield. Chinese cabbage was found to require more irrigation in spring than in autumn and increased yields were obtained with more frequent irrigation (Suh *et al.*, 1987). Sprinkler and rain hose irrigation resulted in increased yields of Chinese cabbage in both spring and autumn compared to furrow irrigation (Eom and Im, 1990). Yang and Zhang (1992) found that ceasing irrigation nine days prior to harvest gave the highest gross and net weight production compared to ceasing irrigation both earlier and later.

2.2.1.3 Nutrition

Improved crop nutrition is also associated with increased yields, as well as with the prevention of disorders related to nutrient imbalances. In a study by Hill (1990), the highest marketable yields of Chinese cabbage were obtained with applications of nitrogen fertiliser at rates of 200 $kg.ha^{-1}$ and 300 $kg.ha^{-1}$, compared to rates of 0, 50, 100, and 400 $kg.ha^{-1}$. Hill (1990) also noted an increase in losses due to bacterial soft rot when the fertiliser was applied at a

rate of 400 kg.ha^{-1}. Similarly, McKay (1988) reported an increase in bacterial soft rot due to application of high rates of nitrogen fertiliser late in the growing season.

High rates of nitrogen fertiliser, between 300 to 500 kg.ha^{-1}, have also been associated with the occurrence of gomasho (or petiole spotting} in Chinese cabbage (Takahashi, 1981; Phillips and Gersbach, 1989). Phillips and Gersbach (1989) observed a consistent trend of increased incidence of gomasho in stored Chinese cabbages that had received rates of nitrogen fertiliser of up to 500 kg.ha^{-1}. In general, produce containing higher than normal levels of nitrogen does not have good storage characteristics compared with similar produce containing lower levels (Thompson, 1996). Weichmann (1981) however, found that different rates of nitrogen fertiliser, between 80 and 240 kg.ha^{-1}, applied during growth did not affect Chinese cabbages during storage.

Another nutrient imbalance, calcium deficiency, is closely associated with the disorder tipburn (Figure 2.1), which affects Chinese cabbage and many other leafy vegetables (Thibodeau and Minotti, 1969; Shear, 1975). Because tipburn affects the young leaves growing in the inner part of the plant, causing browning and necrosis (Saure, 1998), it is rarely evident in the field and is usually detected after harvest (Rogers *et al.*, 1989). Foliar sprays of calcium are sometimes effective in controlling tipburn (Thibodeau and Minotti, 1969), but

are not always successful, possibly due to the inaccessibility of the inner leaves (van Berkel, 1988). The incidence and severity of tipburn is influenced by adverse growing conditions, such as water stress and soil compaction, and by high temperatures, increased light intensity, and extended photoperiods, suggesting that tipburn may be induced by stress which interferes with the supply of calcium to growing leaves (Saure, 1998).

Figure 2.1. A Chinese cabbage severely affected by tipburn.

2.2.1.4 Temperature

The temperatures that growing vegetables are exposed to in the field affect the growth rate, maturation, composition and, consequently, the quality of the vegetables at harvest and during storage (Kader *et al.*, 1974). Field temperature affects turgidity, thereby influencing susceptibility to physical damage, and can also promote the initiation and spread of diseases (Kader *et al.*, 1974). Fritz and Weichmann (1981) found that high field temperatures (unspecified) prior to harvest increased trimming loss in Chinese cabbage and suggested that this may be due to nutrient and metabolic imbalances resulting from accelerated growth. Exposure of Chinese cabbage to low temperatures, generally below 15°C, can initiate flower stalk development, referred to as bolting, which makes the cabbage head unmarketable (Daly and Tomkins, 1998).

2.2.1.5 Harvest maturity

The harvest maturity of leafy, head-forming vegetables such as Chinese cabbage is usually determined by the solidity and size of the head, and both these factors contribute to the quality and postharvest life of the harvested crop (Reid, 1992b). For example, Chinese cabbages with more compact heads at harvest stored better than those with less compact heads (Ludford and Isenberg, 1987).

2.2.2 *Postharvest factors*

After harvest, the storage life of produce can be maximised and the quality maintained by various methods and treatments designed to inhibit the processes of senescence. Management of the produce temperature, immediately after harvest and during storage, is considered to be the most important factor (Kader, 1992b; Thompson, 1996; Wills *et al.*, 1998). Modification of the storage environment to reduce respiration and water loss, handling to minimise injury, and the use of treatments to counteract the deleterious effects of ethylene are examples of other techniques that can be used (Kader, 1992b; Wills *et al.*, 1998).

2.2.2.1 Harvesting and cooling

Cooling produce as quickly as possible after it has been harvested is a crucial first step in maintaining quality and maximising storage life (Kader *et al.*, 1974; Thompson, 1996; Wills *et al.*, 1998). In the field, the temperature of the crop is close to ambient air temperature and, depending on the season, the immediate weather conditions and the time of day, may be 40°C or higher (Wills *et al.*, 1998). An increase in temperature leads to an increase in respiration rate and the generation of vital heat of the crop (Thompson, 1996; Wills *et al.*, 1998). Harvesting in the early morning, when both the temperature and the respiration rate are low, aids the process of cooling the produce as quickly as possible (Thompson, 1996; Wills *et al.*, 1998). With

leafy vegetables, however, this opposes the view that harvesting should be done in the late afternoon, when leaves are less turgid and less likely to be damaged (Phan, 1987a). Harvesting late in the afternoon, after a full day of photosynthetic activity, may also give produce the advantage of high levels of sugar, which have been associated with long storage life in lettuce and cabbage (Lipton, 1987).

2.2.2.2 Storage

The storage temperature directly affects the postharvest life of leafy vegetables (Lipton, 1987). Lowering the temperature reduces the rate of respiration and other metabolic activities, which in turn reduce the rate of deterioration and senescence (Phan, 1987b; Mitchell, 1992a). The lowest rate of senescence is achieved when the storage temperature is just above the freezing point of the produce, or the chilling injury threshold in chilling-sensitive crops (Wills *et al.*, 1998). Studies have shown that the lower the storage temperature for Chinese cabbage, the longer the storage life (Buschmann and Heinen, 1978; Emura, 1978; Peters *et al.*, 1986). Hansen and Bohling (1981) reported that storage at temperatures below 0°C could extend storage life of Chinese cabbage and that cultivar influenced storage life. In the same study, the authors observed no freezing damage in samples stored at −1°C, when allowed to thaw at 3.5°C, whilst Peters *et al.* (1986) reported severe frost injury at -2°C. Apeland (1984a) proposed that brown discolouration of midribs observed in Chinese cabbage stored at 0°C for up

to 105 days was due to chilling injury, and that the degree of injury differed between cultivars, with 'WR Green 60' being the most susceptible and 'Treasure Island' the least. Daly and Tomkins (1998) observed chilling injury symptoms in Chinese cabbage cultivar 'WR Green 60' stored for nine weeks at 0°C and in various controlled atmospheres. Two other cultivars used by Daly and Tomkins (1998), 'Yuki' and 'Green Rocket', showed no symptoms of chilling injury, however, 'Yuki' and another cultivar 'Kasumi II' showed symptoms of a disorder named Patchy Papery Necrosis, which the authors suggested may be linked to cold storage.

Storage temperatures of less than 10°C can also retard the growth and development of some pathogens. Yoder and Whalen (1975) reported that the optimum temperature for growth of *Botrytis cinerea* on cabbage was 20 to 25°C, and that at temperatures below 10°C rates of growth and decay were very low. Of eight fungal species studied by Li *et al.* (1994) only five could infect Chinese cabbage stored at 10°C and only three were able to sporulate at 5°C or less. Li *et al.* (1994) concluded that temperature control is important in the inhibition of storage fungi.

Humidity also affects the growth of pathogens in storage environments, with relative humidities of 95% or more favouring the growth of fungi (Wills *et al.*, 1998). Yoder and Whalen (1975) recorded that stored cabbage suffered the most decay by *Botrytis cinerea* at 97% to 100% relative humidity, but that no

damage was found when the relative humidity was below 94%. It was also noted that even at high relative humidity, healthy tissues were not infected if there were no wounds and no nutrients on the leaf surface.

Maintaining a high relative humidity in storage is an important method of reducing the rate of water loss from produce (Wills *et al.*, 1998). In a study by van den Berg and Lentz (1978), outer leaves of Brussels sprouts, cabbage, and Chinese cabbage wilted when stored at 90%-95% relative humidity but not at 98%-100%. For Chinese cabbage, a longer storage life (10-14 weeks) was achieved at 98%-100% relative humidity than at 90%-95% (8-12 weeks). In their investigation, van den Berg and Lentz (1978) found that moisture loss, yellowing, and decay were the main limiting factors of storage life of Chinese cabbage stored at 90%-95% relative humidity, compared to decay only at 98%-100%.

Controlled atmosphere (CA) storage lowers the respiration rate and slows down ethylene production, retarding senescence in stored produce (Kader, 1992a; Wills *et al.*, 1998). Other benefits of CA storage include slowed chlorophyll destruction (Wills *et al.*, 1998), alleviation of some physiological disorders (Kader, 1992a), suppression of postharvest pathogens (Brecht, 1980), and reduced effects of ethylene (Ludford and Isenberg, 1987). With the storage of Chinese cabbage, sub-atmospheric levels of O_2 appear to be most effective whilst super-atmospheric CO_2 levels have proved harmful. Wang and Ji (1988) reported reduced yellowing of outer leaves and delayed

browning of outer midribs of Chinese cabbage during storage in 1% O_2 for 12 weeks. In a previous study, Wang (1983) found that outer leaves of Chinese cabbage retained 60% of initial amounts of chlorophyll after five months storage in 1% O_2, at 0°C. In the same investigation, Chinese cabbage exposed to CO_2 levels of 30% to 40% for five or ten days sustained high trimming losses after storage for one month (Wang, 1983). Weichmann (1981) found that increased weight loss occurred as CO_2 levels during storage were increased, and that trimming losses were higher and marketable quantities lower for Chinese cabbage stored for 120 days in 7.5% CO_2 compared to 5% and 2% CO_2. Results from other studies confirm that levels of CO_2 of approximately 5% or greater are detrimental to long term storage of Chinese cabbage, and that best results are achieved with O_2 levels of 4% or less (Pelleboer and Schouten, 1984; Mertens, 1985; Wang and Kramer, 1989; Yang and Pek, 1996). Investigations into atmospheres with O_2 concentrations over 21% have also shown benefits for postharvest physiology and quality of some horticultural produce (Kader and Ben-Yehoshua, 2000) but have not been assessed for Chinese cabbage. Super-atmospheric O_2 atmospheres, either alone or in combination with different levels of CO_2, have been shown to avert anaerobic conditions in packages of blueberries (Rosenfeld *et al.*, 1999) and inhibit microbial growth on agar (Amanatidou *et al.*, 1999) and on strawberries (Wszelaki and Mitcham, 2000).

2.2.2.3 Treatments

The level of ethylene present in the storage atmosphere also influences the rate of senescence (Reid, 1992a). Ethylene is produced by all vegetative matter and is associated with leaf abscission, loss of chlorophyll, and senescence of a wide range of crops (Lougheed *et al.*, 1987). Ethylene can easily reach harmful levels during storage if preventative measures are not taken. Even relatively small amounts of ethylene, as little as 0.005 $\mu L.L^{-1}$, may be sufficient to promote senescence (Wills *et al.*, 1999), reducing storage life and postharvest quality. Chinese cabbage stored at 0°C had a storage life of 51.1 days in 0.005 $\mu L.L^{-1}$ ethylene compared to 26.6 days in 0.1 $\mu L.L^{-1}$ ethylene (Wills *et al.*, 1999). There are three main strategies for protecting against ethylene exposure - avoidance, removal and inhibition (Sherman, 1985). Avoidance of ethylene includes careful handling and temperature management to suppress ethylene production and storage of produce away from external sources of ethylene (Knee *et al.*, 1985; Sherman, 1985). Ethylene can be removed from storage areas by ventilation and also by oxidation with reagents such as potassium permanganate and ozone or by using a catalytic oxidiser (Sherman, 1985; Reid, 1992a; Wills *et al.*, 1998).

The effects of ethylene can be reduced by CA storage and by treatment of produce with various chemicals that either inhibit ethylene synthesis, such as aminoethoxyvinyl glycine (AVG) (Knee *et al.*, 1985), or inhibit ethylene

action, such as silver thiosulphate (STS) (Wills *et al.*, 1998). Neither AVG nor STS are safe for use on edible crops (Knee *et al.*, 1985; Wills *et al.*, 1998) and STS is hazardous to the environment (Serek *et al.*, 1995). Another compound, 1-methylcyclopropene (1-MCP), has also been found to inhibit the action of ethylene, by blocking the ethylene binding site, and is considered non-toxic to mammals and the environment (Wills *et al.*, 1998). 1-MCP has proved to be effective in protecting cut flowers (Serek *et al.*, 1995; Sisler *et al.*, 1996a), bananas, tomatoes, potted plants, and pea seedlings (Sisler *et al.*, 1996b) against ethylene. 1-MCP was also found to inhibit the degreening action of ethylene in oranges; however, it did not inhibit the negative effects of ethylene on oranges during storage and was shown to increase the incidence of chilling injury symptoms, microbial decay and volatile off-flavours (Porat *et al.*, 1999).

2.2.2.4 Handling

Fruit and vegetables are susceptible to damage during and after harvest caused by rough or excessive handling, and inappropriate packaging. Mechanical damage encompasses injuries caused by cuts, impact, compression, and vibration (Wills *et al.*, 1998) and such injuries can increase respiration, ethylene production, and the risk of microbial infection, thus shortening the storage life of the produce. In a study of the effects of handling method on storage losses by Kim and Kim in 1992 (cited in Thompson (1996), p.13), cabbages that had been damaged during harvesting and handling had storage losses approximately three-and-a-half times that of

undamaged cabbages after storage for two months. In Eastern-central China, mechanical damage can account for losses of up to 31% of Chinese cabbage before the produce reaches the retail market (Wang and Bagshaw, 2001). Most of this mechanical damage resulted from rough handling during weighing and loading of the fresh Chinese cabbage at collection centres and transportation to markets (Wang and Bagshaw, 2001).

2.2.2.5 Packaging

Storing harvested produce in packaging can reduce water loss, especially when the packaging material is an effective moisture barrier, such as polyethylene film or wax-coated board (Mitchell, 1992b; Wills *et al.*, 1998). In an investigation into high humidity storage, Daly and Tomkins (1998) stored Chinese cabbage in cartons with and without "high humidity box liners" at various temperatures. They reported that the storage in the "high humidity box liners" significantly reduced weight loss, at all temperatures, and wilting compared to normal air storage. The authors also noted that rots developed on the Chinese cabbage stored in the "high humidity box liners" at temperatures of 8° and 12°C, but not at the lower temperatures of 0° and 3°C. Emond *et al.* (1995) found significant reductions in water loss and condensation formation using perforated plastic packaging, and suggested that perforated films had the potential to extend shelf life of fruit and vegetables.

2.2.2.6 Minimal processing

Minimal processing is a convenient and increasingly popular way to supply fresh fruit and vegetables to the user (Cantwell, 1992; Gorny, 2001). Depending on the product, minimal processing usually involves washing, trimming, peeling, slicing, or shredding, and in most cases heightens perishability by increasing the rate of senescence and the risk of pathogen infection (Cantwell, 1992). The major factors affecting the quality of minimally processed products are temperature, atmosphere, relative humidity, and sanitation (Watada *et al.*, 1996). In a study by Kim and Klieber (1997), preservative dips and low temperatures were tested as a means of counteracting the increased perishability and reduced shelf life of minimally processed Chinese cabbage. Results showed that citric acid dip extended storage life from 10 to 14 days at 5°C and that a longer storage life of 21 days was achieved at 0°C. Modified atmospheres (MA), either actively applied or generated by the product, are also used with packaged minimally processed produce as another means of extending shelf life and maintaining quality (Cantwell, 1992; Watada *et al.*, 1996). The modified atmospheres, which generally consist of super-atmospheric CO_2 and/or sub-atmospheric O_2 levels, act similarly to controlled atmospheres by reducing respiration and ethylene production, and have other benefits such as reduced water loss and suppression of enzymatic browning and microbial spoilage (Gorny, 2001).

2.3 Conclusion

Success in establishing domestic and export markets for Chinese cabbage is dependent upon reliable supplies of quality product. Postharvest techniques are important in maintaining a steady supply of good quality Chinese cabbage. In order to improve postharvest conditions and treatments, a thorough understanding of the physiological processes that are active after harvest and how these are affected by various factors is required.

Research has been carried out on many aspects of postharvest physiology of Chinese cabbage, but there are areas that need investigation or further clarification. Water stress during growth can affect head formation (Kuo *et al.*, 1988) and severity of tipburn (Saure, 1998) in Chinese cabbage. Does it have an effect on postharvest responses, or on the water status of the head at harvest? Full turgidity increases the probability of damage during harvest and handling (Kader *et al.*, 1974; Thompson, 1996), but results in lower weight loss during storage (Fritz and Weichmann, 1981). Do the benefits of early morning harvesting, that is low temperatures and high water status, outweigh the possible loss of outer leaves and increased risk of microbial infections, and does harvesting at different times of the day have any influence on other postharvest processes?

Different cultivars of Chinese cabbage have been found to respond differently to pre- and postharvest conditions. It is therefore necessary to

establish the optimal storage temperature and atmosphere for cultivars to ensure long-term storage with minimal loss of quality. Little or no information is available regarding handling practices or specific postharvest treatments for Chinese cabbage, and investigations concerning the effectiveness of various packaging, trimming methods, or chemical treatments in delaying senescence or optimising quality are needed.

The experimental methods used in this thesis aimed to provide answers to these questions and thereby optimise the growing, harvesting, and postharvest practices used by growers of Chinese cabbage in Australia and other countries.

Chapter 3

3 GENERAL MATERIALS AND METHODS

3.1 Plant material

Chinese cabbage, cv. 'Yuki', was used for all the experiments in this project. This hybrid cultivar, bred by Sakata Seed Co. in Japan, is considered to be resistant to clubroot and tolerant to tipburn and gomasho (P. Shepherd, Fairbank's Seeds Co. Pty Ltd, pers. comm. 2002). Seed was purchased from Fairbank's Seeds Co Pty Ltd, Footscray, Victoria.

3.2 Postharvest evaluations

3.2.1 Weight loss

Weight loss was a measure of the change in weight that occurred while the Chinese cabbage heads were kept in storage. Cabbages were weighed immediately before being placed in storage (initial weight) and again upon removal from storage (final weight). Weight loss was the difference between the initial and final weights expressed as a percentage of the initial weight.

3.2.2 *Trimming loss*

Trimming loss was a measure of the amount of leaf, and occasionally core, material that needed to be removed from a Chinese cabbage head before it was considered to be marketable. Cabbages were weighed (pre-trimmed weight), trimmed of senescing or damaged leaves and any rotting core, and then reweighed (trimmed weight). The trimming loss was the difference between the pre-trimmed and trimmed weights expressed as a percentage of the pre-trimmed weight.

3.2.3 *Quality scores*

3.2.3.1 Experiments conducted in 1999

The location and severity of the visual symptoms of senescence (yellowing, browning, and rotting) and of pre- and postharvest disorders (tipburn, gomasho, pest damage, patchy papery necrosis) were recorded. This was done during the trimming process, and after, when the head was dissected and further inspected. The severity of each of the symptoms and disorders was allocated a score, between 0 (none) and 10 (severe). This score took into account the importance of each symptom or disorder in determining the quality of the Chinese cabbage. Mild cases of all senescence symptoms and disorders were rated 1 and moderate cases were rated 2. As senescence symptoms such as yellowing and browning are generally restricted to outer

leaves or leaf tips, and rarely affect the interior of the cabbage head, severe instances of these symptoms were rated 4. Severe instances of pest damage were rated 5 as these generally penetrated several layers of leaves. Severe instances of disorders, which can occur throughout the entire cabbage head, influence quality much more than severe senescence symptoms and were, therefore, given higher ratings. A rating of 10 was given for severe cases of gomasho, tipburn, patchy papery necrosis, and rotting, as cabbages with this level of these symptoms were of such poor quality to be completely unusable. The total of these scores indicated the overall quality of each cabbage. Total scores of 0 (good) to 3 (average) indicated marketable quality and scores above 3 (below average) indicated unmarketable quality. The highest score possible was 49.

3.2.3.2 Experiments conducted in 2000 and 2001

The presence and severity of the visual symptoms of senescence (yellowing, browning, and rotting) and of pre- and postharvest disorders (tipburn, gomasho, pest damage, patchy papery necrosis, bolting) were noted during the trimming process, and again when the head was dissected and further inspected. The Chinese cabbage was then allocated a quality score of between 1 (good) and 5 (poor) based on the presence and severity of the symptoms and disorders, as well as the overall appearance of the head. Scores of between 1 and 3 indicated marketable quality and scores over 3 indicated unmarketable quality. The highest score possible was 5.

3.2.4 *Chlorophyll fluorescence*

Chlorophyll fluorescence was measured in experiments conducted in 1999 only. The fluorescence of chlorophyll in one outer leaf trimmed from each Chinese cabbage was measured using a Fluorescence Induction Monitor (FIM 1500, ADC BioScientific Ltd, Hoddesdon, England). Key fluorescence parameters of Fo (minimum fluorescence), Fm (maximum fluorescence), Fv (variable component – the difference between Fm and Fo), and the ratio of Fv/Fm were recorded and used as an indication of the photosynthetic capacity of the leaf. As chlorophyll degradation is a characteristic of senescence, reduced photosynthetic capacity may denote the onset of senescence before visual symptoms can be seen (DeEll *et al.*, 1999). The measurements were taken from an area in the uppermost portion of an outer leaf, approximately 1 cm from the leaf margin and as close to the centre line as possible. The measurement area was dark-adapted for 20 minutes prior to illumination, the light intensity was set at 1800 μmol.m^{-2}.s^{-1} and the reading was taken over five seconds. The correct dark adaptation time and light intensity setting are required in order to obtain accurate maximum fluorescence measurements and were determined in preliminary trials as per the manufacturers instructions (Anonymous, undated).

3.2.5 *Energy substrates*

Energy substrate levels were measured in experiments conducted in 1999, and only in pre-storage samples taken from Chinese cabbages grown in the second crop. The levels of sucrose, glucose, and fructose in samples were determined using an enzymatic assay. Four samples from each cabbage (an outer, middle, and inner leaf, and the core) were frozen to -80°C, freeze-dried and then ground into a homogeneous powder. Samples of 5 mg were deproteinised by adding 640 µL 0.6 M $HClO_4$, mixing and then adding 360 µL of 2 M KOH (adapted from Witherspoon and Jackson (1995)). The mixture was centrifuged for 15 minutes at 17000 x g and 750 µL of the resulting supernatant was adjusted to pH 8.0 using 0.5 M KOH (Witherspoon and Jackson, 1995) and then diluted with an equal volume of sterile milliQ water. Fifty µL of this extract were assayed using a technique based on the Sucrose/D-Glucose/D-Fructose Enzymatic BioAnalysis kit (Catalogue No. 716260, Boehringer Mannheim, Germany). The levels of sucrose, glucose, and fructose were estimated from the change in absorbance of NADPH at 340 nm measured in a Varian Cary 1 UV-Visible Spectrophotometer (Varian Australia, Mulgrave, Victoria) (Figure 3.1).

The following formula (3.1) was used to calculate the concentrations in $g.L^{-1}$:

$$\text{Concentration } (g.L^{-1}) = \frac{V \times MW}{\varepsilon \times d \times v \times 1000} \times \Delta Abs \quad \ldots\ldots\ldots (3.1)$$

where V = final volume in mL

MW = molecular weight of substance assayed in $g.mol^{-1}$, which is 180.16 for glucose and fructose and 342.3 for sucrose

ε = extinction coefficient of NADPH at 340 nm, which is 6.3 $L.mmol^{-1}.cm^{-1}$

d = light path in cm

v = sample volume in mL

ΔAbs = difference in absorbance of NADPH at 340 nm

The concentrations were then converted to $mg.g^{-1}$ dry weight (D.W.) using the following formula (3.2):

$$\text{Concentration } (mg.g^{-1} \text{ D.W.}) = \frac{\text{concentration in } g.L^{-1} \text{ sample solution}}{\text{sample weight in } g.L^{-1} \text{ sample solution}} \times 1000 \quad \ldots\ldots (3.2)$$

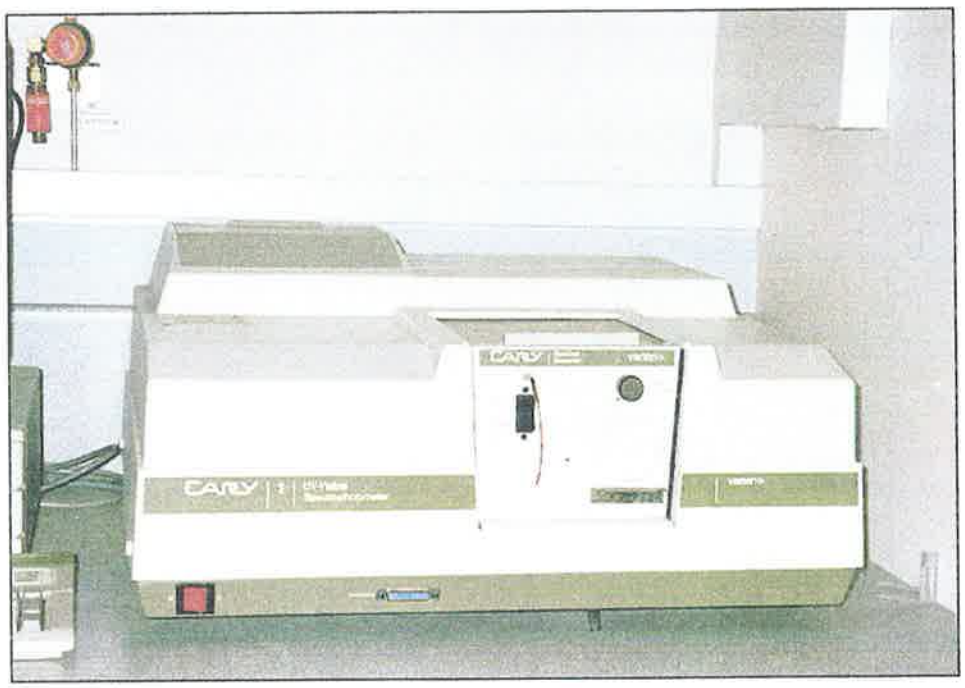

Figure 3.1. The Varian Cary 1 UV-Visible Spectrophotometer (Varian Australia, Mulgrave, Victoria) used to measure the change in absorbance of NADPH at 340 nm.

3.2.6 Respiration rate

The respiration rate of the Chinese cabbages was determined by measuring the levels of carbon dioxide produced by the cabbage heads over time. Cabbages were weighed and then enclosed in 15 L plastic buckets with lids fitted with rubber septa and tightly sealed with vacuum grease. Headspace gases were sampled after 24 hours for all cabbages except those stored at 20°C, as described in Chapter 6, which were sampled after two hours.

Cabbages were kept at their respective storage temperatures during the procedure and the plastic buckets were precooled for approximately one hour, where necessary. The samples were obtained by piercing the rubber septum with a needle and drawing headspace gas into an attached 1 mL syringe. To determine the levels of carbon dioxide present, the 1 mL gas sample was injected into a Varian 3300 thermal conductivity gas chromatograph (Varian Australia, Mulgrave, Victoria) equipped with a silica column (35 cm x 3.1 mm i.d.) of 80/100 and calibrated using 0.5% CO_2 gas standard (BOC Gases, Torrensville, SA). Temperature conditions were 90°C for the injector and detector and 28°C for the column, and the flow rate of helium (carrier gas) was 5 $mL.min^{-1}$. The results were expressed as mL of CO_2 produced per kg of fresh weight per hour (mL $CO_2.kg^{-1}.hr^{-1}$).

3.2.7 Ethylene production

Ethylene production by the Chinese cabbages was determined by measuring the levels of ethylene produced by the cabbage heads over time. Cabbages were weighed and then enclosed in 15 L plastic buckets with lids fitted with rubber septa and tightly sealed with vacuum grease. Headspace gases were sampled after 24 hours for all cabbages except those stored at 20°C, as described in Chapter 6, which were sampled after two hours. Cabbages were kept at their respective storage temperatures during the procedure and the plastic buckets were precooled for approximately one hour, where necessary.

The samples were obtained by piercing the rubber septum with a needle and drawing headspace gas into an attached 1 mL syringe. Ethylene levels were detected by injecting the 1 mL gas sample into a Varian 3400 flame ionisation gas chromatograph (Varian Australia, Mulgrave, Victoria) equipped with a Porapak Q stainless steel column (60 cm x 3.1 mm i.d.) of 80/100 mesh and calibrated using a 1.9 ppm C_2H_4 standard (BOC Gases). Temperature conditions were 50°C for the column, 135°C for the injector and 150°C for the detector. Flow rates of the carrier gases nitrogen, hydrogen, and air were 50, 40, and 300 $mL.min^{-1}$ respectively. The results were expressed as nL C_2H_4 per kg fresh weight per hour (nL $C_2H_4.kg^{-1}.hr^{-1}$).

Chapter 4

4 THE EFFECT OF TIME OF DAY OF HARVEST ON THE POSTHARVEST LIFE OF CHINESE CABBAGE

4.1 Introduction

Early morning is considered to be the best time of day to harvest vegetables, as this is when the water status of produce is high and the temperature and respiration rate are low (Thompson, 1996; Wills *et al.*, 1998). These conditions may be beneficial in maintaining quality of produce and prolonging postharvest life. For leafy vegetables, however, harvesting in the late afternoon may be preferred, when leaves are less turgid and therefore less likely to be damaged (Phan, 1987a). Energy substrate levels at this time of the day are high, and this has been associated with increased storage life in lettuce and cabbage (Lipton, 1987).

Chinese cabbage is a leafy vegetable that forms a densely packed head. Harvested heads store well for long periods at low temperatures, but are prone to various postharvest disorders such as gomasho and chilling injury (Hansen and Bohling, 1981; Gajewski and Skapski, 1994; Daly and Tomkins, 1998). This study was conducted to investigate whether length of storage,

quality, water status, or energy substrate level of the cabbages is influenced by the time of day of harvest or by delays in cooling of the harvested heads.

4.2 Materials and methods

4.2.1 Harvest time and holding period

For this experiment, two crops of Chinese cabbage cv. 'Yuki' were grown at the Ovens Research Centre, Ovens, in Victoria, Australia. Each crop consisted of three adjacent raised beds containing two rows of approximately 120 plants each, giving a total of 720 plants per crop. Seeds for the first crop were sown on November 9, 1998 and the seedlings were transplanted by machine on December 22, 1998. For the second crop, seeds were sown on January 5, 1999 and seedlings were transplanted on February 17, 1999. During bed preparation, a standard fertiliser, comprising nitrogen, phosphorus, potassium, and sulphur at the ratio of 8:11:10:7 was incorporated at the rate of 500 $kg.ha^{-1}$. A side dressing of calcium nitrate at the rate of 125 $kg.ha^{-1}$ was applied approximately five weeks after transplanting. The herbicide, Dual® (Novartis International AG, Switzerland, active ingredient metolachlor), and insecticide, Lorsban 500EC® (Dow Elanco, Indianapolis, Indiana, USA, active ingredient chlorpyriphos), were applied immediately after transplanting at rates of 3 $L.ha^{-1}$ and 2 $L.ha^{-1}$ respectively. Fixed sprinklers provided overhead watering at a rate of 14 $mm.hr^{-1}$. The first crop received approximately 168 mm irrigation and 77 mm rain and was last

watered on March 6, 1999. The second crop received approximately 203 mm irrigation and 102 mm rain and was last watered on April 26, 1999. The first crop was harvested on March 9 and the second on May 4, 1999.

4.2.1.1 Treatments

Each raised bed represented one replicate and was divided into ten plots, each containing a similar number of cabbages suitable for testing (Figure 4.1). Ten harvest treatments, made up of five harvest times (dawn, mid-morning, midday, mid-afternoon and dusk), each with two holding periods (cooled immediately or kept in the field for 30 minutes) were randomly allocated to the plots in each bed as a randomised complete block design. The cabbages were then harvested according to the allocated treatments, with 14 heads per replicate harvested for each treatment. Harvest times and the corresponding air temperatures are shown in Table 4.1. The temperatures during harvesting were within the range for autumn when Chinese cabbages are most likely to be harvested in southern Australian growing regions.

Figure 4.1. Raised beds of mature Chinese cabbage cv. 'Yuki' plants. Each bed represents one replicate and is divided into ten plots for application of the harvest treatments.

Table 4.1. Time of day of harvesting and associated field air temperatures and relative humidity for two crops of Chinese cabbage cv. 'Yuki' grown at Ovens Research Centre, Ovens, Vic.

Treatment	1st Crop March 9, 1999			2nd Crop May 4, 1999		
	Time	Temp. °C	RH%	Time	Temp. °C	RH%
Dawn	7.00	17.3	99	8.10	6.1	99
Morning	10.00	22.3	83	10.40	16.8	67
Midday	13.00	27.0	48	12.45	20.3	47
Afternoon	16.00	27.1	43	14.45	21.5	38
Dusk	19.00	26.8	45	16.50	17.9	63

The harvested cabbages, trimmed of wrapper leaves in the field, were packed into waxed cardboard cartons fitted with polyethylene liners and stored, either immediately or after a 30 minute delay, at 0°C overnight. One head from each treatment was sampled to determine the relative water content. Three leaves from each head - one outer, one middle and one inner leaf - were weighed before (fresh weight) and after (dry weight) drying in a fan-forced oven set at 60°C. The percent relative water content was calculated as (fresh weight – dry weight) ÷ dry weight x 100.

After overnight storage, the heads had cooled to between 2° and 4°C. The cartons were then palletised and transported, within two days, to The

University of Adelaide, Waite Campus, Urrbrae, South Australia, in refrigerated road transport. Temperatures during transport ranged between 2° and 8°C. In Adelaide, the Chinese cabbages were placed in individual perforated polyethylene bags and stored, in treatment/replicate groups in cartons at 0°C. Three cabbages per replicate from each of the ten harvest treatments were removed from storage for postharvest evaluation at zero, three, six, and nine weeks.

4.2.1.2 Postharvest evaluation

Weight loss, trimming loss, quality scores, chlorophyll fluorescence parameters, and energy substrate levels were determined according to methods described in General Materials and Methods, sections 3.2.1 to 3.2.5. Weight loss and energy substrate levels were measured only for the first and second crops, respectively, because of restraints on time and storage space.

4.2.1.3 Data analysis

All numerical data were analysed for variance (ANOVA) as a three-way factorial (harvest time x holding period x storage period) using Genstat 5, 4th Edition for Windows (Lawes Agricultural Trust, IACR, Rothamsted). Quality score data were not normally distributed and required transformation using square root ($\sqrt{\{score + 0.5\}}$) (Steel and Torrie, 1960). Differences in mean

values between treatments and between storage periods were determined using the Least Significant Difference (LSD) at the 5% level.

4.2.2 *Head temperatures in field*

For this experiment, the temperatures at various points inside and outside mature Chinese cabbage heads were measured using temperature data loggers. Three Chinese cabbage plants cv. 'Yuki', of uniform size and maturity and situated adjacent to each other, were selected in a crop grown at Virginia, South Australia. Each cabbage plant was fitted with five temperature data loggers (Tinytalk Temperature Datalogger, Gemini Data Loggers, UK), with stab probes of approximately 8 cm attached (Figure 4.2). Two probes were inserted inside the cabbage head, one at the base and one in the centre. A third probe was placed under the leaves at the top of the head, a fourth inserted inside the midrib of a wrapper leaf, and a fifth was suspended 2 cm above the ground, approximately 2 cm from the cabbage plant (Figure 4.5, p. 52), and was shaded from direct sunlight. Loggers began recording at 0.00 am on May 11, 2000 and were removed from the plants at 11.00 am on May 16, 2000.

Figure 4.2. Mature Chinese cabbage plants fitted with temperature data loggers.

4.3 Results

4.3.1 Harvest time and holding period

4.3.1.1 First crop

The first crop developed tipburn and was infested with aphids shortly before harvest, resulting in poor quality heads. This, together with problems encountered with data gathering during evaluation of cabbages from the first crop, lead to the results from the first crop being regarded as preliminary.

The average relative water content of leaves from Chinese cabbages varied from 92.9% to 95.0% and was not significantly affected by either the harvest times or the holding periods. Leaves taken from cabbages harvested at dawn, morning, midday, afternoon and dusk had average relative water contents of 94.2%, 94.4%, 93.9%, 94.6% and 94.2% respectively. Leaves taken from cabbages cooled immediately had an average relative water content of 94.5% whilst those taken from cabbages held in the field for 30 minutes averaged 94.0%.

Weight loss increased with length of storage to a maximum of 1.3% after nine weeks (Table 4.2). The maximum weight loss recorded for an individual head was 4.5% and the minimum was 0%, and this parameter was not significantly affected by either the harvest times or the holding periods. Cabbages

harvested at dawn, morning, midday, afternoon and dusk treatment times had an average weight loss of 0.74%, 0.61%, 0.47%, 0.65%, and 0.60% respectively. An average weight loss of 0.63% was recorded for cabbages cooled immediately and 0.59% for cabbages held in the field.

Trimming loss ranged from 13.5% to 73.6% across all treatments and storage periods. The amount trimmed from Chinese cabbages increased with the increase in storage period from three to six weeks and then remained constant until week nine (Table 4.2). No values for trimming loss at zero weeks were recorded. Average trimming loss for the harvest treatments was 34.6% for the dawn harvest, 31.5% for the morning harvest, 32.7% for the midday harvest, 35.6% for the afternoon harvest and 30.2% for the dusk harvest. Cabbages held in the field for 30 minutes averaged 31.5% trimming loss and cabbages cooled immediately averaged 34.3%. No significant effects were recorded for either the harvest times or the holding periods.

The quality of the stored Chinese cabbages decreased, as shown by the increase in average quality scores, as the length of storage period increased (Table 4.2). The average scores for Chinese cabbages assessed at all storage periods were outside the marketable range (3 or below). Neither harvest time nor holding period significantly affected the quality scores, with average scores of 7.4, 7.5, 7.5, 7.7 and 7.3 recorded for cabbages harvested at dawn, morning, midday, afternoon and dusk respectively, and an average score of 7.5 for both holding period treatments. Minimum and maximum scores for

individual cabbages were 1 and 28 (out of a possible 49), respectively. The major causes of the deterioration in quality were the yellowing and senescence of outer leaves and the development of rots and postharvest disorders such as gomasho and patchy papery necrosis during storage.

Table 4.2. The average weight loss, trimming loss and quality scores of Chinese cabbage cv. 'Yuki' from the first crop stored at 0°C for up to nine weeks. Values are means of 90 cabbages (three replicates of 30 heads each). Different letters within columns denote significant difference using LSD (P=0.05).

Storage period	Weight loss (%)	Trimming loss (%)	Quality score[Z]
0 weeks	0.0a	n/a[Y]	4.3a
3 weeks	0.4b	24.4a	5.4b
6 weeks	0.7c	35.9b	8.3c
9 weeks	1.3d	38.4b	12.0d

[Z] Scores between 0 and 3 denote good (marketable) quality and scores >3 denote poor (unmarketable) quality. Data were analysed after transformation using square root (√{score + 0.5}), with back-transformed means shown.

[Y]Data were not recorded for this storage period.

The readings for the chlorophyll fluorescence parameters Fm and Fv ranged from 1247 to 3982 and from 595 to 3761, respectively, and decreased

significantly between three and six weeks of storage and thereafter remained relatively unchanged (Table 4.3). Data for zero weeks were not available due to equipment failure. Neither harvest time nor holding period significantly affected these parameters. Average Fm readings for the dawn, morning, midday, afternoon and dusk harvest treatments were 2645, 2930, 2787, 2656 and 2804 respectively, and for the 0 hours and 0.5 hours holding periods were 2748 and 2781 respectively. Average Fv readings were 2059, 2291, 2164, 2087, and 2137 for the dawn, morning, midday, afternoon and dusk harvest treatments respectively, and 2115 and 2181 for the 0 hours and 0.5 hours holding period treatments respectively. Analyses of variance performed on Fo and Fv/Fm data were inconclusive due to a large amount of variation in the data (25% and 27%, respectively) unaccounted for by the treatments and the experimental design.

Table 4.3. Average data for chlorophyll fluorescence parameters, maximum fluorescence (Fm) and variable fluorescence (Fv), for Chinese cabbages cv. 'Yuki' from the first crop stored at 0°C for up to nine weeks. Values are means of 90 cabbages (three replicates of 30 heads each). Different letters within columns denote significant differences using LSD (P=0.05).

	Chlorophyll fluorescence parameters	
Storage period	Fm	Fv
3 weeks	2976a	2407a
6 weeks	2709b	2096b
9 weeks	2608b	1939b

4.3.1.2 Second crop

The relative water content of leaves from Chinese cabbages averaged between 94.7% and 94.8% and was not significantly affected by either the harvest times or the holding periods. Average relative water content of leaves from cabbages harvested at dawn, morning, midday, afternoon, and dusk were 94.8%, 94.7%, 94.8%, 94.9% and 94.8% respectively. Leaves from cabbages cooled immediately had an average relative water content of 94.9% and those from cabbages held for 30 minutes prior to cooling, 94.7%.

Trimming losses were lower for this crop than for the first, but as with the first crop, losses increased significantly during the first six weeks of storage,

and then remained constant, at about 25%, until week nine (Table 4.4). The initial trimming loss of 16% was mainly due to damage of the outer leaves by aphids. Individual trimming varied from a minimum of 0% to a maximum of 59.6%. Neither harvest times nor holding periods significantly affected trimming loss. Means for harvest times ranged were 22.6% for the dawn harvest, 21.7% for the morning harvest, 21.3% for the midday harvest, 21.6% for the afternoon harvest and 21.8% for the dusk harvest. Cabbages cooled immediately averaged 21.5%, whereas those held in the field for 30 minutes averaged 22.1%.

Table 4.4. The average trimming loss and quality scores of Chinese cabbage cv. 'Yuki' from the second crop stored at 0°C for up to nine weeks. Values are means of 90 cabbages (three replicates of 30 heads each). Different letters within columns denote significant difference using LSD (P=0.05).

Storage period	Trimming loss (%)	Quality score[z]
0 weeks	16.2a	0.7a
3 weeks	21.2b	1.6b
6 weeks	24.9c	2.5c
9 weeks	24.8c	3.6d

[z] Scores between 0 and 3 denote good (marketable) quality and scores >3 denote poor (unmarketable) quality. Data were analysed after transformation using square root (√{score + 0.5}), with back-transformed means shown.

The average quality scores of the stored Chinese cabbages increased significantly with an increase in the length of storage period (Table 4.5). The individual scores for cabbages from the second crop were lower than those from the first crop, ranging from 0 to 15, and average scores at zero, three, and six weeks were within the marketable range (3 or below). Only Chinese cabbages assessed after nine weeks of storage were considered unmarketable. Yellowing of outer leaves and the development of patchy papery necrosis contributed most to the decrease in quality.

Table 4.5. The average quality scores of Chinese cabbages cv. 'Yuki' from the second crop harvested at different times during the day and kept in the field for different periods prior to cooling and stored at 0°C for up to nine weeks. Scores between 0 and 3 denote good (marketable) quality and scores >3 denote poor (unmarketable) quality. Harvest time values are means of 18 cabbages (three replicates of six heads each) and cooling delay values are means of 45 cabbages (three replicates of 15 heads each). Different letters across rows denote significant difference using LSD (P=0.05). Data were analysed after transformation using square root (√{score + 0.5}), with back-transformed means shown.

	Harvest Time					Cooling Delay	
	Dawn	Morning	Midday	Afternoon	Dusk	0 hours	0.5 hours
0 weeks	0.8a	0.6a	0.7a	0.6a	0.7a	0.6A	0.8A
3 weeks	1.5a	1.5a	1.4a	2.2a	1.4a	1.6A	1.7A
6 weeks	3.1a	2.1a	2.1a	2.3a	2.1a	2.2A	2.8A
9 weeks	3.6a	3.6a	3.2a	4.4a	3.2a	3.4A	3.7A

The quality scores were not affected significantly by the harvest times and holding periods (Table 4.5). Quality scores for Chinese cabbages from the five harvest times and from the two holding periods were similar at each storage period assessment and deteriorated during storage at similar rates. Cabbages from all treatments except the dawn harvest time were still

marketable after six weeks of storage. Cabbages from the dawn harvest time were scored as marketable at three weeks but were unmarketable by six weeks, and scores for all harvest treatments indicate that the heads were unmarketable after nine weeks. Cabbages harvested at midday had the lowest overall average score at 1.8, whereas those harvested in the afternoon had the highest at 2.4. Mean quality scores for the holding period treatments were 1.9 for cabbages cooled immediately, and 2.2 for those held for 30 minutes.

Individual readings of chlorophyll fluorescence parameters Fm and Fv ranged from 924 (six weeks) to 4087 (zero weeks) and from 374 (nine weeks) to 3535 (zero weeks), respectively. As with the first crop, average readings decreased significantly over the first six weeks of storage and then remained relatively constant (Table 4.6). Neither Fm nor Fv were significantly affected by the harvest treatments. Average Fm readings for the dawn, morning, midday, afternoon and dusk harvest times were 3238, 3095, 3275, 3117, and 3321 respectively, and for the 0.0 hours and 0.5 hours holding periods were 3243 and 3175 respectively. Average Fv readings of 2484, 2433, 2647, 2470, and 2573 were recorded for the dawn, morning, midday, afternoon and dusk harvest times respectively, and 2561 and 2482 were recorded for the 0 hours and 0.5 hours holding periods respectively. Results from the other chlorophyll parameters measured, Fo and Fv/Fm, were unclear, with large variations in the data (21% and 19% respectively) unaccounted for by treatments and experimental design.

Table 4.6. Average data for chlorophyll fluorescence parameters, maximum fluorescence (Fm) and variable fluorescence (Fv), for Chinese cabbages cv. 'Yuki' from the second crop stored at 0°C for up to nine weeks. Values are means of 90 cabbages (three replicates of 30 heads each). Different letters within columns denote significant differences using LSD (P=0.05).

	Chlorophyll fluorescence parameters	
Storage period	Fm	Fv
0 weeks	3644a	3028a
3 weeks	3315b	2635b
6 weeks	2902c	2209c
9 weeks	2976c	2214c

There were no significant differences between either harvest times or holding periods in the amounts of glucose, sucrose, and fructose in samples taken at zero weeks from Chinese cabbages harvested at dawn, midday, and dusk (Figure 4.3). The average amount of glucose found in all samples for the different harvest treatments was approximately 198 $mg.g^{-1}$ dry weight and ranged from 11 $mg.g^{-1}$ dry weight in a core sample to 321 $mg.g^{-1}$ dry weight in a mid leaf sample. Sucrose levels averaged around 87 $mg.g^{-1}$ dry weight for the harvest treatments and ranged from less than 1 $mg.g^{-1}$ dry weight in an outer leaf sample up to 260 $mg.g^{-1}$ dry weight in a core sample. Fructose levels ranged from 37 $mg.g^{-1}$ dry weight in an outer leaf sample to 246 $mg.g^{-1}$

dry weight in a mid leaf sample, and averaged about 139 $mg.g^{-1}$ dry weight across the harvest treatments.

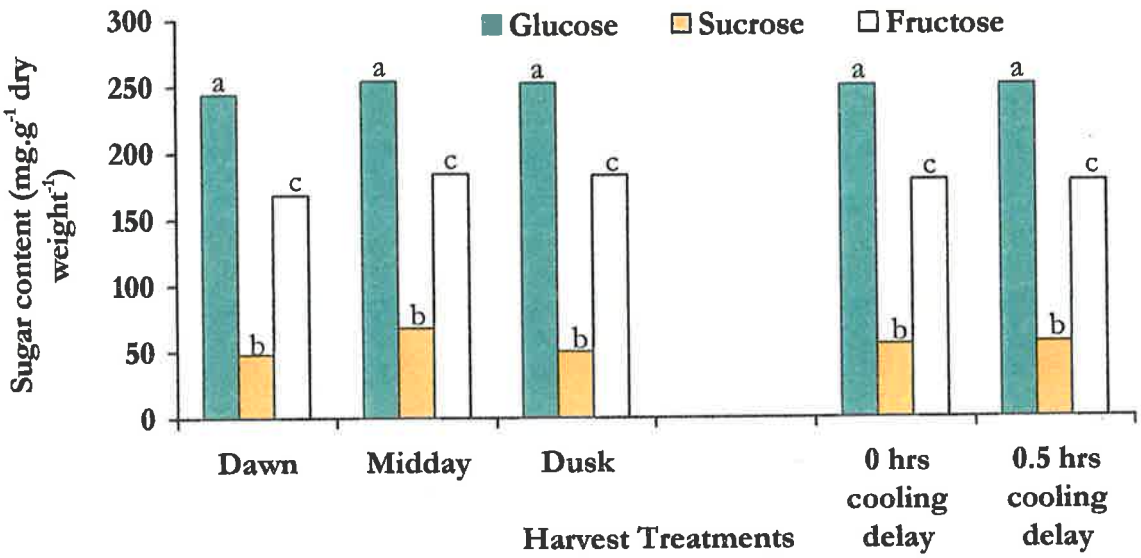

Figure 4.3. Concentrations of three sugars in middle leaf samples taken from Chinese cabbages, cv. 'Yuki', harvested at different times during the day and kept in the field for different periods prior to cooling. Harvest time values are means of 18 cabbages (three replicates of six heads each) and cooling delay values are means of 27 cabbages (three replicates of nine heads each). Different letters atop columns denote significant differences between treatments using LSD (P=0.05).

The levels of the different sugars varied between sampling positions within the heads (Figure 4.4), but neither harvest times nor holding periods significantly affected sugar content at any position. Glucose and fructose levels were highest in leaves sampled from the middle of the heads, while sucrose levels were highest in the core. Glucose levels were lowest in the core, and fructose and sucrose levels were lowest in the outer leaves. Total sugar levels (glucose + sucrose + fructose) for individual samples ranged from 149 $mg.g^{-1}$ dry weight to 629 $mg.g^{-1}$ dry weight.

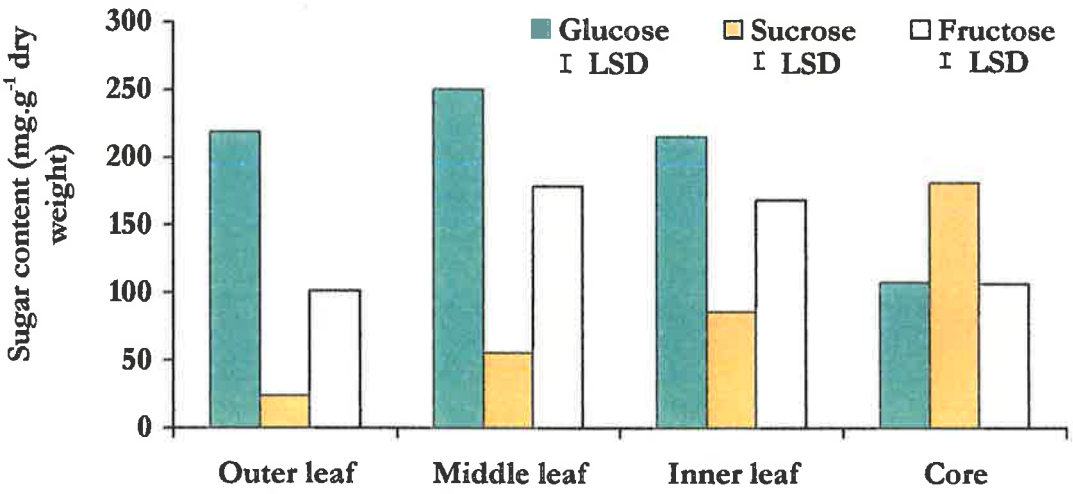

Figure 4.4. Concentrations of three sugars in various tissue samples taken from Chinese cabbages, cv. 'Yuki', at zero weeks. Values are means of 54 cabbages (three replicates of 18 heads each). The bars represent the least significant difference (P=0.05) between different tissue samples for each of the three sugars.

4.3.2 *Head temperatures in field*

Recordings from the temperature data loggers on a typical day are shown in Figure 4.5, and for all five days in Figure 4.6. The temperature inside the cabbage heads, at positions 1 and 2, was less variable than at the other three positions measured. Temperatures at positions 1 and 2 were lower during the day and higher at night, and reached their maximum and minimum levels later than temperatures at the other positions. Assessment of the temperature data over time reveals that the temperature fluctuations at the different positions varied and that the three cabbages tested responded in the same way.

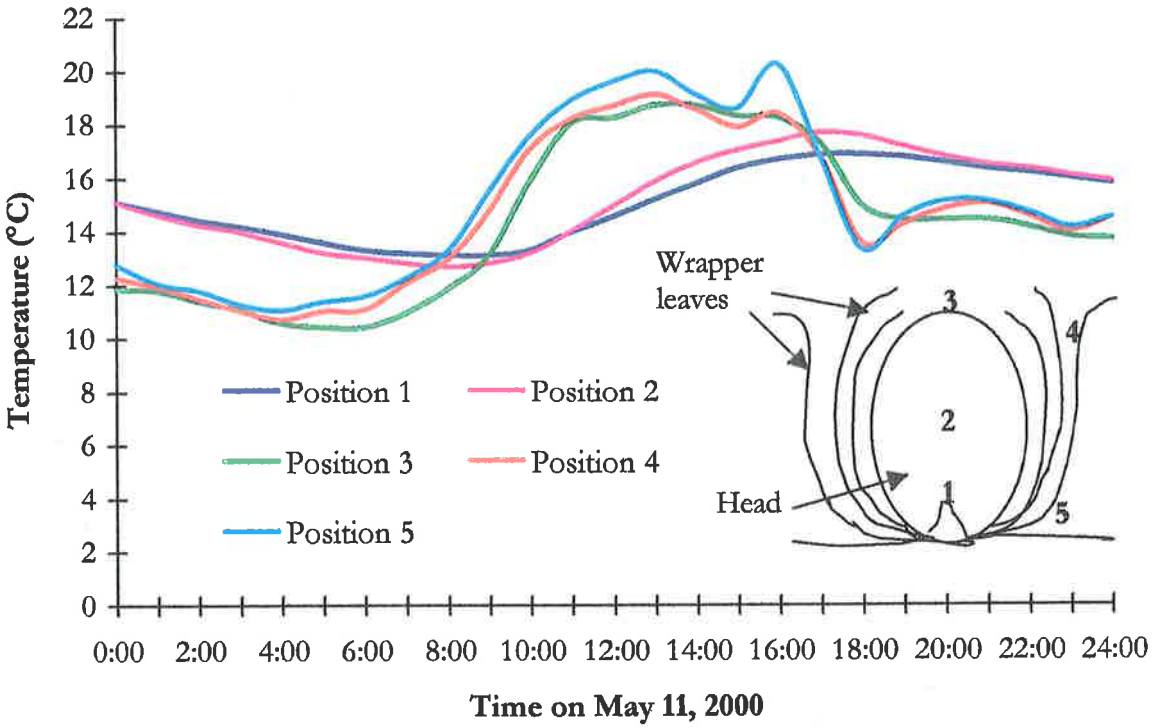

Figure 4.5. Temperature fluctuations at various positions inside and outside mature Chinese cabbage, cv. 'Yuki', heads in the field over a 24-hour period. Minimum and maximum temperatures for the same period, as recorded by the Bureau of Meteorology weather station situated approximately 10 km from the growing site, were 13°C and 22°C, respectively. Values are means of three heads.

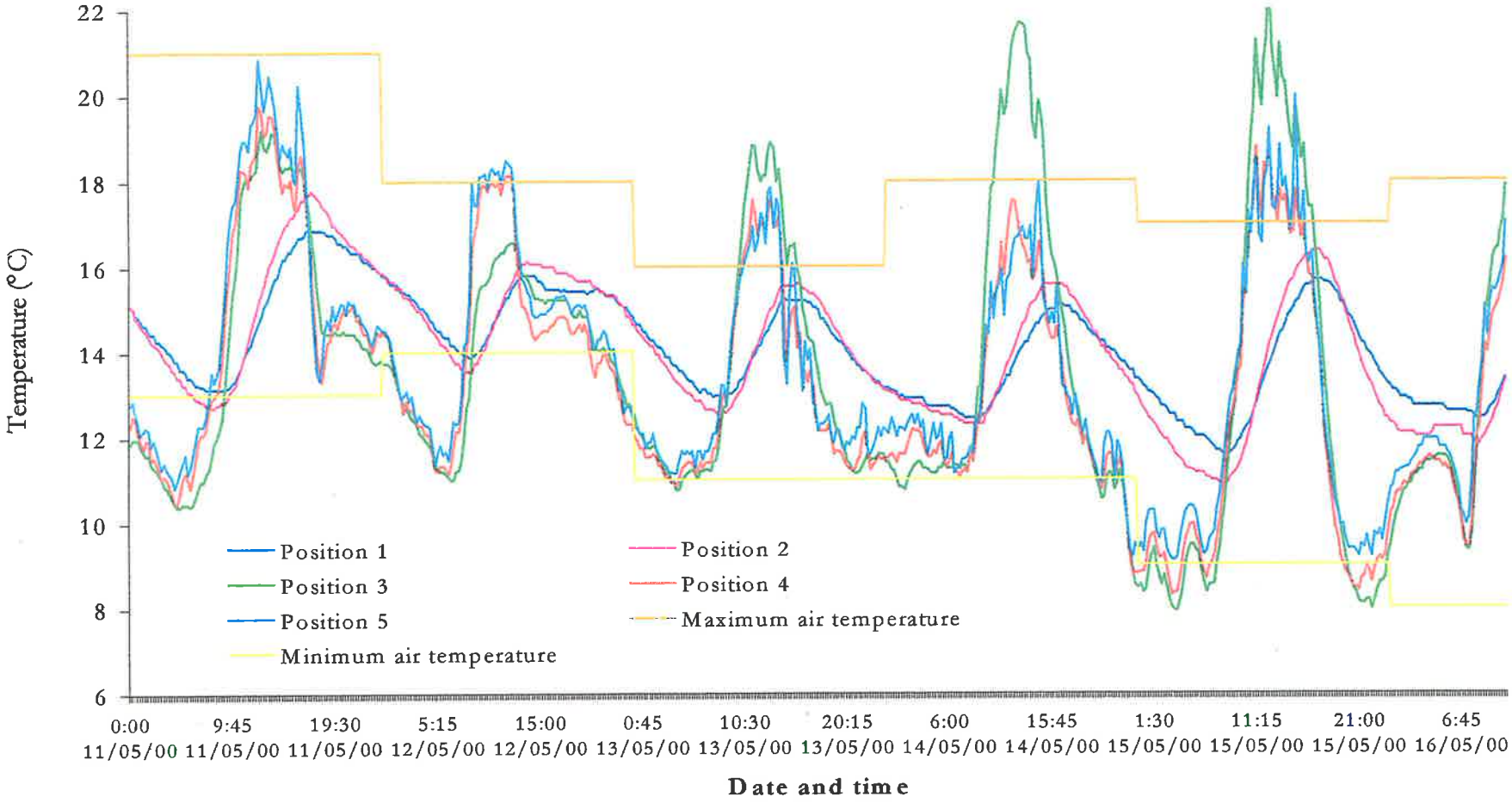

Figure 4.6. Temperature fluctuations at various positions inside and outside mature Chinese cabbage cv. 'Yuki' heads in the field over a five-day period. Values are means of three heads.

4.4 Discussion

This experiment was designed to determine if either harvesting Chinese cabbages at different times of the day, or a delay in cooling the harvested heads, would have any impact on their postharvest life. Two crops were grown and harvested at different times during the season in order to attain a range of climatic conditions during the application of the harvest treatments.

The relative water content and energy substrate levels of leaves from the harvested cabbages were measured to discover if the different harvest treatments had any effect on water status or sugar levels. During low temperature storage, trimming loss and quality were assessed at regular intervals to find out if the storage life and marketability of the cabbages were affected by the harvest treatments. Chlorophyll fluorescence was also measured during storage to see if it could be used to detect the onset of senescence. In addition, an investigation into the relationship between air temperature fluctuations and the temperature inside heads of Chinese cabbage was completed.

The postharvest evaluations show that neither time of day of harvest nor a half-hour delay in cooling affected the postharvest behaviour of the Chinese cabbages. The relative water content data from both crops indicates that these treatments did not influence the water status of the harvested heads. Neither crop had received water for at least three days prior to harvesting,

increasing the likelihood of any temperature-related water stress to be observed. In addition, relative humidity levels at the midday and mid-afternoon harvest times were low, compared to those at the dawn harvest time, adding to the probability of water stress at the later harvest times. Cabbages from all harvest treatments had similar relative water content, trimming losses, and overall quality despite maximum variances in air temperature of up to 15°C between the harvest times. In addition, light exposure throughout the day had no influence on either chlorophyll fluorescence or energy substrate levels. Similarly, harvested cabbages that were left out for half an hour in the midday sun were no different, in the parameters measured, than their neighbours that were transported immediately to the coolroom after harvest.

Field temperature affects turgidity (Kader *et al.*, 1974) and thus influences the susceptibility of leafy vegetable crops to physical damage during harvesting and handling (Phan, 1987b). For this reason, it was expected that the leaves of Chinese cabbages exposed to warm daytime temperatures, such as those harvested at midday or later, would be less turgid and less likely to sustain injury than cabbages harvested earlier in the day. No evidence was found in this study to support this, and the relative water content data suggest that the water status of the Chinese cabbage heads was not affected by field temperature. This could be due to the relatively mild maximum temperatures of 27.1°C and 21.5°C not being sufficient to elicit a response. Levitt (1980)

sets the threshold for high temperature stress for higher land plants at between 45°C and 65°C.

Thompson (1996) and Wills *et al.* (1998) suggest that lower respiration rates of heads harvested in the early morning would positively influence their postharvest life when compared to Chinese cabbage heads harvested later in the day. However, no evidence was found in the present study to support this. Harvested Chinese cabbages kept in the field for half an hour prior to cooling, even those harvested during the hotter times of the day, did not lose quality more rapidly than heads cooled immediately, contrary to the views expressed by Kader *et al.* (1974), Thompson (1996) and Wills *et al.* (1998). A 30-minute delay before being cooled is a relatively short time when compared with the time required to cool the Chinese cabbages (over 24 hours) and the length of time the cabbages spent in low temperature storage (up to nine weeks). It is unlikely that significant harm could result in such a comparatively short time, even in commercial operations where longer delays may be encountered.

The results presented in this study indicate that Chinese cabbage heads have a mechanism that protects against exposure to high temperatures. This is supported by the in-field head temperature data, which suggest that the interior of the head is insulated against temperature extremes by the outer and wrapper leaves. These leaves are exposed to the surrounding environment and their temperature was found to fluctuate to the same or greater extent as

that of the air temperature. Therefore the wrapper and outer leaves are the most likely part of the Chinese cabbage to be affected by temperature. Most wrapper leaves and, depending on their condition, some of the outer leaves were removed when the cabbages were harvested, and consequently had no influence on the postharvest behaviour of the remainder of the head that they had previously protected. The effect of the harvest treatments on the energy substrate levels and water status of the wrapper leaves is unknown, as they were discarded at harvest.

Fritz and Weichmann (1981) found that the maximum temperature from 20 to 11 days prior to harvest had some influence on the marketable quantity (amount of head left after trimming and weight loss) of Chinese cabbage after storage, although duration of storage was a more important factor. In this study, the temperature was recorded only at the time of harvest and was not monitored for any prior period. Kader *et al.* (1974) noted that cabbages may be subject to solar injury during harvest and transport, and that blistering and desiccation of affected leaves may increase the risk of decay. No evidence of either blistering or desiccation was observed in the assessed heads, as any leaves that may have been affected were most likely removed at harvest or prior to storage.

Chlorophyll fluorescence parameters, Fm and Fv, declined in value as the length of storage increased. This may be attributed to the degradation of chlorophyll in association with the onset of senescence. These parameters,

however, were not influenced by exposure of heads to light throughout the day or darkness throughout the night. Toivonen (1992) found that Fv measurements of broccoli declined during storage and that the value for Fv was correlated with respiration and vitamin C content. Toivonen (1992) attributed the decline in Fv to the initiation of chloroplast deterioration associated with water loss, rather than senescence, due to the lack of visual yellowing or chlorosis of the samples. It is possible that chlorophyll fluorescence measurements could be used to determine the onset of senescence in stored Chinese cabbage via early detection of changes in chlorophyll activity. In this study, however, not all chlorophyll fluorescence parameters measured were useful and those that showed some promise, Fm and Fv, differed in value between the two crops. More thorough investigations would be required to identify meaningful parameters and appropriate measurement levels.

Glucose, sucrose, and fructose levels in various samples taken from the Chinese cabbages were the same regardless of the harvest treatments applied. It was expected that energy substrate levels would be higher later in the day due to excess photosynthates from the day's photosynthetic activity being stored in the leaves (Zimmermann, 1969). This was not reflected in the data and could be due to the day's energy gains being stored in another form, such as starch, rather than the three sugars measured. It could also be that the wrapper leaves of the cabbages were the most likely to be photosynthetically active, being dark green in colour and more exposed to daylight, and that

translocation of newly manufactured energy substrates from these leaves to other parts of the head had not taken place prior to harvesting, which included removal of the wrapper leaves. The distribution of the three sugars in leaves throughout the cabbage head is similar to that described by Wang (1983) who found higher levels of glucose and fructose in leaves from the interior of the head than in outer leaves. Wang (1983) also noted that sucrose levels were low in all leaf samples.

The length of storage was a major factor in the postharvest life of the Chinese cabbages. This is an important consideration for growers/wholesalers when supplying local buyers or exporting to overseas markets. Trimming loss increased with the increase in storage period due to the greater number of outer leaves senescing or succumbing to microbial infection at wound sites over time. This also contributed to the deterioration in quality over the storage period, as did the increase in the occurrence and severity of postharvest disorders.

4.5 Summary

The results of this study show that the postharvest behaviour of the Chinese cabbages was not affected either by the time of day when they were harvested, or by the half-hour delay in cooling after harvest. This can be explained by the protective function of the wrapper leaves that cover the head and mitigate the stresses of field temperatures. More important factors in the

postharvest life of Chinese cabbage appear to be the presence of field disorders and pests, the length of storage time, and the development of postharvest disorders whilst in storage.

Chapter 5

5 THE EFFECT OF WATER STRESS DURING GROWTH ON THE POSTHARVEST LIFE OF CHINESE CABBAGE

5.1 Introduction

Water stress during growth can affect quality characteristics of fresh vegetables at harvest (Weston and Barth, 1997). Reduced photosynthetic rates (Janoudi *et al.*, 1993), the development of the disorder, tipburn (Saure, 1998), and shortened shelf life (Wurr *et al.*, 2002) have been associated with water stress during growth. Head formation in Chinese cabbage is closely linked to leaf turgidity (Kuo *et al.*, 1988), which is influenced by water availability, but high rainfall reduced the storage life of spinach (Johnson *et al.*, 1989). Other studies have found that quality, particularly in fruit, improved after drought stress (Beverly *et al.*, 1993).

In leafy vegetables, such as Chinese cabbage, the water status of the leaves influences the progress of senescence (Lipton, 1987). Fritz and Weichmann (1981) concluded that a completely turgid state was favourable for Chinese cabbage storage, as this resulted in lower weight loss during storage. Phan (1987a), however, suggests that leafy vegetables are susceptible to damage when turgid, and are best harvested and handled when their water status is

lower. Grant *et al.* (2001) found that sustained water stress during growth affected the water status of pak choi at harvest, but that intermittent water stress did not.

Water deficit stress, also referred to as water stress or drought stress (Levitt, 1980), in its simplest meaning is a stress imposed through a lack of water. Water stress in plants is usually measured by the soil moisture content in the root zone or by the water potential of the leaves (Kramer, 1980; Levitt, 1980). This study was conducted to investigate whether the length of possible storage, quality, water status, or energy substrate level of harvested Chinese cabbages was influenced by temporary water stress during growth.

5.2 Materials and methods

Two crops of Chinese cabbage cv. 'Yuki' were grown at the Ovens Research Centre in Victoria, Australia. Each crop consisted of three adjacent raised beds containing two rows of approximately 54 plants each, giving a total of 324 plants. Sowing and transplanting dates, and applications of fertilizer, insecticide, and herbicide were as described in Section 4.2.1 (p. 33). The first crop was harvested on March 10, 1999 and the second crop was harvested on May 5, 1999.

5.2.1 Treatments

For the first three weeks after transplanting, seedlings were irrigated normally to facilitate plant establishment, receiving approximately 70 mm of irrigation and rain. For the remainder of the growing period, the cabbage plants were subjected to water stress treatments applied via different irrigation regimes. Each of the raised beds was divided into three plots, giving nine plots of 36 plants (Figure 5.1). Each plot was then randomly allocated one of three water stress treatments in a randomised complete block design, with the raised beds representing the blocks and allowing for three replicates of each treatment. One tensiometer (Jet Fill Model 2725A, Soilmoisture Equipment Corp., Santa Barbara, California) was placed in the centre of each plot, approximately 30 cm from the closest cabbage plants, and with the porous tip of the tensiometer at a depth of 10 cm.

Figure 5.1. Immature Chinese cabbage cv. 'Yuki' plants grown in raised beds, representing blocks, divided into three plots. Water stress treatments were randomly allocated to each plot in a randomised complete block design.

Water stress treatments were applied according to soil moisture levels as indicated by tensiometer readings and were as follows:

- No stress - plants irrigated when tensiometer readings reached –35 to –40 kPa;
- Moderate stress - plants irrigated when tensiometer readings reached –55 to –60 kPa; and
- High stress - plants irrigated when tensiometer readings reached –75 to –80 kPa.

When the appropriate tensiometer readings were reached, plots were irrigated to saturation (0 kPa) using drip irrigation. Table 5.1 shows the amount of water each treatment received via irrigation during application of the treatments as well as the amount of rainfall during the same period. Relative humidity in the growing region during the treatment period for the first crop ranged from 50% to 70% in the mornings and from 30% to 50% in the afternoons. During the treatment period for the second crop, relative humidity in the mornings ranged from 60% to 90% and in the afternoons ranged from 40% to 70%. Wilting of the outer leaves of Chinese cabbages subjected to the high stress treatment was observed on some occasions prior to irrigation.

Table 5.1. The amount of water received by each crop from irrigation and rainfall during application of water stress treatments. Average maximum temperatures during the same period were 39°C and 31°C for the first and second crops respectively.

	Amount of water received (mm)	
	1st Crop	2nd Crop
Irrigation – No stress	414.0	122.3
– Moderate stress	301.1	94.1
– High stress	235.3	23.5
Rainfall	73.5	80.6

All plots were irrigated to near saturation twenty-four hours prior to harvesting to prevent any water stress at harvest confounding the treatment effects. Crops were harvested in the early morning, with harvested cabbages packed into waxed cardboard cartons fitted with polyethylene liners and transported immediately to a coolroom, set at 0°C, for cooling and overnight storage. One head from each treatment was sampled to determine the relative water content. Three leaves from each head - one outer, one middle, and one inner leaf - were weighed before (fresh weight) and after (dry weight) drying in a fan-forced oven set at 60°C. The percent relative water content was calculated as (fresh weight – dry weight) ÷ dry weight x 100.

The Chinese cabbage heads had cooled to between 2° and 4°C after overnight storage. The cartons were then palletised and transported, within two days, to The University of Adelaide, Waite Campus, Urrbrae, South Australia, in refrigerated road transport. Air temperature within the load during transport ranged between 2° and 8°C. In Adelaide, the Chinese cabbages were placed in individual perforated polyethylene bags and stored, in treatment/replicate groups in cartons, at 0°C. Three cabbages per replicate from each of the three water stress treatments were removed from storage for postharvest evaluation at zero, three, six, and nine weeks.

5.2.2 *Postharvest evaluation*

Weight loss, trimming loss, quality scores, chlorophyll fluorescence parameters, and energy substrate levels were determined according to methods described in General Materials and Methods, sections 3.2.1 to 3.2.5. Weight loss and energy substrate levels were measured only for the first and second crops, respectively, because of restraints on time and storage space.

5.2.3 *Data analysis*

All numerical data were analysed for variance (ANOVA) as a two-way factorial (water stress treatment x storage period) using Genstat 5, 4th Edition for Windows (Lawes Agricultural Trust, IACR, Rothamsted). Quality score data were not normally distributed and required transformation using square

root ($\sqrt{\{score + 0.5\}}$) (Steel and Torrie, 1960). Differences in mean values between treatments and between storage periods were determined using the Least Significant Difference (LSD) at the 5% level.

5.3 Results

5.3.1 First crop

The following results from the first crop are regarded as preliminary. This is mainly due to the poor condition of the harvested Chinese cabbages caused by the development of tipburn and an aphid infestation prior to harvest. Other contributing factors are problems encountered with data gathering during the postharvest evaluation of the cabbages.

The relative water content of leaves from the Chinese cabbages varied from 93.2% to 95.1% and was not significantly affected by the water stress treatments. The average relative water contents for no stress, moderate stress and high stress treatments were 94.3%, 94.0%, and 93.8%, respectively.

The amount of weight lost from the cabbages increased with the increase in storage period to a maximum of 1.4% after nine weeks (Table 5.2). The maximum weight loss recorded for an individual head was 2.8% and the minimum was 0.1%. Weight loss was not significantly affected by the water stress treatments, with an average of 0.7% for each.

The amount trimmed from Chinese cabbages to reach a marketable head ranged from 14.5% to 63.3% across treatments and storage periods. Trimming loss remained constant during the initial stages of storage, until week six, and then increased with the longer storage period of nine weeks (Table 5.2). No values were recorded for trimming loss at zero weeks. Microbial infection of wound sites and the progressive yellowing of outer leaves during storage were responsible for the increased trimming losses. The water stress treatments had no significant effect and the average trimming losses were 33.0%, 33.4%, and 33.9% for the no stress, moderate stress, and high stress treatments, respectively.

Table 5.2. The average weight loss, trimming loss and quality scores of Chinese cabbages cv. 'Yuki' from the first crop stored at 0°C for up to nine weeks. Values are means of 27 cabbages (three replicates of nine heads each). Different letters within columns denote significant difference using LSD (P=0.05).

Storage period	Weight loss (%)	Trimming loss (%)	Quality score[Z]
0 weeks	0.0a	n/a[Y]	4.8a
3 weeks	0.6b	27.4a	7.2b
6 weeks	0.7b	32.5a	10.7c
9 weeks	1.4c	40.4b	11.1c

[Z] Scores between 0 and 3 denote good (marketable) quality and scores >3 denote poor (unmarketable) quality. Data were analysed after transformation using square root (√{score + 0.5}), with back-transformed means shown.

[Y]Data were not recorded for this storage period.

The average quality scores of the stored heads increased, meaning that the quality decreased, as the length of storage increased (Table 5.2). The average scores for Chinese cabbages were above the marketable range (0 to 3) for all storage periods. Water stress treatments did not significantly affect the quality scores, with average scores of 8.3, 7.7, and 9.4 for the no, moderate, and high stress treatments, respectively. The minimum score for an individual cabbage was 1 and the maximum was 23 (out of 49). The main causes of the decline

in quality were the yellowing of outer leaves, the development of rots at wound sites and postharvest disorders such as gomasho and patchy paper necrosis.

The readings for chlorophyll fluorescence parameters Fm and Fv ranged from 838 to 4081 and 638 to 3452 respectively. Average values for Fm and Fv decreased significantly during storage (Table 5.3). Similarly, average readings for chlorophyll fluorescence parameter Fv/Fm decreased over the nine weeks and individual readings ranged from 0.369 to 0.868. Water stress treatments did not affect any of these parameters, with averages of 3190, 3057, and 3001 for Fm, 2371, 2433 and 2368 for Fv, and 0.74, 0.79 and 0.79 for Fv/Fm for the no, moderate and high water stress treatments respectively. Analysis of variance performed on Fo data was inconclusive due to a large amount of variation in the data (32%) unaccounted for by the treatments and the experimental design.

Table 5.3. Average data for chlorophyll fluorescence parameters, maximum fluorescence (Fm), variable fluorescence (Fv), and the ratio Fv/Fm, for Chinese cabbages cv. 'Yuki' from the first crop stored at 0°C for up to nine weeks. Values are means of 27 cabbages (three replicates of nine heads each). Different letters within columns denote significant differences using LSD (P=0.05).

	Chlorophyll fluorescence parameters		
Storage period	Fm	Fv	Fv/Fm
0 weeks	3481a	2867a	0.82a
3 weeks	3100b	2368b	0.77bc
6 weeks	3033b	2353b	0.78ab
9 weeks	2716c	1974c	0.72c

5.3.2 Second crop

The relative water content of leaves from Chinese cabbages ranged between 92.3% and 96.6% and was not significantly affected by the water stress treatments. The average relative water contents for no stress, moderate stress and high stress treatments were 94.9%, 94.5%, and 94.6%, respectively.

Trimming losses increased significantly with the increase in storage period initially, from zero to three weeks, and then remained constant, at about 25%, until week nine (Table 5.4). Overall, trimming loss was lower for this crop

than for the first. The trimming loss of 17% at zero weeks was due mostly to damage of the outer leaves by aphids. The amount trimmed from individual heads varied from a minimum of 11.6% to a maximum of 40.6%. The water stress treatments did not significantly affect trimming loss with averages of 23.1%, 23.9%, and 21.5% for the no stress, moderate stress, and high stress treatments, respectively.

The average quality scores of the stored Chinese cabbages increased significantly with the increase in storage period from three weeks onwards (Table 5.4). Individual scores for cabbages from this crop ranged from 0 to 12 and were lower than those from the first crop. Average scores at zero, three, and six weeks were within the marketable range (3 or below) and only cabbage heads assessed after nine weeks were considered unmarketable. The deterioration in quality was mostly due to the yellowing of outer leaves and the development of patchy papery necrosis during storage.

Table 5.4. The average trimming loss and quality scores for Chinese cabbages cv. 'Yuki' from the second crop stored at 0°C for up to nine weeks. Values are means of 27 cabbages (three replicates of nine heads each). Different letters within columns denote significant difference using LSD (P=0.05).

Storage period	Trimming loss (%)	Quality score[z]
0 weeks	16.9a	1.0a
3 weeks	24.4b	1.5a
6 weeks	25.1b	2.3b
9 weeks	24.9b	3.6c

[z] Scores between 0 and 3 denote good (marketable) quality and scores >3 denote poor (unmarketable) quality. Data were analysed after transformation using square root ($\sqrt{\{score + 0.5\}}$), with back-transformed means shown.

The quality scores were not affected significantly by the water stress treatments (Table 5.5). The quality of the Chinese cabbages was similar at each storage period assessment and deteriorated at similar rates during storage for each of the water stress treatments.

Table 5.5. Quality scores of Chinese cabbages cv. 'Yuki' from the second crop subjected to different levels of water stress during growth and then stored at 0°C for up to nine weeks. Scores between 0 and 3 denote good (marketable) quality and scores >3 denote poor (unmarketable) quality. Values are means of nine cabbages (three replicates of three heads each). Data were analysed after transformation using square root (√{score + 0.5}), with back-transformed means shown. Different letters across rows denote significant difference using LSD (P=0.05).

	Water Stress Treatments		
Storage Period	No Stress	Moderate Stress	High Stress
0 weeks	1.0a	1.2a	0.8a
3 weeks	1.3a	1.8a	1.3a
6 weeks	2.4a	2.0a	2.6a
9 weeks	3.6a	3.3a	3.9a

Readings for the chlorophyll fluorescence parameters Fm and Fv ranged from 1709 to 4071 and from 1359 to 3447, respectively. As with the first crop, average readings for Fm decreased significantly over the storage period (Table 5.6). Average values for Fv, however, only decreased from zero weeks to three weeks and then remained constant until the end of storage. Water stress treatments did not affect either Fm or Fv, with averages of 3215, 3255, and 3447 for Fm and 2474, 2478 and 2596 for Fv for the no, moderate and

high stress treatments respectively. There were no significant differences in readings for chlorophyll fluorescence parameter Fv/Fm between storage periods or between water stress treatments. Average readings for the no, moderate and high stress treatments for Fv/Fm were 0.77, 0.76, and 0.76 respectively. Results from the chlorophyll parameter Fo were unclear, with approximately 39% of the variation in the data unaccounted for by treatments and experimental design.

Table 5.6. Average data for chlorophyll fluorescence parameters, maximum fluorescence (Fm) and variable fluorescence (Fv), for Chinese cabbages cv. 'Yuki' from the second crop stored at 0°C for up to nine weeks. Values are means of 27 cabbages (three replicates of nine heads each). Different letters within columns denote significant differences using LSD (P=0.05).

	Chlorophyll fluorescence parameters	
Storage period	Fm	Fv
0 weeks	3591a	2890a
3 weeks	3381ab	2514b
6 weeks	3154bc	2324b
9 weeks	3097c	2334b

The water stress treatments did not affect the amounts of glucose, sucrose and fructose found in samples taken from Chinese cabbages from the second crop at zero weeks (Figure 5.2). The average amount of glucose found in all samples for the different water treatments was approximately 197 $mg.g^{-1}$ dry weight and ranged from 85 $mg.g^{-1}$ dry weight in a core sample to 302 $mg.g^{-1}$ dry weight in a mid leaf sample. Sucrose levels averaged around 75 $mg.g^{-1}$ dry weight and ranged from less than 1 $mg.g^{-1}$ dry weight in an outer leaf sample up to 243 $mg.g^{-1}$ dry weight in a core sample. Fructose levels ranged from 56 $mg.g^{-1}$ dry weight in an outer leaf sample to 232 $mg.g^{-1}$ dry weight in a mid leaf sample, and averaged about 142 $mg.g^{-1}$ dry weight across the water stress treatments.

The levels of the different sugars varied between sampling positions within the heads (Figure 5.3), but water stress treatments did not significantly affect sugar content at any position. Glucose and fructose levels were highest in leaves sampled from the middle of the heads, while sucrose levels were highest in the core. Glucose levels were lowest in the core, and fructose and sucrose levels were lowest in the outer leaves. Total sugar levels (glucose + sucrose + fructose) for individual samples ranged from 216 $mg.g^{-1}$ dry weight to 526 $mg.g^{-1}$ dry weight.

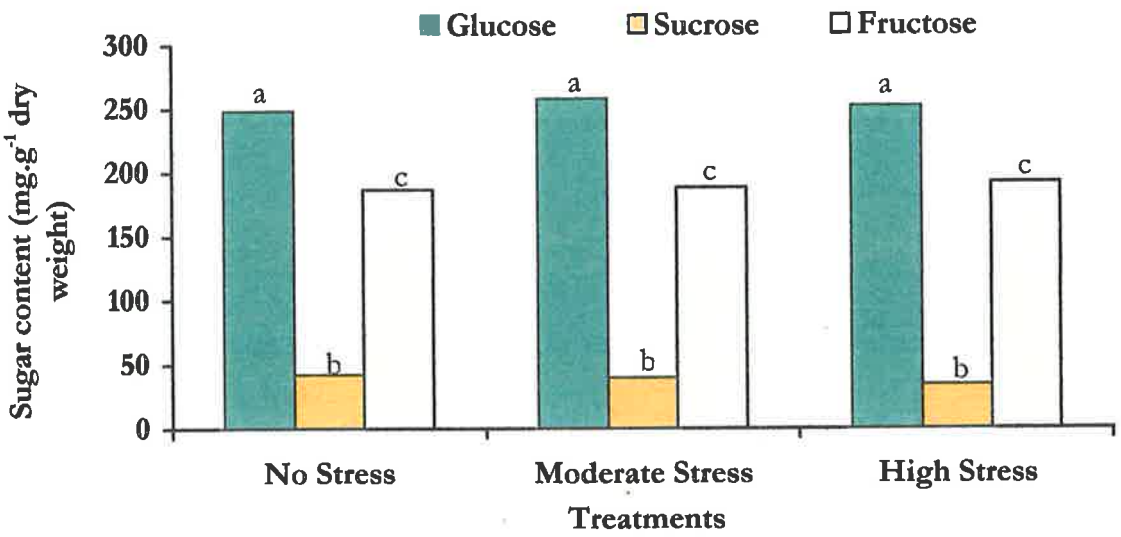

Figure 5.2. Concentrations of three sugars in middle leaf samples taken at zero weeks storage from Chinese cabbages cv. 'Yuki' subjected to water stress treatments during growth. Values are means of nine cabbages (three replicates of three heads each) and different letter atop columns denote significant differences between treatments using LSD (P=0.05).

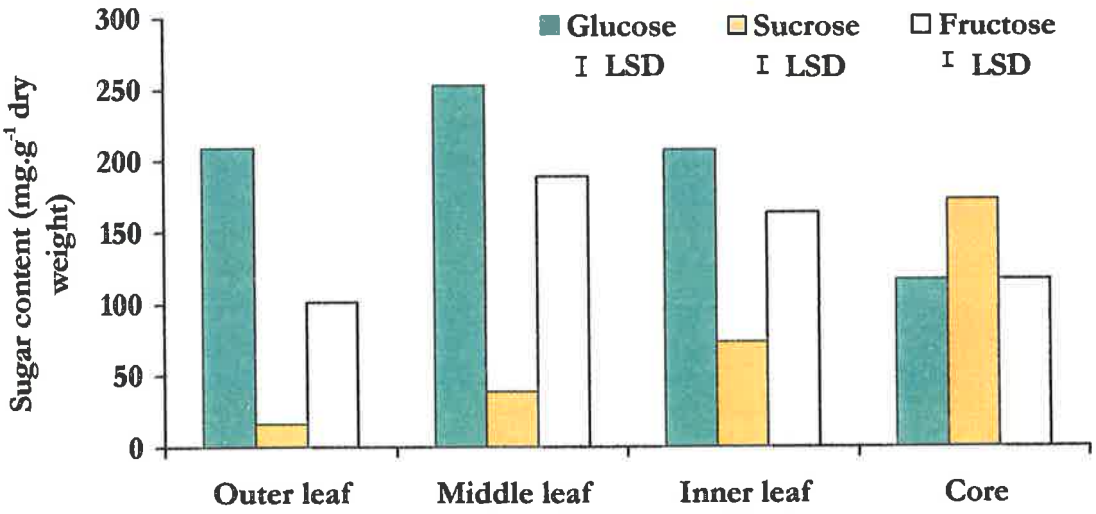

Figure 5.3. Concentrations of three sugars in various tissue samples taken from Chinese cabbages cv. 'Yuki' at zero weeks. Values are means of 27 cabbages (three replicates of nine heads each). The bars represent the least significant difference (P=0.05) between different tissue samples for each of the three sugars.

5.4 Discussion

In this experiment, intermittent water stress was applied to growing Chinese cabbage plants to ascertain what effects, if any, this might have on the postharvest behaviour of the cabbage heads. Measurements of relative water content, weight loss, trimming loss, quality, chlorophyll fluorescence, and sugar content were made to compare the three levels of water stress treatments applied.

No differences were found between water stress treatments in the relative water content of the Chinese cabbage leaves immediately after harvest. It is possible that irrigation of the plants 24 hours prior to harvest negated any effects the treatments had on the water content of the cabbages. Yang and Zhang (1992) found no difference in head moisture content of greenhouse-grown Chinese cabbages harvested up to 15 days after the cessation of watering. Grant *et al.* (2001) found that a single six-day period of water stress during growth, followed by full watering for up to 10 days, did not affect the relative water content of harvested pak choi. However, sustained water stress of the pak choi plants for six weeks throughout the growth period resulted in lower relative water content at harvest.

Weight loss of Chinese cabbages from the first crop during storage was not affected by the water stress treatments. Levitt (1985) found that acclimation of detached cabbage leaves to water deficit conditions increased their

tolerance to dehydration, most likely due to stomatal control of water loss, osmotic adjustment and other unknown factors. Potted miniature roses produced under water stress conditions took longer to wilt under adverse post-production conditions than optimally watered control plants (Williams *et al.*, 2000). This suggests that Chinese cabbage plants subjected to water stress during growth could produce heads that would lose less water, the major factor in weight loss during postharvest storage, than heads from plants that were fully watered. As no differences were observed in the current study, it is likely the water stress treatments applied were not sufficient to acclimatise the Chinese cabbage plants to adverse conditions. This may also explain the lack of effect on trimming loss, with leaves from stressed and non-stressed heads wilting and senescing at similar rates.

Quality scores for the Chinese cabbages were unaffected by the water stress treatments. In a study of the effect of water stress on the postharvest quality of broccoli, Wurr *et al.* (2002) found that water stress applied at different stages of growth affected different shelf-life characteristics. Water stress applied early adversely affected stem turgor, head colour, bud elongation and floret looseness, whilst stress imposed close to maturity resulted in better head colour and stem turgor than control heads. Grant *et al.* (2001) found no difference in shelf life between water stressed and control pak choi, although leaves of the stressed plants were greener in colour at harvest.

Water stress results in reduced photosynthetic activity of leaves, with the effect attributed to stomatal closure as well as metabolic and turgor related factors (Levitt, 1980; Janoudi *et al.*, 1993). No evidence was found in this study to suggest that water stress affects the chlorophyll fluorescence of Chinese cabbage leaves either after harvest or during storage.

Janoudi *et al.* (1993) found much higher concentrations of sucrose in leaves from water stressed cucumber plants than well-watered plants. No such differences in sucrose levels were found between leaves taken from water stressed and those taken from non-water stressed Chinese cabbage plants in the current study. Nor were any differences found in the concentrations of glucose and fructose between water stress treatments. Similarly, intermittent water stress during growth did not affect levels of glucose, sucrose, or fructose in pak choi leaves (Grant *et al.*, 2001), and ratios of these three sugars are similar to those found in inner leaf samples of Chinese cabbage.

Kuo *et al.* (1988) found that heat tolerant Chinese cabbage cultivars had some form of drought avoidance mechanism, such as thickened leaves, low stomatal numbers, extensive root growth, and high leaf sap electrical conductivity. Even though the cultivar, 'Yuki', used in this study is not known for its heat or drought tolerance, it is possible that the cabbage plants utilised one or more of these mechanisms to alleviate any water stress experienced as a result of the treatments. No investigation into the presence or use of such mechanisms was made during this study.

In a study of dehydration and drought response of cabbage (*Brassica oleracea* var. *capitata*) leaves, Levitt (1985) found that when young cabbage plants were water stressed, the older leaves wilted, shriveled and abscised first whilst the younger leaves stayed turgid. Levitt (1985) hypothesises that the older leaves may act as a source, transporting water and solutes to the younger leaves during drought conditions. The oldest leaves of the mature Chinese cabbage plants used in this investigation were the large wrapper leaves surrounding the head. The effects of the water stress treatments on these leaves were not determined as they were trimmed from the head and discarded during harvesting. In experiments described in Chapter 4 the wrapper leaves were found to protect the head from temperature fluctuations in the field, thereby alleviating the possible effects of temperature stress.

The length of storage is an important aspect of the postharvest life of Chinese cabbage cv. 'Yuki'. Weight loss, trimming loss and quality scores of cabbages from both crops all increased, to varying degrees, during storage. Yellowing of outer leaves and the development of postharvest disorders during storage were the main causes for the increases in trimming loss and quality scores. Comparison of the results from the two crops shows that the condition of the cabbages being placed into storage also influences their storability. Trimming losses and quality scores from the first crop were much higher than those from the second, and trimming losses at three, six, and nine weeks for

cabbages from the second crop were static, while those from the first crop increased as microbial infections developed at preharvest wound sites.

5.5 Summary

This study has shown that temporary water stress experienced during plant growth does not affect the postharvest behaviour of Chinese cabbage. This could be due to the plant's ability to either recover from any adverse effects upon rewatering, or use some type of mechanism to tolerate the lack of water. It is possible that only the older leaves of the Chinese cabbage plants were affected by the water stress treatments applied, leaving the head unimpaired. The initial condition of the Chinese cabbages and the length of storage are important factors influencing the postharvest outcome.

Chapter 6

6 THE EFFECT OF STORAGE TEMPERATURE ON THE POSTHARVEST LIFE OF CHINESE CABBAGE

6.1 Introduction

Storage at low temperature is an important part of prolonging the postharvest life of fresh produce. Low temperatures can reduce moisture loss, respiration rate, ethylene production and sensitivity, and the growth of pathogens (Mitchell, 1992a). Although earlier studies (Hansen and Bohling, 1981; Gajewski and Skapski, 1994) showed that Chinese cabbage can be stored for long periods at low temperatures, some cultivars appear to store better than others, for example 'Treasure Island' stores better than 'WR Green 60' (Apeland, 1984b; Daly and Tomkins, 1998), and storage temperatures of around 0°C can cause chilling injury in some cultivars.

Chinese cabbage cv. 'Yuki' was chosen for this study because it produced high yields, was tolerant to gomasho, and had a high percentage of marketable heads after storage in production and storage trials carried out in Victoria, Australia (Daly and Tomkins, 1998). Three storage temperatures, 0°C, 2°C and 20°C, were used to examine the differences in postharvest physiology at

ambient and cool storage temperatures. The low temperatures, 0°C and 2°C, were also chosen to investigate the role of low temperature in the development of a disorder described and named Patchy Papery Necrosis (PPN) by Daly and Tomkins (1998) that is often seen in cv. 'Yuki'.

6.2 Materials and methods

Chinese cabbages cv. 'Yuki' were grown at a market garden in Virginia, South Australia using commercial growing practices. The experimental area consisted of a raised bed containing two rows of approximately 360 plants each. Mature Chinese cabbages were harvested mid-season over three days, on May 29 and 31 and June 2, 2000, with cabbages harvested on each date representing one replicate. Based on results presented in Chapter 4, no specific time of the day was selected for harvesting.

The harvested cabbages were packed into waxed cardboard cartons in the field and transported to the Waite Campus of the University of Adelaide within three hours of harvest. Upon arrival, the cabbages were randomly allocated storage temperature treatments, either 0°C, 2°C, or 20°C, and were placed in the appropriate controlled temperature room. Chinese cabbages stored at 20°C were placed immediately into individual perforated polyethylene bags to slow down moisture loss, whilst cabbages stored at the lower temperatures were left unbagged for 24 hours to facilitate cooling. Cabbages from the different harvest dates (replicates} were stored in separate

cartons in each controlled temperature room. On the day of harvest, five cabbages were randomly selected from each replicate and sampled for weight, trimming loss, presence and severity of disorders, and overall quality.

6.2.1 Postharvest evaluation

Chinese cabbages were stabilised at their storage temperature (24 hours at 20°C and 72 hours at 0° and 2°C) before commencement of the study. Weight, respiration rate and ethylene production were measured from five cabbages per replicate per storage temperature at intervals of zero, one, two, and three weeks for 20°C, or zero, three, six, and nine weeks for 0°C or 2°C. At the same intervals, a further five cabbages from each replicate/treatment combination were destructively sampled to determine trimming loss, disorders and quality. All postharvest evaluations were determined as described in General Materials and Methods, sections 3.2.1 to 3.2.3, 3.2.6 and 3.2.7.

During quality assessment, the occurrence and severity of symptoms of the disorder Patchy Papery Necrosis (PPN) were recorded. Severity of the symptoms were rated either 1, indicating no symptoms, 2, indicating mild symptoms, 3, indicating moderate symptoms, or 4, indicating severe symptoms.

6.2.2 *Data analysis*

All numerical data, apart from quality scores and PPN severity scores, were analysed as a two-way factorial (temperature x storage period) using the General Analysis of Variance test (ANOVA) in Genstat 5, 4th Edition for Windows (Lawes Agricultural Trust, IACR, Rothamsted). Quality scores and PPN severity scores were compared using means and standard errors. The experiment was set up as a Randomised Complete Block design, with the harvest dates (replicates) as blocks and cabbages harvested on each date randomly assigned to temperature treatments and storage period. Differences between 0°C and 2°C temperature treatments and between storage periods were determined using the Least Significant Difference (LSD) at the 5% level.

6.3 Results

Table 6.1 shows the data for the effects of storage time on respiration rate and ethylene production of the Chinese cabbages. The significance, or otherwise, of within-treatment effects is indicated. There were significant differences between storage periods for respiration rate at all temperatures and for ethylene production at 2°C and 20°C. For individual cabbages stored at the lower temperatures, respiration rates ranged from 0.4 to 1.5 mL $CO_2.kg^{-1}.hr^{-1}$ and ethylene production ranged from 1.0 to 55.8 $nL.kg^{-1}.hr^{-1}$, whilst at 20°C, respiration rates ranged from 11.6 to 37.1 mL $CO_2.kg^{-1}.hr^{-1}$

and ethylene production ranged from 45.6 to 1439 $nL.kg^{-1}.hr^{-1}$. At the lower temperatures, the respiration rate of the cabbages decreased slowly over the storage period whilst ethylene production was relatively constant up to six weeks for 2°C and nine weeks for 0°C. The data for 0°C and 2°C at zero weeks were unreliable and were therefore excluded from the analysis. The rates of respiration and ethylene production of Chinese cabbages stored at 20°C were higher than those for cabbages stored at the lower temperatures. At 20°C both respiration and ethylene production decreased significantly in the first week but increased again to be at their highest level after three weeks. The analysis of variance of between-treatment effects showed there were no significant differences between 0°C and 2°C for respiration rate and for ethylene production during the nine weeks of storage ($P > 0.05$).

Table 6.1. Rate of respiration and ethylene production of Chinese cabbage cv. 'Yuki' during storage at three different temperatures. Values are means of 15 cabbages (three replicates of five heads each). Different letters within columns denote significant differences between storage periods using LSD (P=0.05).

	Respiration rate (mL CO_2.kg^{-1}.hr^{-1})			Ethylene production (nL.kg^{-1}.hr^{-1})		
	0°C	2°C	20°C	0°C	2°C	20°C
0 weeks	-[Z]	-	18.1c	-	-	486bc
1 week			8.1a			160a
2 weeks			11.8b			318ab
3 weeks	0.8a	1.1a	23.6d	2.6a	3.8a	718c
6 weeks	0.7b	1.0ab		1.6a	3.5a	
9 weeks	0.5c	0.9b		5.2a	14.0b	

[Z]Values not available due to problems with sample gathering and detection.

Significant differences in weight loss were found between storage periods at each of the temperatures (Table 6.2). Weight loss increased with the increase in storage time. Weight loss of individual cabbages stored at 20°C ranged from a minimum of 0.9% to a maximum of 8.1%, and for cabbages stored at 0°C and 2°C ranged from 0.2% to 2.8%. Cabbages stored at 20°C for three weeks lost about 10 times more weight than cabbages stored for the same period at 0°C and 2°C, but weight loss between the two low temperature

treatments, for comparable storage periods, was not significantly different. Trimming losses at 0°C and 20°C increased initially and then stabilised, whilst trimming losses at 2°C increased significantly during the storage period (Table 6.2). Trimming losses were high after one week at 20°C, almost half the initial weight. By three weeks cabbages stored at 20°C were so severely infected by a postharvest bacterial pathogen that it was not possible to trim them to marketable quality and trimming losses were not calculated. Trimming loss for individual cabbages ranged from 14.4% prior to storage up to 62.6% after three weeks at 20°C.

Table 6.2. The weight loss and trimming loss of Chinese cabbages cv. 'Yuki' at various intervals during storage at three different temperatures. Values are means of 15 cabbages (three replicates of five heads each). Different letter within columns denote significant differences between storage periods using LSD (P=0.05).

	Weight loss (%)			Trimming loss (%)		
	0°C	2°C	20°C	0°C	2°C	20°C
0 weeks	0.0a	0.0a	0.0a	28.6a	28.6a	28.6a
1 week			1.8b			47.2b
2 weeks			4.0c			46.4b
3 weeks	0.7b	0.5b	5.6d	43.6b	35.7b	-[z]
6 weeks	1.1c	1.0c		38.8b	41.9bc	
9 weeks	1.6d	1.3d		42.4b	43.5c	

[z]This value was not obtained, as Chinese cabbage heads could not be trimmed to a marketable standard.

The quality scores increased, that is the quality decreased, over the storage periods for all three temperatures (Table 6.3). The quality of cabbages stored at 20°C deteriorated to show an average quality score of 4.92, indicating poor quality, after two weeks. In general, cabbages stored at the lower temperatures were assessed as below average quality after three weeks, although scores were variable. Results of PPN assessment show that six

times more cabbages were affected at 0°C than at 2°C and that symptoms were twice as severe (Figures 6.1 and 6.2). Symptoms presented as brown discolouration and necrosis of leaf tissue between veins, usually near the midrib of the leaf (Figure 6.3, p. 96). Only one or two inner leaves showed symptoms in mild cases but in severe cases large numbers of leaves throughout the head were affected. No PPN was observed in cabbages stored at 20°C.

Table 6.3. The average quality scores of Chinese cabbages cv. 'Yuki' at various intervals during storage at three different temperatures. A score of 1 indicates good quality, >3 indicates unmarketable quality, and 5 indicates poor quality. Scores are means of 15 cabbages (three replicates of five heads each) plus or minus the standard error.

	Quality score		
	0°C	2°C	20°C
0 weeks	1.53 ± 0.13	1.53 ± 0.13	1.53 ± 0.13
1 weeks			3.33 ± 0.23
2 weeks			4.92 ± 0.08
3 weeks	3.27 ± 0.27	2.60 ± 0.34	-[z]
6 weeks	3.73 ± 0.30	3.20 ± 0.33	
9 weeks	3.00 ± 0.17	3.00 ± 0.26	

[z]This score was not obtained due to the deteriorated condition of the cabbages at that time.

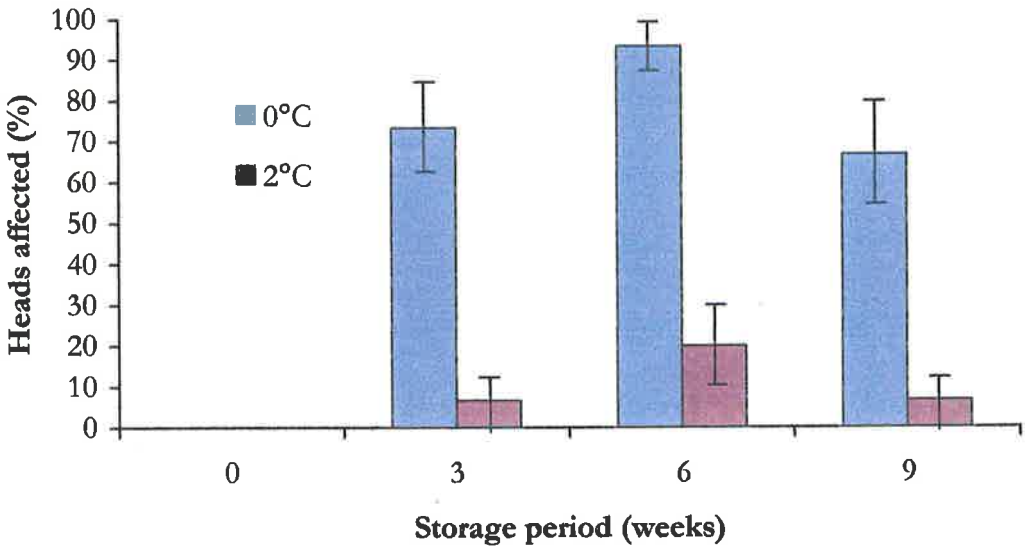

Figure 6.1. The percent occurrence of the disorder, Patcy Papery Necrosis, observed in Chinese cabbages cv. 'Yuki' during low temperature storage. Values are means of 15 cabbages (three replicates of five heads each) and bars represent the standard error.

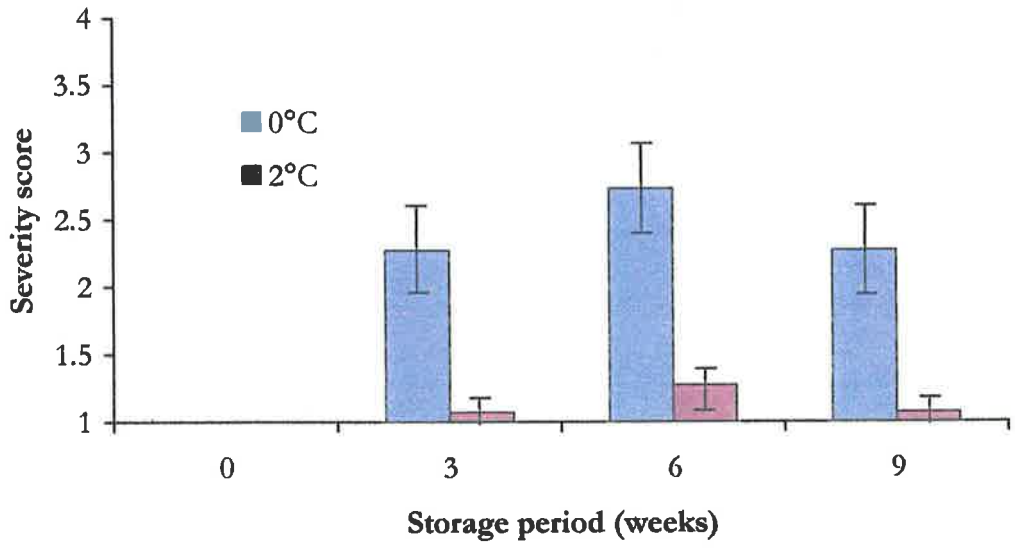

Figure 6.2. The severity score of the disorder, Patchy Papery Necrosis, observed in Chinese cabbages cv. 'Yuki' during low temperature storage. A score of 1 indicates no symptoms and a score of 4 indicates severe symptoms. Values are means of 15 cabbages (three replicates of five heads each) and bars represent the standard error.

6.4 Discussion

This experiment aimed to examine the effects that different storage temperatures could have on the postharvest outcomes for Chinese cabbage cv. 'Yuki'. The use of three storage temperatures, 0°C, 2°C, and 20°C, allowed comparisons to be made between cold storage, as used during long term storage or export, and non-refrigerated storage, as used for the fresh, domestic markets. Comparisons between the two low temperatures, 0°C and 2°C, were useful in determining the optimum storage temperature and whether this cultivar was susceptible to chilling injury.

An investigation of the respiration rates of Chinese cabbages stored at various temperatures by Daly and Tomkins (1998) reported rates of approximately 2 mL $CO_2.kg^{-1}.hr^{-1}$ at 0°C and 3 mL $CO_2.kg^{-1}.hr^{-1}$ at 3°C after six weeks storage. In comparison, rates recorded in this study for cv. 'Yuki' after six weeks storage were approximately 0.7 and 1.0 mL $CO_2.kg^{-1}.hr^{-1}$ for 0°C and 2°C respectively. This difference might be due to variation between cultivars. In this investigation, respiration rates of between 8 mL $CO_2.kg^{-1}.hr^{-1}$ (one-week storage) and 23 mL $CO_2.kg^{-1}.hr^{-1}$ (three-week storage) were found at 20°C, although the higher rate was most likely influenced by the pathological deterioration of the cabbages.

The results show that cultivar 'Yuki' produces very little ethylene during storage. At 20°C rates of ethylene production ranged from 160 to 690 nL $C_2H_4.kg^{-1}.hr^{-1}$, which is classified as low for vegetables by Kader (1992b), and even the higher value is probably be exaggerated due to pathogen infection. Ethylene production rates at 0°C and 2°C were considerably lower than those for 20°C and the increase detected at nine weeks is most likely due also to the action of various fungal and bacterial pathogens (Kader, 1992b). Even at low levels, ethylene is known to promote senescence (Wills *et al.*, 1999), and increased levels of production would quicken deterioration and shorten the postharvest life.

The Chinese cabbages lost weight during storage at all three temperatures although the amount lost at the low temperatures was small compared to that lost at 20°C. After nine weeks storage at 0°C and 2°C cabbages had lost approximately 1.5%, but after three weeks at 20° they had lost only 5.6% of their original weight. Water loss is a major factor in weight loss, and storing the individual cabbages in perforated plastic bags inside waxed cartons may have contributed to the low results by reducing moisture loss. Daly and Tomkins (1998) found the use of plastic carton liners reduced weight loss of Chinese cabbages stored at various temperatures, on average, by 90%.

Trimming losses increased initially during storage and then stabilised. Insect damage and the presence of tipburn on outer leaves at harvest resulted in the

high initial values. To attain marketable quality later during storage, it was necessary to increase trimming because of wilting and yellowing of outer leaves and pathogen infection at wound sites. At 20°C, it was not possible to produce marketable cabbages by trimming after three weeks. The development of rots and the wilting and yellowing of outer leaves, were delayed at the lower storage temperatures.

The quality of the stored cabbages deteriorated over the storage periods at all temperatures. Initial quality scores were influenced by preharvest factors such as the incidence of tipburn and pest damage. The decline in quality of cabbages stored at 20°C was due mainly to pathogen infection and senescence-related factors such as yellowing and wilting. The development of PPN during storage adversely affected the quality of cabbages stored at 0°C (Figure 6.3). At 2°C cabbages were less severely affected by PPN and the decrease in quality at this storage temperature was influenced more by wilting and yellowing.

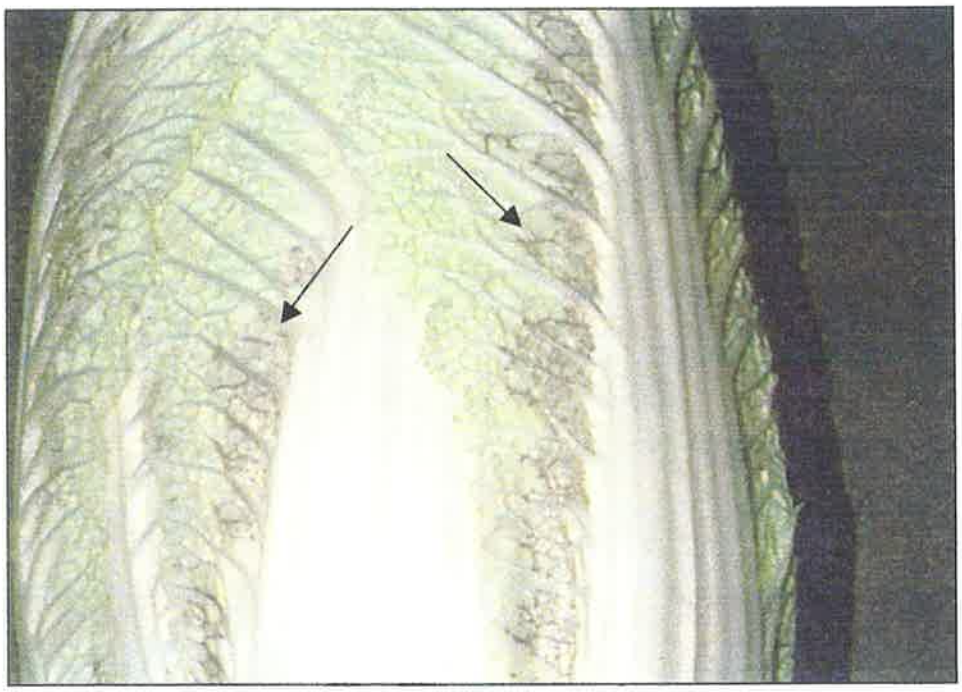

Figure 6.3. Trimmed Chinese cabbage cv. 'Yuki' showing symptoms (indicated) of Patchy Papery Necrosis on leaves after storage at 0°C for nine weeks.

Daly and Tomkins (1998) reported severe wilting for cv. 'Yuki' stored for 40 days in normal air at 0°C and 3°C, compared to low wilting for heads stored in high humidity at the same temperatures. In a study by Gajewski and Skapski (1994) good quality scores were reported for cultivars 'Yoko' and 'Hanko' after storage at 0°C to 2°C for 12 weeks, but only after the heads had been trimmed. In the same experiment, approximately 35% of heads were

considered unmarketable after the storage period and undefined natural losses of up to 16.8% were recorded.

The occurrence and severity pattern of PPN at different temperatures suggests that this disorder is a form of chilling injury. No PPN was found in cabbages immediately after harvest, but it had developed after three weeks in low temperature storage. Cabbages stored at 20°C were not affected at all, whilst cabbages stored at 0°C were more severely affected than those stored at 2°C. The symptoms observed here are not the same as those reported elsewhere for chilling injury of Chinese cabbage, most commonly described as brown midribs (Apeland, 1984a; Daly and Tomkins, 1998). They do, however, fit the general visual symptoms of chilling injury in horticultural crops, that is, internal discolouration and breakdown of tissues (Morris, 1982). Cell membranes and metabolic functions are affected by chilling and the resultant changes eventually lead to cell death (Bramlage and Meir, 1990). Apeland (1984a) observed chilling injury in Chinese cabbage stored for more than 45 days at temperatures of 0°C and 2.5°C, and reported that the critical temperature varied between cultivars. In a study by Daly and Tomkins (1998) three cultivars out of seven, 'Hector', 'Kasumi II' and 'Yuki', developed PPN after storage for seven weeks at 0°C. In the same study 'Hector', 'Kasumi II' and another cultivar, 'WR Green 60', also developed the brown midrib form of chilling injury.

6.5 Summary

The results indicate that Chinese cabbage cv. 'Yuki' can be stored for a maximum of six weeks at 2°C. 'Yuki' exhibited modest rates of respiration, ethylene production and weight loss at 0°C and 2°C. Trimming losses were high but were caused mainly by the less than perfect condition of the cabbages at harvest. This also influenced the quality scores, as did the development of PPN. Considering the differences in occurrence and severity of this disorder between 0°C and 2°C it is clearly a form of chilling injury. Apart from PPN, little or no differences were found between 0°C and 2°C indicating that this cultivar might store just as well at temperatures high enough to exclude chilling injury, such as 3° or 4°C. A limiting factor to postharvest storage appears to be the development of rots, which in this study were exacerbated by the presence of wound sites caused by field pests and disorders. The differences in results between 20°C and the two low temperatures reinforce the importance of using appropriate low storage temperatures to delay senescence and the onset of rots, and to lengthen storage times for Chinese cabbage.

Chapter 7

7 THE EFFECT OF WOUNDING AND 1-MCP ON THE POSTHARVEST LIFE OF CHINESE CABBAGE

7.1 Introduction

Physical damage of harvested produce is a major cause of postharvest losses. Injuries sustained during and after harvest can increase respiration, ethylene production and water loss, provide sites for pathogen infection, and cause unsightly blemishes and discolouration (Kays, 1991; Kader, 1992b; Thompson, 1996). Most injuries occur during postharvest handling, that is, during sorting, packing, transportation, storage and preparation for market, and commonly include cuts, punctures, bruising, splits or cracks, abrasions, and deformation.

Handling practices that lead to injuries in Chinese cabbages are dropping or throwing of heads into piles or bins, overloading of containers, pallets or trucks, and trimming off damaged or senescing leaves. In an assessment of postharvest handling systems in Eastern-central China, Wang and Bagshaw (2001) noted that most damage to Chinese cabbages occurred during weighing and loading at local collection centres. In Australia, injuries are

more likely to result from rough handling and overloading of cartons during transport to markets.

Ethylene is a gaseous plant hormone that is involved in many processes, including growth regulation, fruit ripening, leaf abscission, chlorophyll degradation and senescence (Abeles *et al.*, 1992). It is produced by all vegetative matter, even after harvest, and may be effective at levels as low as 5.0 $nL.L^{-1}$ in promoting senescence (Wills *et al.*, 1999) thereby reducing postharvest storage life and quality. The gaseous compound 1-methylcyclopropene (1-MCP) has been shown to inhibit the effects of ethylene in several ornamental species (Serek *et al.*, 1995; Sisler *et al.*, 1996a; Cameron and Reid, 2001) and has also been tested on various fruits and vegetables.

Studies of the effects of 1-MCP on the shelf life of *Brassica* species vegetables have produced both positive (Ku and Wills, 1999b) and mixed results (Able *et al.*, 2002). Results presented in Chapter 6 showed that Chinese cabbages cv. 'Yuki' produce low levels of ethylene, suggesting that ethylene might not be a major influence on the initiation and progression of senescence in this cultivar.

This chapter investigated the effect of three different wounding treatments, and various concentrations of 1-MCP on the postharvest life of Chinese cabbage cv. 'Yuki'.

7.2 Materials and methods

7.2.1 Wounding experiment

Chinese cabbages cv. 'Yuki' were grown at a market garden in Virginia, South Australia using commercial growing practices. The experimental area consisted of a raised bed containing two rows of approximately 360 plants each. Mature Chinese cabbages were harvested over three days, on June 19, 23, and 26, 2000, with cabbages harvested on each day representing one replicate. Based on results presented in Chapter 4, no specific time of the day was selected for harvesting.

The harvested cabbages were packed into waxed cardboard cartons in the field and were transported to the Waite Campus of The University of Adelaide within three hours of harvest. Upon arrival, the cabbages were placed in a coolroom set at 2°C and allowed to cool for 24 hours before being placed into individual perforated polyethylene bags to slow down moisture loss. Cabbages from the different harvest dates (replicates) were stored in separate cartons. On the day of harvest, five cabbages from each replicate were sampled for weight, trimming loss, the presence and severity of disorders, and overall quality.

7.2.1.1 Wounding treatments

Wounding treatments were applied to simulate common mishaps and handling practices seen in Australia and during export, that is, dropping, trimming, and compression. Fifteen cabbages from each of the three replicates were randomly allocated to the wounding treatments. A control treatment of no wounding was also included. To apply the dropping treatment, cabbages were dropped twice, on their side, from a height of 50 cm onto a concrete floor. The trimming treatment was applied by cutting off two to three of the outermost leaves from the cabbage head initially and again at three, six and nine weeks storage. This was to simulate the removal of damaged or senescing leaves from harvested cabbages at each stage of transit from grower to wholesaler to retailer. During transport and storage, Chinese cabbages in the lower cartons of loads are often compressed under the weight of those above. To apply the compression treatment, cabbage heads contained in polyethylene bags were laid on their sides on a concrete floor of a 2°C coolroom and were compressed under a weight of 3 kg per cabbage. The weight was applied using two planks of wood with small buckets of water spaced evenly along their length, for approximately 42 hours. The dropping and trimming treatments each took approximately one minute to apply whereas the compression treatment took approximately 42 hours to apply. All of the wounding treatments were applied 48 hours after harvest, and, after treatment, cabbages were stored in individual perforated polyethylene bags, in cartons, in a 2°C coolroom for up to nine weeks.

7.2.1.2 Postharvest evaluation

Measurements of weight, respiration rate and ethylene production were taken from five cabbages per replicate per wounding treatment after treatments were applied. Due to differences in the time taken to apply the different treatments, gas samples from compressed cabbages were taken around 66 hours after the initiation of their wounding treatment compared to only 24 hours for cabbages that had been either dropped or trimmed. The same five cabbages were used to measure weight loss, respiration rate, and ethylene production at intervals of three weeks up to a maximum of nine weeks.

At the same intervals, a further five cabbages from each replicate/treatment combination were destructively sampled to determine trimming loss, disorders, and quality. All postharvest evaluations were determined as described in General Materials and Methods, sections 3.2.1 to 3.2.3, 3.2.6 and 3.2.7.

7.2.1.3 Data analysis

All numerical data from the wounding experiment, apart from quality scores, were analysed for variance (ANOVA) as a two-way factorial (wounding treatment x storage period) using Genstat 5, 4th Edition for Windows (Lawes Agricultural Trust, IACR, Rothamsted). Quality scores were compared using

means and standard errors. The experiment was set up in a Randomised Complete Block design, with the harvest dates (replicates) as blocks, and cabbages harvested on each date randomly assigned to wounding treatments and storage periods. Differences between treatments and between storage periods were determined using the Least Significant Difference (LSD) at the 5% level.

7.2.2 1-MCP experiment

Chinese cabbages cv. 'Yuki' were grown at a market garden in Virginia, South Australia using commercial growing practices. The experimental area consisted of a raised bed containing two rows of approximately 360 plants each. Mature Chinese cabbages were harvested over two days, on June 10 and 18, 2001, with cabbages harvested on each day representing one replicate. Based on results presented in Chapter 4, no specific time of the day was selected for harvesting.

The harvested cabbages were packed into waxed cardboard cartons in the field and were transported to the Waite Campus of The University of Adelaide within three hours of harvest. Upon arrival, the cabbages were randomly allocated to one of four treatment groups and kept in the cartons at room temperature, approximately 22°C, awaiting treatment application. On the day of harvest, six cabbages from each replicate were sampled for weight, trimming loss, the presence and severity of disorders, and overall quality.

7.2.2.1 1-MCP treatments

Four different concentrations of 1-methylcyclopropene (1-MCP), 0 $\mu L.L^{-1}$ (control), 0.01 $\mu L.L^{-1}$, 0.1 $\mu L.L^{-1}$ or 1.0 $\mu L.L^{-1}$ were applied to four lots of six Chinese cabbages from each replicate. The cabbages were placed inside cardboard cartons on raised wire mesh to allow for air circulation around the cabbage heads. The cartons were enclosed inside close-fitting, 100 μm thick polyethylene bags sealed with plastic strip seal. A measured quantity of gaseous 1-MCP was injected into each sealed bag/carton to apply the treatment concentration to the cabbages inside.

Two stock gases that contained approximately 100 $\mu L.L^{-1}$ and 1500 $\mu L.L^{-1}$ gaseous 1-MCP were prepared by activating 5.3 mg and 70.7 mg of EthylBloc® (3.3% active ingredient, Rohm and Haas, Melbourne) powder with 132.6 μL and 1.768 mL of 2% KOH, respectively, in separate 520 mL stoppered glass flasks. The concentration of 1-MCP in the flasks was measured during gas evolution, at 15 and 30 minutes after activation for the 100 $\mu L.L^{-1}$ stock gas and at 30, 60 and 90 minutes after activation for the 1500 $\mu L.L^{-1}$ stock gas. The level of gaseous 1-MCP evolved was determined by injecting a 1 mL gas sample into a Varian 3400 flame ionisation gas chromatograph (Varian Australia, Mulgrave, Victoria) equipped with a Porapak Q stainless steel column (60 cm x 3.175 mm i.d.) of 80/100 mesh

and calibrated using a 103 $\mu L.L^{-1}$ iso-butylene standard (Jiang *et al.*, 1999). Temperature conditions were 70°C for the column, 135°C for the injector, and 150°C for the detector. Flow rates of air, hydrogen, and the carrier gas nitrogen were 300, 40 and 50 $mL.min^{-1}$, respectively.

After the concentrations of the stock gases were confirmed, gaseous 1-MCP was extracted from the flasks using syringes fitted with needles and injected into the sealed bags containing the Chinese cabbages. Bags containing cabbages receiving 0.01 $\mu L.L^{-1}$ were injected with 4.3 mL of the 100 $\mu L.L^{-1}$ stock gas, bags containing cabbages receiving 0.1 $\mu L.L^{-1}$ 1-MCP were injected with 2.9 mL of the 1500 $\mu L.L^{-1}$ stock gas and bags containing cabbages receiving 1.0 $\mu L.L^{-1}$ 1-MCP were injected with 28.7 mL of the 1500 $\mu L.L^{-1}$ stock gas. The volume inside the sealed bags fitted over the cartons containing the cabbages was approximately 43 L and the bags remained sealed for 12 hours after the injection of 1-MCP. Bags containing cabbages receiving 0 $\mu L.L^{-1}$ 1-MCP (control) were situated away from the other treatments to minimise the risk of contamination when the bags were opened.

After the 1-MCP treatments were applied, the Chinese cabbages were placed into individual perforated polyethylene bags to slow down moisture loss and then stored in cartons in a coolroom set at 3°C. Cabbages from different treatment/replicate combinations were stored in separate cartons.

7.2.2.2 Postharvest evaluation

Measurements of weight, respiration rate, and ethylene production were taken from six cabbages for each replicate of the 1-MCP treatments before and after treatments were applied, after cooling, one week post-treatment, and at intervals of three weeks post-treatment up to a maximum of nine weeks. These cabbages were then destructively sampled to determine trimming loss, disorders, and quality.

Six cabbages from each replicate/treatment combination were destructively sampled immediately after harvest to establish trimming loss, disorders, and quality prior to treatment. All postharvest evaluations were determined as described in General Materials and Methods, sections 3.2.1 to 3.2.3, 3.2.6 and 3.2.7.

7.2.2.3 Data analysis

All numerical data, apart from quality scores, were analysed for variance (ANOVA) as a two-way factorial (1-MCP treatment x storage period) using Genstat 5, 4th Edition for Windows (Lawes Agricultural Trust, IACR, Rothamsted). Quality scores were compared using means and standard errors. The experiment was set up in a Randomised Complete Block design, with the harvest dates (replicates) as blocks, and cabbages harvested on each

date randomly assigned to 1-MCP treatments. Differences between treatments and between storage periods were determined using the Least Significant Difference (LSD) at the 5% level.

7.3 Results

7.3.1 Wounding experiment

Most of the dropped treatment cabbages sustained damage to their outer leaves, such as cracking of midribs and tearing of leaf tissue (Figure 7.1). Trimming treatment cabbages had two or three clean-cut wounds close to the base where the trimmed leaves were removed. Compressed cabbages were generally flattened on two sides with some sustaining cracks in the outermost leaves, especially in the midribs.

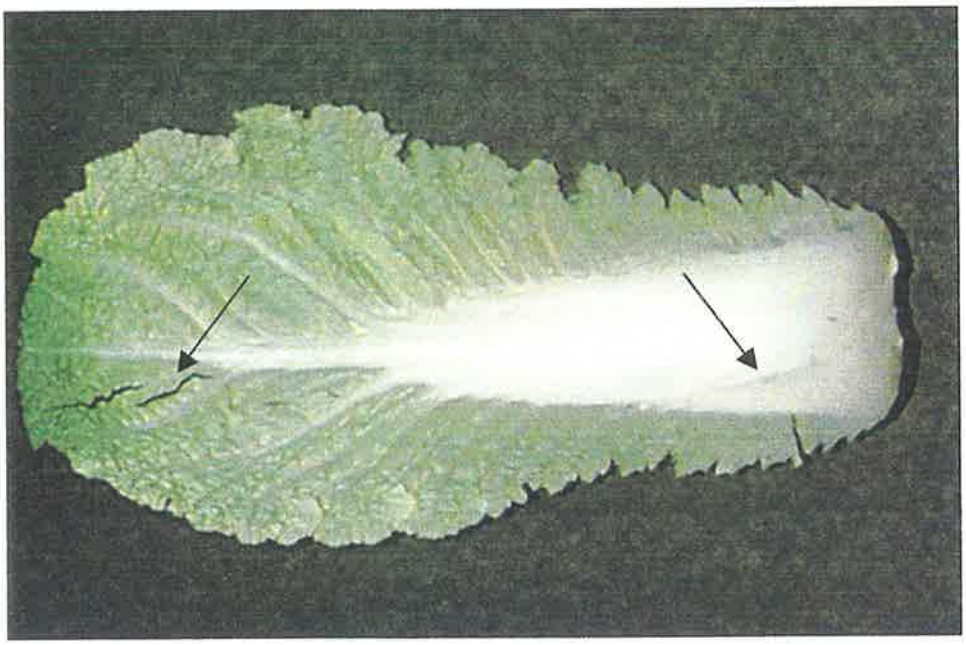

Figure 7.1. Chinese cabbage cv. 'Yuki' leaf showing tears in leaf tissue (left) and cracks in the midrib (right) resulting from application of the dropped wounding treatment.

The respiration rate of the cabbages was highest at zero weeks, that is three days after harvest after the wounding treatments had been applied (Figure 7.2). The lowest rates were recorded after the cabbages had been in low temperature storage for three to six weeks, but rates increased by nine weeks. Respiration rates for individual cabbages ranged from 0.7 mL to 3.9 mL $CO_2.kg^{-1}.hr^{-1}$. The dropping treatment took approximately one minute to apply whereas the compression treatment took approximately 42 hours to apply. After treatment, the wounded cabbages were placed directly into the plastic buckets for gas sampling 24 hours later, so that gas samples from

compressed cabbages were taken around 66 hours after the initiation of their wounding treatment compared to only 24 hours for the dropped cabbages.

Ethylene production was low after wounding and remained so during storage up until six weeks (Figure 7.3). After nine weeks storage, production had increased in all treatments except trimmed which, at 2.0 nL $C_2H_4.kg^{-1}.hr^{-1}$, was significantly lower than the dropped, compressed, and control treatments. Ethylene production for individual cabbages ranged from a minimum of 0.4 nL $C_2H_4.kg^{-1}.hr^{-1}$ to a maximum of 62.1 nL $C_2H_4.kg^{-1}.hr^{-1}$.

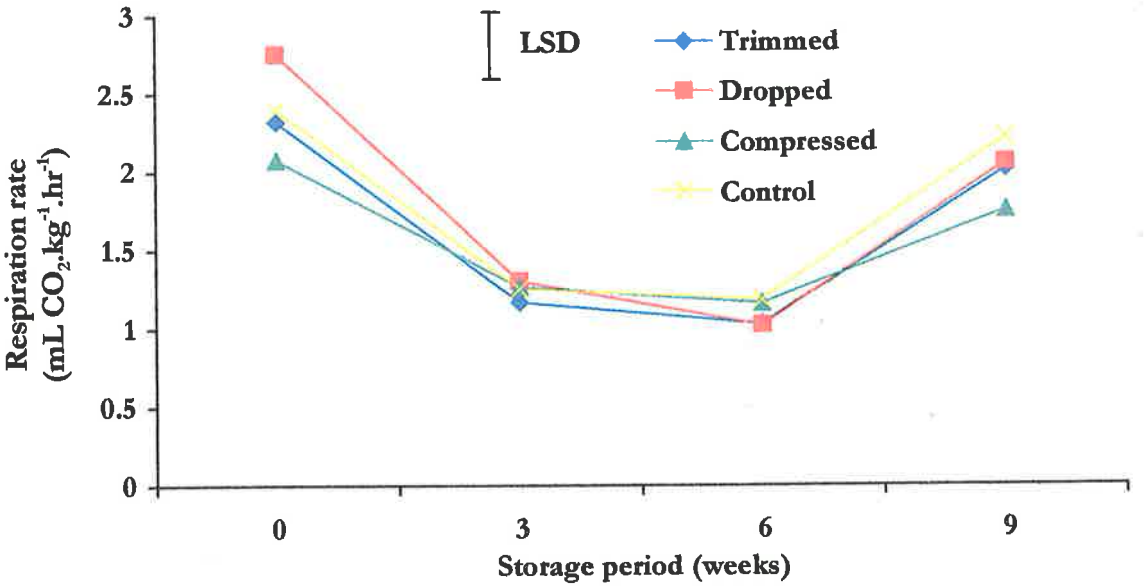

Figure 7.2. Respiration rates of wounded Chinese cabbages cv. 'Yuki' during storage at 2°C. Values are means of 15 cabbages (three replicates of five heads each). The bar represents the least significant difference between treatments over the storage period (P=0.05).

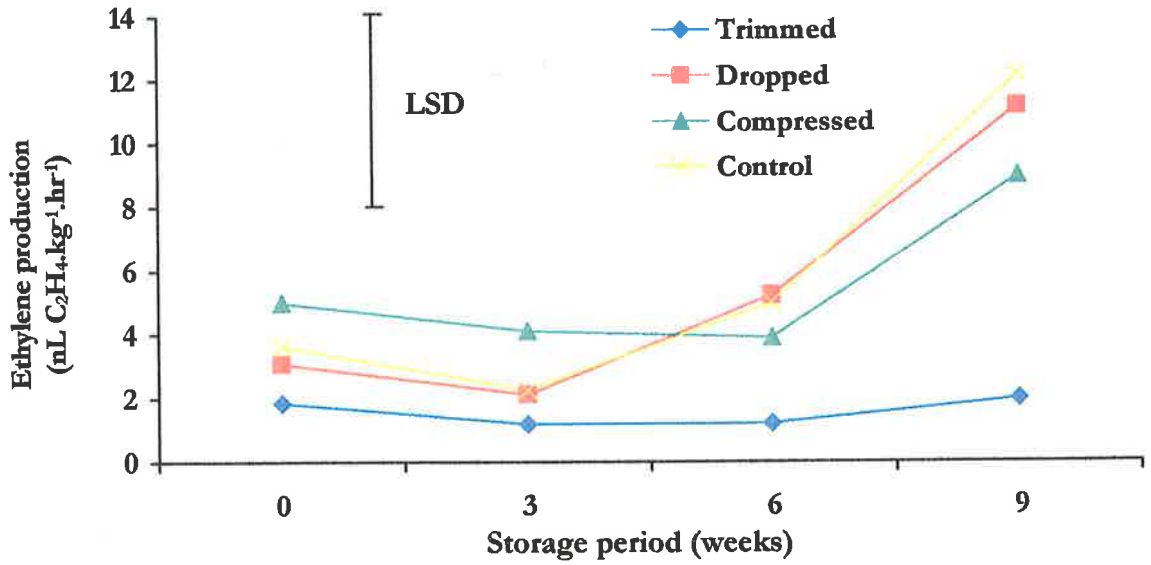

Figure 7.3. Ethylene production of wounded Chinese cabbages cv. 'Yuki' during storage at 2°C. Values are means of 15 cabbages (three replicates of five heads each). The bar represents the least significant difference between treatments over the storage period (P=0.05).

Weight loss and trimming loss of wounded Chinese cabbages increased significantly during storage (Table 7.1), but no differences were found between the dropped, compressed, and control treatments for either weight loss or trimming loss. The lowest weight loss for an individual cabbage during storage was 0.4% and the highest was 4.8%. Trimming loss for individual cabbages ranged from 12.7% up to 54.4%. Similar weight loss and trimming loss data were not collected for the trimmed treatment due to the way this treatment was applied. All four wound treatments were compared for total losses (weight loss plus trimming loss) after nine weeks storage (Table 7.2), with the trimmed treatment having the highest percentage loss and being significantly higher than the dropped and compressed treatments. Total losses for individual cabbages ranged from a minimum of 27.9% up to a maximum of 52.7%, with both these figures recorded for trimmed treatment cabbages.

Table 7.1. Weight loss and trimming loss of wounded Chinese cabbages cv. 'Yuki' during storage at 2°C. Values are means of 15 cabbages (three replicates of five heads each) and different letters within columns denote the least significant difference between storage periods (P=0.05).

	Weight loss (%)			Trimming loss (%)		
	Control	Dropped	Compressed	Control	Dropped	Compressed
0 weeks	0.0a	0.0a	0.0a	24.2a	24.2a	24.2a
3 weeks	0.8b	0.9b	0.9b	32.3b	31.5b	29.5b
6 weeks	1.4c	1.6c	1.6c	37.5c	34.5b	34.3c
9 weeks	2.1d	2.3d	2.4d	42.7d	40.5c	38.6d

Table 7.2. The total losses (weight plus trimming) of wounded Chinese cabbages cv. 'Yuki' to achieve a visually marketable head after storage for nine weeks at 2°C. Values are means of 15 cabbages (three replicates of five heads each) and different letters denote the least significant difference between treatments (P=0.05).

Total losses (%)			
Control	Trimmed	Dropped	Compressed
43.9ab	46.6a	41.9b	40.1b

Quality scores for the wounded Chinese cabbages generally increased over the storage period, that is, the quality of the cabbages decreased (Table 7.3). The average score for all cabbages at zero weeks was 1.9 and at nine weeks was 3.3. Cabbages from the trimmed and control treatments had a similar score to those for cabbages from the compressed treatment (3.3) and the dropped treatment (3.7). Wilting, yellowing, and small areas of pathogen infection at preharvest and postharvest wound sites, were the major causes of the decrease in quality in all treatments.

Table 7.3. The quality scores of wounded Chinese cabbages cv. 'Yuki' during storage at 2°C. A score of 1 indicates good quality and a score of 5 indicates poor quality. Scores are means of 15 cabbages (three replicates of five heads each) plus or minus the standard error.

	Quality score			
	Control	Trimmed	Dropped	Compressed
0 weeks	1.9 ± 0.3	1.9 ± 0.3	1.9 ± 0.3	1.9 ± 0.3
3 weeks	1.9 ± 0.3	1.7 ± 0.2	1.7 ± 0.2	1.9 ± 0.2
6 weeks	2.3 ± 0.2	1.9 ± 0.3	2.3 ± 0.3	1.9 ± 0.3
9 weeks	3.1 ± 0.3	3.1 ± 0.2	3.7 ± 0.2	3.3 ± 0.2

7.3.2 *1-MCP Experiment*

The respiration rates of cabbages of the 0.1 $\mu L.L^{-1}$ and 1.0 $\mu L.L^{-1}$ 1-MCP treatments were significantly higher than those of the 0.01 $\mu L.L^{-1}$ 1-MCP and control treatments after fumigation (Figure 7.4). After cooling, respiration rates for all treatments fell to similar levels and remained constant for the whole nine weeks of storage. Respiration rates for the 0.01 $\mu L.L^{-1}$ 1-MCP and control treatments after fumigation with 1-MCP were not significantly different to those measured before the treatments were applied, whilst rates for the 0.01 $\mu L.L^{-1}$ and 1.0 $\mu L.L^{-1}$ 1-MCP treated cabbages increased significantly after treatment. Chinese cabbages assigned to the 0.01 $\mu L.L^{-1}$ 1-MCP treatment had a significantly higher average respiration rate prior to fumigation than the cabbages assigned to the other treatments, but as there was no significant difference between the before- and after-treatment respiration rates for those cabbages, the former data were retained in the analysis. The respiration rates for individual cabbages ranged from 0.15 mL to 11.5 mL $CO_2.kg^{-1}.hr^{-1}$.

Ethylene production for Chinese cabbages before and after treatment with 1-MCP, after cooling and during storage are shown in Figure 7.5. Production for cabbages fumigated with 1.0 $\mu L.L^{-1}$ 1-MCP after treatment was significantly higher than for the other treatments. Cabbages fumigated with 0.1 $\mu L.L^{-1}$ 1-MCP produced significantly higher amounts of ethylene

compared to both the control cabbages and those fumigated with 0.01 $\mu L.L^{-1}$ 1-MCP. Ethylene production increased significantly for both the 0.1 $\mu L.L^{-1}$ and 1.0 $\mu L.L^{-1}$ 1-MCP treatments after fumigation and decreased significantly for all treatments after cooling. Production was relatively stable for the nine-week storage period with no differences between treatments. The lowest ethylene production recorded for an individual cabbage was 1.0 nL $C_2H_4.kg^{-1}.hr^{-1}$ and the highest was 238 nL $C_2H_4.kg^{-1}.hr^{-1}$.

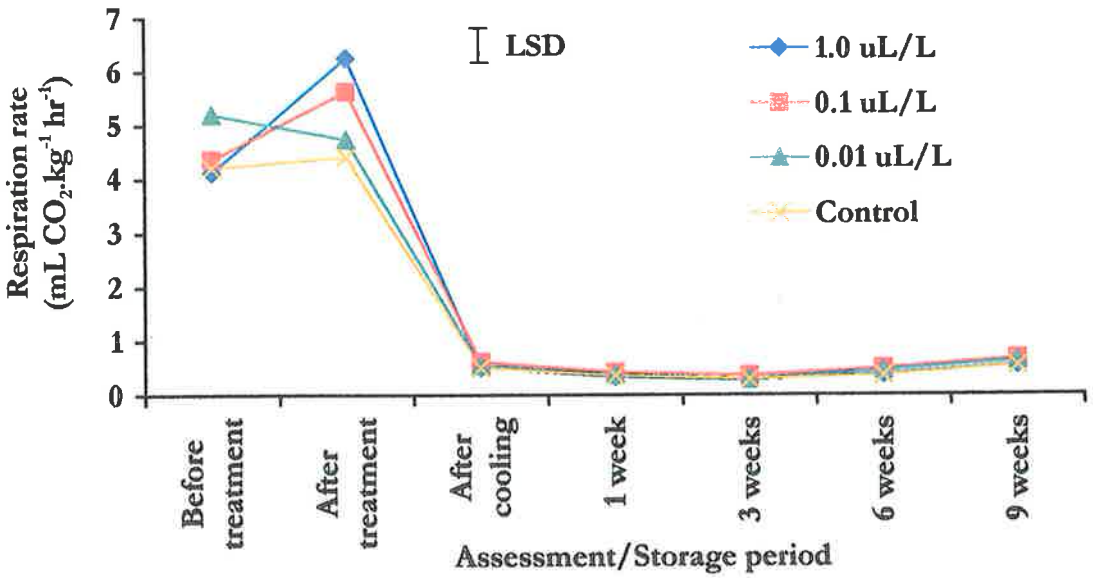

Figure 7.4. Respiration rates of Chinese cabbages cv. 'Yuki' fumigated with different concentrations of 1-MCP and stored, after treatment, at 3°C for nine weeks. Values are means of 12 cabbages (two replicates of six heads each). The bar represents the least significant difference between treatments over the assessment and storage period (P=0.05).

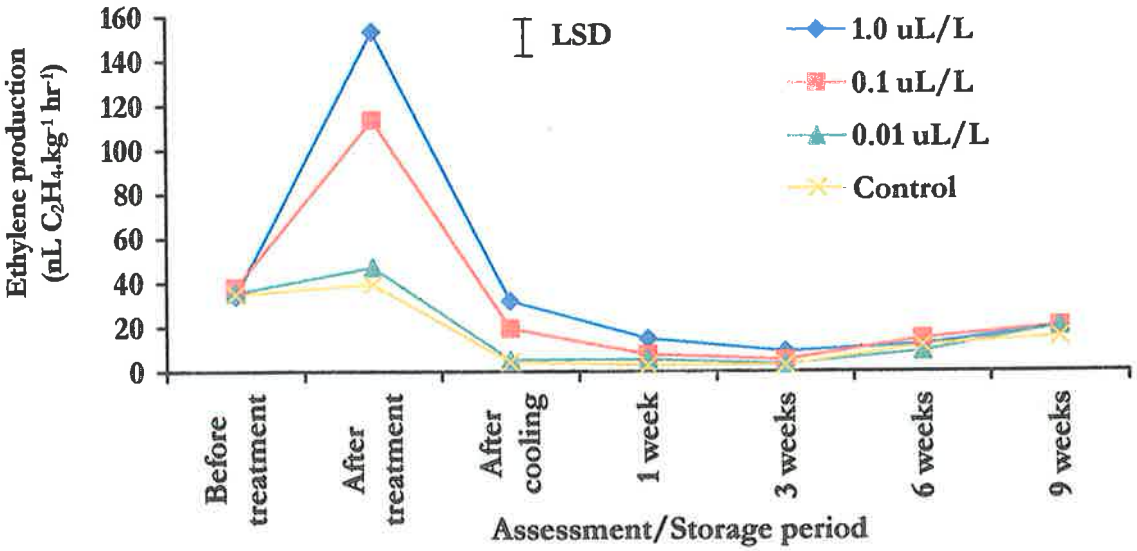

Figure 7.5. Ethylene production of Chinese cabbages cv. 'Yuki' fumigated with different concentrations of 1-MCP and stored, after treatment, at 3°C for nine weeks. Values are means of 12 cabbages (two replicates of six heads each). The bar represents the least significant difference between treatments over the assessment and storage period (P=0.05).

Weight loss of the Chinese cabbages increased steadily after fumigation with 1-MCP and during cooling and storage (Table 7.4). After cooling and up to three weeks of storage, weight loss of control cabbages was significantly higher than that of the other treatments, but later was similar to the 0.01 $\mu L.L^{-1}$ and 1.0 $\mu L.L^{-1}$ 1-MCP treatments. After six and nine weeks storage, the weight loss of cabbages treated with 0.1 $\mu L.L^{-1}$ 1-MCP was significantly lower than that of the control and the 0.01 $\mu L.L^{-1}$ and 1.0 $\mu L.L^{-1}$ 1-MCP treatments. Maximum weight loss of 3.9% was recorded for a control cabbage after nine weeks storage and minimum weight loss of 0.3% was recorded for a 0.01 $\mu L.L^{-1}$ 1-MCP cabbage after treatment.

Table 7.4. Weight loss of Chinese cabbages cv. 'Yuki' fumigated with different concentrations of 1-MCP and stored, after treatment, at 3°C for nine weeks. Values are means of 12 cabbages (two replicates of six heads each) and different letters across rows denote least significant difference between treatments (P=0.05).

	Weight loss (%) of 1-MCP treated heads			
	Control (0 $\mu L.L^{-1}$)	0.01 $\mu L.L^{-1}$	0.1 $\mu L.L^{-1}$	1.0 $\mu L.L^{-1}$
Before treatment	0.0a	0.0a	0.0a	0.0a
After treatment	0.9a	0.6a	0.6a	0.7a
After cooling	2.0b	1.6a	1.5a	1.7a
1 week	2.1b	1.9a	1.7a	1.9a
3 weeks	2.3b	2.1a	1.9a	2.2a
6 weeks	2.6b	2.4b	2.2a	2.6b
9 weeks	3.0b	2.8b	2.4a	2.9b

Trimming loss for Chinese cabbages before treatment with 1-MCP and after nine weeks storage are shown in Table 7.5. Trimming loss was not calculated at other assessment/storage periods. Trimming loss after treatment and storage was greater than trimming loss before treatment, but not significantly so. There were no significant differences between the 1-MCP treatments either before fumigation or after fumigation and storage for nine weeks. The lowest trimming loss for an individual cabbage was 11.3% recorded for a

before-treatment cabbage and the highest was 56.6% for a 1.0 $\mu L.L^{-1}$ 1-MCP treated cabbage after nine weeks storage.

Table 7.5. The trimming loss of Chinese cabbages cv. 'Yuki' fumigated with different concentrations of 1-MCP and stored, after treatment, at 3°C for nine weeks. Values are means of 12 cabbages (two replicates of six heads each) and letters across rows denote the least significant difference between treatments (P=0.05).

	Trimming loss (%) of 1-MCP treated heads			
	Control (0 $\mu L.L^{-1}$)	0.01 $\mu L.L^{-1}$	0.1 $\mu L.L^{-1}$	1.0 $\mu L.L^{-1}$
Before treatment	28.8a	28.8a	28.8a	28.8a
9 weeks	30.3a	35.7a	36.0a	38.2a

The quality scores for Chinese cabbages before treatment with 1-MCP and after nine weeks storage are shown in Table 7.6. No scores were allotted at other assessment/storage periods due to the destructive nature of the scoring process. The quality scores of the cabbages stored for nine weeks averaged 4.4 and were higher than those of the cabbages prior to treatment and storage, which averaged 2.0. The quality of cabbages prior to treatment was rated between good and average, and after treatment and storage the quality had deteriorated to poor. Treated and stored cabbages were observed at three and six weeks and their quality was estimated at between 2 and 3, and

between 3 and 4, respectively, but did not take into account any internal symptoms or disorders.

Table 7.6. Quality scores of Chinese cabbages cv. 'Yuki' fumigated with different concentrations of 1-MCP and stored at 3°C for nine weeks. A score of 1 indicates good quality and a score of 5 indicates poor quality. Values are means of 12 cabbages (two replicates of six heads each) plus or minus the standard error.

	Quality scores of 1-MCP treated heads			
	Control (0 $\mu L.L^{-1}$)	0.01 $\mu L.L^{-1}$	0.1 $\mu L.L^{-1}$	1.0 $\mu L.L^{-1}$
Before treatment	2.0 ± 0.2	2.0 ± 0.2	2.0 ± 0.2	2.0 ± 0.2
9 weeks	4.2 ± 0.2	4.4 ± 0.2	4.3 ± 0.2	4.7 ± 0.1

7.4 Discussion

7.4.1 Wounding experiment

The aim of this experiment was to study the effect that physical damage of Chinese cabbages has on their postharvest life. Cabbages with injuries inflicted to simulate three common handling procedures and mishaps – dropping, compression, and trimming – were compared to control cabbages with no damage.

No differences in the respiration rate of Chinese cabbage cv. 'Yuki' were found between the wounding treatments during storage at 2°C for nine weeks. This indicates that any effect of the wounding treatments on the respiration rate of the cabbages was not detected by the methods used. The respiration rate of the cabbages was very low despite the application of wounding treatments. In an investigation of the respiration rate of Chinese cabbages, Daly and Tomkins (1998) reported values of around 2 mL $CO_2.kg^{-1}.hr^{-1}$ at 0°C and close to 3 mL $CO_2.kg^{-1}.hr^{-1}$ at 3°C after six weeks storage, whereas in the present study, rates for wounded cv. 'Yuki' after six weeks storage at 2°C were between 1.0 and 1.25 mL $CO_2.kg^{-1}.hr^{-1}$. Differences in respiration rate between cultivars may account for this variation. The small increase in respiration recorded after nine weeks in storage is most likely due to the action of pathogens at both preharvest and postharvest wound sites, as well as the onset of senescence (Kays, 1991). The difference in the initial (zero weeks) values between the dropped (2.75 mL $CO_2.kg^{-1}.hr^{-1}$) and compressed (2.08 mL $CO_2.kg^{-1}.hr^{-1}$) treatments is most likely due to time differences in the application of the two wounding treatments.

Application of the wounding treatments had little effect on the rate of ethylene produced by the Chinese cabbages during storage at 2°C. Production rates for all treatments remained relatively stable until six weeks, and until nine weeks for the trimming treatment cabbages. Trimming two to

three of the outermost leaves from these cabbages kept ethylene production to levels of 2 $nL.kg^{-1}.hr^{-1}$, even when the other treatments recorded an increase after nine weeks storage to between 9 $nL.kg^{-1}.hr^{-1}$ and 12 $nL.kg^{-1}.hr^{-1}$. This suggests that the outermost leaves of the cabbages from the dropping, compression, and control treatments were responsible for the increased ethylene production. This increase is most likely due to the senescence of these outer leaves (Mayak and Halevy, 1972; Aharoni and Lieberman, 1979b) and also to pathogen action at preharvest and harvest wound sites (Pratt and Goeschl, 1969; Abeles *et al.*, 1992; Lund *et al.*, 1998). Ethylene production by pathogens at postharvest wound sites on cabbages that had been dropped or compressed was obviously not sufficient to cause a difference in results between these two wound treatments and the control treatment after nine weeks.

Wounding of plant tissue is usually followed by an increase in ethylene production (Yu and Yang, 1980; Yang and Hoffman, 1984; Kader, 1992b), although responses are variable. Bruised tomatoes showed increased ethylene production within an hour of wounding, but results differed between cultivars (MacLeod *et al.*, 1976). Increases in ethylene production were recorded two to three hours after wounding of leaves and petioles from cotton plants, with the leaf tissue having the larger increase (McAfee and Morgan, 1971). Rates for both tissue types decreased after six to seven hours. Ke and Saltveit Jr. (1989) found that an increase in ethylene production accompanied wounding

in iceberg lettuce and the effect lasted about six hours. Any increase in ethylene production caused by wounding of the Chinese cabbages in this study was not detected due to the method used for sampling, where headspace gases were allowed to accumulate over a 24-hour period and any transitory increases would be undistinguishable. Attempts to measure ethylene production between one and three hours after wounding were unsuccessful (nil C_2H_4 detected) suggesting that any wound-induced increases in ethylene from the cooled cabbages were gradual.

Ethylene is known to promote senescence and senescence-related processes (Kader, 1985; Abeles *et al.*, 1992) reducing the storage life of harvested produce. Yamauchi and Watada (1991) found that exogenous ethylene accelerated chlorophyll degradation in spinach leaves, and Ke and Saltveit Jr. (1988) observed increased russett spotting and yellowing of lettuce leaves in response to 3 $\mu L.L^{-1}$ ethylene. Wills and Wong (1996) found that the storage life of three Asian leafy vegetables (bak choi, choi sum and gai lan) decreased as the ethylene concentration in the storage atmosphere increased, and Wills *et al.* (1999) reported a similar response with Chinese cabbage. The wounded Chinese cabbages cv. 'Yuki' in the current study had a similar storage life and quality to that of the control cabbages, supporting the idea that any wound-induced ethylene production was not sufficient to influence the rate of senescence or the length of storage life.

Damage inflicted to cabbages by either dropping or compression affected neither the weight loss nor the trimming loss of the Chinese cabbages compared to the control treatment. As found in previous experiments reported in Chapters 4, 5, and 6, weight loss and trimming loss were influenced by the length of storage rather than the treatments applied. Most of the injuries caused by dropping and compression were to the outer leaves of the heads, and these leaves were trimmed as part of the trimming loss evaluation regardless of their injuries, as they were the first to show wilting and yellowing.

The nature of the trimming wound treatment precluded it from comparison to the other treatments for weight loss and trimming loss. The removal of two or three outermost leaves prior to and at three-weekly intervals during storage confounded the weight loss and trimming loss data for this treatment, making any contrast to the other treatments meaningless. The trimming treatment was, however, compared for total losses at the end of storage, that is, cumulative weight loss plus trimming loss after nine weeks. As with the separate weight loss and trimming loss results there were no differences between the dropped, compressed, and control treatments. Total losses for the trimmed treatment were significantly higher than those for the dropped and compressed treatments, but were not different from the control treatment. There was also no difference in quality between trimmed and control treatment cabbages after nine week's storage. This indicates that the regular trimming of senescing leaves from the cabbage heads during storage

was no better than trimming the cabbages once at the end of the storage, and resulted in the highest total loss. It would appear to be uneconomical, with a lower marketable head weight and higher labour costs.

The wounding treatments appear to have had no effect on the quality scores of the Chinese cabbage. Whilst the cabbages were initially scored as acceptable (1.9) they remained within the marketable range (below 3) until six weeks storage, but became unmarketable by nine weeks. The marginally higher score of 3.7 for dropped treatment cabbages is due to higher incidence of brown discolouration and rotting of cracks in the outer leaves. The main causes of the decrease in quality for cabbages in all treatments were wilting, yellowing, and the development of rots at preharvest and postharvest wound sites. Gajewski and Skapski (1994) found little difference in quality, after 12 weeks storage at 0°C to 2°C, between Chinese cabbages that had been trimmed during storage and those that had not.

The wounding treatments applied to the Chinese cabbages in this experiment were designed to approximate handling practices and mishaps commonly occurring in the Australian industry. In general, postharvest handling of Chinese cabbage in Australia is of a good standard, with packaging, refrigerated transport and storage, and minimal handling employed to minimise losses. The wounding treatments were not considered harsh and in most cases the resultant injuries were only superficial and minor. This is in contrast to the more severe damage inflicted on Chinese cabbage in some

areas of China. In an assessment of postharvest handling in eastern-central China, Wang and Bagshaw (2001) found that the majority of postharvest losses were from mechanical damage. This mechanical damage resulted from general rough handling at collection centres and wholesale markets, overloading during transportation and a lack of protective packaging, and accounted for over two-thirds of the total losses.

7.4.2 1-MCP experiment

1-MCP, which has been shown to inhibit the effects of ethylene in a wide range of horticultural produce (Serek *et al.*, 1995; Sisler *et al.*, 1996b; Golding *et al.*, 1998; Porat *et al.*, 1999), was used to investigate the possibility that this substance would prolong the postharvest life of the cabbages.

A significantly higher respiration rate was recorded prior to fumigation for cabbages assigned to the 0.01 $\mu L.L^{-1}$ 1-MCP treatment than for cabbages assigned to the other treatments. There is no evidence that these particular cabbages were in any way different or had been treated differently from the other cabbages and so this variation in before-treatment respiration rates was attributed to measurement error.

The increases in respiration rate and ethylene production for cabbages treated with 0.1 $\mu L.L^{-1}$ and 1.0 $\mu L.L^{-1}$ 1-MCP indicate a possible stress response to the higher concentrations that is not seen for the 0.01 $\mu L.L^{-1}$ 1-MCP

concentration or the control (0 $\mu L.L^{-1}$ 1-MCP) treatments. The rise in respiration rate is similar to the response of non-climacteric fruits to exogenous ethylene (Kays, 1991) and may have resulted from the increased ethylene production (Abeles *et al.*, 1992). The reason for the rise in ethylene production is not clear, but similar responses to 1-MCP have been reported for pak choi leaves and broccoli florets (Able *et al.*, 1999a), bananas (Golding *et al.*, 1998), grapefruit (Mullins *et al.*, 2000), and coriander leaves (Jiang *et al.*, 2002). It has been suggested that the competitive binding of 1-MCP to the ethylene binding site may suppress an autoinhibitory or other feedback mechanism, allowing uncontrolled ethylene production (Golding *et al.*, 1998; Mullins *et al.*, 2000; Jiang *et al.*, 2002). A similar reaction in ethylene production was also recorded in response to CO_2 and Ag^+ in tobacco leaves (Aharoni and Lieberman, 1979a) and a similar hypothesis of disruption to a feedback control mechanism was put forward (Aharoni *et al.*, 1979). This increased ethylene production response, however, may be restricted to particular tissue types as either no increase or a reduction in ethylene production was recorded for carnations (Sisler *et al.*, 1996a), pears (de Wild *et al.*, 1999), and tomatoes (Wills and Ku, 2002). The stress response of the Chinese cabbage in the present study to the higher concentrations of 1-MCP was not permanent and, after cooling, the elevated rates of respiration and ethylene production returned to levels similar to those of the 0.01 $\mu L.L^{-1}$ 1-MCP and control treatment cabbages. This is most likely a temperature effect as elevated ethylene production of 1-MCP treated coriander leaves

stored at 20°C (Jiang *et al.*, 2002) and pak choi stored at 10°C (Able *et al.*, 1999a) took up to seven days to decline to pre-treatment levels.

Treatment with 1-MCP was accompanied by a slower weight loss of the cabbages after cooling, with all 1-MCP treatments recording lower percentage weight losses than the control until three week's storage. After storage for six weeks, however, weight loss for the 0.01 $\mu L.L^{-1}$ and 1.0 $\mu L.L^{-1}$ 1-MCP-treated cabbages had increased to the same level as the control cabbages, with only the 0.1 $\mu L.L^{-1}$ 1-MCP treated cabbages maintaining the initial lower levels. Although statistically significant, the differences between treatments are small. Porat *et al.* (1999) and Wills and Ku (2002) both reported no effect of 1-MCP on weight loss of oranges and tomatoes, respectively, and weight loss is not mentioned in other studies. There is some evidence that ethylene can cause stomatal closure in some plant species (Abeles *et al.*, 1992). Pallas and Kays (1982) reported a decrease in stomatal conductance and stomatal closure in peanut leaves after exposure to 1 $\mu L.L^{-1}$ ethylene for either two and a half or six hours. Increased internal ethylene concentrations of between 0.3 $\mu L.L^{-1}$ and 7.9 $\mu L.L^{-1}$ in leaves of peach, olive, coffee, pepper, fig and cherry, caused by treatment with 1500 $\mu L.L^{-1}$ ethephon, were linked to increased stomatal resistance (Vitagliano and Hoad, 1978). It is possible that the increased ethylene production in response to the 1-MCP treatments, although much lower than those reported, may have induced the closure of stomata on the Chinese cabbage leaves, reducing transpiration, and therefore weight loss,

immediately after fumigation and until the cabbages were cooled. This, however, does not adequately explain why cabbages treated with 0.1 $\mu L.L^{-1}$ 1-MCP had significantly lower weight loss for the entire nine-week storage period. Also, the only Brassica species tested for ethylene effects on stomata, kohlrabi and cabbage, showed no response (Aharoni, 1978).

Trimming loss prior to treatment and storage was already quite high, at around 29%, and this was due to extensive insect damage to the outer layers of the cabbages. The trimming loss after nine weeks in 3°C storage was not different from the before-treatment values for all treatments including the control; this means that most damage had occurred in the field rather than during storage. No beneficial effect by 1-MCP was observed on either yellowing or rot development at wound sites, which were the main reasons for the removal of leaves. Able *et al.* (1999a) observed no effect of 1-MCP on the rate of yellowing and the shelf life of pak choi leaves, suggesting that endogenous ethylene had no influence on yellowing or shelf life of pak choi. 1-MCP fumigation was only beneficial in the presence of exogenous ethylene. This was in contrast to the effects of 1-MCP observed on broccoli, which showed extended shelf life and reduced yellowing with and without exogenous ethylene applications (Able *et al.*, 1999a; Ku and Wills, 1999b; Fan and Mattheis, 2000). At low temperatures, the extension of shelf life of broccoli by 1-MCP was related to delays in the onset of rots (Able *et al.*, 1999a; Ku and Wills, 1999b); however 1-MCP increased the incidence of

fungal rots in oranges (Porat *et al.*, 1999) and enhanced the onset of rots in strawberries when applied in concentrations higher than 15 $nL.L^{-1}$ (Ku and Wills, 1999a).

The quality of the Chinese cabbages had deteriorated after nine weeks storage, but there were no differences between the treatments. The inhibition of ethylene action by 1-MCP did not affect the yellowing of the older outer leaves, suggesting that either endogenous ethylene is not involved in chlorophyll degradation in Chinese cabbage cv. 'Yuki' or that the 1-MCP is not permanently bound to the ethylene binding site. Similar results were reported by Able *et al.* (2002) with pak choi, albeit at higher storage temperatures and using 12 $\mu L.L^{-1}$ 1-MCP, leading to an equivalent speculation. Other contributing factors to the poor quality of the Chinese cabbages were small amounts of bacterial and fungal infection at wound sites and mild tipburn of inner leaves.

7.5 Summary

Chinese cabbage cv. 'Yuki' suffered very little adverse effect from the application of wounding treatments designed to simulate common postharvest handling and mishaps. No sustained physiological response to the wounds was observed during assessments throughout the storage period. Only minor visual symptoms resulted, such as cracks in midribs (dropped treatment) and misshapen heads (compressed treatment), and these had no

impact on quality or any of the other parameters measured. Regular trimming of senescing leaves during storage has no advantage over trimming once at the end of storage and would not be economical when time, labour, and market weight are considered. Whilst it appears that Chinese cabbages cv. 'Yuki' are well able to withstand some rough postharvest handling, there is an increased risk of pathogen infection at wound sites and this will limit storage time and diminish quality. Rough handling can lead to substantial losses, as high as 31% in some regions in China, as reported by Wang and Bagshaw (2001). Therefore, it is recommended that postharvest handling of Chinese cabbages should be aimed at minimising physical damage and maintaining quality.

Results from the 1-MCP experiment appear to confirm the notion that senescence of Chinese cabbages cv. 'Yuki' is independent of endogenous ethylene. The data presented here did not provide sufficient evidence for a link between 1-MCP and ethylene in Chinese cabbage, but it has been shown in other brassica vegetables (Able *et al.*, 1999a; Ku and Wills, 1999b) and is assumed to be true in this study. Treatment with 1-MCP did not delay the yellowing and senescence of the outer leaves of the cabbages compared to the control. Low levels of ethylene production reported previously in this chapter and in Chapter 6 were also recorded for this experiment. These results also indicate that the use of 1-MCP as a postharvest treatment for Chinese cabbage cv. 'Yuki' would have no benefit.

Chapter 8

8 MODIFIED ATMOSPHERE PACKAGING OF MINIMALLY PROCESSED CHINESE CABBAGE

8.1 Introduction

The benefits of modifying storage atmospheres have been known for a long time (Kays, 1991; Wills *et al.*, 1998). Atmospheres low in O_2 and high in CO_2 are used to reduce the respiration rate of stored produce and can also reduce the effects of ethylene, inhibit the growth of decay microorganisms, and reduce some physiological disorders (Kays, 1991; Kader, 1992a; Wills *et al.*, 1998). These atmospheres, however, can also have harmful effects, such as anaerobic fermentation due to too little O_2 (Weichmann, 1987; Kader, 1992a), and increased incidence of some disorders and injury due to high levels of CO_2 (Herner, 1987; Kays, 1991). High concentrations of CO_2 are reported to have increased rots in Chinese cabbage during storage (Wang, 1983; Daly and Tomkins, 1998) and caused off-odours during the storage of other Brassicas (Kays, 1991; Wong *et al.*, 1997). Recent investigations into the effects of high O_2 atmospheres, either alone or in combination with different levels CO_2, have returned encouraging results in inhibiting microbial spoilage (Amanatidou *et al.*, 1999; Wszelaki and Mitcham, 2000) and preventing anaerobic conditions (Rosenfeld *et al.*, 1999).

Modified atmosphere packaging is often used to maintain quality and prolong shelf life of minimally processed produce (Cantwell, 1992; Schlimme and Rooney, 1994). The modified atmospheres can be generated by the plant material or introduced into the package prior to sealing. Strict temperature control is required to maintain the desired internal atmosphere or to slow down its rate of change, but optimum temperatures are not always adhered to under commercial conditions, and this can limit the effectiveness of the altered atmospheres (Wiley, 1994).

Very little work has been carried out on the storage of minimally processed Chinese cabbage. Kim and Klieber (1997) investigated the effects of temperature and preservative dips on the quality characteristics of minimally processed Chinese cabbage. They found better quality and longer shelf life at 0°C compared to 5°C, and also that none of the treatment dips – calcium chloride, citric acid, and ascorbic acid - extended shelf life at 0°C. Other studies have looked at the effect of temperature and low O_2 modified atmospheres on other minimally processed Brassica species. Prasad *et al.* (1997) found the longest storage life (15 days) for minimally processed pak choy was at 1°C, whilst at 10°C, atmospheres of 5% CO_2 plus 0.5% O_2 extended the shelf life of Chinese mustard (Wong *et al.*, 1997) and 5% CO_2 plus 2% O_2 extended the shelf life of minimally processed pak choy and broccoli florets (Able *et al.*, 1999a).

For Chinese cabbage, storage atmospheres high in O_2 may be an alternative to low O_2/high CO_2 atmospheres, overcoming the detrimental effects sometimes observed with high CO_2 and removing the risk of anaerobic conditions. In this experiment, actively modified atmosphere packaging of minimally processed Chinese cabbage was used to compare high O_2 atmospheres to air, both with and without the addition of high CO_2.

8.2 Materials and methods

Chinese cabbages cv. 'Yuki' were grown at a market garden in Virginia, South Australia using commercial growing practices. The experimental area consisted of a raised bed containing two rows of approximately 100 plants each and from these 30 mature Chinese cabbages were harvested on August 15, 2001. Based on results presented in Chapter 4, no specific time of the day was selected for harvesting.

The harvested cabbages were packed into waxed cardboard cartons in the field and were transported to the Waite Campus of The University of Adelaide within three hours of harvest. Upon arrival, the cabbages were placed in a coolroom set at 3°C and allowed to cool overnight.

8.2.1 *Minimal processing*

Ten Chinese cabbages were selected from the 30 harvested heads for minimal processing, based on their visual quality and uniform size. Using a stainless steel knife sterilised with 70% ethanol, the heads were trimmed of any damaged and wilted outer leaves and were then cut longitudinally into quarters. One quarter from each cabbage was allocated to each of four different storage atmosphere treatments and the quarters were kept separate throughout preparation and processing. Core tissue was removed from each cabbage quarter and the remaining leaf tissue was cut to obtain leaf pieces no larger than 70 mm x 30 mm. Leaf pieces were washed in 0.1g.L^{-1} chlorinated water at 4°C and drained using a hand centrifuge (480rpm, Zyliss, Switzerland). The leaf pieces from each quarter were then placed into EVA-PVDC barrier bags (Cryovac Australia Ltd, Fawkner, Vic.) with each bag containing between 100 g and 250 g of sliced Chinese cabbage leaves (Figure 8.1). The unsealed bags of cabbage were kept at 7°C for approximately eight hours until the different storage atmosphere treatments were applied. Each bag was fitted with a rubber septum secured to the outer surface of the bag using silicon sealant and a crimp cap.

Figure 8.1. EVA-PVDC barrier bags containing between 100 g and 250 g of sliced Chinese cabbage cv. 'Yuki' leaves and fitted with rubber septa secured to the outer surface of the bag using silicon sealant and a crimp cap.

8.2.2 Atmosphere treatments

Four storage atmosphere treatments were chosen to test the effects of high levels of CO_2 and/or O_2 on the minimally processed Chinese cabbage. The treatments were 30% CO_2 and 70% O_2 (30:70), 0% CO_2 and 70% O_2 (0:70), 30% CO_2 and 21% O_2 (30:21), and air, which is described as 0% CO_2 and 21% O_2 (0:21) and was the control treatment. The balance of gas, where necessary, was made up with N_2. Carbon dioxide (99.9%), oxygen (99.5%),

and nitrogen (99.99%) (Linde Gas, Cavan, SA) were mixed to the required combination using a flow board.

The concentrations of the gases were confirmed by injecting 1 mL samples of the gas mixture into a Varian 3300 thermal conductivity gas chromatograph (Varian Australia, Mulgrave, Victoria) equipped with a silica column (35 cm x 3.1 mm i.d.) of 80/100 and calibrated using 0.5% CO_2 gas standard (BOC Gases, Torrensville, SA). Temperature conditions were 90°C for the injector and detector and 28°C for the column, and the flow rate of helium (carrier gas) was 5 $mL.min^{-1}$. The percent concentrations of gases in the mixtures were calculated by comparing the areas of their peaks to the area of a reference peak for each individual gas. The reference peaks were obtained by injecting three samples of the source gases and averaging the results. The control atmosphere, 0:21, was applied using compressed air.

The flow rates of the gas mixtures were measured using a 1-10-100 mL soap-film flowmeter (Hewlett Packard, Melbourne, Victoria) and were approximately 7.5 $mL.sec^{-1}$ for the 30:70 and 0:70 treatments, approximately 8.5 $mL.sec^{-1}$ for the 30:21 treatment, and more than 10 $mL.sec^{-1}$ for the 0:21 treatment (control). The 2.7 L barrier bags containing the minimally processed Chinese cabbage were initially flushed with compressed air and then with the gas mixture of the atmosphere treatment being applied for a minimum of seven minutes. After flushing, a vacuum was created in the bags

using suction. The bags were then filled with the appropriate gas mixtures, immediately heat sealed, and placed at 7°C. The gas mixtures, compressed air, and suction were applied to the bags by means of plastic tubing.

Twenty-four hours after application of the atmosphere treatments and every three days thereafter, the concentrations of CO_2, O_2, and N_2 in the atmospheres inside the bags were measured. A 1 mL sample of gas was withdrawn from the bags through the attached septum using a 1 mL syringe fitted with a needle and injected into a Varian 3300 thermal conductivity gas chromatograph (Varian Australia, Mulgrave, Victoria), set up and calibrated as stated previously. The concentrations of the gases were determined as previously described.

Approximate respiratory quotients (RQ) were calculated from measurements of the changing concentrations of CO_2 and O_2 in the internal atmospheres of the bags of minimally processed Chinese cabbage. Differences in concentrations between day 1 and day 7 and between day 7 and day 13 were used to calculate the estimated mL of CO_2 evolved and O_2 consumed during these times, and approximate RQ was determined as the ratio of mL CO_2 evolved to mL O_2 consumed. These data are considered approximate due to variations in the volume of the headspace within each bag and because only the initial weight of the minimally processed Chinese cabbage was used for calculations, which does not account for changes in weight during storage.

8.2.3 *Quality evaluation*

Visual quality assessments of the minimally processed Chinese cabbage were made daily for 14 days after the storage atmosphere treatments were applied. The cabbage pieces in each bag were given an overall quality rating based on ratings for individual characteristics as described in Table 8.1. The overall quality rating was determined as the majority rating of the individual characteristics.

Table 8.1. Ratings of characteristics used for visual quality assessment of minimally processed Chinese cabbage cv. 'Yuki' stored in modified atmospheres.

Characteristics	Rating				
	5	4	3	2	1
Browning of cut surface	None	Trace on <5 pieces	Very light on <10 pieces	Light on >10 pieces	Dark on >10 pieces
Leaf yellowing	Green	Light green	Yellowy green	Yellow	Whitening
Texture loss	None	Slightly limp	Limp	Soggy	Mushy
Black speck	None	Specks on <5 pieces	Specks on <10 pieces	Specks on <20 pieces	Specks on >20 pieces
Microbial spoilage	None	Trace on 1 piece	Trace on 2-5 pieces	Spoilage on 6-10 pieces	Spoilage on >10 pieces
Appearance	Very fresh, no deterioration	Fresh	Marketable	Non-marketable	Not edible

(Adapted from Kim & Klieber, 1997)

At the end of the 14-day storage period, three bags from each treatment were opened and the internal atmospheres were inhaled to check for the presence of off-odours.

8.2.4 *Data analysis*

The experiment was set up in a completely randomised design, with four treatments and 10 replicates of each treatment. Quarters from each of 10 cabbages harvested on the same date were randomly assigned to storage atmosphere treatments. Quality scores were compared using means and standard errors. The changes in concentrations of CO_2 and O_2 during storage were analysed for variance (ANOVA) as a two-way factorial (atmosphere treatment x storage period) using Genstat 5, 4th Edition for Windows (Lawes Agricultural Trust, IACR, Rothamsted). The significance or otherwise of the differences between treatments and between storage period were assessed using the Least Significant Difference (LSD) at the 5% level.

8.3 Results

Figure 8.2 shows the concentrations of CO_2 and O_2 in the atmospheres surrounding the minimally processed Chinese cabbage during storage. There was a general increase in the levels of CO_2 and a decrease in the levels of O_2 for all four treatments. For treatments 30:21 and 0:21, which started with

lower levels of O_2 than the other two treatments, most of the O_2 had been depleted to approximately 2% after 10 days of storage. Oxygen levels in the treatments that received 30:70 and 0:70 were similar and still high, around 34%, on day 13. The concentrations of CO_2 in treatments 30:70 and 30:21 were markedly different by day 13, at approximately 70% and 50% respectively, despite being similar initially. Carbon dioxide levels in the 0:70 and 0:21 treatments increased to 26% and 20%, respectively.

The amounts by which the concentrations of CO_2 and O_2 changed during 13 days in storage are presented in Figures 8.3 and 8.4 respectively. The rate of increase in CO_2 in the 30:70 treatment was significantly greater than for the other three treatments from day 4 onwards, and the increase in CO_2 in the 0:70 treatment was significantly greater than the 30:21 and 0:21 treatments by day 13. The rate of decrease in the level of O_2 slowed after day 7 for the 30:21 and 0:21 treatments and was significantly less than the decrease in O_2 in the other two treatments from day 10 onwards. The decrease in O_2 for the 30:70 treatment was significantly more than the 0:70 treatment on day 10, but was not so evident by day 13.

Approximate RQ values for all four treatments from day 1 to day 7 were close to one, with the averages for the 30:70 and 0:70 treatments around 1.3 and for the 30:21 and 0:21 treatments around 0.9. From day 7 to day 13, the RQ values for the 30:70 and 0:70 treatments were little changed, at

approximately 1.2 and 0.8 respectively. The approximate RQ value from day 7 to day 13 for the 30:21 treatment was around 18 and for the 0:21 treatment was around 10 and these values were much larger than for day 1 to day 7 for the same treatments.

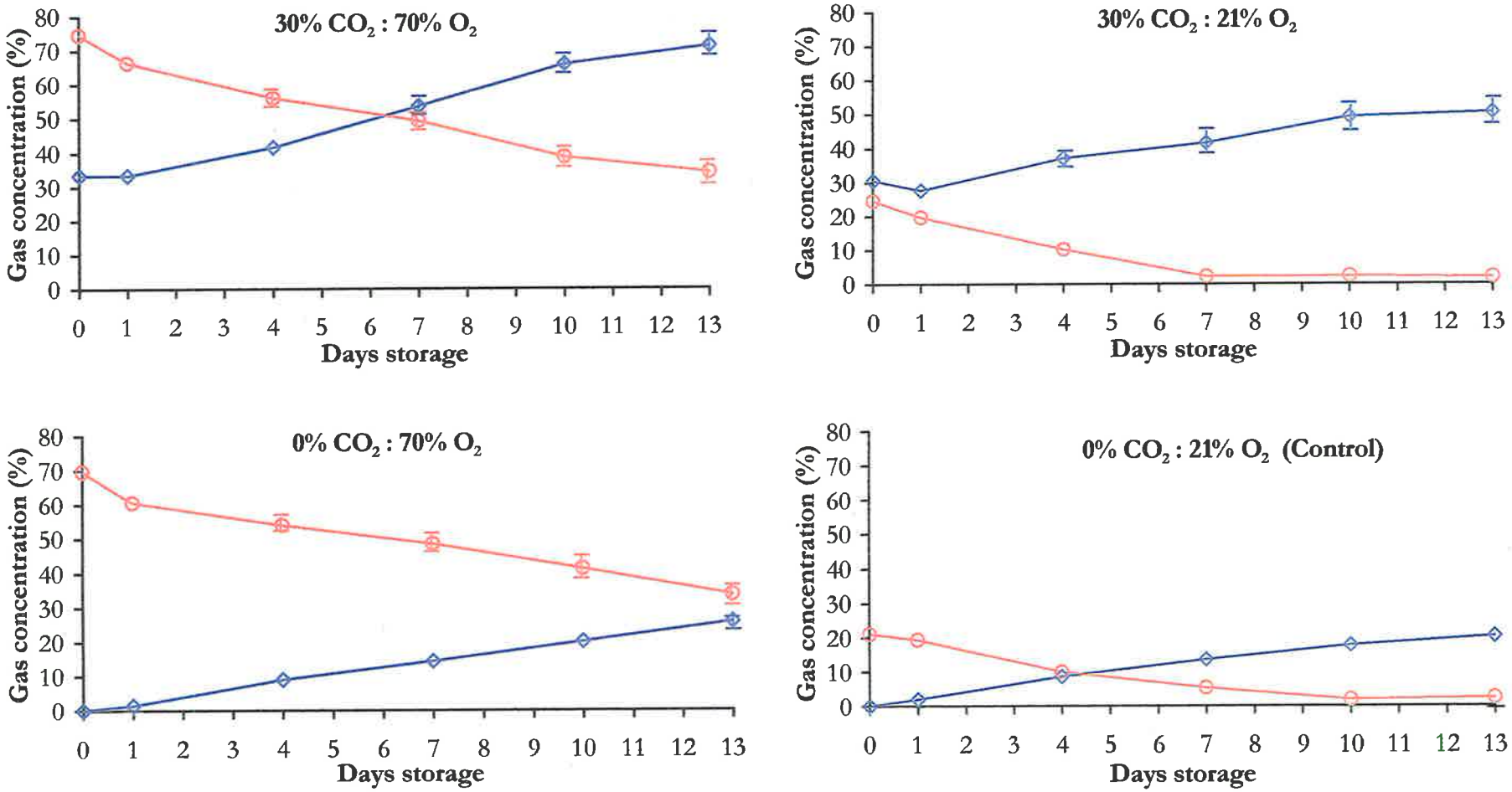

Figure 8.2. The concentration of CO_2 (◇) and O_2 (○) inside bags of minimally processed Chinese cabbage cv. 'Yuki' during storage at 7°C. Initial atmosphere treatments, as indicated, were applied on Day 0 of the storage period. The balance of the gas in each treatment was made up with N_2. Values are means of 10 bags. Bars represent the standard error and points with no bars have standard errors of one or less.

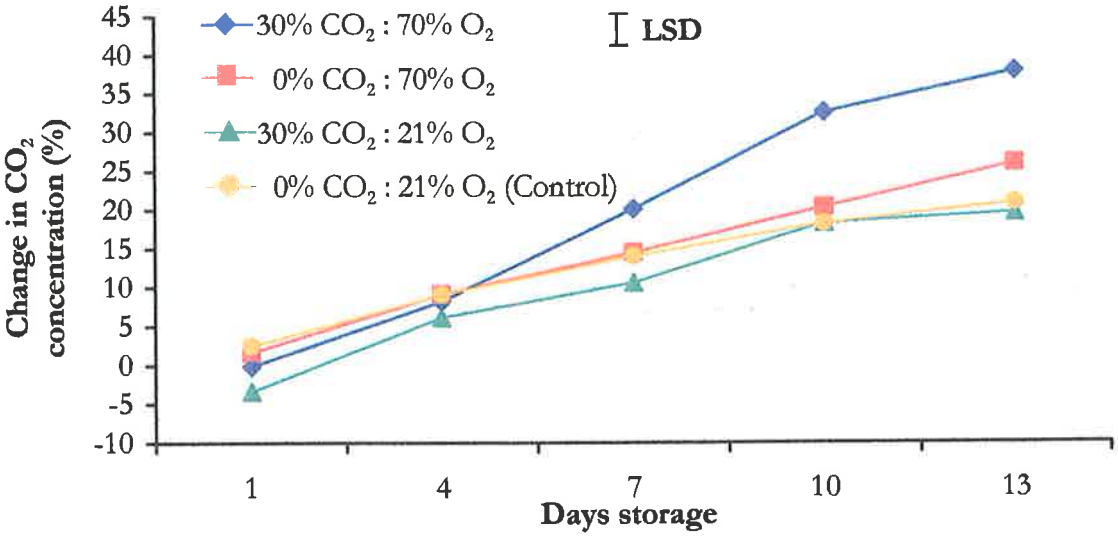

Figure 8.3. The change in the concentration of CO_2 inside bags of minimally processed Chinese cabbage cv. 'Yuki' with different initial atmospheres during storage at 7°C. Values are means of 10 bags. The bar represents the least significant difference between atmospheres over the storage period. (P=0.05).

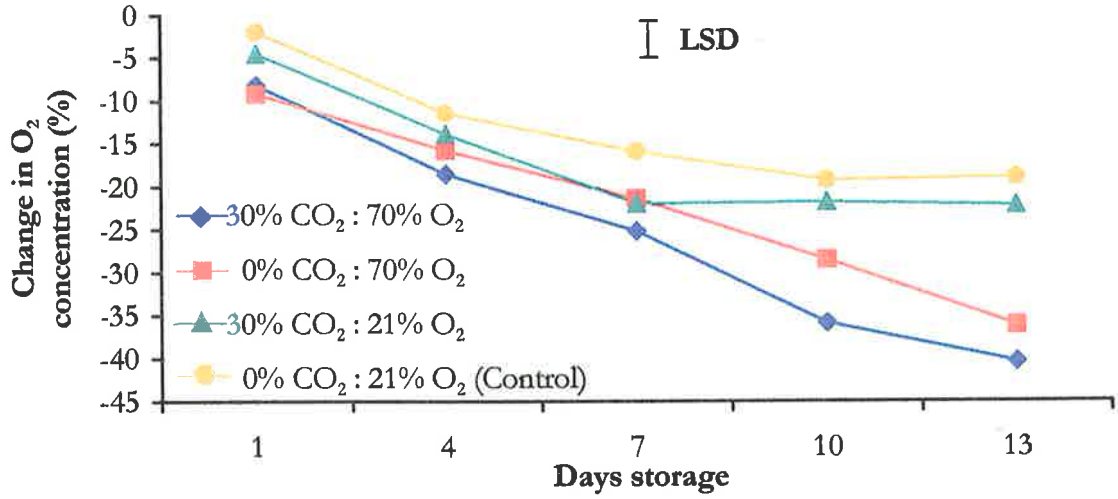

Figure 8.4. The change in the concentration of O_2 inside bags of minimally processed Chinese cabbage cv. 'Yuki' with different initial atmospheres during storage at 7°C. Values are means of 10 bags. The bar represents the least significant difference between atmospheres over the storage period (P=0.05).

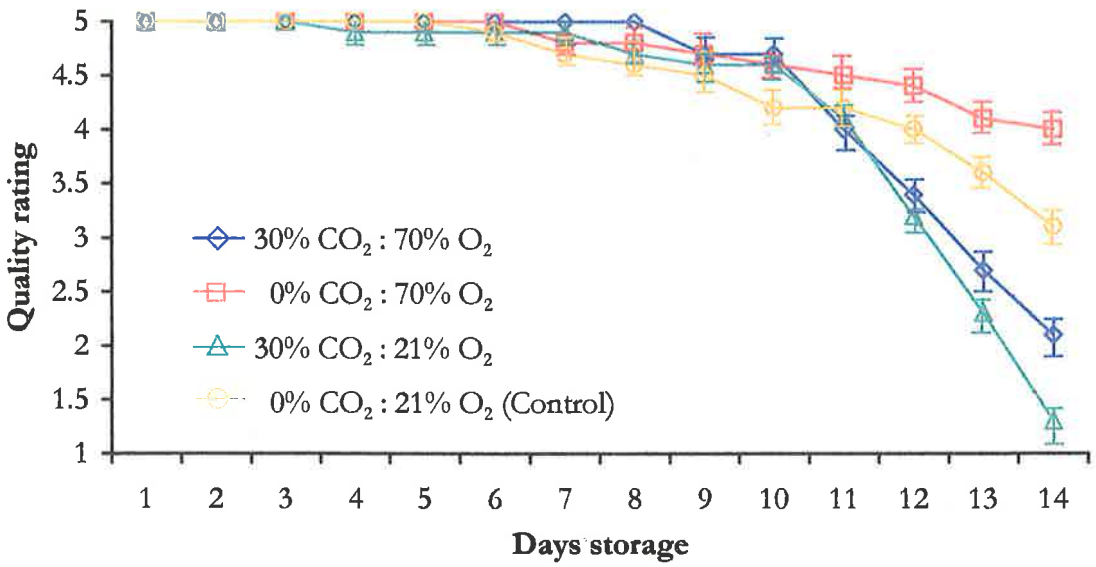

Figure 8.5. The average quality ratings of minimally processed Chinese cabbage cv. 'Yuki' stored at 7°C in bags with different initial atmosphere treatments as indicated. The balance of the gas in each treatment was made up with N_2. A rating of 5 indicates good quality and a rating of 1 indicates poor quality. Values are means of 10 bags and bars indicate the standard error.

The quality ratings of the minimally processed Chinese cabbage in all four treatments decreased during storage for 14 days at 7°C (Figure 8.5). The greatest decrease occurred for treatment 30:21, which averaged 1.3 by day 14, and the least for treatment 0:70, which averaged 4.0 by the same day. The mean quality for all atmospheres was rated at 5 for the first three days and remained above 4 until day 10. Almost all the deterioration in quality

occurred after 10 days and was slower for the 0:70 and 0:21 treatments than for the 30:70 and 30:21 treatments. Browning of cut surfaces, texture loss, and yellowing were the main causes for the decline in quality ratings (Figure 8.6). No microbial spoilage was observed in any of the treatments over the storage period and only a small number of black specks were detected.

Figure 8.6. Minimally processed Chinese cabbage cv. 'Yuki' leaves after 14 days storage in actively modified atmospheres at 7°C, showing browning of cut surfaces, texture loss, and yellowing.

Sampling of the internal atmospheres on day 14 revealed that only the 0:70 treatment was free from off-odours. The 30:70, 30:21 and 0:21 treatments all had alcohol- and methane-like odours to varying degrees as well as a 'rotten

cabbage' odour. The 0:70 treatment had an odour similar to that of fresh Chinese cabbage.

8.4 Discussion

The aim of this experiment was to investigate the usefulness of actively modified atmospheres for the storage of minimally processed Chinese cabbage cv. 'Yuki' and, in particular, the effects of high concentrations of O_2 and/or CO_2 compared to air. The minimally processed Chinese cabbage was stored in the modified atmospheres inside EVA-PVDC barrier bags to minimise gas exchange with the external atmosphere.

The increases in CO_2 levels and decreases in O_2 levels in all four treatments were due to the respiration of the minimally processed Chinese cabbage. The 30:70 treatment had the largest increase in CO_2 suggesting that the respiration rate of the cabbage stored in this treatment may have been higher than in the other treatments. High levels of CO_2, generally greater than 20%, can cause injury (Herner, 1987; Kader, 1992a) and increase the incidence of some physiological disorders, such as internal browning in cabbage and surface blemishes on tomatoes (Kays, 1991). Wang (1983) reported that Chinese cabbage exposed to 40% CO_2 atmosphere for 10 days showed an increase in decay and deduced that Chinese cabbage was susceptible to injury from high CO_2 levels. Daly and Tomkins (1998) studied the storage life of Chinese cabbage heads in controlled atmospheres of 5% CO_2 : 5% O_2 and 10% CO_2 :

10% O_2 and concluded that increased losses, due mainly to bacterial rots, could be attributed to the relatively high levels of CO_2 compared to the controls. It is possible, then, that the elevated CO_2 in the 30:70 treatment in the current study may have injured the minimally processed cabbage resulting in an increased respiration rate (Herner, 1987; Kays, 1991). Makhlouf *et al.* (1989) reported an increase in respiration rate coinciding with observable tissue injuries in broccoli stored for six weeks at 1°C in atmospheres of 10% and 15% CO_2 both with 2.5% O_2.

The differences in the levels of CO_2 and O_2 between the 30:70 and 30:21 treatments can be explained by the difference in the initial O_2 concentration. Low O_2 levels suppress aerobic respiration (Weichmann, 1987; Kays, 1991; Wills *et al.*, 1998) so as the concentration of O_2 in the 30:21 treatment decreased so did the respiration rate of the cabbage in that treatment, masking any increase in respiration due to injuries caused by the high CO_2. In addition, the decreasing amount of O_2 found for the 30:21treatment from day 7 and the 0:21 (control) treatment from day 10 also increased the risk of anaerobic fermentation. Whilst O_2 levels below 2% are conducive to anaerobic respiration (Weichmann, 1987) the critical concentration of O_2 below which anaerobic respiration proceeds is dependent on many factors such as respiration rate, temperature, length of exposure, and the level of CO_2 present (Wills *et al.*, 1998). Whole Chinese cabbage have stored well for up to 120 days in controlled atmospheres of 2% CO_2 : 2% O_2 (Weichmann, 1981; Daly and Tomkins, 1998) and for as long as five months in 1% O_2 and 99%

N_2 (Wang, 1983; Wang and Ji, 1988). This suggests that in the presence of low levels of CO_2 the critical O_2 concentration may be less than 2% and in the absence of CO_2 may be less than 1%.

The presence of alcohol- and methane-like odours in the 30:21 and 0:21 (control) treatments at the end of the storage period suggests that anaerobic respiration had resulted as a consequence of the low O_2 concentrations. High RQ values are indicative of anaerobic respiration (Kader, 1987) and the approximate RQ values determined for these two treatments, 18 for 30:21 and 10 for 0:21, from day 7 to day 13 support this idea. Another contributing factor to the off-odours in the 30:70 and 30:21, and perhaps even the 0:21, treatments may have been the high CO_2 levels (Herner, 1987; Kays, 1991). Wang (1983) reported off-odours from whole Chinese cabbage treated with 30% and 40% CO_2 for 10 days prior to storage and Lipton and Harris (1974) found that broccoli stored in 10% CO_2 at 5°C and 1% O_2 : 10% CO_2 at 7.5°C for up to 20 days developed "unpleasant" odours.

Most of the deterioration that occurred in the quality of the minimally processed Chinese cabbage took place in the last four days of storage. Prior to day 10, deterioration was evident as browning of cut surfaces and some yellowing, but after day 10 there was a marked loss of texture, particularly in the 30:70 and 30:21 treatments, and increased amounts of browning and yellowing. The greatest amounts of texture loss occurred in the treatments where CO_2 levels became higher than O_2 levels and only the cabbage leaf

pieces in the 0:70 treatment, where O_2 and CO_2 were of similar concentrations at day 13, retained crispness and good texture. Again, this suggests that elevated CO_2 concentrations may have caused damage to the Chinese cabbage tissue, in this case, in atmospheres where the O_2 level is lower than the CO_2 level. Inhibition of respiration by high levels of CO_2 can lead to a build up of acetaldehyde and ethanol, in a similar manner to anaerobic fermentation, causing damage to tissue and affecting cell membranes (Kader, 1987; Kays, 1991). Beaudry (1993) reported a linear correlation between ethanol concentration and respiratory quotient (RQ) of blueberries stored under increasing levels of CO_2, which indicated that the increase in RQ was due to CO_2-induced fermentation. High CO_2 levels are known to affect mitochondrial activity in apples, resulting in the suppressed oxidation of several substrates including citrate, pyruvate, succinate and NADH (Shipway and Bramlage, 1973). This was suggested to cause an accumulation of organic acids in apples and other fruit stored under high CO_2. Shipway and Bramlage (1973) found the effect of high CO_2 on succinate and NADH oxidation to be progressive with time and irreversible, suggesting permanent damage to the mitochondria. Similar consequences of excess CO_2 may have occurred in the minimally processed Chinese cabbage leaves in this study, leading to the breakdown of cell membranes and tissue structure, and an overall loss of texture.

The low incidence of black speck, also known as gomasho, found in this study is due to a high level of tolerance shown by cv. 'Yuki' (Daly and

Tomkins, 1998) and the modified atmospheres had no effect on this attribute. The absence of any visible microbial spoilage could be due to washing the cut leaves in chlorinated water prior to bagging, but it is also possible that the altered storage atmospheres suppressed the growth of any microorganisms present. High CO_2 levels are known to inhibit pathogen activity (Daniels *et al.*, 1985; Herner, 1987; Wills *et al.*, 1998) whilst the effect of high O_2 concentrations on various microorganisms has had mixed results (Amanatidou *et al.*, 1999). Amanatidou *et al.* (1999) found that combinations of 80-90 % O_2 and 10-20 % CO_2 produced stronger and more consistent inhibitory effects on all of the 10 microbial species studied compared to O_2 or CO_2 alone. Wszelaki and Mitcham (2000) reported that extremely high levels of O_2 (close to 100 %) were effective in controlling decay in strawberries caused by *Botrytis cinerea*, but were little better than combinations of 15% CO_2 with 40% O_2 or air and had adverse effects on quality. Without any tangible evidence of microbial spoilage, especially in the control, the effect of the different storage atmosphere treatments on pathogen activity in the bags of minimally processed Chinese cabbage could not be assessed.

The anaerobic conditions produced in the 30:21 and 0:21 treatments in the latter stages of storage pose a potential risk for the growth of anaerobic pathogens. Several microorganisms, such as *Clostridium botulinum*, *Listeria monocytogenes*, and *Yersinia enterocolitica*, can grow in atmospheres with little or no O_2, at low temperatures and in elevated CO_2, and are capable of causing disease in humans (Farber, 1991). High levels of O_2, either alone or in

combination with CO_2, remove the risk of anaerobic conditions and therefore suppress the growth of obligate anaerobes, such as *C. botulinum*, and can also inhibit the growth of several facultative anaerobes. Amanatidou *et al.* (1999) reported an increased lag phase in the growth of *L. monocytogenes* and *Salmonella typhimurium* under 90% O_2, and a reduction in the growth rate of *Enterobacter agglomerans* under 80% O_2 and 20% CO_2.

The other major influence on the quality of the minimally processed Chinese cabbage and on the changing atmospheres was the storage temperature. The optimum temperature for minimally processed fruit and vegetables in modified atmosphere packaging is dependent on both the respiration rate and sensitivity to chilling injury of the commodity. Low temperatures are considered necessary for storage of minimally processed produce (Cantwell, 1992; Wiley, 1994) and strict temperature maintenance is required for modified atmosphere storage and packaging (Kader, 1992a; Reid and Serek, 1999). The recommended temperature for minimally processed Chinese cabbage in modified atmospheres is 0°C - 5°C (Gorny, 2001). Kim and Klieber (1997) found minimally processed Chinese cabbage had a longer storage life in air at 0°C than at 5°C. Packages of minimally processed fruit and vegetables are vulnerable to temperature abuse during handling, transportation, storage, and retailing (Cantwell, 1992; Wiley, 1994; Silva *et al.*, 1999) and this can affect the atmosphere inside the package and ultimately the quality and shelf life of the produce. Varoquaux and Wiley (1994) suggested

that investigations into minimally processed produce should be conducted at temperatures between 8° and 10°C because of the prevalence of temperature abuse. The storage temperature of 7°C used in this study was higher than recommended for Chinese cabbage and may have influenced the respiration rates of the leaf pieces and therefore the rate of change in the atmospheres. A lower storage temperature is likely to have slowed respiration and delayed the depletion of O_2 in the 30:21 and 0:21 treatments. Rosenfeld *et al.* (1999) reported that storage temperature had the most influence on the decrease in O_2 levels in modified atmosphere packages of blueberries, with O_2 decreasing sooner at 12°C than at 4°C regardless of package film type or initial atmosphere.

8.5 Summary

Modified atmosphere packaging of minimally processed Chinese cabbage incorporating high levels of O_2 and low levels of CO_2 may have advantages over packaging in air or in gas mixtures with high CO_2 levels. High O_2 concentrations in the initial atmospheres were not depleted after 13 days in storage, thus avoiding anaerobic respiration and the related risk of growth of anaerobic microorganisms. High CO_2 levels contributed to the off-odours encountered in the 30:70, 30:21 and 0:21 treatments and also had a role in the deterioration in quality of the Chinese cabbage stored in these treatments. Based on visual assessment, none of the storage atmosphere treatments affected the growth of decay pathogens.

Chapter 9

9 GENERAL DISCUSSION

The Asian vegetable industry in Australia is expanding, with production value and grower numbers increasing more than 100% since 1995 (Anonymous, 2003). Chinese cabbage makes up a considerable portion of the industry and is grown commercially in all states except Tasmania. The multicultural nature of the Australian population and the popularity of ethnic-based cuisine have resulted in a strong domestic market for Asian vegetables such as Chinese cabbage. Export markets are also important, with Chinese cabbage making up almost all of the Asian vegetables exported each year (Anonymous, 2003).

Postharvest handling of Chinese cabbage, as is the case with most horticultural produce, is an important factor in the maintenance of quality until retail sale and, therefore, economic returns to the producer and wholesaler. Problems encountered with Chinese cabbage after production are similar to those for other leafy produce in Australia, such as mechanical damage during harvest, handling, and transport, incorrect or inconsistent temperature conditions for transport and storage, and the development of disorders and microbial infections. In a recent report (Anonymous, 2003) cool chain breakdown, leading to quality problems, was identified as one of the weaknesses in Australia's Asian vegetable industry. These problems also affect the export of Chinese cabbage, which is mainly to Singapore, Hong

Kong, and Taiwan, and some shipments in the past have been rejected because of postharvest disorders. Short storage life of Australian-grown product was cited as one reason, along with competition from other countries and low prices, for the decline in exports of Chinese cabbage from Western Australia over the past 10 years (Anonymous, 2003).

Compared to Australia, the emphasis placed on postharvest handling and technology in China is low, and postharvest losses of Chinese cabbage in some areas can be as high as 60% (Wang and Bagshaw, 2001). Most of these losses are due to mechanical damage, weight loss, and disease during storage and transport (Wang and Bagshaw, 2001) (Figure 9.1). The majority of postharvest storage is still traditional, such as in pits or covered ditches in fields (Figure 9.2), or in "conventional warehouses" (Feng, 2001), although in the Beijing area approximately 10% of stored Chinese cabbage is kept in temperature controlled coolrooms (Zheng *et al.*, 2001). Rough handling, overloading of trucks (Figure 9.3), and the lack of suitable packaging and refrigerated transport are the main reasons for mechanical damage and weight loss of fresh market Chinese cabbage (Zheng *et al.*, 2001). Chinese cabbage destined for export is generally handled better, being precooled, packaged, and kept at low temperatures prior to shipment (Zheng *et al.*, 2001).

Figure 9.1. Bundles of rotting Chinese cabbages on a truck in rural China.

Figure 9.2. An example of pit storage for Chinese cabbage in a farmer's field in rural China.

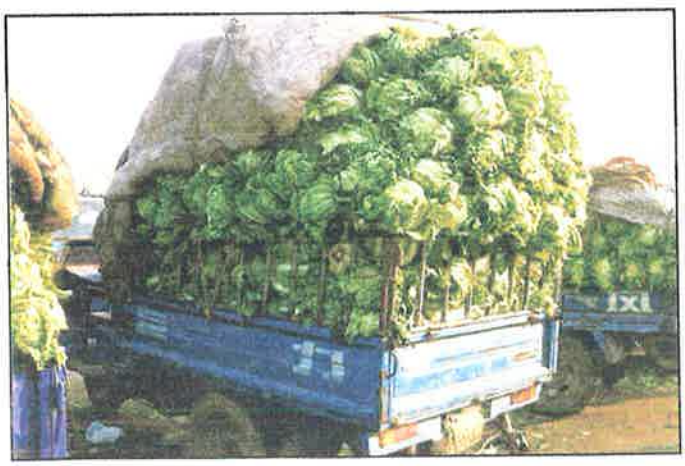

Figure 9.3. A small truck overloaded with Chinese cabbage in rural China.

There were two main aims for this research project. The first was to investigate the effects of various pre- and post-harvest factors on the postharvest condition of Chinese cabbage in order to address some of the problems encountered by the industry in Australia. Problems included the postharvest disorder, Patchy Papery Necrosis, and how to prolong storage/shelf life whilst maintaining quality. The second aim was to extend the general knowledge of the postharvest physiology of this increasingly popular Asian vegetable. Most of the earlier research on Chinese cabbage in Australia had concentrated on production issues, such as nutrition (McKay, 1988; Hill, 1990), cultivar performance, and field disorders (Rogers *et al.*, 1989). A notable exception was the work conducted by Daly and Tomkins (1998) that included investigations into storage and some aspects of postharvest quality and physiology.

An investigation into the best time of day to harvest Chinese cabbage revealed that there are no consequential differences between cabbage heads harvested at various times during the day. Cabbages harvested and left for half-an-hour during the hottest part of the day, prior to cooling, suffered no ill effects compared to those harvested when temperatures were cooler. This means that harvesting can be carried out whenever it is most convenient for the producer in order to relay the heads to market. Any benefits of harvesting in warmer temperatures, however, must be weighed against the increased costs of cooling the cabbages after harvest. Further investigation found that there were significant differences in temperature fluctuations

between the inner and outer leaves, identifying the important role of the large outer or wrapper leaves in protecting the cabbage head from extreme temperatures. The wrapper leaves are generally removed at harvesting and so do not influence the postharvest life of the cabbage.

The effects on the postharvest behaviour of Chinese cabbage by intermittent water stress during growth were investigated. Some plant species are known to become acclimatised to water stress making them better able to withstand subsequent stresses (Kays, 1991). The water status of leafy vegetables can affect postharvest issues such as weight loss (Fritz and Weichmann, 1981) and the rate of senescence (Lipton, 1987). The intermittent water stress treatments had no effect on any of the postharvest assessments, including water status immediately after harvest and weight loss during storage. It is possible that the treatment applying the most stress was not sufficient to evoke a response. It may also be that the Chinese cabbage plants employed one or more mechanisms to either avoid or tolerate the lack of water. A study by Levitt (1985) suggests that, in cabbage (*Brassica oleracea* var. *capitata*), the older leaves act as a source of water and solutes for the rest of the plant during drought and are the first to wilt and die. In this study, it is not possible to say whether or not the oldest leaves of the Chinese cabbage plants act similarly to those of the cabbage plants, or whether they showed any effects of water stress, as they were trimmed off at harvest and not included in the postharvest evaluations.

It has not been possible to determine from this study the reasons for the lack of effect by the intermittent water stress treatments. Experiments imposing harsher water deficits in controlled situations, e.g. in greenhouses or under cover, may reveal more information regarding water/plant relations in Chinese cabbage.

Many studies have shown that Chinese cabbage can be stored for long periods of time at low temperatures, although results vary between different cultivars (Hansen and Bohling, 1981; Apeland, 1984a; Gajewski and Skapski, 1994; Daly and Tomkins, 1998). Some cultivars develop chilling injury if stored at very low temperatures, such as 'Hector' and 'Kasumi II' when stored at 0°C for seven weeks (Daly and Tomkins, 1998). In the same study, the cultivar 'Yuki' did not develop the brown midrib symptom of chilling injury, but did develop other symptoms of a disorder named Patchy Papery Necrosis (PPN). To further investigate this disorder and to learn more about the postharvest physiology of 'Yuki', an experiment examining the effects of different storage temperatures was undertaken. Comparisons between storage at 20°C, 2°C, and 0°C reinforced the importance of low temperatures for prolonging postharvest life. It was found that Chinese cabbage cv. 'Yuki' has low rates of respiration and ethylene production compared to many other leafy vegetables, even when kept at 20°C, making it well suited to long term storage or export via seafreight.

The disorder, PPN, as described by Daly and Tomkins (1998), was detected in cabbages used in this investigation. Differences in the presence and severity of the symptoms of PPN at the three different storage temperatures led to the conclusion that this disorder is temperature related. It is most likely a form of chilling injury, even though the PPN symptoms are different from those previously described for chilling injury in Chinese cabbage. Differences between cultivars in the presentation of symptoms of chilling injury is not unusual, with apples, pears and potatoes being well known examples (Bramlage and Meir, 1990).

Mechanical damage caused by poor handling practices and lack of suitable packaging contributes to postharvest losses of Chinese cabbage. In Australia, Chinese cabbage is a moderately valuable crop, with heads retailing for up to AUD4 each, and is usually handled and packaged with care. Chinese cabbage sells for as little as the equivalent of 20 Australian cents in China's domestic markets, so little emphasis is put on careful handling or costly packaging. Mechanical damage was responsible for up to 36% of postharvest losses of Chinese cabbage by the time the heads reached retail markets in eastern-central China (Wang and Bagshaw, 2001).

An experiment was conducted to assess the effects of some types of mechanical damage on the postharvest physiology of Chinese cabbage and to understand how this contributes to postharvest loss. Wound treatments were designed to simulate Australian handling practices and were considered mild

compared to those reported from China. The postharvest physiology of the Chinese cabbages was little affected, and almost no changes in respiration and ethylene production were detected. This endorses the importance placed on good postharvest handling practices in Australia and shows that Chinese cabbage will sustain only minor losses when handled correctly.

Ethylene, which is produced by all vegetative matter, is known to promote senescence (Wills *et al.*, 1999). 1-methylcyclopropene (1-MCP), a gaseous compound that inhibits the effects of ethylene in some horticultural species (Serek *et al.*, 1995; Sisler *et al.*, 1996b; Golding *et al.*, 1998; Porat *et al.*, 1999), was tested with Chinese cabbage cv. 'Yuki' to determine its effect on postharvest life. Fumigation with 1-MCP did not have any beneficial effects on the postharvest life, but a possible stress response was detected in heads treated with 1.0 and 0.1 $\mu L.L^{-1}$ 1-MCP directly after fumigation. It is, therefore, not recommended for use as a postharvest treatment for Chinese cabbage cv. 'Yuki'. The low levels of ethylene produced by the cabbages in previous experiments, together with the lack of beneficial effects from treatment with 1-MCP, suggest that ethylene does not play a major role in the senescence of Chinese cabbage cv. 'Yuki'. It is likely that other factors, such as the depletion of energy substrates, influence the progression of senescence in Chinese cabbage. In a study of the postharvest physiology of pak choi, Able *et al.* (1999b) found that senescence was correlated with the depletion of soluble sugars and the degradation of proteins. Wang (1983) noted a

considerable decrease in sugars, particularly fructose and glucose, in Chinese cabbages stored for two months at 0°C but did not relate this to any symptoms of senescence.

Another postharvest treatment used for prolonging storage life and maintaining quality is controlled atmosphere (CA) storage. Due to spatial and technical limitations, the evaluation of CA storage on whole Chinese cabbage heads was not possible, so a smaller scale experiment using minimally processed Chinese cabbage stored in barrier bags with actively modified atmospheres (MA) was conducted. A previous study had identified Chinese cabbage as a good candidate for minimal processing (Kim and Klieber, 1997) and atmospheres with various levels of O_2 and CO_2 had been tested with whole Chinese cabbages (Weichmann, 1981; Wang, 1983; Daly and Tomkins, 1998). Encouraging results from recent studies using super-atmospheric levels of O_2 to inhibit microorganisms and avoid anaerobic conditions prompted the inclusion of super-atmospheric O_2 levels in this investigation. Chinese cabbage cv. 'Yuki' performed well as a minimally processed product, storing for up to 10 days at 7°C with little deterioration in quality. Whether MA packaging of minimally processed Chinese cabbage would be successful in the market place, however, depends more on such factors as its value as a commodity, its tolerance to a range of temperatures and gas concentrations, and whether it can be stored just as well in air (Wills *et al.*, 1998).

The minimally processed cabbage leaves stored better in the atmospheres with no CO_2 and either 21% or 70% O_2 than in the atmospheres with 30% CO_2. This suggests that storage atmospheres with high O_2 concentrations and little or no CO_2 may be better for Chinese cabbage than conventional CA storage utilising high CO_2 levels. Further studies would be needed to evaluate these atmospheres for storage of whole Chinese cabbage heads, but if found beneficial could be of use for exporting via seafreight. Any future investigations would also have to address the safety issues involved in using large quantities of highly concentrated O_2.

One of the main conclusions from this study is the importance of the quality of the Chinese cabbage at harvest and how that influences the postharvest life and storability of the heads. In each separate investigation it was found that damage caused by field pests and disorders had a substantial impact on the quality of the heads prior to storage. Caterpillars, aphids, and slugs were the predominant pests found on and in the harvested heads, and tipburn was the major disorder affecting the cabbages in the field. Whilst damage for the most part was confined to the outer layers of leaves, severe cases of tipburn, and some of the more voracious pests, were able to affect leaves further inside the heads. The extent of this damage on particular crops was evidenced in their high quality scores and large amounts of trimming loss prior to storage. Future studies to quantify the impact of the various pests and disorders may be helpful for directing quality improvement strategies.

Tipburn resistant varieties need to be developed and growers must be diligent in the application of pest control measures to ensure better quality heads for export or for storage.

Differences between cultivars are a factor not only in production, but also in postharvest performance. A comparison of some of the results from this study, in particular those regarding storage temperatures, with previous work reveals that different cultivars may require different storage temperatures and that some may store for longer periods than others. The development of PPN in cultivar 'Yuki' at 0°C and 2°C indicates that the recommended storage temperature should be greater than 2°C. Apeland (1984a) reported that there were differences in the length of storage at 0°C before chilling injury was observed for three cultivars, 'WR Green 60', 'Tip Top' and 'Treasure Island', and suggested that each cultivar had a different critical temperature for chilling injury. This indicates that Chinese cabbage cultivars selected for seafreight export and for long-term storage should be tested for the appropriate temperatures to preclude losses from chilling injury. Cultivars that are not suited to lengthy storage could be grown for fresh markets. Scientists at the Beijing Vegetable Research Centre report that 'Summer' Chinese cabbage cultivars, which are becoming popular in China, have high initial rates of ethylene production and can only be stored for seven to ten days (W. Li, Beijing Vegetable Research Centre, pers. comm., 2001). These

cultivars are of the open, semi-heading type of Chinese cabbage, which is different to the heading type such as cultivar 'Yuki' used in this study.

Results from energy substrate assessments in this study highlight the differences between leaves from different areas of the Chinese cabbage head and also the core. High sucrose levels found in the core tissue could be used as a source of energy for the remainder of the head during storage. Cultivars with large core to leaf ratios may be better suited to long term storage or export, and this trait could be selected for when breeding cultivars especially for these purposes.

Other compositional differences have been identified between leaves throughout Chinese cabbage heads, such as differences in ascorbic acid content (Klieber and Franklin, 2000). This stresses the need for assaying different leaf or tissue samples in leafy vegetables such as Chinese cabbages, and the inappropriateness of averaging measurements or data for whole heads. Whilst the latter may make for easier reporting, the former gives a clearer indication of the complex nature of the postharvest life of the Chinese cabbage head.

The findings of this study will be useful to many involved in the Chinese cabbage industry, even though the results are specific to cultivar 'Yuki'. The importance of production issues, especially resistance to field disorders and control of pests, and their effect on the quality of the harvested heads is

emphasised. Also, growers should be aware of the protective function of the large wrapper leaves and can use this to their advantage when harvesting in various climatic conditions, especially when cooling is not immediately available. Wholesale and retail marketers and exporters are advised of the importance of low temperatures for prolonging storage time and maintaining quality, but must be aware that different cultivars may require different temperatures to avoid chilling injury. The emphasis placed on careful handling and packaging in Australia is justified in the case of Chinese cabbage, resulting in minimal postharvest losses. This is in contrast to the situation in China, which would benefit from the introduction of improved postharvest technology. The use of the ethylene inhibitor, 1-MCP, is not recommended for Chinese cabbage cv. 'Yuki' although it may be beneficial for cultivars with higher rates of ethylene production. Minimally processed Chinese cabbage stored either in air or in high O_2 modified atmosphere packaging, has potential as a value-added, convenience product, but is reliant more on marketing factors rather than postharvest factors for success.

Several issues examined in this study would benefit from further investigation and some findings indicate areas for future research. Continued investigation into water relations of Chinese cabbage, in particular the effects of water deficits during growth, could identify drought tolerance mechanisms or traits that may help in the development of drought tolerant cultivars or may provide information to improve water-use efficiency of current commercial cultivars.

Research into breeding new cultivars resistant to field disorders, especially tipburn, would be beneficial as would research into better control of field pests. Cultivar 'Yuki' used in this study is resistant to clubroot, but is only tolerant to tipburn and this was not sufficient to prevent the sometimes-severe symptoms of tipburn. Integrated pest management may offer improved control of pests over purely chemical means and is worth investigating.

Controlled atmosphere storage using elevated O_2 levels and/or no CO_2 may have potential and requires assessment of whole heads stored in constant atmospheric conditions. Lower levels of O_2 than used in this study may be sufficient if the levels are steady and the CO_2 levels are kept low or absent. This may also minimise the fire hazard involved when using oxygen-enriched atmospheres.

Future research into modified atmosphere packaging (MAP) of minimally processed Chinese cabbage needs to identify the correct packaging film required to maintain the desired levels of atmospheric gases. In this study, barrier bags with very low permeability were used to examine the effects of the changing gas levels on the minimally processed cabbage leaves. If minimally processed Chinese cabbage is to be stored in air or in modified atmospheres, packaging films of differing permeability will be required to

keep the atmospheric gases at the correct concentrations. Consideration should also be given to films that perform over a range of temperatures.

Any further research into these issues will provide information that will be useful to those involved in the Chinese cabbage industry. Improved cultivars, better quality heads at harvest, and refined postharvest treatments are all desirable outcomes from future investigations. The results from this study have added to our knowledge regarding the postharvest physiology of Chinese cabbage and will be of benefit to both the local and global industries.

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Harvesting at different times of day does not influence the postharvest life of Chinese cabbage

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Abstract

Chinese cabbages cv. 'Yuki' were harvested at dawn, mid-morning, midday, mid-afternoon, and dusk, and cooled either immediately or after a half an hour delay, to determine the effects on postharvest life. Temperatures during harvesting ranged from 6.1 to 21.5 °C. Water status levels were determined immediately after harvest and then heads were stored at 0 °C with destructive assessment for trimming loss, chlorophyll fluorescence, quality, and energy substrate levels after 0, 3, 6, and 9 weeks. Results indicate that harvesting at different times of the day and the half an hour delay in cooling did not affect any of these postharvest parameters of Chinese cabbage. This can be attributed to the protective function of wrapper leaves that are removed at harvest.

Keywords: Chinese cabbage; Harvest; Postharvest; Storage life; Quality; Energy substrates

1. Introduction

Early morning is generally considered to be the best time of day to harvest vegetables, as the water status of produce is high and the temperature and respiration rate are low (Thompson, 1996; Wills et al., 1998). This is thought to be favourable to maintain quality of produce and prolong postharvest life. For leafy vegetables, however, it has been suggested that harvesting be carried out in the late afternoon, when leaves are less turgid and therefore less likely to be damaged (Phan, 1987a). Energy substrate levels at this time of the day are high, and this has been associated with long storage life in lettuce and cabbage (Lipton, 1987).

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Chinese cabbage (*Brassica campestris* L. ssp. *pekinensis* (Lour.) Olsson) is a leafy vegetable that forms a densely packed head. Harvested heads store well for long periods at low temperatures, but can be prone to various postharvest disorders such as gomasho and chilling injury (Daly and Tomkins, Undated; Gajewski and Skapski, 1994; Hansen and Bohling, 1981). This study was conducted to investigate whether the length of storage, the quality, water status, or energy substrate level of the cabbages is influenced by the time of day of harvest or by delays in cooling of the harvested heads.

2. Materials and methods

2.1. Harvest time and holding period

For this experiment, a crop of Chinese cabbage cv. 'Yuki' was grown at the Ovens Research Centre in Victoria, Australia, using cultural practices developed previously during production trials. The crop consisted of three adjacent raised beds containing two rows of approximately 120 plants each, giving a total of 720 plants. The crop was harvested on 4 May 1999.

2.1.1. Treatments

Prior to harvesting, the raised beds, each representing one replicate, were divided into 10 plots each containing a similar number of cabbages suitable for testing. Ten harvest treatments, made up of five harvest times (dawn, mid-morning, midday, mid-afternoon and dusk), each with two holding periods (cooled immediately and kept in the field for 30 min) were randomly allocated to the plots in each bed as a randomised complete block design. The cabbages were then harvested according to the allocated treatments, with 14 heads per replicate harvested for each treatment. Harvest times and the corresponding air temperatures are shown in Table 1.

The harvested cabbages were packed into waxed cardboard cartons fitted with polyethylene liners and were then transported, either immediately or after a 30 min delay, to a coolroom, set at 0 °C, for cooling and overnight storage. One head from each treatment was sampled to determine the relative water content. Three leaves from each head were weighed before (fresh weight) and after (dry weight) being dried in a fan-forced oven set at 60 °C, with the relative water content being ascertained by dividing the difference between the weights by the fresh weight and expressing the result as a percentage.

Table 1
Time of day of harvesting and associated field air temperature for Chinese cabbage cv. 'Yuki' grown at Ovens Research Centre, Victoria, and harvested on 4 May 1999

Treatment	Time	Temperature (°C)
Dawn	8.10 a.m.	6.1
Morning	10.40 a.m.	16.8
Midday	12.45 p.m.	20.3
Afternoon	14.45 p.m.	21.5
Dusk	16.50 p.m.	17.9

After overnight storage, the heads had cooled to between 2 and 4 °C. The cartons were then palletised and transported, within 2 days, to Adelaide University, Waite Campus, Urrbrae, South Australia, in refrigerated road transport. Temperatures during transport ranged between 2 and 8 °C. In Adelaide, each Chinese cabbage was placed in a separate perforated polyethylene bag and stored, in cartons, at 0 °C. Three cabbages per replicate from each of the 10 harvest treatments were removed from storage for postharvest evaluation at 0, 3, 6, and 9 weeks.

2.2. Postharvest evaluation

Upon removal from cool storage, cabbages were weighed, trimmed of senescing or damaged leaves to achieve a marketable standard, and then reweighed. The trimming loss was calculated by subtracting the trimmed weight from the pre-trimmed weight and recorded as a percentage of the pre-trimmed weight.

The location and severity of visual symptoms of senescence (yellowing, browning, rotting) and of pre- and postharvest disorders (tipburn, gomasho, pest damage, patchy papery necrosis) were recorded. The severity of the symptoms was allocated a score, between 0 (none) and 10 (severe), that was weighted according to the importance of the disorder in determining the quality of the Chinese cabbage. The total score indicated the overall quality of each cabbage. Total scores of 0 (good) to 3 (average) indicated marketable quality and scores above 3 (below average) indicated unmarketable quality.

The fluorescence of chlorophyll in an outer leaf of each cabbage was measured, before trimming, using a fluorescence induction monitor (FIM 1500, ADC BioScientific Ltd.). Key fluorescence parameters of F_o (minimum fluorescence), F_m (maximum fluorescence), F_v (variable component—the difference between F_m and F_o), and the ratio of F_v/F_m were measured and used as an indication of the photosynthetic capacity of the leaf. As chlorophyll degradation is a characteristic of senescence, reduced photosynthetic capacity may denote the onset of senescence before visual symptoms are seen (DeEll et al., 1999). The measurements were taken from an area in the uppermost portion of an outer leaf, approximately 1 cm from the leaf margin and as close to the centre line as possible, that had been dark-adapted for 20 min prior to illumination. Light intensity was set at 1800 $\mu M\ m^{-2}\ s^{-1}$ and the reading was taken over 5 s.

The levels of sucrose, glucose and fructose in samples taken from cabbages harvested at dawn, midday and dusk, and stored for 0 weeks were determined using an enzymatic assay technique. Four samples from each cabbage (an outer, middle and inner leaf, and the core) were frozen to −80 °C, freeze-dried and then ground into a homogeneous powder. Samples were deproteinised by adding 640 µl 0.6 M $HClO_4$ to 5 mg of sample, mixing and then adding 360 µl 2 M KOH. The mixture was centrifuged for 15 min at 17,000*g* and 750 µl of the resulting supernatant was adjusted to pH 8.0 using 0.5 M KOH and then diluted with an equal volume of milliQ water. Fifty microlitres (50 µl) of this extract was used in an assay technique based on the Boehringer Mannheim Sucrose/D-Glucose/D-Fructose Enzymatic BioAnalysis kit (Catalogue No. 716260). The levels of sucrose, glucose, and fructose (mg g^{-1} DW) were estimated from the absorbance of NADPH at 340 nm measured in a Varian Cary 1 UV–visible Spectrophotometer (Varian Australia, Mulgrave, Victoria).

2.2.1. Data analysis

All numerical data were analysed for variance using Genstat 5, 4th Edition for Windows (Lawes Agricultural Trust, IACR, Rothamsted). Differences between treatments were determined using least significant difference (LSD) at the 5% level.

2.3. Head temperatures in field

For this experiment, the temperatures at various points inside and outside mature Chinese cabbage heads were measured using temperature data loggers. Three Chinese cabbage plants cv. 'Yuki' of uniform size and maturity and situated adjacent to each other, were selected in a crop grown at Virginia, South Australia. Each cabbage plant was fitted with five temperature data loggers (Tinytalk Temperature Datalogger, Gemini Data Loggers, UK), with stab probes attached. Two probes were placed inside the cabbage head, one at the base and one in the centre. A third probe was placed under the leaves at the top of the head, another was placed inside the midrib of a wrapper leaf, and one was suspended above the ground next to the cabbage plant (Fig. 3). Loggers began recording at 0.00 a.m. on 11 May 2000 and were removed from the plants at 11.00 a.m. on 16 May 2000, and data from a representative day, 11 May, are shown.

3. Results

3.1. Harvest time and holding period

The relative water content of leaves from Chinese cabbages was not affected by the harvest times or the holding periods, with averages around 94.7 to 94.8% ($P > 0.05$).

The amount trimmed from Chinese cabbages increased with the increase in storage period from 0 to 6 weeks and then remained constant, at about 25%, until week 9 (Table 2). Trimming loss at 0 weeks was 16% due to aphid damage of the outer leaves. Trimming loss was not affected by the harvest times or the holding periods (Table 3).

Table 2
Trimming loss, quality score, and chlorophyll fluorescence parameters for Chinese cabbages stored at 0 °C for up to 9 weeks

Storage period (weeks)	Trimming loss (%)	Quality score[a]	F_m	F_v
0	16.2 a[b]	0.7 a[c]	3644 a	3028 a
3	21.2 b	1.6 b	3315 b	2635 b
6	24.9 c	2.5 c	2902 c	2209 c
9	24.8 c	3.6 d	2976 c	2214 c

[a] Scores between 0 and 3 denote good (marketable) quality and scores >3 denote poor (unmarketable) quality.

[b] Values are means of 30 heads × three replicates and different letters in columns denote significant differences using LSD ($P = 0.05$).

[c] Data were analysed after transformation using square root, with back-transformed means shown.

Table 3
Trimming loss, quality score, and chlorophyll fluorescence parameters for Chinese cabbage harvested at different times of the day or kept in the field for different periods prior to cooling

	Harvest time					Holding period	
	Dawn	Morning	Midday	Afternoon	Dusk	0 h	0.5 h
Trimming loss (%)	22.6 a[a]	21.7 a	21.3 a	21.6 a	21.8 a	21.5 a	22.1 a
Quality score[b]	2.2 a[c]	1.9 a	1.8 a	2.4 a	2.0 a	1.9 a	2.2 a
F_m	3238 a	3095 a	3275 a	3117 a	3321 a	3243 a	3175 a
F_v	2484 a	2433 a	2647 a	2470 a	2484 a	2461 a	2482 a

[a] Values are means of 24 heads × three replicates and different letters in rows for each factor denote significant differences using LSD ($P = 0.05$).
[b] Scores between 0 and 3 denote good (marketable) quality and scores >3 denote poor (unmarketable) quality.
[c] Data were analysed after transformation using square root, with back-transformed means shown.

The quality of the stored Chinese cabbages decreased, as shown by the increase in average quality scores, as the length of storage period increased (Table 2). The scores for Chinese cabbages assessed at 0, 3, and 6 weeks were within the marketable range (3 or below), while Chinese cabbages assessed after 9 weeks of storage were considered unmarketable. Harvest times and holding period did not affect the quality (Table 3).

Average data of the chlorophyll fluorescence parameters F_m and F_v decreased with the increase in storage period from 0 to 6 weeks and then remained constant (Table 2). Harvest times and holding periods did not affect these parameters (Table 3). Analyses of variance performed on F_o and F_v/F_m data were inconclusive due to large variation in the data unaccounted for by the treatments and the experimental design.

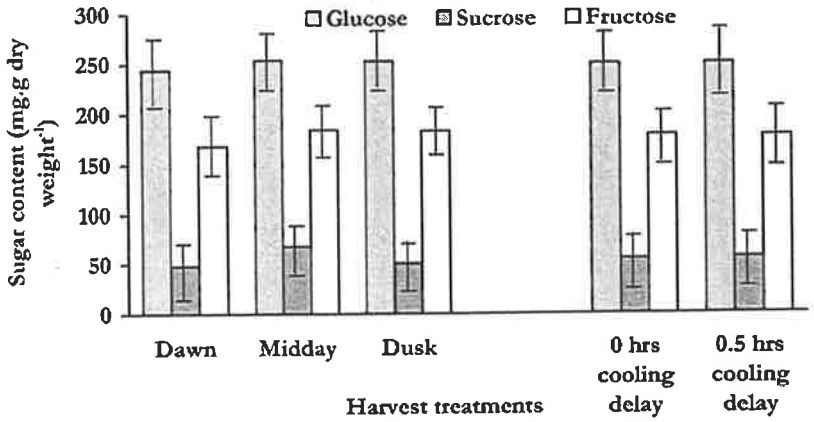

Fig. 1. Levels of three sugars in middle leaf samples taken from Chinese cabbage harvested at different times during the day and kept in the field for different periods prior to cooling. Harvest time values are means of six heads × three replicates and cooling delay values are means of nine heads × three replicates. Bars represent the standard deviation for each value.

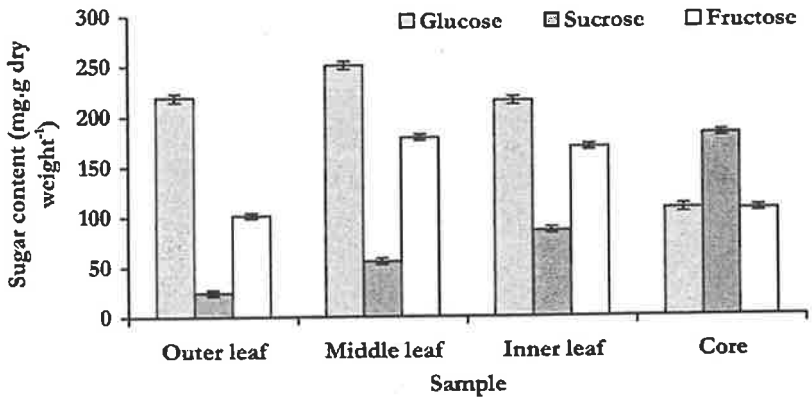

Fig. 2. Concentrations of three sugars in various tissue samples taken from Chinese cabbage. Values are means of 27 heads × three replicates and bars represent the LSD ($P = 0.05$) between samples.

There were no differences between harvest times or between holding periods in the amounts of glucose, sucrose and fructose in samples taken from Chinese cabbages at 0 weeks for dawn, midday and dusk harvest treatments. In Fig. 1, the data for middle leaf samples are shown, and while levels of the different sugars varied between sampling locations (Fig. 2), harvest time and holding period did not affect sugar content at any location. Glucose and fructose levels were highest in the middle leaf samples, while

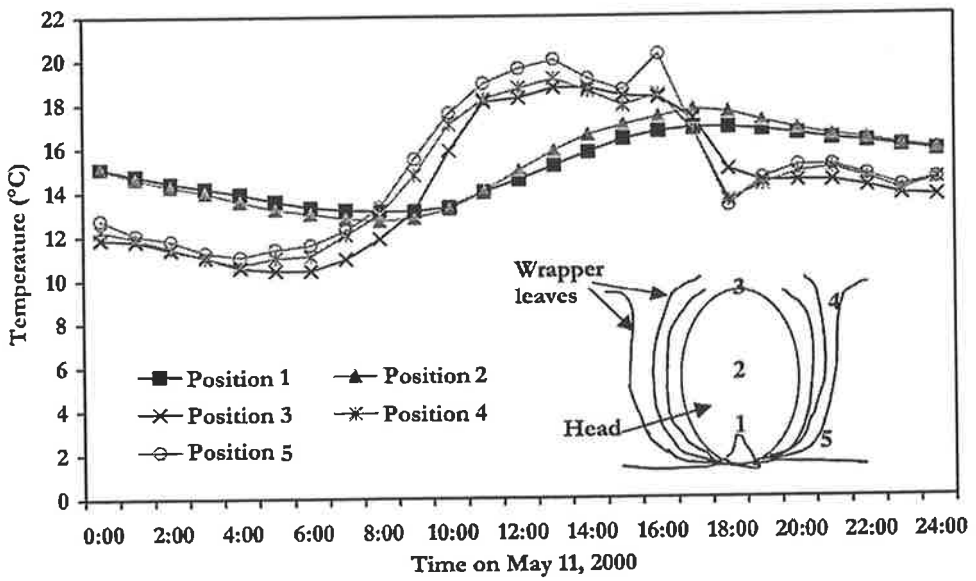

Fig. 3. Temperature fluctuations at various positions inside and outside mature Chinese cabbage heads in the field over a 24-h period. Minimum and maximum temperatures in the region for the same period, as recorded by the Bureau of Meteorology, were 13 and 22 °C, respectively. Values are means of three heads.

sucrose levels were highest in the core. Glucose levels were lowest in the core, and fructose and sucrose levels were lowest in the outer leaves.

3.2. Head temperatures in field

Typical recordings from the temperature data loggers are shown in Fig. 3. The temperature at Positions 1 and 2 inside the heads did not fluctuate as widely or as quickly as the temperature at the other three positions, at the top of the head, in the wrapper leaves, or in air.

4. Discussion

The postharvest evaluations showed that time of day of harvest and a half an hour delay in cooling had no impact on postharvest behaviour of Chinese cabbage. The relative water content data indicates that these treatments did not influence the water status of the harvested heads. Despite a maximum variance of approximately 15 °C in air temperature between the dawn and afternoon harvests, cabbages from all harvests had similar relative water content, trimming losses and overall quality. In addition, light exposure through the day had no effect on either chlorophyll fluorescence or levels of energy substrates. Similarly, harvested cabbages that were left out for half an hour in the midday sun were no different than their neighbours that were taken immediately to the coolroom after harvest.

The harvest air temperatures in this study ranged from 6 to 22 °C, which are typical temperatures experienced for Chinese cabbage at harvest. In fact, the monthly average maximum temperature for May at the trial location is 15 °C. Normal maximum temperatures during harvest months of Chinese cabbage in the southern Australian growing regions in north east Victoria and the Adelaide Plains are 24 °C in February/March and 12 °C in June (Bureau of Meteorology, 2002).

Field temperature affects turgidity (Kader et al., 1974) and thus influences the susceptibility of leafy vegetable crops to physical damage during harvest and handling (Phan, 1987b). For this reason, it was expected that the leaves of Chinese cabbages harvested at midday or later, after exposure to warm daytime temperatures, would be less turgid and less likely to sustain injury than Chinese cabbages harvested earlier in the day. No evidence was found in our results to support this, and the relative water content data suggest that the water status of Chinese cabbage heads was not affected by field temperature. This may, in part, be due to the relatively mild maximum temperatures that Chinese cabbages experience during harvest.

Contrary to our findings, Thompson (1996) and Wills et al. (1998) suggest that lower respiration rates of heads harvested in the early morning would positively influence their postharvest life when compared to Chinese cabbage heads harvested later in the day. Also, the harvested Chinese cabbages kept in the field for half an hour prior to cooling, especially those harvested during the hotter times of the day, should lose quality more rapidly than heads cooled immediately (Kader et al., 1974; Thompson, 1996; Wills et al., 1998).

Our results indicate that the Chinese cabbage heads have a mechanism for protection against exposure to high temperatures. This is supported by the in-field head temperature data, which suggest that the interior of the head is insulated against temperature extremes by the outer and wrapper leaves. These leaves are exposed to the surrounding environment and their temperature was found to fluctuate to the same or greater extent as that of the air temperature. Therefore, the wrapper and outer leaves are the most likely to be affected by temperature stress and other weather-related stresses. Most wrapper leaves and, depending on their condition, some outer leaves were removed when the cabbages were harvested, and therefore had no influence on the postharvest behaviour of the remainder of the head that they had previously protected. However, the effect of time of day on the energy substrate levels and water status of the wrapper leaves is unknown, as they were discarded at harvest.

Fritz and Weichmann (1981) found that the maximum temperature 20 to 11 days prior to harvest had some influence on the marketable quantity (amount left after trimming and weight loss) of Chinese cabbage after storage, although duration of storage was a more important factor. In this study, the temperature was recorded only at the time of harvest and was not monitored for any prior period. Kader et al. (1974) noted that cabbages may be subject to solar injury during harvest and transport, and that blistering and desiccation of affected leaves may increase the risk of decay. No evidence of either blistering or desiccation was observed in the assessed heads, as any leaves that may have been affected were most likely removed at harvest or prior to storage.

The length of storage was a major factor in the postharvest life of the Chinese cabbages. Trimming loss increased with the increase in storage period due to the greater number of outer leaves senescing or succumbing to microbial infection at wound sites over time. This was due to mechanical damage during transport and insect damage. In addition, postharvest disorders such as gomasho and patchy papery necrosis increased in severity with time.

Chlorophyll fluorescence parameters, F_m and F_v, declined in value as the length of storage increased. This can be attributed to the degradation of chlorophyll in association with the onset of senescence. These parameters, however, were not influenced by light exposure of heads throughout the day or darkness throughout the night. Toivonen (1992) found that F_v measurements of broccoli declined during storage and that the value for F_v was correlated with respiration and vitamin C content. He attributed the decline in F_v to the initiation of chloroplast deterioration associated with water loss, rather than senescence, due to the lack of visual yellowing or chlorosis of the samples.

This study shows that when harvested under normal conditions the postharvest behaviour of Chinese cabbage is not affected either by the time of day when it is harvested, or a short delay in cooling after harvest. This can be explained by the protective function of the wrapper leaves that cover the head and mitigate the stresses of field temperatures. More important factors in the postharvest life of Chinese cabbage appear to be the presence of field disorders and pests, and the development of postharvest disorders while the heads are in storage. It is likely that chlorophyll fluorescence measurements can be used to determine freshness or the onset of senescence in stored Chinese cabbage, via the early detection of changes in chlorophyll activity, but more research is required to identify meaningful parameters.

Acknowledgements

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Chilling injury limits low temperature storage of 'Yuki' Chinese cabbage

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Abstract

Chinese cabbages cv. Yuki were harvested and stored at 0, 2 and 20 °C to investigate the effect of these temperatures on quality, metabolic rates, weight and trimming loss during storage. Assessments were made at 0–3 weeks for 20 °C, and at 0, 3, 6 and 9 weeks for 0 and 2 °C. The previously unknown cause of the storage disorder, Patchy Papery Necrosis (PPN), was also investigated. Cabbages stored at 20 °C had higher respiration rates, ethylene production, weight loss and trimming loss, and lower quality than cabbages stored at 0 and 2 °C. Heads kept at 0 °C lost quality faster than at 2 °C due to PPN occurring earlier and more severely than at 2 °C. It was not observed in cabbages prior to storage or those stored at 20 °C, suggesting that this disorder is a form of chilling injury.

Keywords: Chinese cabbage; Postharvest; Storage temperature; Patchy Papery Necrosis

1. Introduction

Low temperature storage is an important part of prolonging the postharvest life of fresh produce. Low temperatures can reduce respiration rate, ethylene production and sensitivity, moisture loss, and the growth of pathogens (Mitchell, 1992). Previous studies (Hansen and Bohling, 1981; Gajewski and Skapski, 1994) have shown that Chinese cabbage (*Brassica campestris* L. ssp. *pekinensis* (Lour.) Olsson) can be stored for long periods at low temperatures. There is evidence, however, that some cultivars store better than others (Apeland, 1984b; Daly and Tomkins, 1998) and that storage temperatures of around 0 °C may induce chilling injury in some cultivars.

Chinese cabbage cv. Yuki was chosen for this study due to its good performance in production and storage trials carried out in Victoria, Australia (Daly and Tomkins, 1998). Three storage temperatures, 0, 2 and 20 °C, were used to investigate the differences in postharvest physiology at ambient and cool storage temperatures. The two low temperatures were also chosen to examine the role of low temperature in the development of a disorder described and named Patchy Papery

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Necrosis (PPN) by Daly and Tomkins (1998) that is typically seen in cv. Yuki (Fig. 2).

2. Methods and materials

Chinese cabbage cv. Yuki was grown at Virginia, South Australia using commercial growing practices. The crop consisted of a raised bed containing two rows of approximately 360 plants each, giving a total of 720 plants. Mature cabbages were harvested mid-season over 3 days, on 29 and 31 May and 2 June 2000, with cabbages harvested on each date representing one replicate.

The harvested cabbages were packed into waxed cardboard cartons in the field and were transported to the Waite Campus of Adelaide University within 3 h of harvest. Upon arrival, the cabbages were allocated storage temperature treatments, either 0, 2 or 20 °C, and were placed in the appropriate controlled temperature room. Chinese cabbages stored at 20 °C were immediately placed into individual perforated polyethylene bags to slow down moisture loss, whilst cabbages stored at the lower temperatures were left unbagged for 24 h to facilitate cooling. Cabbages from different harvest dates (replicates) were stored in separate cartons in each controlled temperature room. Cartons of one replicate were kept within one location within the room. For each storage removal time and replicate, five cabbages were randomly sampled from the relevant boxes for weight, trimming loss, presence and severity of disorders, and overall quality.

2.1. Postharvest evaluation

Chinese cabbages were stabilised at their storage temperature (24 h at 20 °C and 72 h at 0 and 2 °C) before commencement of the study. Measurements of weight, respiration rate and ethylene production were taken from five cabbages per replicate per storage temperature at regular intervals over the course of the study—at 0–3 weeks for 20 °C, or 0, 3, 6, and 9 weeks for 0 or 2 °C.

Cabbages were weighed and then enclosed in 15 l plastic buckets with lids fitted with rubber septa and tightly sealed with vacuum grease. Headspace gases were sampled after 2 h for cabbages stored at 20 °C, and after 24 h for cabbages stored at 0 and 2 °C. The samples were obtained by piercing the rubber septum with a needle and drawing headspace gas into an attached 1 ml syringe. To determine the levels of CO_2 present a 1 ml gas sample was injected into a Varian 3300 thermal conductivity gas chromatograph (Varian Australia, Mulgrave, Vic.) equipped with a silica column (35 cm × 3.1 mm i.d.) of 80/100 and calibrated using a 0.5% CO_2 gas standard (BOC Gases, Torrensville, SA). Temperature conditions were 90 °C for the injector and detector and 28 °C for the column, and the flow rate of helium (carrier gas) was 5 ml min^{-1}. The results were expressed as mg of CO_2 produced per kg of fresh weight per h.

Ethylene levels were detected by injecting a 1 ml gas sample into a Varian 3400 flame ionisation gas chromatograph (Varian Australia) equipped with a Porapak Q stainless steel column (60 cm × 3.1 mm i.d.) of 80/100 mesh and calibrated using a 1.9 μl l^{-1} C_2H_4 standard (BOC Gases). Temperature conditions were 50 °C for the column, 135 °C for the injector and 150 °C for the detector. Flow rates of the carrier gas nitrogen, hydrogen and air were 50, 40 and 300 ml min^{-1}, respectively. The results were expressed as ng C_2H_4 per kg fresh weight per h.

At the same intervals, a further five cabbages from each replicate/treatment combination were destructively sampled to determine trimming loss, incidence and severity of PPN and quality. Upon removal from storage, cabbages were weighed, trimmed of senescing or damaged leaves to achieve a marketable head, and then reweighed. The trimming loss was calculated as a percentage of the trimmed weight relative to the pre-trimmed weight.

Visual symptoms of senescence (yellowing, browning), pest damage, pathogenic spoilage, and of pre- and post-harvest disorders (tipburn, gomasho, PPN) were noted before trimming and by dissecting the head for further inspection of internal symptoms. Each cabbage was allocated an overall quality score between 1 (good) and 5 (poor) that took into account the severity of symptoms and the degree of impact of the disorders on visual appearance. Scores between 1

Table 1
Weight loss and trimming loss of Chinese cabbage cv. Yuki at intervals during storage at three different temperatures

Storage period (weeks)	Weight loss (%)			Trimming loss (%)		
	0 °C	2 °C	20 °C	0 °C	2 °C	20 °C
0	0a[a]	0a	0a	29a[a]	29a	29a
1			1.8b			47b
2			3.8c			46b
3	0.7b	0.5b	5.6d	44b	36b	–[b]
6	1.1c	1.0c		39b	42bc	–
9	1.6d	1.3d		42b	44c	–

Values are means of 15 cabbages (three replicates of five heads each). Weight loss was determined on the same cabbages at all intervals, whereas different heads were used to determine trimming loss as the weight of outer leaves trimmed off to achieve a subjective marketable quality.

[a] Different letters within columns denote significant differences using LSD ($P = 0.05$).

[b] Cabbages could not be trimmed to achieve a marketable quality.

and 3 indicated marketable quality and scores over 3 indicated unmarketable quality.

2.2. Data analysis

All numerical data were analysed using the General Analysis of Variance test in GENSTAT 5, fourth Edition for WINDOWS (Lawes Agricultural Trust, IACR, Rothamsted). The experiment was set up in a Randomised Complete Block design, with the harvest dates (replicates) as blocks and cabbages harvested on each date randomly assigned to temperature treatments and storage period. Differences between treatments and between storage periods were determined using least significant difference (LSD) at the 5% level.

3. Results

The weight loss of the cabbage heads increased with time at all three temperatures (Table 1), but heads lost more weight at 20 °C, exceeding 5%, than at 0 and 2 °C, where it remained below 2%. Weight loss between the two low temperatures was not statistically different ($P > 0.05$). The initial trimming loss upon reception at the laboratory was high at 29%, as heads were harvested with only wrapper leaves removed and then trimmed to marketable quality on reception. The trimming loss increased after 1 week at 20 °C to 47% and after 3 weeks at 0 °C to 44%, and then remained constant (Table 1). After 3 weeks at 2 °C it was 36%, and by 9 weeks increased further to 44% (Table 1). The extent of microbial spoilage prevented evaluation of trimming loss after 3 weeks at 20 °C.

Table 2
Average quality scores of untrimmed, dissected heads of Chinese cabbage cv. Yuki at various intervals during storage at three different temperatures

Storage period (weeks)	Quality score		
	0 °C	2 °C	20 °C
0	1.5±0.5	1.5±0.5	1.5±0.5
1	–	–	3.3±0.9
2	–	–	4.9±0.3
3	3.3±1.0	2.6±1.3	–[a]
6	3.7±1.2	3.2±1.3	–
9	3.0±0.7	3.0±1.0	–

A score of 1 indicates good quality and a score of 5 indicates poor quality. Scores are means of 15 cabbages (three replicates of five heads each) ±S.D.

[a] Cabbages could not be evaluated due to excessive rots.

The quality declined over the storage periods for all three temperatures as can be seen from the increasing quality scores (Table 2). The quality of cabbages stored at 20 °C declined quickly with most unmarketable after 1 week and of poor quality after 2 weeks. Causes of quality loss were senescence with yellowing of leaves and pathogenic spoilage. At 0 °C cabbages were considered to be of unmarketable quality after 3 weeks, although

scores were variable. Scores were increased due to some senescent yellowing and some pathogenic spoilage, but were also greatly influenced by the notable occurrence of PPN, reducing quality significantly after 3 weeks (Fig. 1). Symptoms of PPN were severe at 0 °C. At 2 °C most cabbage heads were of marketable quality, even though pathogens were again noted. However, the incidence of PPN was very low, even after 9 weeks (Fig. 1), and symptoms were not severe. Affected cabbages had areas of brown discolouration and necrosis of leaf tissue between veins, usually near the midrib of the leaf (Fig. 2). In mild cases only one or two inner leaves were affected but in severe cases large numbers of leaves throughout the head showed symptoms. Eventually senescent yellowing and pathogenic spoilage occurred, increasing quality scores similar to those found in cabbages at 0 °C. No PPN was observed in cabbages stored at 20 °C, and mild gomasho (black spot) was observed in only two heads. Mild tip burn was observed in some outer leaves.

The rates of respiration and ethylene production for newly harvested cabbages at 20 °C were 32 mg CO_2 kg^{-1} h^{-1} and 525 ng C_2H_4 kg^{-1} h^{-1}, respectively. Rates had fallen to around 2 mg CO_2 kg^{-1} h^{-1} and 5 ng C_2H_4 kg^{-1} h^{-1} after 3 weeks storage at 0 and 2 °C. Rates for cabbages stored at 20 °C were higher than those for cabbages stored at the lower temperatures, dropping to their lowest values of 15 mg CO_2 kg^{-1} h^{-1} and 173 ng C_2H_4 kg^{-1} h^{-1} after 1 week. From week 3 to 9, the respiration rate of the cabbages further declined by 38 and 18% at 0 and 2 °C, respectively ($P < 0.05$). For cabbages stored at 20 °C, the respiration rate increased markedly after 1 week due to senescence and pathological processes. Ethylene production followed a similar pattern. No significant differences were found between 0 and 2 °C for respiration rate and for ethylene production over the 9 weeks of storage ($P > 0.05$).

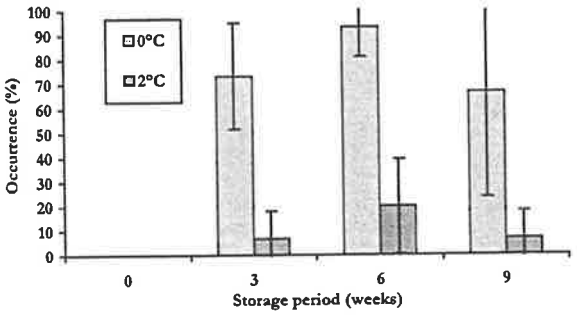

Fig. 1. The occurrence of the disorder, PPN, observed in Chinese cabbage cv. Yuki during low temperature storage. Values are means of 15 cabbages (three replicates of five heads each) expressed as a percentage and bars represent the S.D.

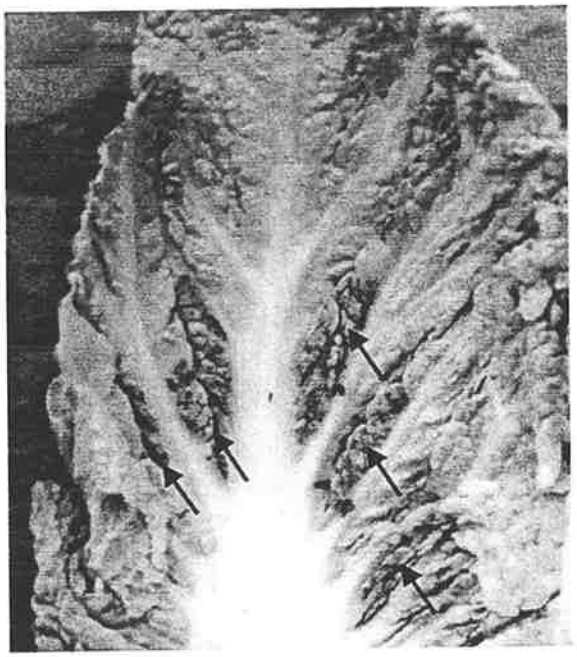

Fig. 2. PPN symptoms on Chinese cabbage cv. Yuki leaves. Symptoms are visible as translucent areas with brown discolouration between the leaf veins and are indicated by the arrows.

4. Discussion

Chinese cabbages lost weight during storage at all three temperatures, but the amounts lost were small at low temperatures. As most weight loss is due to water loss, storing the individual cabbages in perforated plastic bags inside waxed cartons helped to reduce the amount of water lost from the cabbages and contributed to the low results. Daly and Tomkins (1998) found weight loss of Chinese cabbages, stored in cartons at various tempera-

tures, was decreased when plastic carton liners were used. However, the higher vapour pressure deficit at 20 °C compared with lower temperatures caused significant water loss at that temperature.

Chinese cabbages had to be trimmed to a marketable head after harvest due to insect damage and the presence of tipburn on outer leaves; at harvest only the loose wrapper leaves had been removed. Thereafter, the proportion trimmed from the cabbages to achieve a marketable head increased initially over 1 week at 20 °C and 3 weeks at 0 and 2 °C, and then remained virtually constant. The trimming losses after storage were due to wilting and yellowing of outer leaves and pathogen infection at wound sites. At 20 °C it was not possible to produce marketable cabbages by trimming after 1 week. At the lower storage temperatures, the wilting and yellowing of outer leaves and the progress of rots were delayed.

The quality of the cabbages deteriorated during storage at all temperatures. Initial scores were influenced by preharvest factors such as the incidence of pest damage and tipburn. The deterioration in quality of cabbages stored at 20 °C was due mainly to yellowing, wilting, and pathogen infection. The quality of cabbages stored at 0 °C was affected by the development of PPN early in the storage period. Cabbages stored at 2 °C were less severely affected by PPN and senescence-related factors such as yellowing, and wilting caused by moisture loss contributed more to the decrease in quality at this storage temperature.

Daly and Tomkins (1998) reported low wilting for cv. Yuki stored for 40 days in high humidity at 0 and 3 °C, but severe wilting for heads stored in normal air at the same temperatures. Gajewski and Skapski (1994) reported good quality scores for cultivars 'Yoko' and 'Hanko' after storage at 0–2 °C for 12 weeks, but only after the heads had been trimmed. In the same experiment, approximately 35% of heads were considered unmarketable after this storage period and natural (but undefined) losses of up to 16.8% were reported. This is comparable to the trimming losses, approximately 14% after 9 weeks at 0 and 2 °C, observed in this study.

The occurrence and severity pattern of PPN suggests that this disorder is a form of chilling injury. No PPN was found in cabbages at 0 weeks storage, shortly after harvest, but it had developed after 3 weeks in low temperatures. Cabbages stored at 0 °C were more severely affected than those stored at 2 °C, and cabbages stored at 20 °C were not affected at all. Whilst the symptoms observed here are not the same as the 'brown midribs' chilling injury reported elsewhere for Chinese cabbage, they do fit the general visual symptoms of chilling injury in horticultural crops (Morris, 1982), that is, internal discolouration and breakdown of tissues. Chilling affects the cell membrane and metabolic functions and these changes eventually lead to cell death (Bramlage and Meir, 1990). Apeland (1984a) observed chilling injury in Chinese cabbage stored for more than 45 days at temperatures of 0 and 2.5 °C, and reported that the critical temperature varied between cultivars. Daly and Tomkins (1998) observed that three cultivars, 'Hector', 'Kasumi II' and 'Yuki', out of seven developed PPN after storage for 7 weeks at 0 °C. In the same trial 'Hector', 'Kasumi II' and another cultivar, 'WR Green 60', suffered the brown midrib form of chilling injury.

Chinese cabbage cv. Yuki has a low respiration rate, especially when stored at low temperatures. Daly and Tomkins (1998) investigated the respiration rates of Chinese cabbages stored at various temperatures and reported rates of around 4 mg CO_2 kg^{-1} h^{-1} at 0 °C and close to 6 mg CO_2 kg^{-1} h^{-1} at 3 °C after 6 weeks storage. In the present study, in comparison, rates for cv. Yuki after 6 weeks were approximately 1 and 2 mg CO_2 kg^{-1} h^{-1} for 0 and 2 °C, respectively. This difference is minor and may be due to variation between cultivars. Respiration rates were higher at 20 °C at 15 mg CO_2 kg^{-1} h^{-1}, after 1 week of storage, but increased significantly with the onset of senescence and pathological spoilage.

'Yuki' cabbages also produce very little ethylene during storage. At 20 °C rates of ethylene production directly after harvest were 525 ng C_2H_4 kg^{-1} h^{-1} and declined to 173 ng C_2H_4 kg^{-1} h^{-1} after 1 week of storage; this is classified as low by Kader (1992). Rates at 0 and 2 °C were consider-

ably lower still. An increase in ethylene production was found in the last measurement at all three storage temperatures and is most likely due to the action of various fungal and bacterial pathogens (Kader, 1992), particularly at 20 °C. Ethylene, even at low levels, is known to promote senescence (Wills et al., 1999), and increased levels of production would hasten deterioration and shorten the postharvest life.

Chinese cabbage cv. Yuki has low rates of respiration and ethylene production, making it suitable for long term storage at low temperature. Weight loss was not a significant factor at the low temperatures. However, commercial loss due to trimming is likely to be significant at any storage temperature, but in-field insect damage may predispose heads to higher losses. This influenced the deterioration in quality and the development of rots. Rots and senescent yellowing determined the end of storage life at 20 °C, and eventually at 2 °C as well. At 0 °C it was limited by the presence of PPN after 3 weeks, and this is a form of chilling injury. The differences between the three temperatures highlight the need to choose the minimum possible temperature when storing Chinese cabbage, balancing the need to control chilling injury with the need to delay senescence and rots. Another obvious choice would be to screen and select cultivars that do not suffer chilling injury, but both midrib browning and PPN need to be considered.

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THE EFFECT OF TIME OF DAY OF HARVEST ON THE POSTHARVEST LIFE OF CHINESE CABBAGE.

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INTRODUCTION

The early morning, when the temperature and respiration rate of produce is low and water status is high, is considered the best time to harvest vegetables (Thompson, 1996; Wills *et al.*, 1998) in order to maintain quality and prolong postharvest life. Harvesting in the late afternoon, when energy substrate levels are high (Lipton, 1987) and leaves are less turgid (Phan, 1987), may be better for leafy vegetables such as Chinese cabbage (*Brassica campestris* L. ssp. *pekinensis* (Lour.) Olsson).

This study was conducted to investigate whether the length of storage, the quality, the water status, or the energy substrate level of Chinese cabbages is influenced by the time of day of harvest or by delays in cooling the harvested heads.

MATERIALS AND METHODS

A crop of Chinese cabbage cv. 'Yuki' was grown at Ovens Research Centre in Victoria, Australia, and was harvested on May 4, 1999. Harvesting was carried out at five different times during the day (dawn, mid-morning, midday, mid-afternoon and dusk) and at each harvest, half the heads were held in the field for thirty minutes before cooling.

The cabbages were transported to the Adelaide University's Waite campus in refrigerated road transport and were then stored in perforated polyethylene bags, in cartons, at 0°C. Assessments of trimming loss, chlorophyll fluorescence, and quality were carried out at 0, 3, 6, and 9 weeks storage, and levels of energy substrates were measured at 0 weeks.

RESULTS

Neither the time of day of harvest nor the delay in cooling had an effect on the trimming loss, chlorophyll fluorescence, quality, and energy substrate levels of the Chinese cabbage (Table 1 and Figure 1). The length of storage, however, did have an effect with an increase in trimming loss, a decrease in quality, and decreases in maximum fluorescence (Fm) and variable fluorescence component (Fv) as the length of storage increased.

HEAD TEMPERATURES IN FIELD

Subsequent investigations were made into the temperature at various points inside and outside mature Chinese cabbage heads in the field using temperature data loggers. Three adjacent and uniform-sized cabbage plants, in a crop grown at Virginia, South Australia, were each fitted with five temperature data loggers with stab probes attached.

Typical recordings for a 24-hour period from the temperature data loggers are shown in Figure 2. The temperature inside the heads did not fluctuate as widely or as quickly as the temperature of the outer areas of the cabbages or in air.

Table 1. Trimming loss, quality score, and chlorophyll fluorescence parameters for Chinese cabbage harvested at different times of the day or held in-field for different periods prior to cooling.

	Harvest time					Holding period	
	Dawn	Morning	Midday	Afternoon	Dusk	0 hours	0.5 hours
Trimming loss (%)	22.6a[Z]	21.7a	21.3a	21.6a	21.8a	21.5a	22.1a
Quality score[Y]	2.2a[X]	1.9a	1.8a	2.4a	2.0a	1.9a	2.2a
Fm	3238a	3095a	3275a	3117a	3321a	3243a	3175a
Fv	2484a	2433a	2647a	2470a	2484a	2461a	2482a

[Z]Values are means of 24 heads x 3 replicates and different letters in rows for each factor denote significant differences using LSD (P=0.05).

[Y]Scores between 0 and 3 denote good (marketable) quality and scores >3 denote poor (unmarketable) quality.

[X]Data was analysed after transformation using square root, with back-transformed means shown.

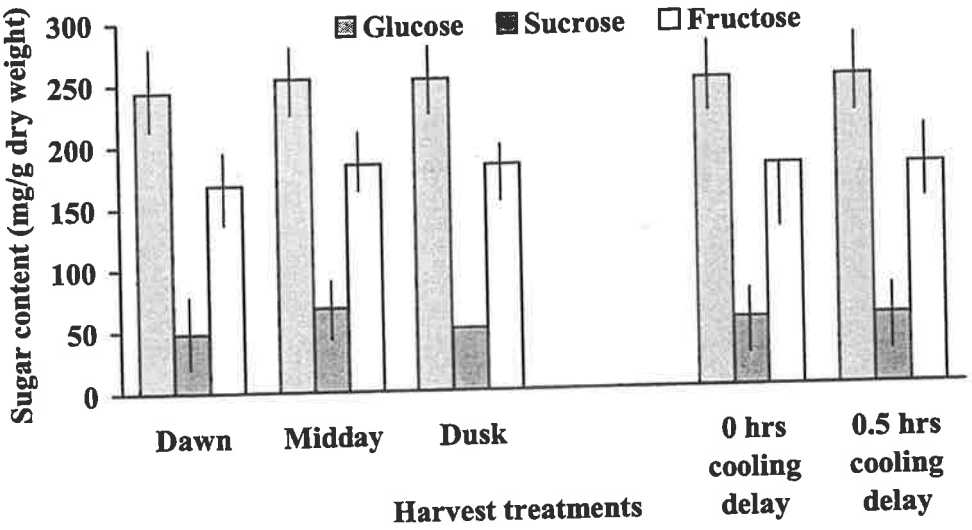

Figure 1. Levels of three sugars in middle leaf samples taken from Chinese cabbage harvested at different times during the day and held in-field for different periods prior to cooling. Harvest time values are means of 6 heads x 3 replicates and cooling delay values are means of 9 heads x 3 replicates. Lines represent the standard deviation for each value.

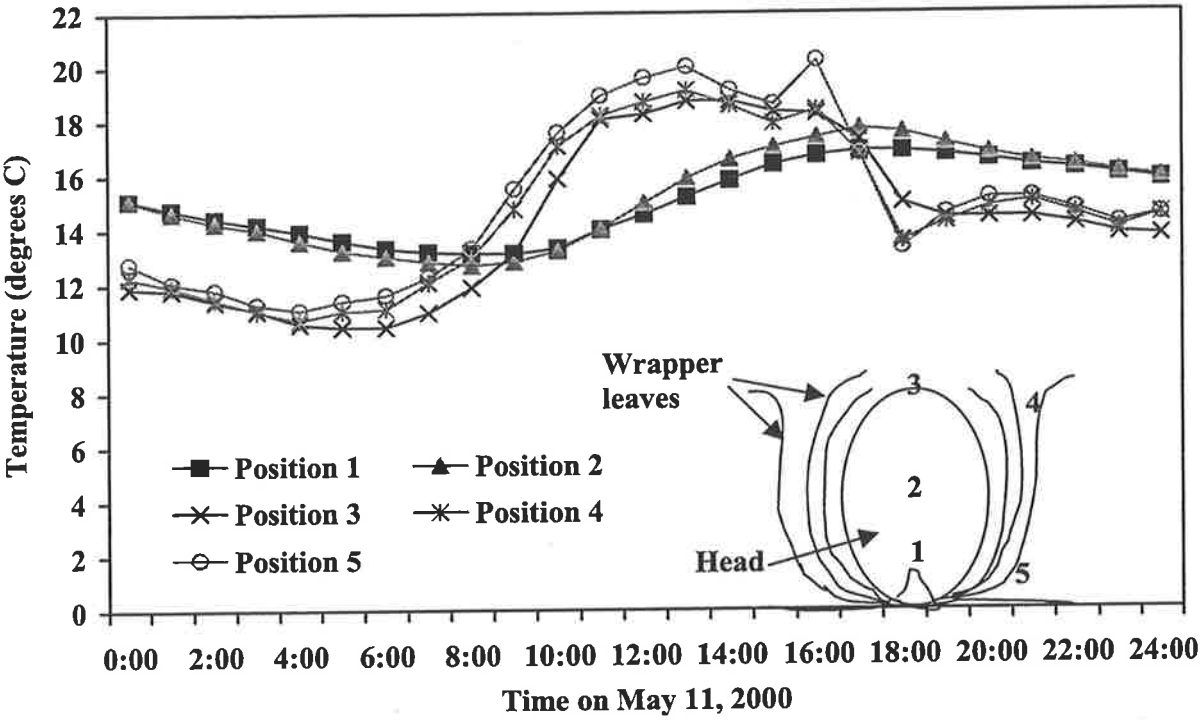

Figure 2. Temperature fluctuations at various positions inside and outside mature Chinese cabbage heads in the field over a 24-hour period. Minimum and maximum temperatures in the region for the same period, as recorded by the Bureau of Meteorology, were 13°C and 22°C, respectively. Values are means of three heads.

DISCUSSION

The postharvest evaluations show that time of day of harvest and a half-hour delay in cooling had no impact on postharvest behaviour of Chinese cabbage. Despite a maximum variance of approximately 15°C in air temperature between the dawn and afternoon harvests, cabbages from all harvests had similar trimming losses and overall quality. The results suggest that the cabbage heads have a mechanism of protection against exposure to high temperatures.

This is supported by the in-field head temperature data, which suggest that the interior of the head is insulated against temperature extremes by the outer and wrapper leaves. Most of these leaves were removed when the cabbages were harvested and therefore had no influence on the postharvest behaviour of the remainder of the head.

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