Curing Kiwifruit: Physical, Physiological and Storage Impacts

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ABSTRACT

Curing of ‘Hayward’ kiwifruit is a postharvest approach to reduce decay and maintain quality during long-term storage. Curing occurs immediately after harvest, with fruit placed in picking bins in a covered packhouse space for a few days. Curing contributes to fruit quality by allowing the picking scar to heal (resulting in reduced *Botrytis* rot) and allows a proportion of water loss, resulting in fruit cells that are less turgid and hence less prone to mechanical damage during packing. In the contemporary packhouse, curing is also used to buffer logistical challenges, since stockpiling fruit has advantages in ensuring the packing line continues to process fruit. In kiwifruit, the rates of cooling to storage temperature have previously been identified as an influence on long-term storage outcomes, including firmness and storage breakdown development (SBD). Little is known about how curing contributes to long-term storage, yet there is potential to impact post-storage fruit quality given that curing occurs immediately prior to packing and cooling. There is a lack of knowledge regarding the range of conditions which fruit are exposed to when bins are stacked under non-controlled conditions. It is also unknown how these conditions may influence fruit quality (i.e. fruit softening and SBD development) after long-term storage. This thesis incorporates monitoring of within bin environmental conditions to assess possible in-stack heterogeneity during curing.

The spatial-temporal variability of temperature and relative humidity (RH) in the curing stack and its effect on fruit weight loss are described for five different trials. At-harvest fruit temperature had the dominant effect on temperature variability in the stack, regardless of other environmental conditions. The temperature variability throughout the stack was 5-8 °C, with the effect of the initial picking temperature lasting up to approximately 24 h after harvest. The temperature variability in the whole stack reduced with increasing curing period, when bin position had a greater influence on temperature heterogeneity in the stack. The highest temperature was recorded at the top of the stack, resulting in a temperature difference between 2 to 5 °C between layers. One possible explanation for this phenomenon is thermal stratification under the packhouse canopy.

Under real conditions, RH increased to saturation (≥ 97% measured) a few (3-7) hours after the start of curing. Fruit weight loss was between approximately 0.3-0.5% over 2 to 3 days. Under the assumption that weight loss can be attributed to water loss, during saturated RH conditions in the bin, there would be a very low driving force for water loss, resulting in the low weight loss observed in the whole stack. Despite the low range of fruit weight loss, an

influence of at-harvest temperature and also bin position on weight loss could be discerned within each trial.

Controlled simulated curing conditions that mimicked real curing conditions were investigated with respect to long-term storage fruit outcomes. Fruit exposed to > 17.4 °C (with > 64% RH) for 4 days were consistently the firmest and had the lowest incidence of SBD after 100 days of storage. However, the effect of source-orchard on fruit quality outcomes were not suppressed by curing conditions. The range of fruit weight loss (0.6-1%) in fruit exposed > 17.4 °C (with > 64% RH) for 4 days was double that measured in industry.

These results suggest that the interaction of time and temperature during curing significantly influence fruit quality in long-term storage. Curing at > 17.4 °C (with > 64% RH) for 4 days was observed to be the best curing treatment to prepare fruit for long-term storage. However, the quantity of weight loss during curing may be an issue as grower payments are made on a mass basis which is first measured after curing when fruit enter the packing line. Applying curing at > 17.4 °C and ≈ 80% RH (ambient conditions) for 4 days is likely to happen in the industry situation during the months of March and mid-May, without needing the large monetary investments for controlled conditions at the packhouse.

The results of this study have potential implications for the kiwifruit industry. Environmental conditions during curing and the consequent spatial and temporal variability in the stack impact fruit weight loss and possibly post-storage quality outcomes. Applying curing under controlled conditions would allow reduction of variability, necessarily for late harvest fruit. Controlling curing conditions could favour maintenance of fruit quality in kiwifruit batches destined for long-term storage and also reduce curing imparted variability.

Further research is required to understand the mechanism of curing and to determine whether the beneficial effect of curing at > 17.4 °C and > 64% RH for 4 days occurred because of the effect of temperature on biochemical reactions on the cell wall or the effect of the physical process driven by the water loss.

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خراب و مست باساقی جان همی کوییم بر آر دست که ما دست ها بر آوردیم

اگر تو کار نکردی و مفلسی از غیر بیا که کار چو تو صد هزار ما کردیم

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CHAPTER 1

1 General introduction

Kiwifruit are harvested when they are firm and mature, but unripe to withstand postharvest handling. They are then immediately transported to the packhouse to complete the following steps of the supply chain. Curing is a postharvest approach which has previously been well-established in the kiwifruit (*Actinidia deliciosa* cv. 'Hayward') industry in order to maintain fruit quality during subsequent storage by controlling *Botrytis* rot (Pennycook & Manning, 1992; Bautista-Baños *et al.*, 1997; Retamales *et al.*, 1997). During this process, fruit are cured in large bins immediately after harvest by stacking them in ambient conditions (10 to 20 °C, 88%-higher than 92% RH) for 2-3 d at the packhouse (Bautista-Baños *et al.*, 1997; Retamales *et al.*, 1997). Fruit remain in these harvest bins until packed, often in large stacks and without environmental control. Curing for 1 week at 17 °C led to a 4-fold reduction in rot incidence for 'Hayward' after 12 weeks of storage at 0 °C (Wurms, 2005). Curing is likely to contribute to fruit quality by allowing time for the picking scar to heal (resulting in reduced *Botrytis* rot) (Wurms, 2005) and allows a proportion of water loss (Bautista-Baños *et al.*, 1995). In addition to fruit maturity, the time of application and environmental conditions (temperature and RH) during this period could have profound effects on the fruit outcomes.

Temperature management in the first 2 weeks subsequent to the harvest has been associated with influencing the development of chilling injury (CI) symptoms, referred to as storage breakdown disorder (SBD), and softening after long-term storage (Lallu, 1997; Lallu & Webb, 1997; Koutsoflini *et al.*, 2013; Zhao, 2017). CI is a major postharvest disorder which causes fruit losses in kiwifruit during prolonged storage at 0 °C (Koutsoflini *et al.*, 2013). Factors including fruit maturity at harvest, acclimation, cooling rate, storage time and temperature have all been shown to influence SBD incidence and fruit softening in kiwifruit in long-term storage (Lallu *et al.*, 1989; Burdon *et al.*, 2007; Yang *et al.*, 2013; Zhao *et al.*, 2015; Burdon *et al.*, 2017; Zhao, 2017). Given that curing is usually conducted in a non-controlled environment, there is a lack of certainty about what conditions fruit experience during this period, and how variable this may be through the curing stack. In particular, there is lack of representative research and data collected in real world conditions that demonstrate the actual conditions experienced by harvested fruit. Valentine and Goedhals-Gerber (2017) measured temperatures of apples in the first 48 h after picking. It was found that apples had the potential to increase in temperature by approximately 0.5 to 3.5 °C between the orchard and the packhouse facility.

Schick and Toivonen (2002) provided data of temperature and RH for bins of cherries between orchard and packhouse, and demonstrated that covering the bins had the potential to maintain high RH and more consistent fruit temperature.

In the first phase (see Chapter 2), this project aimed to provide better understanding of the conditions that may occur during a real full-scale curing. These include developing an understanding of the sources of variability that may be imparted onto a typical batch of kiwifruit, as well as the effects of the spatial and temporal environmental conditions related to bin positioning in the curing stack over fruit weight loss during curing. In the second phase (see Chapter 3), a curing practice simulation was developed to investigate the impact of curing condition. This included time and environmental conditions (temperature and RH) and their interactions on fruit quality outcome (fruit firmness and SBD development) during the subsequent long-term storage (25 w).

1.1 Literature review

1.2 Kiwifruit industry importance in NZ

Kiwifruit belong to the genus *Actinidia*. In comparison with other commercial plants, it has a short history of cultivation around the world. *A. deliciosa* and *A. chinensis* are the two main commercially well-known and significant species. They are usually regarded as distinct species but are sometimes considered as different varieties. In the last decade, it has been reported that *Actinidia* has 55 species but about 76 distinct taxa. These numbers are constantly changing through the results of new research (Burdon & Lallu, 2011).

The centre of *Actinidia* diversity is located in south central and southwest China (Liang, 1983). It was in the late 19th century when *A. deliciosa* was introduced into cultivation. In 1904, Isabel Fraser, a missionary, brought a handful of kiwifruit seeds from China to New Zealand. It then took three decades from that initial introduction of seed until the first commercial orchards were established around 1930 (Ferguson, 2004). Different kiwifruit cultivars such as ‘Abbott’, ‘Allison’, ‘Bruno’, ‘Hayward’ and ‘Monty’, were introduced with a commercial capability to export. Export of the first New Zealand kiwifruit load took place in the 1960s. Since then a major goal has been to maintain fruit postharvest qualities and storability to reduce fruit loss.

Actinidia deliciosa [A. Chev.] C. F. Liang and A. R. Ferguson var. *deliciosa* 'Hayward' marketed as ZESPRI™ GREEN is New Zealand's most important export cultivar (Schroder & Atkinson, 2006). The long storage life of 'Hayward' allowed the development of a New Zealand kiwifruit industry based on exports by ship to distant markets (Debersaques *et al.*, 2010). It became the most dominant cultivar which includes 85% of the produced kiwifruit around the world (Hancock, 2008). The other species, *A. chinensis*, covers about 15% of the worldwide demand for kiwifruit (Hancock, 2008). There are other cultivated *Actinidia* species such as *A. arguta, A. eriantha, A. kolomikta and A. polygama*, which haven't reached the top position in the ranking of commercially important species. 'Hayward' was able to overcome other cultivars commercially, because of its high postharvest qualities and better flavour. All the early cultivated *A. deliciosa* including 'Hayward' are selections of a few seedlings grown from introduced seeds to New Zealand from China in the early twentieth century. There are probably only a few generations from the original seeds brought by Isabel Fraser (Schroder & Atkinson, 2006). The fruit was larger, and much wider in relation to the length, had a better taste and appearance compared to other cultivars. Although 'Hayward' has some disadvantages such as being less productive and manageable compared with other kiwifruits, its advantages outweigh the above mentioned disadvantages (Debersaques *et al.*, 2010). Therefore, the New Zealand kiwifruit industry motivated other countries to imitate the growing of 'Hayward', which was made possible by the (in retrospect very commercially unwise from an NZ-perspective) export of large quantities of plants by NZ nurseries. This international dependency and reliance of kiwifruit industry on a particular cultivar is somehow unusual and unique. It has specific advantages such as standardisation amongst suppliers from different countries. However, the standardisation makes more challenges in branding and competing in the same market, because companies with strong brand identity and strong reputation will gain the most benefits from standardisation approach. Moreover, the standardisation simply ignores different needs and tastes of different markets and their preferences (Alwazir, 2013). Other countries developed their kiwifruit production based on 'Hayward' originally from New Zealand. Some important 'Hayward' bud mutations selected as clones for production are 'Clone 8', 'Clone K', 'CloneMaeba®', 'Top Star®', 'Green Light®', 'Earligreen®' and 'BO-Erica®' produced in Italy (Debersaques *et al.*, 2010).

Despite the domination of 'Hayward', the introduction and marketing of new cultivars have changed the kiwifruit industry. For many years the kiwifruit industry worldwide was based on 'Hayward'-until the release of 'Hort16A'. 'Hort16A' was the result of a cross and created by

HortResearch (now the New Zealand Institute for Plant & Food Research Limited). It appeared in 1987 and was marketed as ZESPRI® GOLD Kiwifruit. *A. chinensis* 'Hort16A' was released as a commercial product in 2000. It has a yellow flesh, and is more aromatic, flavoursome and quite different from 'Hayward', but is highly susceptible to Psa-V. Thus it has been replaced by new, more-tolerant varieties mainly Gold3 (Zespri SunGold) (NZ Kiwifruit Growers, 2016).

Kiwifruit is one of the most widely studied fruit systems in the world (Schroder & Atkinson, 2006). Understanding postharvest issues of new cultivars which have been recently released could be quite challenging and costly, but it is still worthy. Monoculture, even when there is an internationally well-established cultivar as 'Hayward', may not be a best practice, because a single threat can destroy the whole industry globally. As mentioned above, in 2010, the deadly bacterial infection Psa-V which is a virulent form of the disease, first became established in New Zealand kiwifruit orchards. After 6 years, it has affected about 80 percent of kiwifruit orchards in New Zealand and has become a big problem for the kiwifruit industry. This failure can be blamed on the dominance of monoculture in the kiwifruit industry worldwide (Rainey, 2012; NZ Kiwifruit Growers, 2016).

The volume of internationally traded kiwifruit in comparison with some other fruit is relatively low, but for some countries, like New Zealand, kiwifruit sits on top of the horticultural exports list. In 2016, the total area of cultivated kiwifruit in New Zealand was about 12,185 ha which yielded 10,157 trays/ha, the export valued at $1.672 billion. New Zealand kiwifruit was exported to 58 countries. The top three on this list were Asian countries, i.e. Japan $390m; China $373m and Taiwan $154m in the same year. To introduce new kiwifruit selections, more than $10 million has been invested by Zespri, Plant and Food Research and the New Zealand Government in the world's largest kiwifruit breeding programme in 2015.

This overview of kiwifruit production illustrates how this growing industry has a critical impact on New Zealand's economy (FreshFacts, 2016).

1.3 Fruit maturity in kiwifruit

Harvest index and physiological maturity are two different concepts, although they are usually used interchangeably (Burdon & Lallu, 2011). A harvest index would assist the grower to predict the fruit performance in long-term from harvest to storage time. Fruit may be picked at different maturity stages which will affect the fruit storability for a short or long cold storage.

Optimum harvest time is when fruit growth has slowed down or almost completed. In kiwifruit orchards, fruit are usually harvested all at once. Therefore, fruit at a range of maturity may be seen in a load of harvested fruit. At harvest, fruit are firm and mature, but unripe and starchy. Since 1980, the New Zealand kiwifruit industry has considered 6.2% SSC content as a minimum maturity index for harvesting 'Hayward' kiwifruit (Snelgar *et al.*, 1993; Crisosto & Crisosto, 2001). SSC content is important because it shows fruit physiology changes when starch degradation is initiated. It could also increase fruit tolerance to low temperature or chilling-stress during storage (Crisosto & Crisosto, 2001). In addition, fruit firmness is the principal quality criterion, because it determines fruit capability for commercial handling practices through the entire supply chain, from the orchard through to the consumers (Lallu, 1997; Burdon *et al.*, 2017). Maturation is usually defined as a stage leading to the attainment of ripening capacity, and this stage of development occurs after growth completion and before fruit ripening and senescence.

1.3.1 Maturity, ripening, and ethylene

In the plant kingdom, the growth hormone ethylene acts to stimulate and regulate physiological processes such as fruit ripening (Wang *et al.*, 2002). The ripening process is accompanied by a respiratory peak and a burst of ethylene production. The ethylene burst results from autocatalytic stimulation of ethylene synthesis (Pech *et al.*, 2008) and is representative of a multitude of events affected by ethylene during fruit ripening which have been discovered (Chaves & Mello-Farias, 2006). However, ethylene independent regulation also exists in climacteric fruit (Pech *et al.*, 2008) such as citrus fruit, strawberries, pineapples, and pomegranates etc. An increase in respiration rate and ethylene was either not observed or it occurred only temporarily after the application of exogenous ethylene (Paul & Pandey, 2014). The mechanisms involved in ethylene and fruit ripening are different between climacteric and non-climacteric fruit. Ethylene involves in regulation of physiological activities such as initiation of fruit ripening, softening, increased respiration rate and autocatalytic ethylene production (Chiaramonti & Barboni, 2010).

Kiwifruit has been considered as a climacteric fruit (Boukouvalas & Chouliras, 2005; Chiaramonti & Barboni, 2010; Paul & Pandey, 2014), although it is unique in that softening occurs independently of climacteric ethylene production (Atkinson *et al.*, 2011; Burdon *et al.*,

2017). Kiwifruit produces little ethylene (<0.01 nL kg^{-1} h^{-1}) at harvest), unless the fruit firmness drops to less than 1 kg_f and reaches the eating softness (Burdon & Lallu, 2011).

During long-term storage, ethylene concentration should remain less than 0.01 µL L^{-1}, because kiwifruit is very sensitive to ethylene and softening increases with ethylene (Mcdonald, 1990; Ritenour *et al.*, 1999). Ethylene concentrations are held to less than 0.03 µL L^{-1} during long-term storage in the New Zealand kiwifruit industry (Burdon & Lallu, 2011). In kiwifruit, softening and ethylene production do not occur concurrently. The climacteric burst takes place in the third phase of softening when it develops an edible quality and acceptable flavours. The initial and the second phases of softening occur independently of ethylene production. Ethylene treatment on firm kiwifruit (mature but unripe) could decrease softening time from 3-4 w to 6-7 d and also cause more uniform ripening in fruit (Schroder & Atkinson, 2006). The response of fruit to exogenous ethylene treatment varies with fruit maturity at harvest. It has been reported that early harvested (less mature) kiwifruit stored at 0 °C, and then held at room temperatures (20 °C) to ripen were more responsive to exogenous ethylene sources than late harvested (more mature) fruit. It has also been found that ethylene treatment facilitates the rapid softening early harvested fruit (Lallu *et al.*, 1989). Ripening is an irreversible phenomenon which consists of a series of particular physiological and metabolic changes which influence the cell wall's components. Ripening finally results in fruit softening when the fruit firmness decreases from 9 kg_f to 1 kg_f before 'eating ripe' and develops a soft edible texture with desirable quality attributes (Redgwell & Percy, 1992).

Different factors such as fungal rot, low temperature break down, and respiration could induce the ethylene production and cause fruit softening (Feng *et al.*, 2002).

1.4 Key factors in fruit loss in the kiwifruit industry

Kiwifruit are capable of long-term storage (more than four to six months), while still keeping their main fruit quality properties such as texture and flavour, without being affected by postharvest diseases and disorders (Chiaramonti & Barboni, 2010). In 'Hayward', this phase occurs after about 160 d after fruit set (Burdon & Lallu, 2011). Early maturing kiwifruit usually have lower dry matter associated with the higher fruit firmness at harvest. These fruits are more susceptible to low-temperature injury (Burdon & Lallu, 2011). On the opposite side, over-mature fruit are vulnerable to losing their edible quality as perceived by the consumer, because

of damage during the postharvest handling (Boukouvalas & Chouliras, 2005; Burdon & Lallu, 2011).

1.4.1 Softening

Softening, as determined by fruit firmness, is one of fruit quality attributes which directly determines storability and is used as kiwifruit-storage quality index (Harman & Mcdonald, 1989). It can determine the limitations of commercial handling procedures from storage to export, thus it is critical to understand fruit softening (Burdon *et al.*, 2017).

'Hayward' has also been found to have a lower respiration rate (Saltveit *et al.*, 2004) and lower ethylene sensitivity than other genotype (Kim, 1999). These two factors play a critical role in storability of 'Hayward' and in its commercial success.

Fruit softening is an integral part of fruit ripening (Satake *et al.*, 2002). Both physical and biochemical changes are involved in the kiwifruit softening process. The cell turgor level or water loss during storage as the main physical factor and the relevant biochemical changes in cell wall contribute to fruit softening (Li *et al.*, 2016). Kiwifruit softening follows a sigmoidal pattern (Burdon *et al.*, 2017). Atkinson *et al.* (2011) have shown that the typical softening curve of kiwifruit can be distinguished as four different phases, each with different physiological activities involved in the process. Fruit are harvested firm with high starch content and then they soften slightly, which signals the beginning of the initiation phase (Phase 1). In this phase, the fruit does not produce endogenous ethylene but it is very responsive to exogenous ethylene. The fruit then enters the Phase 2 which is a rapid softening. Although fruit firmness reduces significantly at this stage, because of starch degradation (Macrae *et al.*, 1989) and pectin solubilisation is mediated by amalyse and pectin methyl esterase (PME) activity. In Phase 3 (slow stage), the rate of fruit softening slows down and the fruit softens to 'eating ripe' (0.6-0.8 kg_f). Other processes of ripening include physiological events, such as cell wall swelling, the breakdown of the middle lamella, and the highest rate of endogenous ethylene production occur in the third phase. Fruit flavour and aroma enhancement happen at this stage of fruit softening. In Phase 4, ethylene production continues, until fruit are not edible anymore and will be considered as 'over-ripe' (Figure 1.1) (Atkinson et al., 2011). However, in the literature, it is mostly the first three phases that have been discussed in relation to kiwifruit softening,

because the over-ripe fruit of the fourth phase are not commercially acceptable (Burdon *et al.*, 2017).

Figure 1.1: Schematic representation of kiwifruit softening, showing the timing of the main physiological events (Atkinson *et al*. 2011).

Fruit softening on the vine and during storage both show a similar pattern. At-harvest Fruit firmness has a direct impact on the progress of the fruit softening curve during storage. There is a lower chance for harvest fruit at a less mature stage to develop thoroughly during storage. Therefore, the first phase of fruit softening may be prolonged at storage, but these fruits are more susceptible to low-temperature disorders (Burdon & Lallu, 2011), because they may soften rapidly at higher temperature. While, more mature fruit which pass the first phase of softening completely on the vine, the second and third phases will occur during or after storage.

Schroder and Atkinson (2006) have conducted and reviewed a vast amount of research on cell wall texture, microstructure and cell wall composition changes and related enzyme activity associated with fruit softening. They reported that the complicated process of softening starts with pectin softening, solubilisation, and de-esterification, an increase in PME and cell wall

swelling. The sequence of some complicated physiological events, such as the soluble pectin and galactose degradation and xyloglucan's molecular weight reduction, take place in the cell wall during rapid softening. Further pectin solubilisation and maximal cell wall swelling occur when the fruit firmness reaches around $1kg_f$ and then the rate of softening slows down (Schroder & Atkinson, 2006). The rate of fruit softening decreases at low temperatures, because the degradation of pectins and hemi-celluloses in the cell wall and the water retention capacity decrease (Paliyath *et al.*, 2012).

Some cell wall enzymes such as PME, polygalacturonase (PG), β-galactosidase, xyloglucan endotransglucosylase/hydrolase and mannan transglycosylase have been extracted from kiwifruit (Schroder & Atkinson, 2006). Although these enzymes are associated with cell wall modification and alteration, their roles in the softening and their interaction have not yet been clarified and elaborated.

Temperature management could impact the fruit softening curve. A key industry aim is to prolong the fruit storability by decreasing the rate of softening, and thus delaying the fruit ripening (Macrae *et al.*, 1989; Lallu, 1997).

In fruit ripening, water mobility is more important than the water content. The water vapour pressure deficit (WVPD) outside of the fruit depends on temperature and RH of the air. Therefore, minimal variation of WVPD, which is the main driving force for water loss, could impact the softening rate. It shows the critical role of temperature variation resulting in water loss which influences fruit softening (Waelti, 1991; Taglienti *et al.*, 2009).

Patterson *et al.* (2003) showed that higher temperatures (to a range of –1.0 to 5 °C) during storage (16 w) shortened the initial softening phase and accelerated the second phase. Also, shifting from the second to the later phase occurs in lower fruit firmness (Patterson *et al.*, 2003). Also, shifting from the second to the later phase occurs in lower fruit firmness (Patterson *et al.*, 2003). In two subsequent years, Hertog *et al.* (2016) investigated fruit softening in early harvested 'Hayward' from 14 growers. Fruit were treated with exogenous ethylene levels (0, 0.1, 10 and 200 μL L^{-1}) and stored under temperature conditions (within the range 0, 2, 5 and 10 °C) for 4 weeks, followed by an ethylene free shelf life period (6 w) at (0, 5, 10 and 20 °C) to model and predict the effects of these factors on fruit softening. Firmness levels were monitored using a non-destructive compression technique. It was observed that fruit softening increased in higher temperature. The first phase of fruit softening phase shortened by increasing temperature even when temperature increased only 2 degrees from 0 °C and the second phase

of softening took place immediately at higher temperatures. Increasing ethylene also had a similar effect on reducing the first phase softening time and enhancing fruit softening. Even at low temperature (0 °C), ethylene levels as low as 0.1 μL L^{-1} could accelerate fruit softening.

Burdon *et al.* (2017) compared the pattern of 'Hayward' fruit softening in response to a temperature range of 0-16 °C. This involved two separate studies, one with a short time-frame of three weeks, and one with over 6 d followed by coolstorage of up to 20 weeks. In short study, fruit softened more rapidly at 8 °C compared to lower (4 °C) and intermediate temperature (12 °C). Immediately cooled fruit were the firmest. In the long study, fruit stored at 16 °C for 4 d were the firmest, while fruit stored at 8 °C were the softest.

In a parallel study, Burdon *et al.* (2017) also observed that there was a consistency in fruit response to temperatures from 0 to 16 °C after one week treatment, regardless of fruit maturity (8 harvest time from April to June). The results showed that fruit held at 10 °C softened more rapidly in comparison with other temperatures over a variety of fruit maturity.

According to the fruit response to temperature, the authors suggested that when the temperature dropped from 16 °C to 10 °C, it may trigger fruit softening, but temperatures lower than 8-10 °C decreased the softening rate. They stated that this possibly occurred, due to the biochemical reactions rate or temperature-regulated effects on fruit softening (Burdon *et al.*, 2017).

1.4.2 Storage breakdown disorder

Kiwifruit are capable of being stored in a coolroom at 0 °C for about 4-6 months (Lallu *et al.*, 1989; Burdon & Lallu, 2011). Storage temperature has a crucial role in slowing down the physical and biochemical activities associated with ripening. However, the common storage temperature (0 °C) for 'Hayward' leads to SBD or CI symptom in long-term storage and causes fruit quality loss (Burdon & Lallu, 2011).

'Hayward' has the lowest susceptibility to low temperatures among kiwifruit cultivars, although the reason for this is unknown. Despite high tolerance to CI, 'Hayward' still may show CI symptoms after long-term cold storage. SBD is a form of CI which is the only consistent postharvest disorders in the commercial storage of kiwifruit. Other physiological disorders are largely related to SBD. SBD negatively impacts fruit integrity (firmness) which is the main and basic requirement for fruit storability and could limit commercial export.

SBD is also known as low temperature breakdown (LTB) is one the major disorders that causes noticeable fruit quality losses in kiwifruit during storage (Gerasopoulos *et al.*, 2006; Koutsoflini *et al.*, 2013). In early harvested fruit (i.e. Kiwistart), symptoms appear in about 8 to 10 weeks of storage and continue to development through storage. Initially, Harman (1981) categorised internal breakdown in the outer cortex tissues after long-term storage as symptoms of SBD. Later, SBD symptoms were characterised in more detail by Lallu (1997). To include graininess in the outer pericarp and a water-soaked appearance in the outer and/or inner pericarp at the distal end of the fruit. SBD typically increases gradually towards the equatorial part of the fruit throughout storage and may develop scattered and pitted dark (Lallu & Webb, 1997; Burdon & Lallu, 2011).

SBD symptoms such as a granular and grainy appearance occur in the outer pericarp, due to increasing galactosyl residues level and cell wall materials and the existence of air bubbles in cells (Bauchot *et al.*, 1999). Observation of outer pericarp tissue from unaffected and disordered fruit by light microscopy and scanning electron microscopy showed graininess appearance is related to the presence of gas bubbles in cells (Bauchot *et al.*, 1999). Cell wall analysis also demonstrated that the cell wall material yields (CWM) were 40% higher in the CI affected tissue compared to healthy tissue. Moreover, in affected tissue, galactosyl content in the CWM of the outer pericarp was 70% higher compared to unaffected tissue (Bauchot *et al.*, 1999). Galactosyl is one of two main side chains of RGs-I (Rhamnogalacturonan I) which is a quantitatively important pectic polysaccharide solubilized from primary cell wall (Albersheim *et al.*, 2010). Given that SBD is a form of chilling injury that could trigger some changes in the microviscosity of the membrane, the sterol level or changes in phospholipid fatty acid structure, all of which could result in enhancing membrane permeability or ion leakage. Electrolyte leakage appears as water-soaked lesions and is used as a marker of damage of cell membrane integrity and the oxidative stress intensity (Gerasopoulos *et al.*, 2006; Aghdam & Bodbodak, 2014).

Different enzymes and their activities are involved in chilling injury. Mealiness or woolly texture, a common symptom of chilling injury in peach during or after coolstorage, is related to endo-polygalacturonase (endoPG) activity which is also involved in fruit softening. Peace *et al.* (2005) have conducted different classical and molecular genetics approach to identify genes involved in physiological pathways of mealiness incidence. It was observed endoPG activity had a significant contribution to the development of mealiness. The F-M/endoPG locus also influenced the development of red pigmentation (bleeding), a symptom of mealiness in

peach. These authors suggested endoPG is probably the first of the relevant genes for mealiness incidence and probably the accumulation of red pigmentation.

1.4.2.1 Factors affecting SBD incidence in kiwifruit

Different preharvest (fruit maturity at harvest, cultural practices, and environmental conditions) and postharvest (cooling rate, cooling time, storage temperature and storage duration) factors influence the susceptibility of kiwifruit to SBD.

Preharvest conditions such as low temperatures in the orchard could acclimatise fruit to lower temperature and lead to lower SBD incidence throughout long-term storage. Orchard temperature impacts the rate of change of starch to soluble solids content particularly in the outer pericarp (Burdon *et al.*, 2007) and also reduces fruit susceptibility to SBD incidence in storage (Sfakiotakis *et al.*, 2005; Burdon *et al.*, 2007). Therefore, fruit susceptibility to low temperature storage is related to fruit maturity at harvest and fruit capability to acclimatise to low temperatures before harvest. 'Tomua' kiwifruit (*A. deliciosa* (A. Chev.) C.F. Liang et A.R. Ferguson var. 'Tomua') harvested at weekly intervals in two successive years and stored at 0 °C were found to have lower SBD incidence. SBD was also reduced when there was more cold nights with temperature lower than (< 7 °C) prior to harvest, this acclimation to low temperature was accompanied by higher soluble solids content (SSC) accumulation. It suggested that consecutive hours of cold temperature is required to convert starch to SSC at a steady rate resulting in lower susceptibility to SBD in 'Tomua' (Burdon *et al.*, 2007). Sfakiotakis *et al.* (2005) investigated the effects of preharvest low temperature on SBD incidence in 'Hayward'. An over-vine mist system was installed in the orchard and the cumulative preharvest hours below 10 °C were recorded during fruit maturation (from last month before harvest in early mature fruit to three months before harvest in late maturity). Fruit were harvested at three harvest dates i.e. the control fruit; no hour of accumulative low temperature (early maturity), 90 h (mid maturity) and 180 h (late maturity) below 10 °C. Fruit firmness and SSC were measured at harvest, while SBD incidence was measured after storage at −0.5 °C and 90% RH for 24 weeks. The results demonstrated that less mature fruit were significantly more susceptible to SBD compared to late harvested fruit. Gerasopoulos and Drogoudi (2005) showed that higher Ca^{2+} in the fruit pericarp that were sprayed with $CaCl_2$ before harvest and also had a summer-pruning decreased the SBD incidence. Given that the fruit pericarp Ca^{2+} content increased up to 64% after the treatment which may be involved in

lower SBD incidence. However, it may not be the only reason for the extended fruit storability after the applied treatments, because summer-pruning treatment also caused a similar response that was the same or similar to $CaCl_2$ spray associated response.

Koutsoflini *et al.* (2013) reported the incidence of SBD was higher in early harvested fruit, than in mid- and late-harvested fruit. In this work, fruit harvested at five different maturities were exposed to delayed storage of 0, 1, 2, 3 and 4 weeks at 20 °C or 1 μL L^{-1} ethylene for 24 h and subsequently stored at −0.5 °C and 90% RH for 24 weeks followed by a shelf life of 5 d at 20 °C. The incidence of SBD increased rapidly with increasing length of delay before storage at 20 °C. Fruit with no delayed storage (control) had 11% SBD incidence. Fruit exposed to delayed storage for four weeks before coolstore demonstrated 95-100% of SBD. Moreover, at-harvest fruit maturity had a significant effect on SBD incidence. Early mature fruit showed 78-82% SBD incidence, while the incidence decreased to 11% at the mid (third) fruit harvest fruit and did not show any change for two late mature fruit harvests in comparison with the mid harvested fruit. For the exogenous ethylene treatment at harvest before storage, ripening was advanced and resulted in an increase of SBD incidence by 17.3% in comparison with control fruit after 24 weeks storage. Early harvested fruit with higher firmness softened faster than late-harvested fruit which showed a higher membrane permeability with the development of maturation and during storage (Abdala *et al.*, 1996). It has been reported that the increase of unsaturated fatty acids causes increased fluidity of the membrane and leads to low temperature adaptation. The unsaturated fatty acids, in particular linoleic (about 2.5 to 3.5%) and linolenic (about 12%), increased significantly in more mature fruit (late-harvest fruit) at harvest and after 2, 4 and 6 months of storage at 0 °C. The increase of membrane permeability by changes of the lipid composition through the ripening progress is associated with low temperature adaptations.

Repeated low temperature exposures have a cumulative effect on chilling injury (Vigneault *et al.*, 2009). This means that the temperature management (gradual cooling or rapid cooling and the exposure time) at the beginning of the cold chain will influence SBD incidence. However, SBD is generally only visible after prolonged storage when fruit firmness decreases to 'eating ripe' level (Burdon, 2018). Temperature management during fruit storage can impact the incidence of SBD in stored kiwifruit. Gwanpua *et al.* (2018) investigated the effect of temperature switching between 0 and 2 °C at different times in storage as a potential technique to improve storage outcomes. 'Hayward' and 'Zesy002' kiwifruit of different maturities were subjected to dual temperature treatments by switching fruit from either 0 or 2 °C to 2 or 0 °C, respectively. It was observed that initial storage of 'Hayward' at 0 °C following by 2 °C

resulted in a lower proportion of soft fruit and reduced SBD incidence. ‘Hayward’ was more susceptible to SBD than ‘Zesy002’. At-harvest maturity had a significant effect on fruit susceptibility to SBD after long-term storage. After 150 d storage, ‘Hayward’ kiwifruit that were stored continuously at 0 °C showed a sudden decline in fruit firmness, but not in the dual temperature treatments. The proportion of soft fruit was correlated with SBD incidence. Lallu (1997) reported up to 99% SBD incidence after 24 weeks storage at −0.5 °C in fruit of some orchards, while only 9% of the fruit showed SBD at 2.5 °C for 24 weeks. Likewise, SBD incidence was significantly higher in rapidly cooled fruit in comparison with passively cooled fruit. The incidence and the severity of SBD significantly decreased when the cooling time increased from 6 hours to one week after harvest. The incidence of SBD in rapidly cooled fruit and passively cooled fruit, held at 0 °C for 20 weeks was 17% and 3%, respectively. In addition, SBD incidence and its severity progressed with storage time. While, there was only 14% SBD incidence with low severity after 20 weeks at 0 °C, it increased to 76% with more than 30% of stored fruit displaying moderate and severe SBD after 24 weeks. It was suggested that SBD incidence and its severity is closely related to the rate of cooling and also storage temperature and its duration. In another experiment, ‘Hayward’ kiwifruit from four orchards were exposed to either forced air cooling (9-12 h) or passive cooling and then stored at 0 °C for 20 weeks (Lallu & Webb, 1997). SBD incidence ranged from 15 to 46% in different orchards after 20 weeks at 0 °C when fruit were precooled from 16 °C (picking temperature) to 2 °C within 9 h before being stored at coolstore 0 °C. The SBD incidence was between 2 to 39% in fruit of the same orchards which were passively cooled down to 0 °C and held for 20 weeks. However, precooled fruit were firmer, but they showed a higher incidence of the stem-end *Botrytis* and physiological pitting and SBD incidence compared to non-precooled fruit for up to 10-15 weeks in storage (Lallu & Webb, 1997). They recommended that the precooling practice should be not used for fruit from the orchards which showed higher susceptibility to physiological pitting and SBD, and also *Botrytis* incidence (Lallu & Webb, 1997). Yang *et al.* (2013) found that low-temperature conditioning (LTC) at 12 °C, 90-95% RH for 3 d effectively reduced SBD incidence and also suppressed fruit softening, respiration rate and ethylene production in stored fruit at 0 °C, 90-95% RH for 120 days. They suggested LTC could alleviate SBD incidence, due to antioxidant system activities enhancement which scavenges oxygen species and maintains membrane integrity. Zhao *et al.* (2015) investigated the effect of rapid cooling (3 d) and gradual cooling (2 w) on fruit softening of ‘Hayward’ kiwifruit during storage (0 °C for 25 w) and also SBD incidence. Rapidly cooled fruit displayed a higher fruit softening rate after 40 d storage compared to gradually cooled fruit. The results also showed that the rate of respiration

increased in rapidly cooled fruit after 120 d storage, probably due to SBD incidence. The authors suggested the lower rate of SBD in coolstore after the gradual cooling condition is possibly associated with the temperature acclimation, thus decreasing the proportion of soft fruit.

Healthy and non-injured kiwifruit do not produce a measurable amount of ethylene unless firmness becomes less than 1 kg_f. However, SBD incidence induces ethylene biosynthesis which causes fruit softening in adjacent healthy fruit (Feng *et al.*, 2002). Jabbar and East (2016) investigated the effect of the continuous application of four exogenous ethylene concentrations (0.001, 0.01, 0.1 and 1 $\mu L\ L^{-1}$) on stored 'Hayward' kiwifruit at 0 °C, 95% RH. Susceptibility to SBD development increased at higher ethylene concentrations (1 $\mu L\ L^{-1}$). These authors suggested ethylene could contribute to SBD incidence accompanied by its effect on fruit firmness.

The Literature Review (Chapter 1) discusses the importance of temperature management and temperature variability during fruit maturity and after harvest even in initial steps of the cold chain including precooling, cooling rate, storage temperature, and its duration impact the physiological responses and quality of fruit, i.e. fruit firmness, SBD incidence and the severity of it to storage condition in prolonged storage. There are consistent results about the potential effects of conditioning temperature and its interaction with time on fruit performance in coolstorage which provided a framework to adequately identify and address the research questions for this study.

1.4.3 *Botrytis cinerea*

Various fungi may cause postharvest rot in kiwifruit, and they attack different parts of the fruit. In New Zealand, grey mould, caused by the fungus *Botrytis cinerea* (Pers.), was a serious postharvest problem of 'Hayward' kiwifruit. It attacks fruit through the picking wound at harvest (Beever, 1991; Wurms, 2005; Prusky & Gullino, 2010). In the 1980s, it caused NZ$10 million per year economic loss in the NZ$200 million NZ kiwifruit industry (Manning *et al.*, 2010). In Korea, postharvest rot of kiwifruit caused 32% of fruit losses (Mari *et al.*, 2015). Nowadays, in New Zealand, the effects of *Botrytis* has been lessened significantly due to the effective orchard management approaches, but because of the size of the industry, the total losses can still be enormous (Wurms, 2005; Prusky & Gullino, 2010).

Apart from the direct losses due to fruit spoilage, the rate of ethylene production increases in infected fruit, and this causes premature softening in the stored fruit (Niklis *et al.*, 1995).

After few months of storage, the symptoms of the disease appear on stored fruit. At harvest, fruit picking creates wounds on fruit skin and facilitates the transfer of pathogens. Therefore, the infected area tends to start from the stem-end of the fruit. It is also observed that in overly ripe fruit fungal conidia enter directly inside the fruit through any damage or injury on fruit skin (Brook, 1992).

The fruit tissue is the principal barrier against infection (Wurms, 2005). The diseased tissues appear darker in colour than healthy tissues and are frequently covered by white mycelium that evolve to a grey colour as conidia are produced. Internal colonized tissues are dark green in colour, water-soaked and soft, and separated from surrounding healthy tissues by clear margins (Mari *et al.*, 2015).

Infected fruit do not pass the importing country's phytosanitary requirements standards and cause severe economic loss (Manning *et al.*, 2016).

The incidence and severity of stem-end rots in harvested fruit could be controlled by pre-harvest production practices which cause the lowest inoculum load on the vine canopy (Manning *et al.*, 2010).

Curing is an important non-pesticidal control of stem-end rot of kiwifruit (Pennycook & Manning, 1992). *Botrytis* apparently increases by reducing cooling rate of fruit at coolroom. However, related biochemical and physiological mechanisms are not fully investigated and understood.

1.5 Transpiration and respiration

Transpiration and respiration are two main physiological processes that lead to fruit water loss and directly impact fruit quality by softening and shrivelling. Fruit are living tissues and continue biochemical metabolic activity which may not be necessarily desirable. The big difference for detached fruit, i.e. after harvest, is that there is no renewable resource from the main plant. Therefore, it is vital to retain fruit water status, because in many horticultural products, a loss of about 3-10% of its initial weight, will result in a loss of visual appeal for the consumer, and cause textural degradation, thus leading to unmarketable product, and

irretrievable economic loss (Ben-Yehoshua, 1987; Satake *et al.*, 2002; Xanthopoulos *et al.*, 2014).

Like other physiological plant processes, different endogenous and exogenous factors affect transpiration rate in fruit. Endogenous factors include surface structure, mass/surface to volume ratio of fruit, skin permeability, surface conductance, cultivar, fruit maturity, while exogenous factors include time, temperature, RH, airflow, diurnal cycle and also the seasonal conditions (Sastry & Buffington, 1983; Becker & Fricke, 1996; Morandi *et al.*, 2010b; Kale & Sundaram, 2014; Paul & Pandey, 2014). It has been reported that the percentage of mass loss has a strong correlation with 'point-in-time' water status of the produce tissue (Morgan, 1984). This water movement in and out of the fruit could impact some fresh produce traits including fruit weight, dry matter and soluble solids (Leonardi *et al.*, 2000).

Different terms which are related to fruit water status need to be defined for a better understanding and description of water loss, namely, water content and water activity. Water content shows how much water is in a fruit, while water activity or a_w is a measure of the energy status of the water in a system. The water activity is defined as the vapour pressure of water in a substance divided by that of pure water at the same temperature. The effect of the pressure forces on tissue is considered in measuring the water activity, therefore it is a more reliable parameter in representing the true water status (Black & Pritchard, 2002; Nguyen *et al.*, 2004). Water activity is the 'effective' water content which is thermodynamically available for different physiological and biochemical activates in cells. This 'effective' water content plays the crucial role in fruit/plant survival under water stress rather the total water content of the tissue (Black & Pritchard, 2002). At the fruit surface, the water content (kg water/kg dry weight) is the result of the equilibrium between water evaporation and internal water migration (Nguyen *et al.*, 2004).

Water loss in fresh products occurs when there is a difference between the products surface water vapour pressure and the surrounding environment. Temperature and RH are the main factors which affect water vapour pressure (Somboonkaew & Terry, 2010). The ambient water vapour pressure can be measured using a psychrometric chart.

WVPD is the difference between the amount of moisture in the air at ambient conditions and how much moisture the air could potentially hold when it is saturated for the same at the same temperature. It is often measured in pounds per square inch (psi) or kilopascal (kPa). A high WVPD (greater than 1.0 kPa) means that the air still has a capacity of absorbing a large amount

of water. Thus, there is a gradient between fresh produce (fruit or vegetables) which is nearly saturated with water and the surrounding air, resulting to transpiration (the loss of water by evaporation which is the reverse action of condensation) of water through the time and weight loss. A low WVPD value indicates the air is near saturation, and transpiration from the produce will decrease. When WVPD is equal to zero, the ambient air is 100% saturated. If absolute humidity is held constant, WVPD increases markedly with temperature. (Kale & Sundaram, 2014; Md Rais Uddin, 2016).

In simple words, the water vapour pressure deficit increases with a decrease in RH and an increase in air temperature.

Effects of temperature and RH on fruit quality parameters have been reported on two cultivars of litchi cvs. 'Kom' and 'Mauritius' that were stored for 9 d at either 5 or 13 °C, under a series of controlled RH conditions (80-100%) to simulate shelf-life conditions during the trial (Somboonkaew & Terry, 2010). They reported that sugars and organic acids contents in aril and pericarp tissue, and anthocyanins in pericarp, were preserved better after 9 d storage at 5 °C and a WVPD of 0 or 0.042 kPa, while both cultivars showed a higher respiration rate and weight loss at 13 °C and a WVPD of 0.274 kPa. They concluded that to maintain fruit physiological and biochemical quality, WVPD should be maintained to lower than 0.068 kPa, and that this was more important than just maintaining the cold chain (Somboonkaew & Terry, 2010). Leonardi *et al.* (2000) observed fruit transpiration was significantly different between 10 a.m. and 2 p.m in tomato (cv. Raissa), with an increase from 0.1 to 0.75 mg cm^{-2} of fruit surface per hour. At 1 p.m. fruit transpiration under high WVPD was twice that under low WVPD. Both temperature and RH had a significant impact on transpiration rate of strawberry (cv. Elsanta). Sousa-Gallagher *et al.* (2013) conducted an experiment on strawberry's transpiration to develop an integrative mathematical model for Modified Atmosphere Packaging (MAP) by considering two factors - temperature (5, 10 and 15 °C) and RH (76%, 86% and 96%). The results showed that increasing RH from 76% to 96% decreased transpiration by 52% at 5 °C, while decreasing the temperature from 15 to 5 °C decreased transpiration by 47% at 96% RH.

When the airflow travels through a box of kiwifruit, it causes evaporation on the skin which works as endothermic reaction reducing skin temperature, therefore the vapour pressure on the fruit skin surface decreases and it causes lower transpiration. It has been reported that transpiration rate increases linearly with water vapour pressure deficit and contributes to the

daily reduction of fruit hydrostatic pressure. The rate of evaporation on the product's surface mainly depends on the cultivar characteristics (Habib *et al.*, 2017).

In general, it is believed that the participation of respiration in fruit water loss in fresh products is low compared to water loss resulting from transpiration. Therefore transpiration usually has been considered as the main driving force for fruit water loss in stored fruit (Xanthopoulos *et al.*, 2017). Kiwifruit has low respiration rates, ranging from 5 to 10 mg CO_2 kg^{-1} h^{-1} at 5 °C (Saltveit *et al.*, 2004). Xanthopoulos *et al.* (2017) showed at 0 °C and 95% RH, respiration contributed 15% of fruit water loss of pears (*Pyrus* communis L., *Kontoula*) due to water vapour pressure deficit, while at 20 °C and 95% RH, respiration constitutes a larger proportion (39%) of total water loss, due to water vapour pressure deficit. They concluded that even at very small or zero water vapour pressure deficit, stored fruit may still lose water.

At harvest, fruit metabolic activities such as respiration continues which results in the degradation of sugar into carbon dioxide, water, and heat – or 'vital heat'. This will increase the fruit temperature which leads to higher vapour pressure deficit of the fruit surface and thus a greater driving force for transpiration. Moreover, the product's temperature mutually affects the respiration rate. Therefore, this can be concluded that even in saturated environments the respiration can cause transpiration, because the fruit surface temperature is higher than the ambient temperature under saturated conditions, and it increases the water vapour pressure at the surface of the product (Becker & Fricke, 1996). Although, Xanthopoulos *et al.* (2014) indicated fruits and vegetables with high sugar content may not necessarily follow the same pattern. The type of stored product and its temperature impact the rate of respiration.

Mahajan *et al.* (2015) studied the moisture loss behaviour of mushrooms, strawberries and tomatoes in a dummy evaporation sphere stored at 13 °C and 100% RH. The results showed that respiratory heat resulted in a higher temperature on the produce's surface rather than the surrounding air. Under saturated conditions mushrooms, strawberries and tomatoes transpired at rates of 712, 122 and 18 mg water kg^{-1} h^{-1}, respectively, while, there was no mass loss from the artificial evaporation sphere. Fruit thermal budget for continuing transpiration even in water vapour saturation mainly depended on three resources including the produce respiratory heat, evaporative cooling effect of the produce surface and convective heat transfer between the produce and its surrounding environment.

Thus, heat and mass transfer within fresh products is a complicated phenomenon involving many factors which should not be neglected.

In many horticultural products, low temperature and high humidity are the optimal conditions for storage to decrease respiratory heat and its subsequent influence on fruit weight loss.

1.5.1 Water relationship and transpiration in kiwifruit

In general, fruit heat is the result of the convection at the product surface and conduction within the produce. The accumulated-internal heat is generated by respiration and the contribution of transpiration in moisture loss and its evaporative cooling effect (Chau & Gaffney, 1990).
When the fruit is picked, its water status impacts postharvest fruit quality. The same amount of water loss in different fruit may influence the fruit metabolism or postharvest quality differently. It mainly depends on water content of fruit at harvest (Burdon & Clark, 2001).

Mazzeo *et al.* (2010) have explained the water loss in kiwifruit by two kinds of resistances. The first one is Rs which is related to the transpiring organ's skin (its dermal layers and cuticle) and the second factor is (Rb) which is associated with the boundary layer of still air around it. In different ambient conditions, Rs or Rb may dominate the other. 'Hayward' kiwifruit has long hair (trichomes-about 2.5-3 mm) which can increase the Rb value. In ambient conditions, when the air flows directly onto fruit, the moist air-layer trapped on fruit's hair will be blown away (lower Rb value), and thus increases fruit transpiration. Their experiment in a climate room at 25 °C and 60% RH with WVPD as 1.27 kPa showed in the early stage of fruit growth (13-50 DAFS), fruit were more sensitive to windspeed. At this stage, boundary layer resistance dominated skin resistance. Therefore, at early stages of development transpiration rate was responsive even at low wind speeds (0.5 and 3 m s^{-1}). As fruit mature, Rs increased over time, and was related to anatomical changes in fruit skin such as outer cell layers suberisiation and wax biosynthesis which caused the death of the outer cells (Celano *et al.*, 2009), while Rb roughly changed, because even in developed fruit there was still more than > 2500 hair with approximately 3 mm length.

Montanaro *et al.* (2011) investigated the effect of weather variables including radiation, air temperature, humidity, and windspeed on fruit transpiration. Temperature and RH showed linear correlation to transpiration with coefficients of 0.89 and 0.88, respectively in the early

stage of fruit growth (23 DAFB). At the same time, radiation and windspeed were not linearly correlated to transpiration, and it was concluded that these factors had a low impact on fruit water loss. A similar pattern was observed in more mature fruit (62 DAFB). Accordingly, it was suggested that temperature and RH are the main weather parameters which closely related to fruit transpiration and weight loss. Transpiration (water loss) causes an increase in the osmotic concentration which decreases water potential and fruit turgor pressure, so it is responsive to vapour pressure deficit (Morandi *et al.*, 2010a). Mazzeo *et al.* (2010) reported fruit transpiration is less sensitive to wind speed. In terms of diurnal cycles, transpiration is relatively high in the afternoon, while at night there is almost no transpiration in kiwifruit (Montanaro *et al.*, 2011). Montanaro *et al.* (2012) model showed temperature, and RH were two main environmental factors affecting transpiration rate in kiwifruit. Transpiration rate showed large diurnal fluctuations and decreases with fruit growth and development. When 'Hayward' kiwifruit were still attached to the mother plant, water loss declined significantly during the 8 weeks after fruit set (AFS). Montanaro *et al.* (2006) reported transpiration per unit fruit area reached the maximum (2.06 ± 0.1 mmol m^{-2} s^{-1}) on the first day AFS, and then declined by 90% over 50 d AFS, then remained steady at a low level until harvest.

Cuticle, lenticel and the stem wound are the main paths for water loss from fresh produce. In general, kiwifruit has small numbers of tiny lenticel on its epidermis. Therefore lenticel conductance has a lower influence on water loss compared to other fruit. Normally, the largest loss of water occurs through the stem end harvest scar or the stylar end (Burdon & Clark, 2001)

Burdon and Clark (2001) investigated the effect of postharvest water loss on 'Hayward' kiwifruit water status over 14 d after harvest. The fruit were stored under dehydrating conditions (20 °C, ~10% RH). It was observed that fruit weight loss was related to decreased water content, relative water content and water potential. In the same experiment, the rate of fresh weight loss, water content and relative water content decreased over time. Their observations also revealed that there was spatial variance in the water content of fruit. Generally, the inner and outer pericarp have higher water content than the core. Water loss directly impacts water status of outer pericarp and fruit size along the stem-calyx axis and fruit mass. Kiwifruit are susceptible to shrivel when 4-5% of the fruit weight at harvest has been lost during storage (Burdon & Lallu, 2011).

Thus, improper storage temperature, RH, air circulation and mechanical damage can impact fresh produce's quality by inducing fruit water loss, postharvest physiological disorders and decay.

1.5.2 Temperature

Harvested produce is transported and stored at low temperature under high RH to maximise its shelf-life. Low temperature is applied to slow ripening and its outcomes such as metabolic changes, respiratory heat, water loss, softening and fresh produce decay (Kale & Sundaram, 2014).

After harvest, temperature is the main environmental factors (extrinsic) that can be controlled or changed to effectively impact fresh produce quality and its shelf life (Lallu & Webb, 1997). It is the main driving force for respiration rate. If the temperature increases 10 °C above the optimum temperature for fresh produce, the respiration will increase by a factor of two to five for every 10 °C rise in the temperature and this will decrease storage time (Vigneault *et al.*, 2009; Kale & Sundaram, 2014).

At-harvest fruit temperature represents the ambient air temperature, absorbed heat from sunlight, and respiratory heat (Schick & Toivonen, 2002). In attached fruit, fruit temperature is a consequence of energy exchanges by radiation, evaporation, convection, conduction and metabolic activity (Cellier *et al.*, 1993). The fresh produce heat is the result of residual field heat and the heat of respiration (Vigneault *et al.*, 2009). Therefore, it is vital to minimize and remove the field heat from the fresh produce by postharvest practices to reach the optimal storage temperature for the produce. Postharvest practices that result in rapid cooling are recommended for most fresh produce.

WVPD is the main reason for water loss and the magnitude of this driving force will depend on the fruit tissue, the surrounding air and tissue resistance to water vapour flow. Whitelock *et al.* (1994) showed that the effect of airflow should not be neglected, and it still plays a part in fruit water loss. Moreover, in their experiment on peach (*Prunus persica* (L.) Batsch.), fruit were firmer when stored in lower airflow condition compared to a higher airflow at a given WVPD over 20 d of storage. They also concluded that storage time plays the most critical role

in fruit weight loss and fruit firmness by increasing the time for driving force (i.e. WVPD) to act.

The importance of the time between harvest and storage should not be neglected in order to maintain fruit quality, because any temperature break in the cold chain has accumulative effects (Goedhals-Gerber, 2015). Nordey *et al.* (2014) developed a model for mango (cv. Cogshall) which showed the heterogeneity of environmental conditions caused temperature gradients within the fruit and also changed its rate of transpiration. Small temperature variability can impact kiwifruit quality. Thus it is important to minimize temperature gradients to maintain fruit quality (Lallu & Webb, 1997). Temperature can significantly impact fruit softening and soluble solids (SSC) accumulation rate and also fruit susceptibility to chilling injury (Ritenour *et al.*, 1999; Burdon *et al.*, 2014; Hertog *et al.*, 2016). Toivonen *et al.* (2004) examined covering blueberries immediately after harvest in a reflective tarp by holding them for 4 h in the field. This could significantly influence fruit quality. Fruit quality was maintained in acceptable level after 7 d storage at 1 °C and also shelf life (2 d) at 13 °C. The proportion of over-ripe fruit, decayed fruit and shriveled were significantly decreased in the tarp treatment. The difference was more significant after moving the trays stacks to the shelf temperature (13 °C) for two days.

Schick and Toivonen (2002) showed that cherry (*Prunus avium* L. 'Lapins') temperature increased steadily from 20 to 25.2 °C from the orchard to the packhouse. While, RH decreased from 95 to about 75% at the orchard immediately after picking and plummeted to 35% during transport to the packhouse. They concluded that maintaining the produce temperature, and RH to the optimum level immediately after harvest is crucial to preserve sweet cherry quality in the subsequent storage.

Thus, it is clearly prudent to monitor temperature variations under real conditions from the orchard or the packhouse in early steps of the supply chain to investigate the effects of the spatial and temporal temperature variability on fruit quality further downstream the supply chain.

1.5.3 Relative humidity

Relative humidity refers to the amount of water vapour in the air versus what it can hold. The amount of water that the air can hold mainly depends on the temperature. Air at a higher

temperature has a greater capacity of holding water, while the opposite is true for colder temperatures. The water-holding capacity of air approximately doubles every 10 °C (Wills & Golding, 2016). RH is one of the psychrometric charts properties which can be measured directly by a hygrometer or by a psychrometric chart reading off its properties, i.e. the 'wet' bulb and the 'dry' bulb air temperatures (Wills & Golding, 2016).

When the fruit skin temperature is equal to or less that the dew point temperature of the surrounding air, then water vapour (the gaseous form) change into liquid water. This process is known as condensation (Holcroft, 2015). Transpiration can impact water loss and cause condensation (free water) on the produce's surface or packaging material, thus influencing the subsequent fruit quality and shelf life (Leonardi *et al.*, 2000; Holcroft, 2015). In the postharvest supply chain, temperature fluctuations can easily cause condensation on the fresh produce, and it is almost unavoidable (Holcroft, 2015). Low RH can lead to fruit deterioration through dehydration and acceleration of respiratory intensity (Castellanos & Herrera, 2015). Most fresh produce requires 85 to 95% RH (Thompson, 1998). When the produce's temperature is equilibrium with the temperature of the surrounding environment, then the ambient RH is the main factor in moisture transfer from the fresh produce (Whitelock *et al.*, 1994).

The vapour pressure inside the fruit is directly related to its temperature. The vapour pressure outside the fruit depends on the temperature and RH of the air. The fruit's skin and the surrounding air resist moisture transfer from the fruit to the air (Waelti, 1991).

There are excessive moisture losses during the first few weeks in storage. Moisture losses are at the highest rate during the coolstore filling period and until the fruit is cooled, which can take two to three weeks. As an example, when fruit temperature was 21.1 °C, resulted in an internal moisture vapour pressure of 0.74 psi, but the cooling air at 18.3 °C (70% RH) had a vapour pressure of only 0.31 psi. This resulted in a vapour pressure deficit of 0.43 psi (Waelti, 1991).

The velocity of airflow over the surface of the fruit has a relatively little effect on moisture loss. However, this has a significant effect on heat transfer from the fruit, or cooling rate. Doubling the air velocity increases the heat transfer by about 40% (Waelti, 1991).

Gaffney *et al.* (1985) developed equations for predicting fruit weight loss in peach. It has been predicted that fruit weight loss at RH >90% would be noticeable, while at saturated ambient conditions (RH >98%). This could show negative weight loss, due to higher transpiration

coefficient at the latter ambient RH. In a saturated microclimate such as a fruit bin, if any temperature variation happens without any airflow, it can easily cause condensation on the fruit skin surface.

1.6 Temperature management of supply chain

1.6.1 Curing-Delayed cooling

The industry has long tried to satisfy consumer health concerns for using alternative methods to control the incidence of postharvest disorders and diseases rather than chemical ones. One of such is temperature conditioning before storage to decrease the risk of decay, chilling injury incidence, and increase the host resistance to pathogens. The term that usually is used to describe this temperature manipulation is 'curing'. It has been reported in various horticultural products such as citrus fruit, peaches, carrots, sweet potatoes and onions (Ben-Yehoshua, 2005). Curing is commercially applied to enhance the produce's resistance to pathogen invasion (Saltveit *et al.*, 2004). Despite the fact that fresh produce should generally be cooled down to the optimal temperature as soon as possible to maximize its storability, there are cases where curing of fruit and vegetable (delays to storage at specific temperature and/or RH) can be beneficial (Kitinoja & Kader, 2002). In this process, the temperature conditioning depends on the mode of application and also the time of exposure for each produce (Ben-Yehoshua, 2005). After harvest, curing can facilitate healing of the picking wound and also create a physical barrier to prevent invasion of pathogens by deposition of cell wall material (Ben-Yehoshua, 2003).

Kiwifruit also benefits from curing which is considered as a cure for picking wounds (Pennycook & Manning, 1992). More than twenty years ago, Pennycook and Manning (1992) reported a delay between harvest time and cold storage by holding fruit in ambient conditions decreased *B. cinerea* incidence in 'Hayward' kiwifruit at 0 °C up to 13 weeks. The positive effect of curing in controlling *Botrytis* increased gradually with increasing curing time up to 7 days.

Kiwifruit may be cured by holding fruit in ambient conditions for 2-3 d, though it starts initially from the orchard when the fruit has been harvested (Lallu *et al.*, 1997). The main considerations are the length of curing and the curing conditions that the fruit is held under it. The latter is

more crucial for an effective curing. The importance of curing time is related to its effect on fruit softening. Longer curing time may cause softer fruit. Thus, it is recommended to cure kiwifruit between 48 to 100 h (Lallu *et al.*, 1997).

Providing a specified condition of temperature and RH is necessary for an effective curing of kiwifruit. These two environmental factors influence fruit weight loss during curing and the following cold storage (Bautista-Baños *et al.*, 1997). Holding fruit for 3 d at temperatures between 10 °C and 20 °C and with RH higher than 92% is an effective combination for a better control of *Botrytis* (Bautista-Baños *et al.*, 1997).

Although the precise biological mechanisms behind curing are not fully understood, curing is an effective postharvest practice that is now adopted in the kiwifruit industry to control *Botrytis* (Mari *et al.*, 2015).

1.6.1.1 Curing effect on postharvest diseases and disorders

Curing inoculated potato tubers with *Phoma exigua* var. 'Foveata' for 7 d decreased the incidence of gangrene to 68% in comparison with the control (Hide & Cayley, 1983). The incidence of skin spot declined from 70% to 4% after fruit were cured at 15 °C for 14 d in dry conditions, but in damp conditions, it decreased only to 53% (Hide & Cayley, 1987).

Research in subsequent years suggested 'Hayward' leaves and fruits are noticeably more susceptible to *B. cinerea* than 'Hort16A' (Wurms *et al.*, 2003; Wurms, 2004). Curing fruit for 1 week at 17 °C triggered wound curing responses in 'Hayward' and 'Hort16A' kiwifruit. The rot incidence decreased a 4-fold and 2-fold in 'Hayward' and 'Hort16A' respectively, following 12 weeks of storage at 0 °C (Wurms, 2005). After curing the incidence of rot declined in 'Hayward' from 80% to 20%, whereas in 'Hort16A', it decreased from 40% to 20%. The effect of curing on controlling rot incidence was observed after long-term storage 6-12 weeks storage, but not necessarily immediately after the curing regime (Wurms *et al.*, 1997; Wurms, 2005). There is a possibility that curing acts as a trigger for chitinase activity in stem plugs and pericarp. In addition, a small increase in phenolic compounds of the pericarp tissue has been reported (Wurms, 2005).

Suberin development and accumulation of phenolics compounds in 1-2 cell layer under the fresh stem wound was observed in cured fruit (48 h at 15 °C). Furthermore, the quantities of

phenylalanine ammonia-lyase and polyphenol oxidase were about 10 times more in the stem wound area of cured kiwifruit than in control fruit 12 h after treatment (Ippolito *et al.*, 1997).

Delayed storage (DS), which is kind of preconditioning treatments at higher temperatures for a short time prior to storage, have been reported to reduce chilling injury incidence in many horticultural produce (Koutsoflini *et al.*, 2013). DS of nectarine (*Prunus persica* cv. 'Flavortop') fruit for 2 d at 20 °C before cold storage triggered the fruit ripening and decelerated it at 0 °C. Therefore, woolliness (chilling injury) incidence was controlled in stored fruit at 0 °C for 4 or 6 weeks. In the DS condition, PG activity was maintained at an optimal level, which led to consistence increase in the subsequent storage and caused normal fruit softening during storage. The ratio between PG/ pectin esterase (PE) immediately at the end of DS impacts the woolliness incidence (Zhou *et al.*, 2000). Curing (16 °C, 7 days) before cold-disinfestation-quarantine treatment (1 °C for 16 days) reduced chilling injury and decay in citrus fruit and could cause huge savings in storage time and conditioning cost (Porat *et al.*, 2000).

1.6.1.2 Curing effect on fruit quality

Curing as a practical cure for the picking wound will have beneficial effects on maintaining fruit qualities in subsequent storage (Pennycook & Manning, 1992).

Harvested kiwifruit showed a higher rate of weight loss and fruit firmness loss after delayed storage (Beever, 1991). Fruit weight loss increase with higher temperature and lower RH, typical of the curing environment (Bautista-Baños *et al.*, 1997). When fruit water loss was about 0.2-0.4% during the curing, the rot incidence decreased in subsequent storage (Lallu et al., 1997). Fruit turgor decreases during the curing which reduces handling damage, especially in early season harvested fruit (Burdon & Lallu, 2011). Curing kiwifruit at an ambient temperature (12 °C-88% RH) for 72 h did not increase ethylene production, soluble solids and softening during the cold storage. It has been suggested that the ambient temperature during curing period has a minor impact on the initial softening phase of kiwifruit, and did not impact fruit outcomes negatively (Retamales *et al.*, 1997). Bautista-Baños *et al.* (1997) observed curing at 10 °C under different RH level (low, medium and high) for 3 d did not influence fruit firmness in subsequent storage. While, harvest date significantly influenced fruit firmness. In that study, RH conditions during curing also affected fruit weight loss.

On the other hand, some studies reported that curing is more effective in reducing *Botrytis* at lower humidity when there is adequate airflow around the fruit. It does not appear to be caused merely by suberisation of the picking wound (Manning *et al.*, 2010).

Thus, according to the literature, there is no agreement on specific RH levels and how it may impact kiwifruit quality (Lallu *et al.*, 1989; Retamales *et al.*, 1997; Manning *et al.*, 2010). The mechanism of curing has not been fully understood, although it is apparently associated with fruit water loss. What is obvious that there is not an effective and appropriate curing procedure, if no weight loss occurs during the curing (Manning *et al.*, 2010).

1.6.2 Precooling

After harvesting fresh produce transpire and respire at high rates at field temperatures. Therefore, it is critical to reduce the time elapse between the picking and initial cooling of the produce (Thompson, 1998). In early research, it was recommended that to prolong fruit storability and maintain fruit quality during storage, it is better to cool harvested kiwifruit to 0 °C as soon as possible (24-48h), because the respiration rate will decrease at 0 °C (Mcdonald, 1990). It is generally believed, this practice slows down physiological and biochemical activities which are involved in fruit deterioration at higher temperatures (field heat) (El-Ramady *et al.*, 2015). In New Zealand, historically there were three main reason for using precooling practice before the coolroom including fruit temperature needed to decrease to the shipping containers temperature, due to the low cooling capacity of these containers. The second and the economic reason for that was the precooler unit was more economic than a coolroom and finally, it was believed that precooling would increase fruit's storage (Lallu & Webb, 1995).

1.6.2.1 Rapid cooling

In rapid cooling, the freshly harvested fruit are rapidly cooled to a low temperature but not a freezing temperature. Cooling kiwifruit within 24 to 72 h after harvest is a postharvest practice which is conducted by passing forced-cold air through graded and packed fruit before cold storage at 0 °C (Lallu, 1997).

Lallu and Webb (1997) investigated the effects of precooling (9-12 h) on 'Hayward' kiwifruit's quality after 20 weeks at 0 °C in coolstore. The results demonstrated that precooled fruit were firmer, but they showed a higher incidence of the stem-end *Botrytis*, physiological pitting and SBD incidence when compared to non-precooled fruit. They recommended the precooling practice should not be used for fruit from the orchards which showed higher susceptibility to physiological pitting and SBD and also *Botrytis* incidence. Although precooling is practical when there is no sufficient cooling capacity at coolstore and/or uniform cooling is not possible, because of the packaging type (Lallu & Webb, 1997).

Retamales *et al.* (1997) observed precooling at 2 and 7 °C did not impact significantly fruit softening and soluble solids at coolstorage (90 d), but rapid cooling (2 °C) caused fruit water loss compared to the delayed cooling treatments for 2 d followed by precooling at 2 °C or 7 °C. Zhao *et al.* (2015) found that rapidly cooled fruit (3 d) were firmer than delayed cooling fruit (2 w) after prolonged storage (120 d). However, the rate of unmarketable fruit after storage was higher, possibly due to SBD incidence. On the other hand, the incidence of rotten fruit was higher in gradually cooled fruit. In general, rapid cooling was not effective to maintain fruit quality in long-term storage, but they recommended that delayed cooling is not practical, because in a two-month harvesting window, a huge volume of harvested fruit needs to be handled in the kiwifruit supply chain (Zhao *et al.*, 2015).

1.6.2.2 Passive cooling

Keeping fruit in cold storage is a fundamental and primary practice to prolong fruit storage life, maintain fruit quality, decrease decay and extend market life.

After harvest, the temperature of fruit bins is usually about 14 to 18 °C (Burdon & Lallu, 2011). In packaging process, fruit temperatures increases approximately 4 to 10 °C. It can be reduced to storage temperature in most coolrooms. It takes about 5-7 d to cool the fruit down to a temperature less than 2 °C, if the airflow around the fruit stack is maintained at about 0.4 to 0.6 m s^{-1} during the cooling process. After achieving the desired temperature, the airflow should then decrease to 0.2 to 0.4 m s^{-1} to reduce water loss and shrivel during long storage (Burdon & Lallu, 2011).

Since kiwifruit are sensitive to chilling injury, fruit temperatures are decreased gradually to reach storage temperatures. 'Hayward' fruit usually will be stored above 0 °C (e.g. 0 to +0.5

°C) under an ethylene-free atmosphere and when the SSC content increases to 10–12%, then the storage temperature may be held below zero (−0.5 to 0 °C) (Burdon & Lallu, 2011).

During storage at 0 °C kiwifruit soften slowly. However, the rate of softening at the coolroom could be the major reason for fruit quality loss and limit the scope of export (Harvey & Harris, 1986; Harman & Mcdonald, 1989).

1.7 Research questions and objectives

Similar to other, the first section of the supply chain of kiwifruit begins at the orchard. This laps of time from the orchard to storage and its effect on fruit quality of the batch of kiwifruit destined for long-term storage usually gets neglected**.**

The temperature to which kiwifruit is exposed between harvest and when the fruit are eventually moved to coolroom is not known. This temperature is likely going to vary depending on ambient conditions, which changes over the harvest season. The first aim of the research is to monitor temperature in a real curing scenario, and to simulate the effect of this temperature fluctuations on quality outcomes following long-term storage. The available research on curing were conducted in simulated conditions mainly to monitor its effectiveness in controlling *Botrytis* and most of the research date back to 90's. This logistical gap in the supply chain could definitely impact fruit quality in the last destination.

Different studies have been conducted to quantify the temperature heterogeneity in a typical refrigerated truck, a reefer container and different type of coolrooms. However, there has not been that much research on spatial and temporal variability of fruit temperature during ambient conditions of curing and how this heterogeneity could influence final fruit quality and constitute a major constraint in the supply chain.

In both phases of this one year study on 'Hayward', the following objectives have been set out

- To monitor and identify the temperature and RH profile of kiwifruit bins during curing and its potential spatial-temporal variability within the bin and the whole system during curing

- To assess the effect of temperature heterogeneity in the stack on fruit weight loss variability within the system

- To determine the impact of simulated curing conditions-delayed cooling (temperature × time) on fruit softening in long-term storage

- To determine the impact of simulated curing conditions-delayed cooling (temperature × time) on the incidence of SBD incidence in long-term storage.

- To identify the suitable curing conditions in terms of temperature management and its interaction with the duration of curing to maintain 'Hayward' fruit quality (firmness and SBD incidence)

To achieve project goals, in the first phase, five industrial trials in different scales (sample size) at different fruit maturity (early-season to late-season fruit) under different environmental conditions were conducted in real conditions. The spatial-temporal variability and temperature heterogeneity within the system were monitored under different environmental conditions from late March (31th March 2016) to mid-June (14th June 2016), and their effect on fruit weight loss.

The second phase of this project has been designed to address the question of how curing condition effects fruit quality traits in long-term storage. In order to fulfil this critical part of the project requirement, a matrix of curing (delayed cooling) time and temperature was been designed with large-scale of fruit samples.

By banding together investigations in real world conditions and also a full matrix of simulated curing conditions (the curing time × temperature), it is expected that the findings from this study will add useful knowledge to the kiwifruit industry. They will provide a better understanding of fruit responses to environmental conditions variability in the early stages of supply chain and their residual impact on fruit quality outcomes. Precise temperature

management through curing (delayed cooling) could positively impact fruit responses which leads to the highest fruit quality performance in commercial handling.

CHAPTER 2

2 Part A-Survey of real industrial conditions

2.1 Introduction

At harvest, kiwifruit are firm and mature, but unripe and starchy. The New Zealand kiwifruit industry has considered 6.2% SSC content as a minimum maturity index for harvesting 'Hayward' kiwifruit (Snelgar *et al.*, 1993; Crisosto & Crisosto, 2001). Fruit also need to have black seeds, be the right colour and weight. In New Zealand, kiwifruit 'Hayward' harvest starts in late March and peaks in May and is usually complete by early June. In New Zealand Kiwifruit growing regions, Bay of Plenty having the earliest harvest most years (NZ Kiwifruit Growers, 2016). The cool season lasts for 3.5 months, from 29th May to 13th September, with an average daily high temperature below 16 °C (Anonymous, 2017a). In March, the average low temperature is approximately 14 °C, and the average high temperature is 22 °C. In late May and early June, the average low and high temperature drop to 10 °C and 16 °C, respectively.

Fruit are harvested and placed into large bins to enable transport from the orchard to the packhouse. Fruit remain in these harvest bins until being packed, often in large stacks and without environmental control. This period between picking and packing without environmental control is known as curing in 'Hayward' kiwifruit. Kiwifruit benefit from curing in order to reduce the subsequent infection in that picking wounds (Pennycook & Manning, 1992). More than twenty years ago, Pennycook and Manning (1992) reported a delay between harvest time and cold storage by holding fruit in ambient conditions decreased *B. cinerea* incidence in 'Hayward' in subsequent storage (0 °C). Wurms (2005) found rot incidence decreased significantly in 'Hayward' kiwifruit in subsequent storage (12 w), following curing at 17 °C for 1 week.

The literature and industry practice clearly indicate that curing plays a positive role in reducing rot incidence in subsequent storage for kiwifruit, but the conditions of curing (time, temperature and humidity) will influence efficacy. Pennycook and Manning (1992) reported the effectiveness of curing to control rot at 14 °C increased in non-inoculated fruit as the duration increased up to 7 days. They suggested the interaction of environmental conditions (temperature × humidity × time) is involved in controlling rot incidence. Bautista-Baños et al. (1997) investigated the effect of curing temperature on reduction in the rot incidence, and found

that 10 °C to be an optimal temperature. In the same study, curing at higher RH (92-97%) was associated with a greater resistance to infection than curing at lower RH (50-80%).

Other than fruit characteristics, environmental conditions (temperature and RH) are the main factors that impact the driving force for water loss (Maguire, 1998). The interaction of environmental conditions and the duration of the interaction (time) during curing will dictate the magnitude of fruit weight loss (attributed to water loss) that occurs during this process. Bautista-Baños *et al.* (1997) observed that fruit weight loss increased at a higher temperature (20 °C) and lower RH conditions (50-80%) at all harvest dates and continued in subsequent storage.

Lallu *et al.* (1997) found that when fruit water loss was about 0.2-0.4% during curing, curing was successful to control rot incidence in subsequent storage. Bautista-Baños *et al.* (1997) reported 0.1% fruit weight loss during curing (10 °C, 92-97% for 3 d) had the lowest rot incidence.

To maintain fruit quality, this is important to minimize temperature gradients (Lallu & Webb, 1997). Burdon *et al.* (2017) reported when temperature decreased from 16 to 10 °C. This temperature range increased fruit softening rate in 'Hayward' kiwifruit.

Now, curing is also used as a logistical tool to enable accumulation of fruit at the packhouse in front of the grading line to keep grading line working during the season in order to achieve packing target and keep labour costs per packed fruit as low as possible.

Given that curing is conducted in a non-controlled environment and involves respiring and transpiring produce, there is a lack of certainty about the conditions fruit experience during curing, and how variable these may be throughout the curing stack. In particular, there is a paucity of data collected in real world conditions that demonstrate the actual conditions experienced by a batch of fruit. In order to be able to understand curing, more knowledge on what occurs within a commercial scale curing stack is required. This study aimed to provide more understanding of the conditions that may occur during real full-scale curing, in order to understand the sources of variability that may be imparted onto a typical batch of kiwifruit. Temperature, humidity and weight loss of full-scale commercial bins of fruit from five blocks of orchards were monitored from harvest to packing each in different trials ranging from late March to mid-June in the 2016 harvest season. The resulting data provides examples of potential positional and temporal variability that is created during curing.

2.2 Materials and methods

2.2.1 Location and local weather condition

The packhouse in which all trials were conducted is situated in Katikati, on the northern end of the Tauranga harbour. The warm season lasts for approximately 3 months, from mid-December to mid-March, with an average daily high above 22 °C. The cool season goes from approximately late May to mid-September, with an average daily high below 16 °C (Anonymous, 2017a).

Climate information (temperature and rainfall) was obtained from the closest local weather station (a Solar Unit**)** to the packhouse (50 m away) to monitor the weather conditions when each trial was conducted (Figure 2.1). The weather station was located in an orchard block and recorded rainfall for all trials, which did not match with personal observations and records at the orchard and the packhouse during the trials. The raw data from the local weather station has been presented for each trial, despite the different observations made at the time. The recorded rainfall data possibly was not related to irrigation or a spray application, because it did not occur at a consistent time. The average temperature was 14.9 °C from 31st March to 30th June 2016 (Figure 2.2), while the minimum and maximum were 0.5 °C and 26.9 °C (Figure 2.2). According to the National Institute of Water and Atmospheric Research (NIWA) climate database, the average temperature is usually about 14.5 °C and the dominant wind direction is from the West (Figure 2.3) (Anonymous, 2017b).

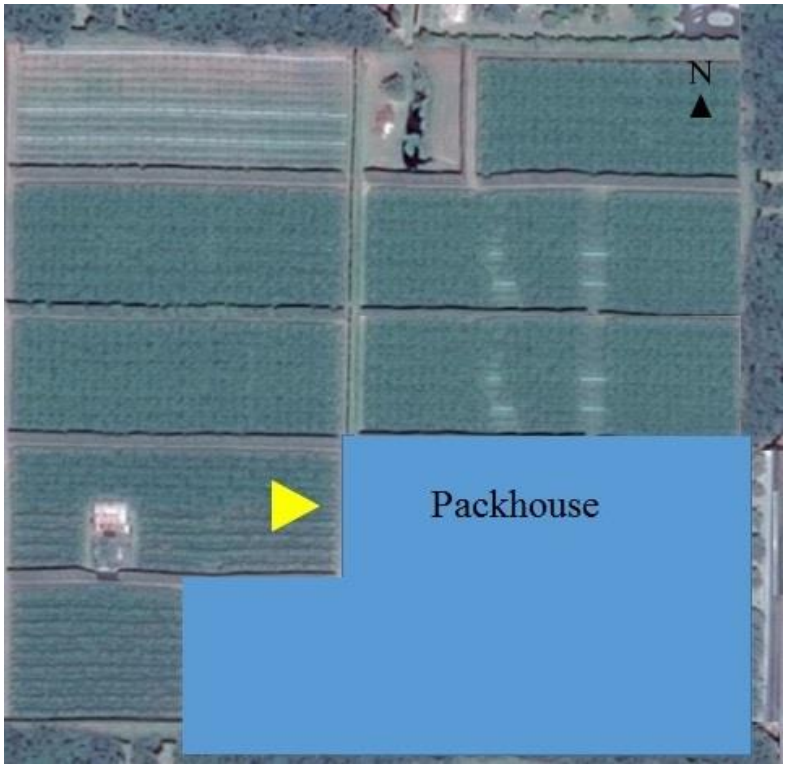


Figure 2.1: The yellow triangle depicts the location of the local weather station.

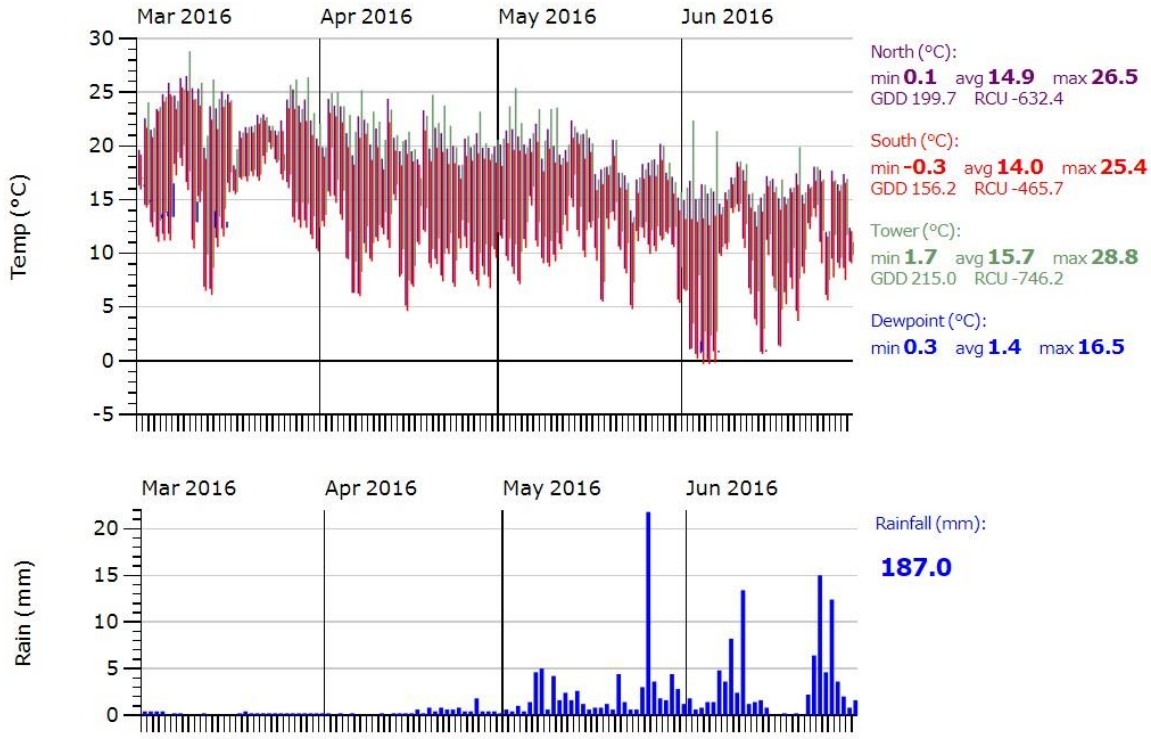


Figure 2.2: (a) Local temperature and (b) precipitation data have been recorded by the local weather station with multiple temperature sensors (green, grey and red lines) during the months that the trials have been conducted from March to June in 2016.

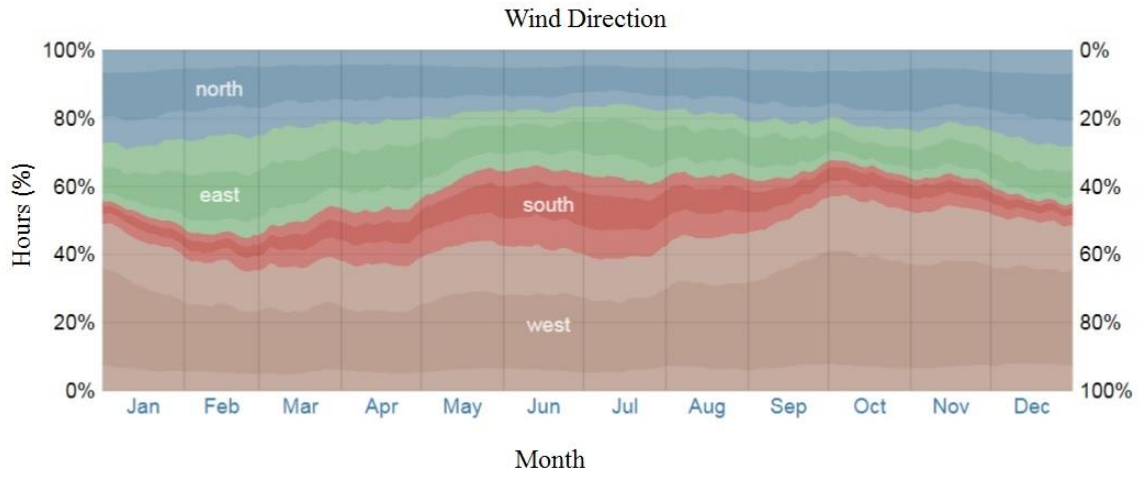


Figure 2.3: The percentage of hours in which the mean wind direction is from each of the four cardinal directions (North, East, South, and West), excluding hours in which the mean wind speed is less than 2 kph. The lightly tinted areas at the boundaries are the percentage of hours spent in the implied intermediate directions (Northeast, Southeast, Southwest and Northwest) (Anonymous, 2017a).

2.2.2 Fruit bins

Trials were conducted in either plastic or wooden bins. Generally, the packhouse attempts was to use plastic bins wherever possible but it did come down to the availability of bins or grower request-these were wooden bins. Plastic kiwifruit bins were polypropylene (HortBin 562 L, Viscount Plastics, New Zealand) and had external dimensions of 1200 x 1200 x 600 (h) mm, resulting in approximately 320 kg of mixed grade 'Hayward' kiwifruit being in each bin. Wooden bins used in the packhouse had dimensions of 1200 x 1200 x 500 (h) mm, with an approximate capacity of 250 kg (Figure 2.4).

Figure 2.4: (a) Typical harvesting wooden and (b) plastic bins which were used in the packhouse have been labelled to track them during curing.

2.2.3 Bin set-up in orchard

At the orchard staging area, sub-sample bags of 20 random fruit were placed in a woven polyethylene onion bag (OBL5R, Jarvis Trading Ltd., New Zealand) (Figure 2.5c).

In the first two trials, each bin had two sub samples. Due to the challenges of operating at the speed required for industrial operation, in the last three trials, the methods were changed so only one bin in every three bins had these two weight loss tracking sub samples.

For these two weight loss tracking sub samples, one bag included a known identity RFID communicable temperature and RH logger (XSense HiTag, BT9, Israel) (Figure 2.5a). The data loggers were connected to the XSense communication units (CU) by RFID at the packhouse (Figure 2.6b). The XSense loggers measured temperature in a range from −35 to 50 °C with an accuracy of ± 0.25 ºC and RH from 30 to 97% with an accuracy of 1% RH. The frequency of measurement is dependent on the ability of each temperature and RH logger to communicate to the local CU either directly or through a self-forming network with other RFID loggers in the environment. As a result temperature and RH measurement were recorded at irregular intervals between 1 and 60 minutes for each and every logger.

Both bags were weighed (initial weight), with the bag with the logger placed in the 3-dimensional centre of the bin (the middle bag), while the second bag was placed in the middle amongst the top of the fruit in the bin (the top bag) (Figure 2.5). At this stage, the bin was externally labelled with a simple numbering system to enable identification in the curing stack (Figure 2.4).

For each monitored bin information logging began in the staging point of the orchard, where bins are accumulated and organised for transport to the packhouse. This point in the orchard could be an open area or sheltered.

Figure 2.5: (a) An XSense HiTag logger, (b) a balance has been placed at the back of a vehicle at the orchard, (c) the middle fruit bags with a logger within each, (d) the position of the top and the middle bags in the relevant bin, (e) a set of three wooden bins ready to be loaded on a truck, (f) the bins being loaded on a track to transport to the packhouse.

2.2.4 Packhouse structure

The curing facility consisted of a single wall in which rows of bins are placed against on a concrete pad (Figures 2.6b and 2.7a). The west side of the remaining three directions was completely open to the environment (Figure 2.7c), while the east wall consisted of a wooden half wall + windbreak net at the top (Figure 2.7d) and a column of old empty bins was placed on the south side of canopy to act as a wooden wall (Figure 2.7b). The stack was covered with a grey reflective steal canopy to provide shade (Figure 2.7). The canopy covered a floor area of 55.3 × 29 m, with the wall being 6.2 m high on the northern dimension and the central peak of the gable roof being 8.3 m (Figure 2.6a and b). In total 18 rows of kiwifruit bins were able to be stacked under 4 of the 6 bays of the canopy, with the bin dump at the front of the packing line located at the east end of the canopy under the other 2 bays (Figure 2.6b). Logistics plans resulted in each grower line of fruit having its own row (i.e. A, B, C … R) within the canopy (Figure 2.6b). There was a neighbouring curing stack that was not monitored during this work.

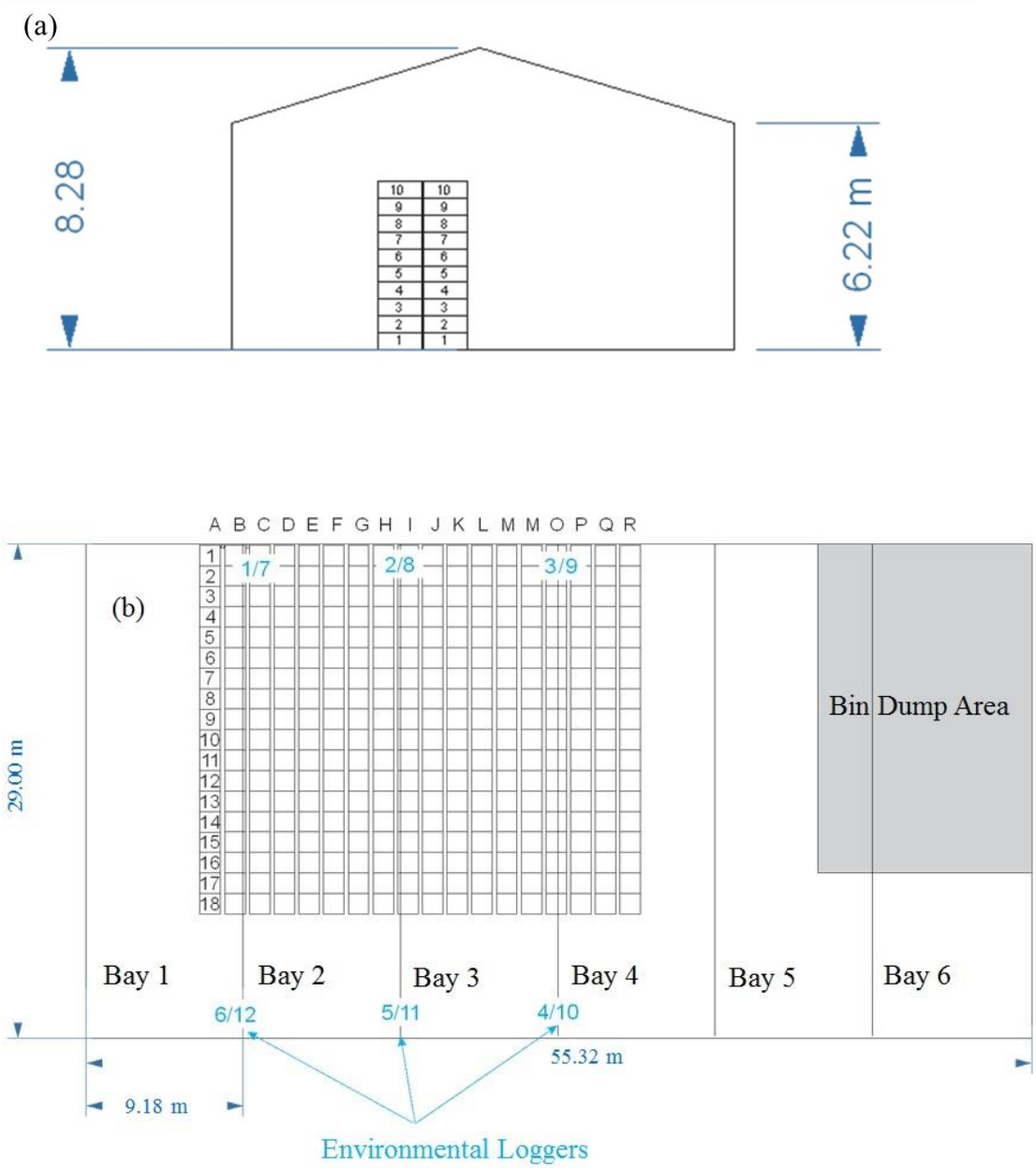


Figure 2.6: (a) The packhouse diagrams including the side view and (b) the plan.

Figure 2.7: Inside-view of the canopy and different sides of the canopy: (a) the North wall, (b) the South side, (c) the West side and (d) the East side.

At the packhouse, stacking arrangement in the curing stack is a result of the logistical constraints, with the first arriving fruit stacked against the wall, and the last arriving fruit of the day being the furthermost from the wall, toward the south side of the canopy. Height location in the 10 bin high stack is very much a result of chance (Figure 2.6b).

2.2.5 Environmental conditions monitoring at the packhouse

The conditions under the canopy were monitored with 12 RFID temperature and RH loggers (XSense HiTag, BT9, Israel) which were located at 1.5 m and 6 m high on vertical frame columns for the canopy (Figures 2.5a and 2.6b). The data loggers were connected to the XSense communication units (CU) by RFID at the packhouse (Figure 2.6b).

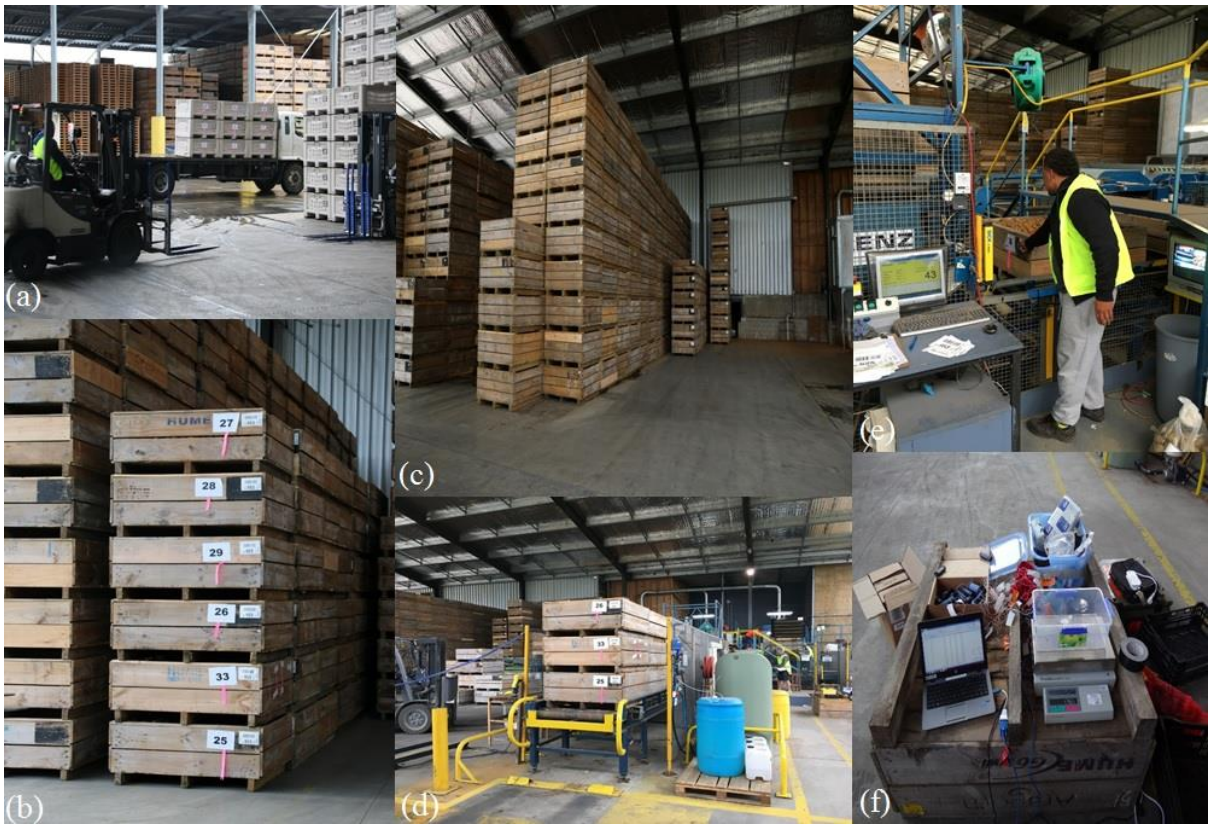


Figure 2.8: (a) Bin handling under the canopy the truck's arrival at the packhouse to off-load bins, (b) a stack of labelled wooden bins, (c) bins stack arrangement under the canopy, (d) the bin dump area, (e) the bins being tagged off and the fruit bags and the loggers retrieved before the bin being tipped on a conveyor belt, (f) the fruit bags were weighed at the packhouse.

2.2.6 Curing time

The time period for curing was considered to be the total time between the two weighing moments and hence represents the time from the staging area in the orchard through to the bin tip at the start of the packing line.

2.2.7 Fruit weight loss

At the packhouse, kiwifruit bins were moved to the bin tip area after curing. Once the bin was tipped into the packing line, the two sub samples bages were retrieved and weighed, hence enabling weight loss to be determined once eliminating the weight of the bag and the Xsense logger (Figure 2.8; Eq 1).

$$Fruit\ weight\ loss = \left[\frac{(X-Y)}{X}\right] \times 100 \qquad \text{(Eq. 1)}$$

X = Initial weight - (the fruit bag's weight + the logger's weight)

Y = Final weight - (the fruit bag's weight + the logger's weight)

2.2.8 Curing conditions

Estimates of temperature, RH conditions and fruit weight loss between each log were conducted by linear interpolation using Matlab 2016b (The Mathworks Inc., Natick, USA). While the nearest neighbour interpolation was used only for interpolating curing time. Given that this work is essentially an extensive survey of a real scenario, much of the data collected was represented for the purposes of determining temporal and spatial variability within the system by creating positionally colour contour maps of each row. Where data did not exist for a bin location linear interpolation was conducted and likewise, a similar approach was applied to estimate the weight loss data for the bins that there was no weight loss data (no sub samples bags or missing labels to track the bin position). Colour contour maps have been created to show curing duration, temporal and spatial variability within the stacked bins and also fruit weight loss during curing time. Tests of normal populations were conducted with the Shapiro-Wilk W test.

Given that these were the first of these types of experiments done, and that the purpose of the work was to measure real industry conditions, part of the process of conducting a number of trials was to develop the method in order to achieve suitable results. Hence part of the learning process for this project was to learn from each experiment and adapt the methods for the

following trials and in order to reduce errors and improve the subsequent data sets. Also, in this study, the conditions of each trial were unique (weather condition, the orchard condition and the packhouse circumstances and schedule) and therefore each trial countered new conditions which impacted the trial observations and results. Therefore in each trial section, further commentary has been provided to explain the specific situation.

2.3 Curing trial one

2.3.1 Trial commentary

The first trial was conducted in a small scale preliminary study in order to evaluate feasibility of the key steps in subsequent full (large)-scale trials and learn how to best achieve the monitoring experiments. The first trial was the first attempt at conducting industry monitoring during high paced picking time. The main target of the first trial was to have learnings of how to conduct a well-organised trial, in order to confidently collect a set of reliable data by the time the 'Hayward' season peak began.

- In total, 20 'Hayward' kiwifruit in wooden bins were used and labelled to monitor temperature and RH conditions during curing time. Later it was discovered that only 14 loggers were switched on properly and started to record the environmental data. Therefore, the data set represents only 14 bins with monitored temperature and RH data

- All bins 20 monitored included the 2 sub samples bags for measuring fruit weight loss. However in subsequent analysis, two negative weight loss data (−1.3 and−2.8%) were found and considered as experimental errors and hence removed from the data set, resulting in the data set being for 18 bins only. Causes of the experimental error may have been placing the balance in the back of the station wagon vehicle, assisting prevention of airflow influences in weight measurement. However, the orchard was located beside a main road and railway, and hence traffic vibration transferred to the scales through the car suspension may have contributed to weighing errors

- On this trial, only 6 loggers located at 1.5 m high on the vertical frame columns of the canopy recording ambient temperature and RH conditions under the canopy. The other 6 loggers were placed 6 m high on vertical frames after first trial time, due to time constraints at the time

2.3.2 Fruit source

The samples were collected from the orchard approximately 29 km away from the packhouse on 31st March 2016. Only a small proportion of all the bins harvested were monitored, starting with bins picked at mid-afternoon (3 pm) and took 2 h 15 min to fill all the bins (20 bins). The whole trial was conducted between 31st March (3 pm) and 1st April (3 pm), 2016. The average temperature which was recorded by the local weather station was 16.3 °C and mean rainfall of 0.6 mm has been collected during these three days (including one day before the start point of the trial to show weather condition) when the trial has been conducted (Figure 2.11).

2.3.3 Trial method specifics

For this trial, all bins had their internal environmental conditions monitored and also two weight loss tracking sub samples established. A total of 14 wooden bins were monitored. The experimental bins were positioned at the end of the curing stack furthermost away from the wall and were stacked with other bins from the same grower harvested earlier in the same day. The bins were stacked 6 high (in row P) in the fourth bay. There were two adjacent complete stacks of empty wooden bins (in rows N and O) in the third bay and six more incomplete stacks of empty bins were in front of them towards the second bay in the canopy (Figure 2.9).

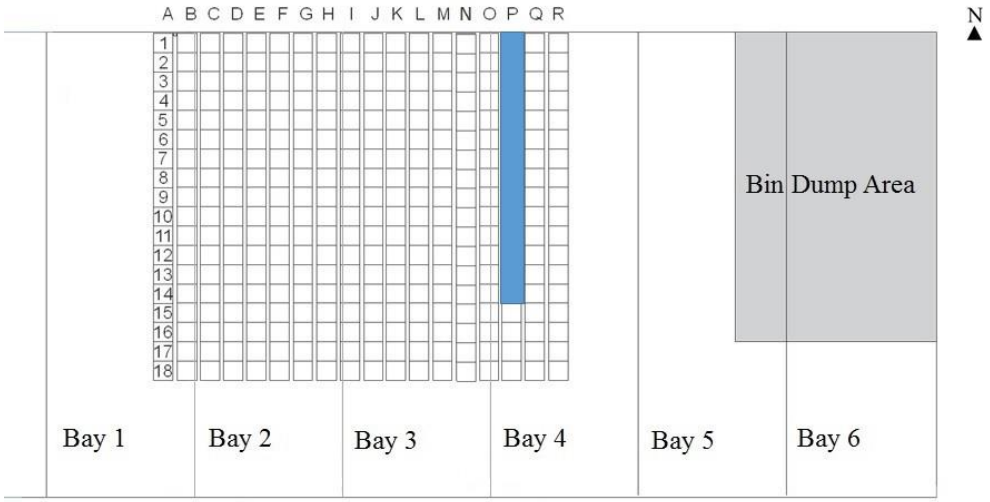


Figure 2.9: Illustration of an aerial view of bin stacking pattern for the first trial. The blue colour depicts the stacked bins for monitoring temperature and RH during curing.

2.3.4 Results

2.3.4.1 Time variability of curing

Harvested fruit were cured for approximately 24 h. The shortest curing time was 22 h 15 min and the longest curing time was 24 h 40 min.

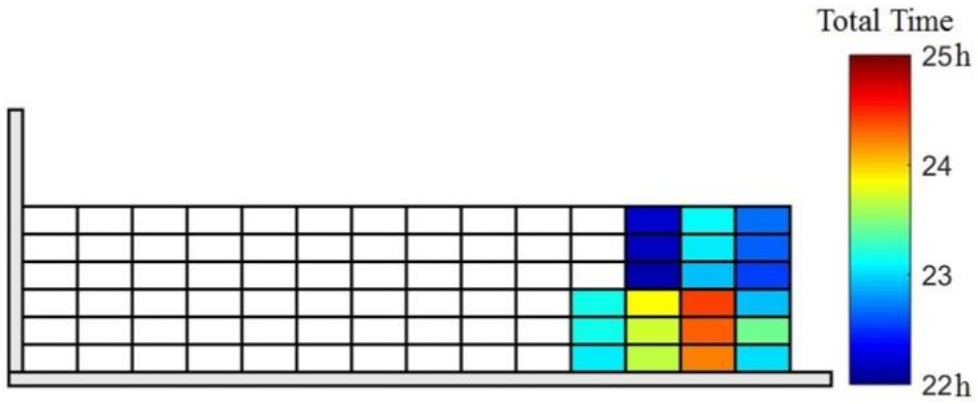


Figure 2.10: Duration of time in curing stack as influenced by position in stacked bins. Each block represents a single bin - a cross-sectional side view of the stack.

2.3.4.2 Ambient conditions during curing

Ambient temperature recorded by the local station was between 11-16.4 °C. The average temperature was 16.2 °C with a stable diurnal cycle over time (Figure 2.11). Average

environmental conditions during the trial time under the canopy was 18.2 °C and 78% RH. The diurnal cycles in the environmental temperature was between 15-21 °C (Figure 2.12).

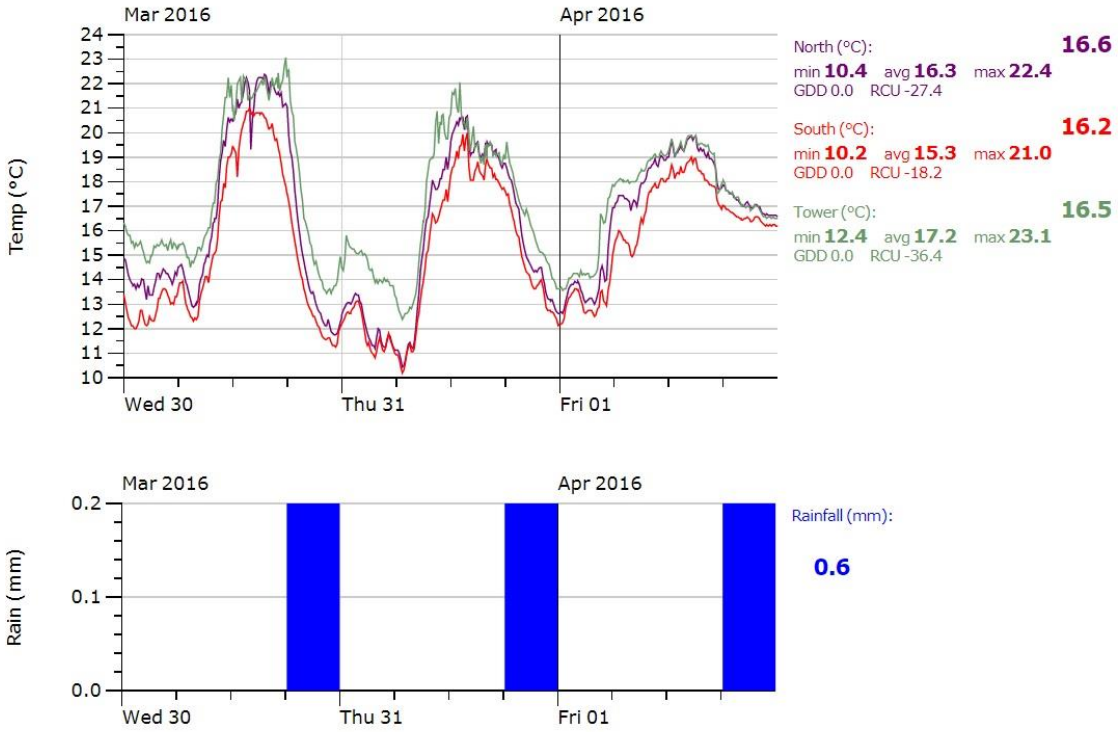


Figure 2.11: Temperature and precipitation recorded by the local weather station for three days from 30th March to 1st April 2016.

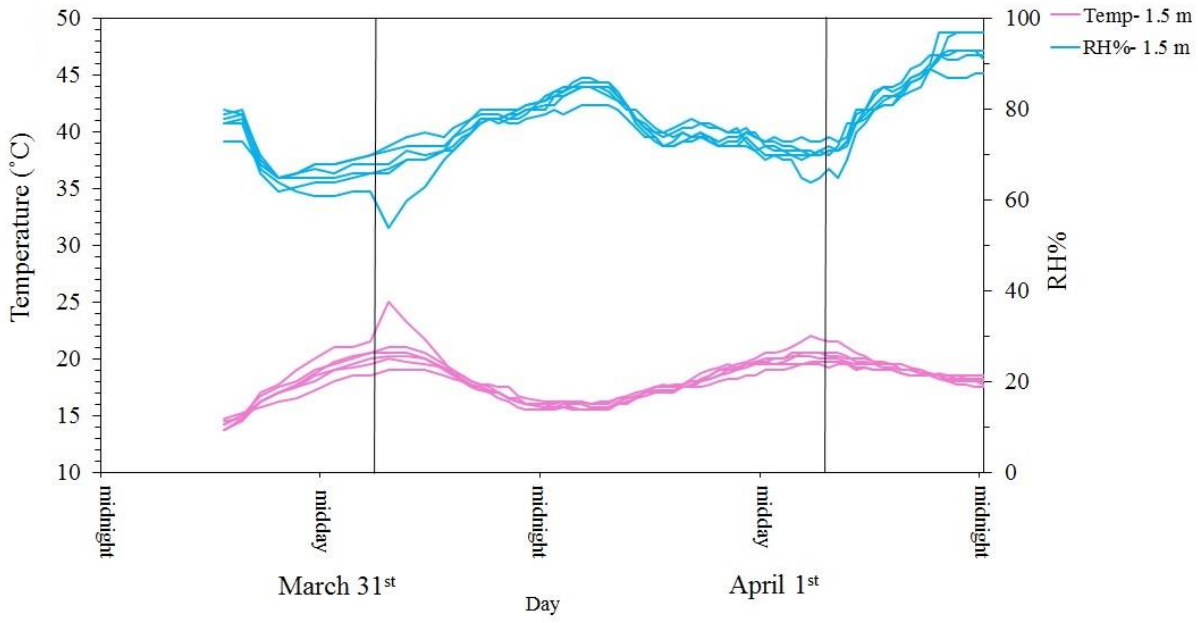


Figure 2.12: Ambient conditions under the canopy around the curing stack during the commercial kiwifruit curing, measured at 6 location at 1.5 m height. The black vertical lines represent the time scale of the curing.

2.3.4.3 Temperature during curing

Due to the small number of bins, conclusions about any spatial variability are difficult to ascertain. At the completion of the harvest day, temperatures in the centre of the bins ranged from 20-26 °C (Figure 2.13a). The temperature dropped in all bins during the night as a result of the cooler ambient conditions. The average temperature of the bins was approximately 21.5 °C at 12:30 am, when the average ambient temperature was about 15.5 °C. As a result, the central temperature of the bins ranged from 18-22 °C, on the following morning (6:30 AM; Figure 2.13h), and the bins temperature remained almost steady until the midday (Figure 2.13d) despite ambient temperature increasing from 17 to 20 °C. After midday fruit temperature increased until the packing time at 3 pm (Figure 2.13e) with all the fruit ranging from 20-22 °C while the environmental temperature was 20.5 °C.

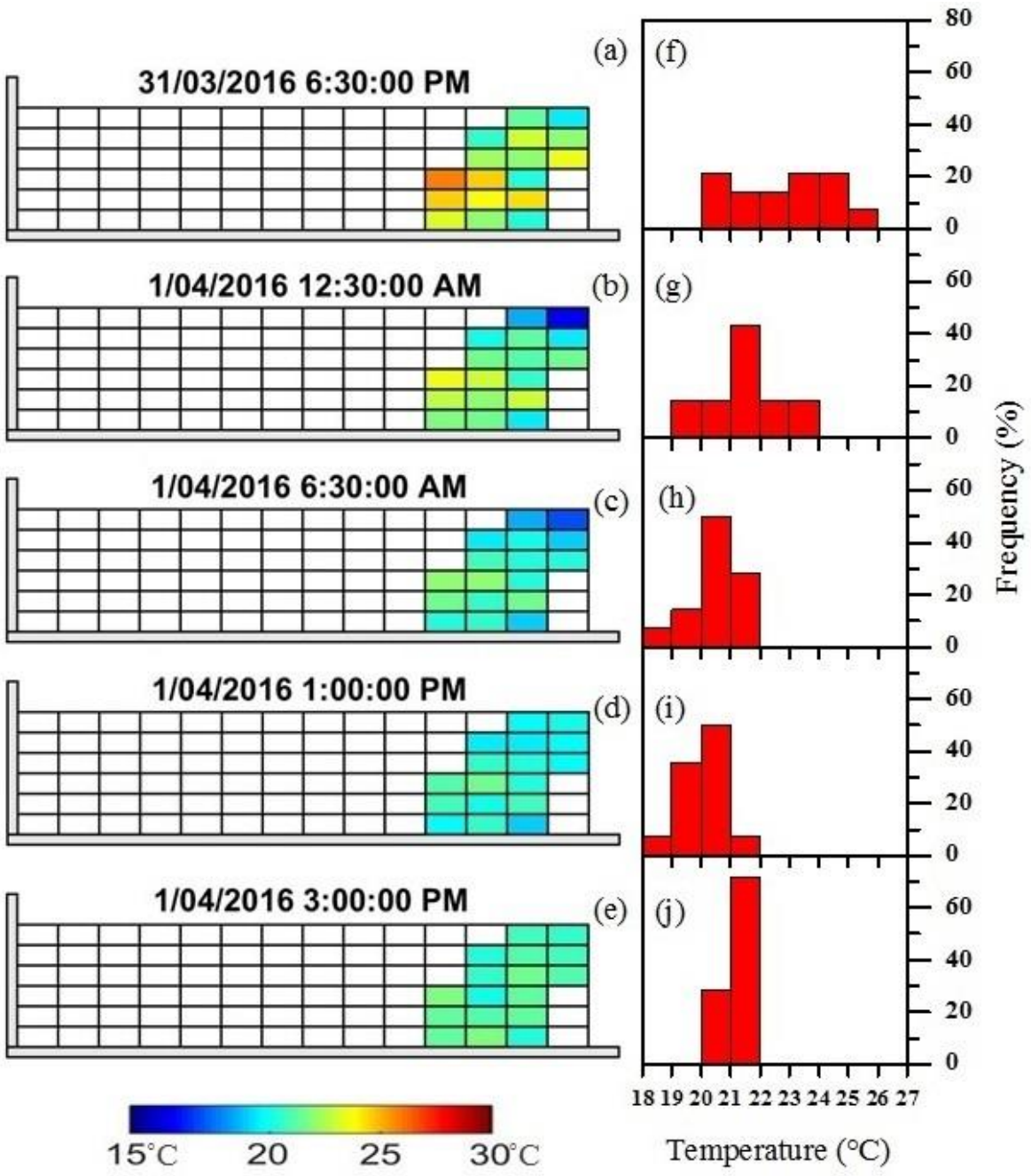


Figure 2.13: Spatial temporal temperature variation of the middle of 250 kg 'Hayward' kiwifruit bins during commercial curing. Maps (a-e) represent the bins interpolation and the histograms (f-j) the frequency of temperature value in the monitored stack (n = 14).

2.3.4.4 Relative humidity during curing

The initial bin humidity conditions was 65-80% about three hours after curing. Regardless of bin position, a steady increase of RH was observed in the stack. The environmental loggers recorded a reduction in RH about 3 hours at night under the canopy (between 3:00 am and 6:00

am from 86% RH to 72% RH), but the ambient RH was still in the range of the bins RH conditions (Figures 2.12 and 2.14c, g). Therefore, this environmental change possibly did not impact the gradual increase of RH in the middle of the bins. At the end of curing after 24 h, the fruit bins RH ranged from 80% up to 97% (Figure 2.14d, h), while the environmental RH was 72% (Figure 2.12). This would result in water loss from the bins, which would likely with any airflow around the stack.

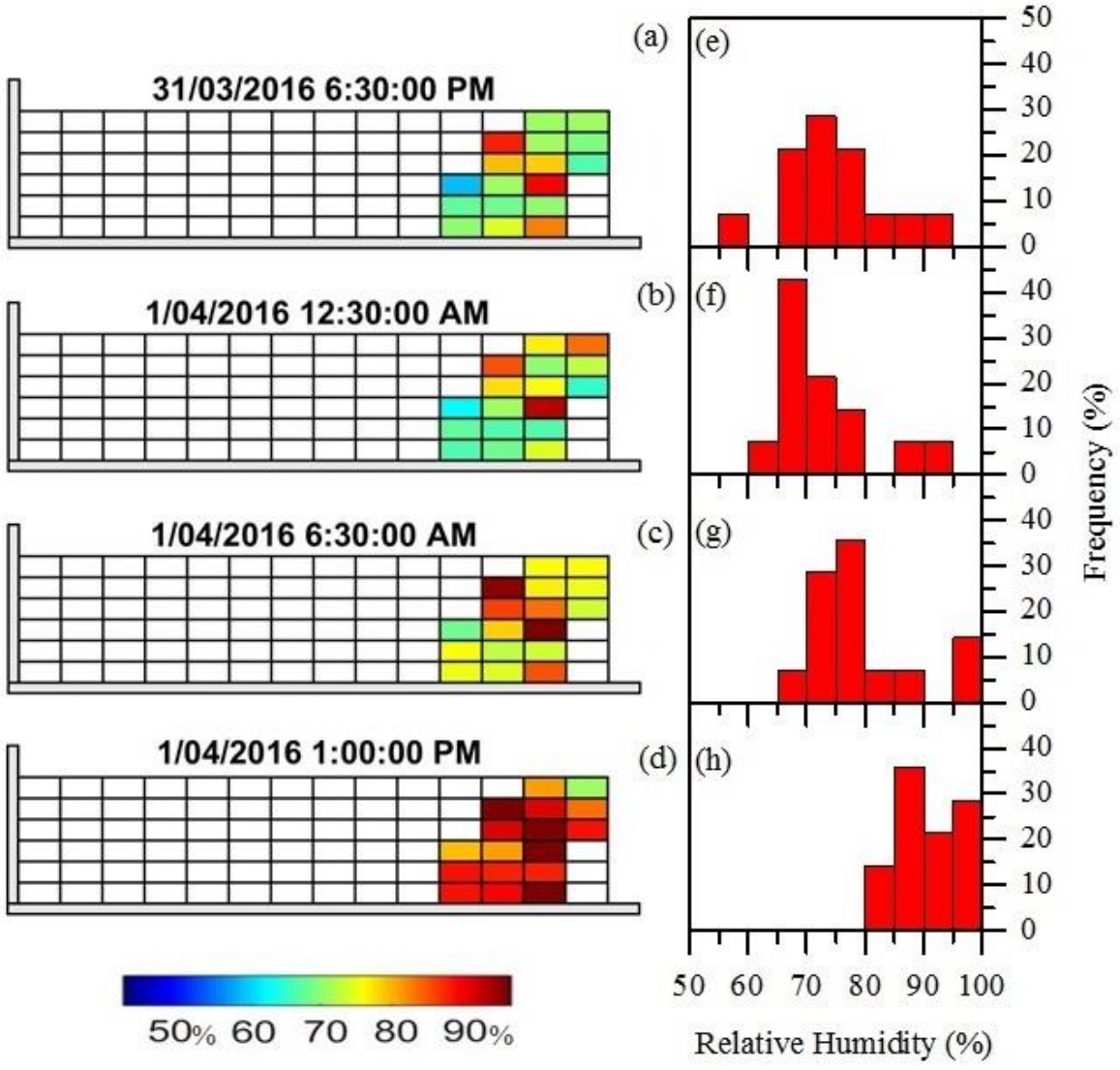


Figure 2.14: Spatial temporal RH variation of the middle of 250 kg ‘Hayward’ kiwifruit bins during commercial curing. Maps (a-d) represent the bins interpolation and the histograms (e-h) the frequency of RH value in the monitored stack (n = 14).

2.3.4.5 Weight loss impact as a result of curing

The average fruit weight loss during curing was similar regardless of the bag position in the bin (Figure 2.15). Weight loss for the bags located on the top of the bin showed a normal distribution (P = 0.12), with a mean of 0.37%, and a standard deviation of 0.13% (Figure 2.15 a). However, the middle bags weight loss did not represent a normal distribution (P = 0.02; mean = 0.33%; SD = 0.19%) (Figure 2.15b) and ranged from 0.25% to 0.6%.

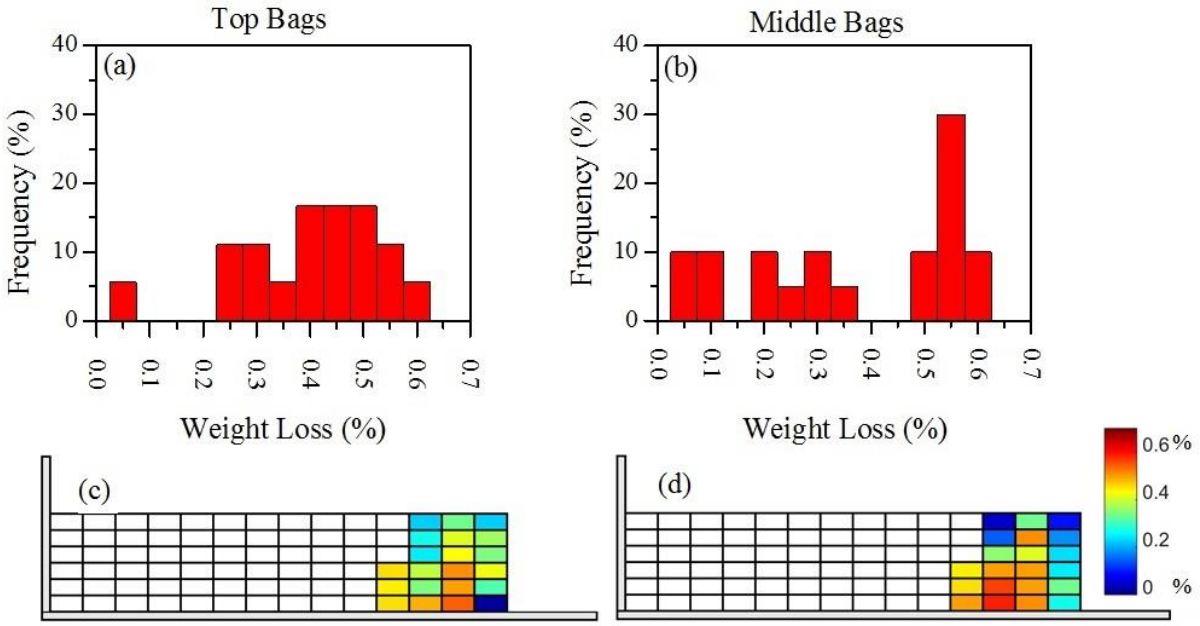


Figure 2.15: Weight loss of measured fruit on top (a, c) and in the middle (b, d) of 250 kg 'Hayward' kiwifruit bins during commercial curing (n = 18). Each block represents a single bin.

Those bags that were located in the middle of the bins at the bottom of the stack showed slightly higher weight loss (Figure 2.15d). The range of fruit weight loss for both top and middle bags was mainly between 0.4 and 0.55% and the bins in the last column or in top layers of the stack represented the lowest fruit weight loss between 0.05 to 0.25%. However, the small sample size undermines the reliability of this data and the observation may not be necessarily related to the bin position. For instance, the last column closest to the south entrance of the canopy is more exposed to the outside environmental airflow and it is expected to show a higher rate of fruit weight loss rate.

2.4 Curing trial two

2.4.1 Trial commentary

- The commercial grower line harvested required 162 plastic bins in a day, of which 146 bins were monitored for temperature and RH conditions

- The primary row consisted of 81 bins, of which 72 were monitored

- 81 bins from the same grower were stacked in another row (the secondary row), of which 74 were monitored

- All bins had internal environmental conditions monitored and also two weight loss tracking sub-samples established

- Both stacks were packed in a single packing run at 11:47 am, 20th April. It means the longest curing time was 27 h and the shortest curing time was 18 h

- Attempts were made to measure each and every bin, but not disturb the usual harvest practices. In this trial, it was discovered that to set two sub-samples bags for measuring fruit weight loss in each bin was too idealistic, especially in large-scale trials and would make the whole process to slow down. Therefore, to keep normal operational activity at the peak harvest window, it was decided in each trial for each set of 3 bins to have the internal environmental conditions monitored for all bins, while only one of these 3 bins also had two weight loss tracking sub samples. The new plan to reduce weighing frequency to 1 in every 3 bins increased the speed and efficiency of experimental efforts under normal operational condition

- When fruit weight loss data had been collected, it was observed that the variability in the values was very high. There were both extremely high and extremely low weight loss values on a number of occasions in this trial with no consistent pattern in data. This occurred, due to experimental error under orchard conditions

2.4.2 Fruit source

Fruit were collected from a commercial orchard located at Waihi Beach about 23.5 km away from the packhouse on 19th April 2016. The filling time started at about noon (11:30 am) and carried on up to 5:45 pm 19th April 2016. The whole trial was conducted between 19th April at 11:30 am and 20th April at 11:47 am, 2016. The average temperature which was recorded by the local weather station was 15.1 °C and rainfall of 1.8 mm was recorded during these two days when the trial was conducted (Figure 2.18).

2.4.3 Trial method specifics

All bins had their internal environmental conditions monitored and also two weight loss tracking sub-samples were established. The commercial grower line harvested required 162 plastic bins, of which 146 bins had monitoring of temperature and RH conditions, and also had fruit weight loss monitored.

Harvest fruit bins from the same grower were stacked on two neighbouring rows (K and L) simultaneously in the third bay at the packhouse. Each row consisted of up to 9 columns of bins stacked 9 high. Both curing stacks were surrounded by two set of wooden bins on both sides (Figure 2.16).

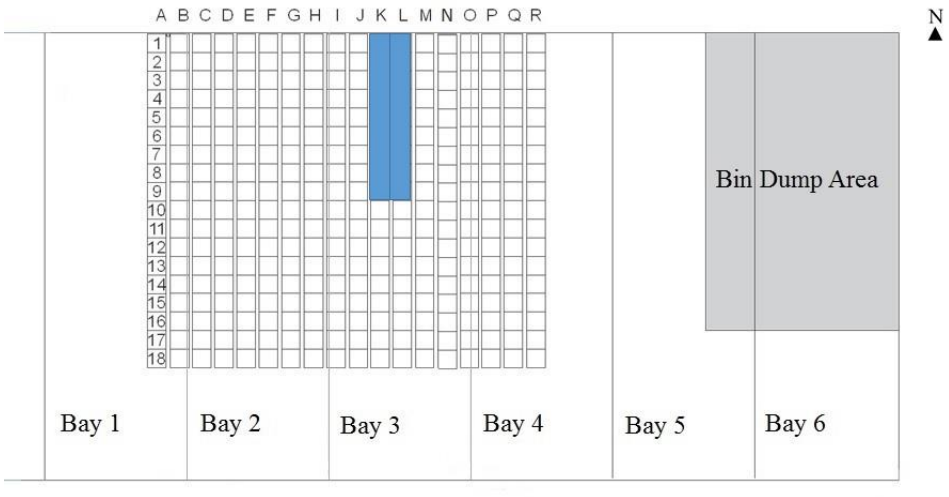


Figure 2.16: Illustration of an aerial view of bin stacking pattern for the second trial. The blue colour depicts the stacked bins for monitoring temperature and RH during curing.

2.4.4 Results

2.4.4.1 Time variability of curing

Harvested fruit were cured for approximately 24 h; the shortest curing time was 18 h and the longest curing time was 27 h. As it was previously indicated, the stacking arrangement in the curing stack was a result of the logistical constraints, with the first picked fruit stacked against the wall, and the last picked fruit of the day being the furthermost from the wall and close to the south side of the canopy. Therefore, depending on the available space at the packhouse, the last stacked bins are the first bins in the process of tipping fruit on the roller conveyor for grading. All bins were stacked in two rows next to each other in the third bay, while there were two stacks of wooden bins on both sides of them. Seventy two (72) bins were cured in the primary row and seventy four (74) bins stacked in the secondary row (Figures 2.16 and 2.17).

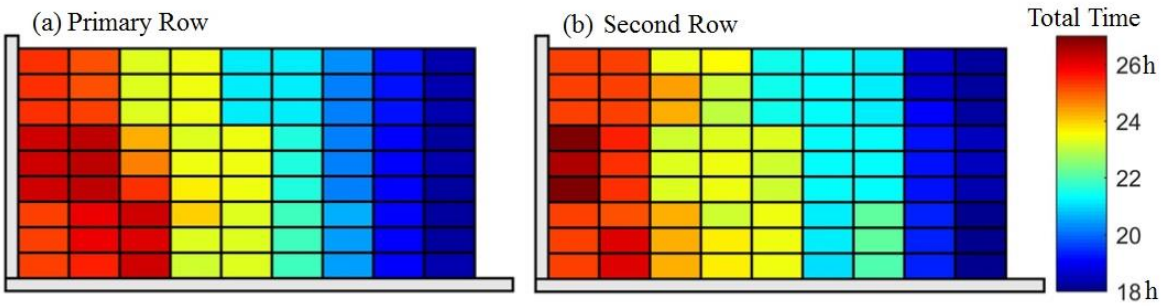


Figure 2.17: Duration of time in curing stack as influenced by position in stacked bins. Each block represents a single bin - a cross-sectional side view of the stack.

2.4.4.2 Ambient conditions during curing

Ambient temperature recorded by the local station was between 9.3-23.1 °C. The average temperature was 15.1 °C with a stable diurnal cycle over time when the trial was conducted (Figure 2.18).

Ambient temperature recorded relatively stable conditions during curing time, although the loggers located at the south side of the canopy showed higher temperatures between 2:00 pm and 4:00 pm (ranging from 18-35 °C) which indicated an error, due to the sunlight exposure in mid-afternoon (Figure 2.19). The average temperature and RH under the canopy were 16.4 °C and 74% respectively. At night, temperature decreased and then increased slightly about 1.2 °C for 6 h and it was between 12.7 °C to 14 °C in the early morning (5:00 am) 20th April (Figure 2.19).

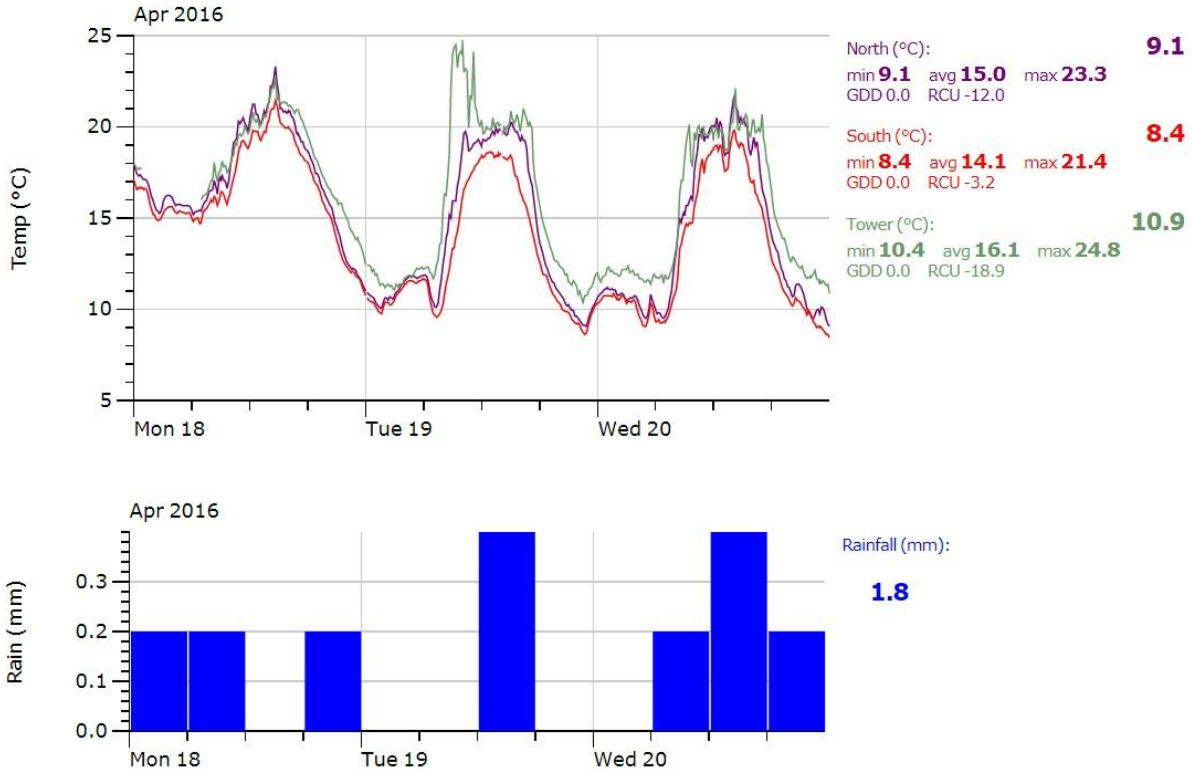


Figure 2.18: Temperature and precipitation data have been recorded at the local weather station for three days from 18th April to 20th April 2016.

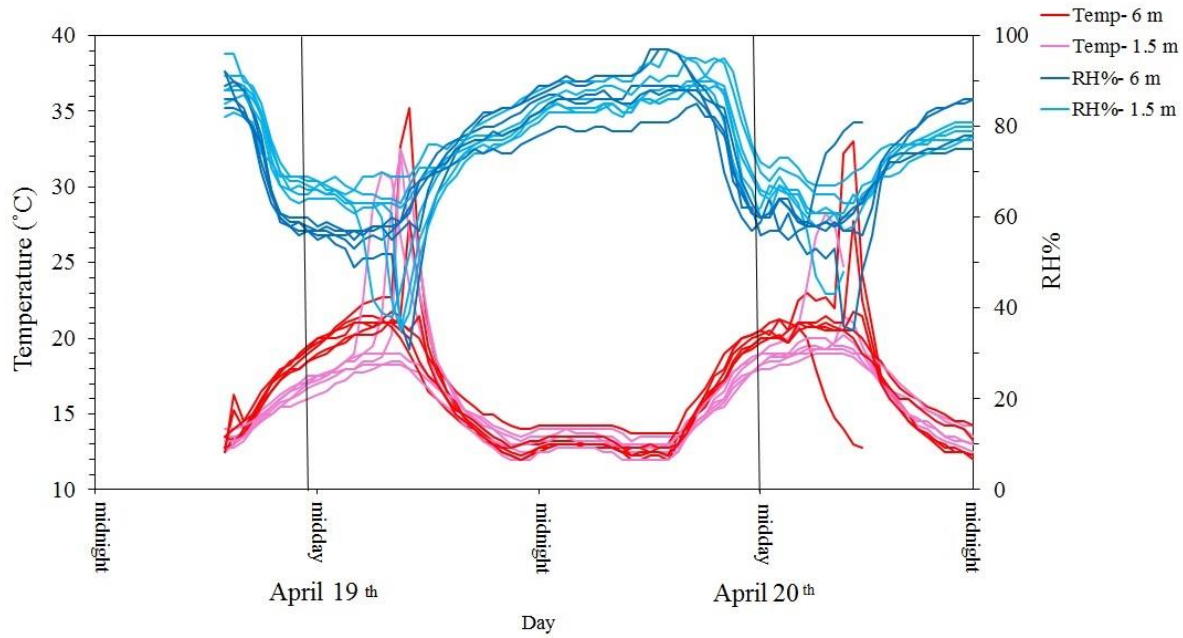


Figure 2.19: Ambient conditions under the canopy around the curing stack during the commercial kiwifruit curing, measured at 6 locations at 1.5 m and 6 m heights. The black vertical lines represent the time scale of the curing.

2.4.4.3 Temperature during curing

The loggers in the stacked bins closer to the wall and higher in the stack were generally higher (approximately 20-21 °C) in temperature and were gradually cooler (about 16-17 °C) progressing towards the side away from the wall. The temperature difference between two sides of the row was about 3-4 °C after 6 hours of filling at 6:00 pm (Figure 2.20a). While the temperature variation in the whole curing stack ranged between 16 °C to 22 °C at the same time (Figure 2.20a). The variation on both sides of the stack was dominated by the picking time. Since the first column close to the wall was stacked at 11:50 am and the far end column away from the wall cured at 6:10 pm in both rows. At midnight after 12 h of filling time, when the surrounding temperature was about 12-14 °C (Figure 2.19), the spatial variation in the bins temperature did not change and still represented at-harvest temperature (Figure 2.20b). However, temperature started to decrease slightly in individual bins in each row until 6:00 am (Figure 2.20c). The bins in the middle and top locations of the stack did not cool down and showed the highest temperature with the maximum being 20.5 °C. In the morning, the bins sitting at the bottom of the stack showed lower temperature (15-17 °C) and the far end columns away from the wall still had the lowest temperature (15-16 °C). Temperature variability in the stack shows the positional variability i.e. the highest temperature in the middle and top locations of the stack and the development of cooler bins at the bottom of the stack. One possible explanation for this phenomenon is a physical effect or mechanical obstruction of the canopy's roof prevents heat transfer from the underside of the canopy to the outside, creating temperature stratification that results in hot/cold air mass accumulating at different levels. At this time scale, there was a minor difference between both sides of the curing stack (Figure 2.20c). The canopy temperature remained relatively steady (12-14 °C) through the night. The temperature variability in the whole stack remained the same till the following day at noon (approximately 24 hours of curing) (Figure 2.20d). However, the ambient conditions showed a higher air temperature (18-20 °C) at noon as expected in diurnal temperature cycle at noon.

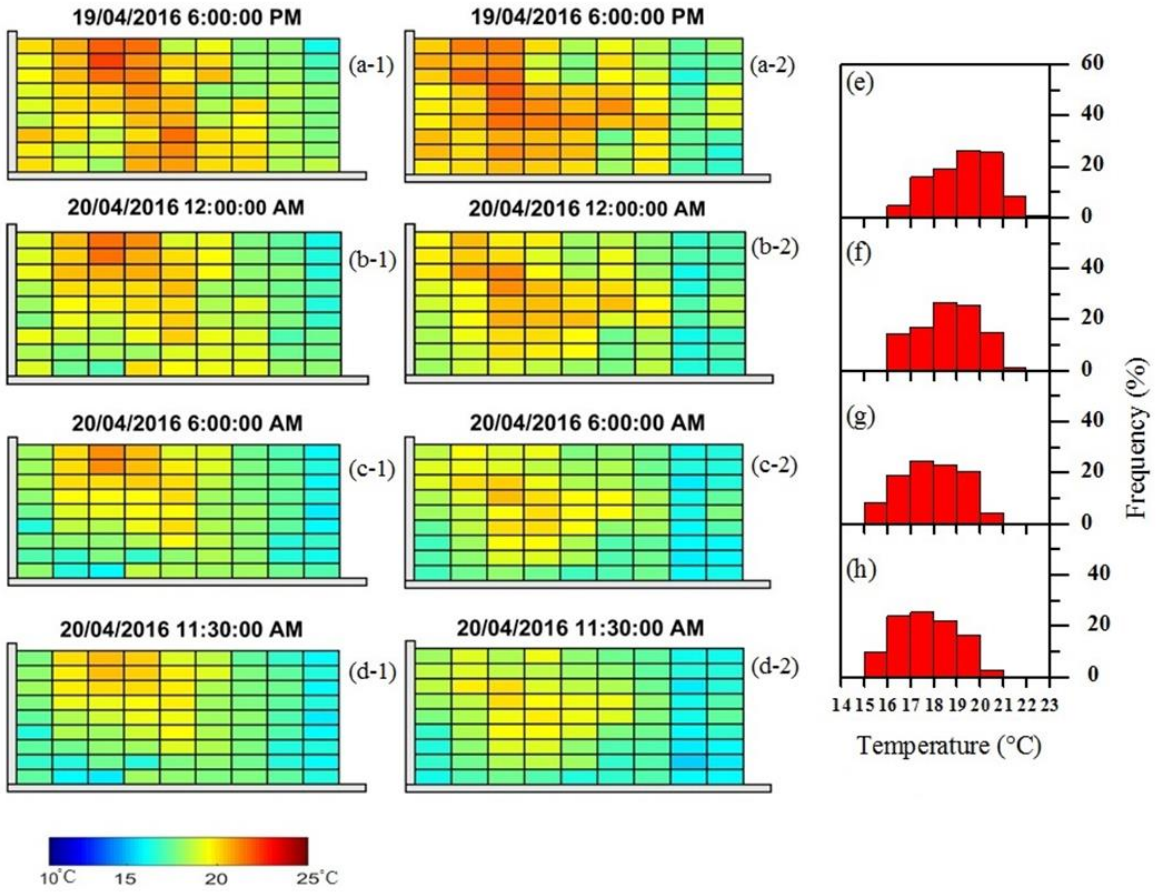


Figure 2.20: A cross sectional view of spatial temporal temperature variation of the middle of 320 kg 'Hayward' kiwifruit bins during commercial curing. The maps on the left labelled from (a-1) to (d-1) represent data for the primary row including interpolation (n = 72) and the maps on the right labelled from (a-2) to (d-2) represent data for the secondary row including interpolation (n = 74), while histograms report data from both rows (n = 146).

2.4.4.4 Relative humidity during curing

High humidity conditions were observed to develop in the stacked bins after about 3 h of filling (70-80%) (the data are not shown, since the stack had not been completed at this time of day) and RH conditions became near saturated in the top-middle bins after approximately 6 h of filling (at 6:00 pm on 19th April), while RH conditions in the bins at the bottom of the stack were about 70-80% (Figure 2.21a).

RH increased gradually in all bins over the night and the RH variation pattern was similar in both rows, the range of RH became smaller at 9:30 am on 20th April (Figures 2.21b, c, d, and e). It is worth taking into consideration that there were more bins in the top-middle position of the curing stack in the primary row with near saturation RH conditions when compared to the

second row. The near saturated RH conditions remained consistent until the following day at noon (Figure 2.21f).

The top-middle bins high humidity was accompanied by high temperature in the middle of the bins, while at the same time, the condition was different in the lower and external bins (Figures 2.20 and 2.21). This can be discussed by the relatively stable condition under the canopy with no air movement. In addition, both curing stacks were surrounded by two set of wooden bins on both sides.

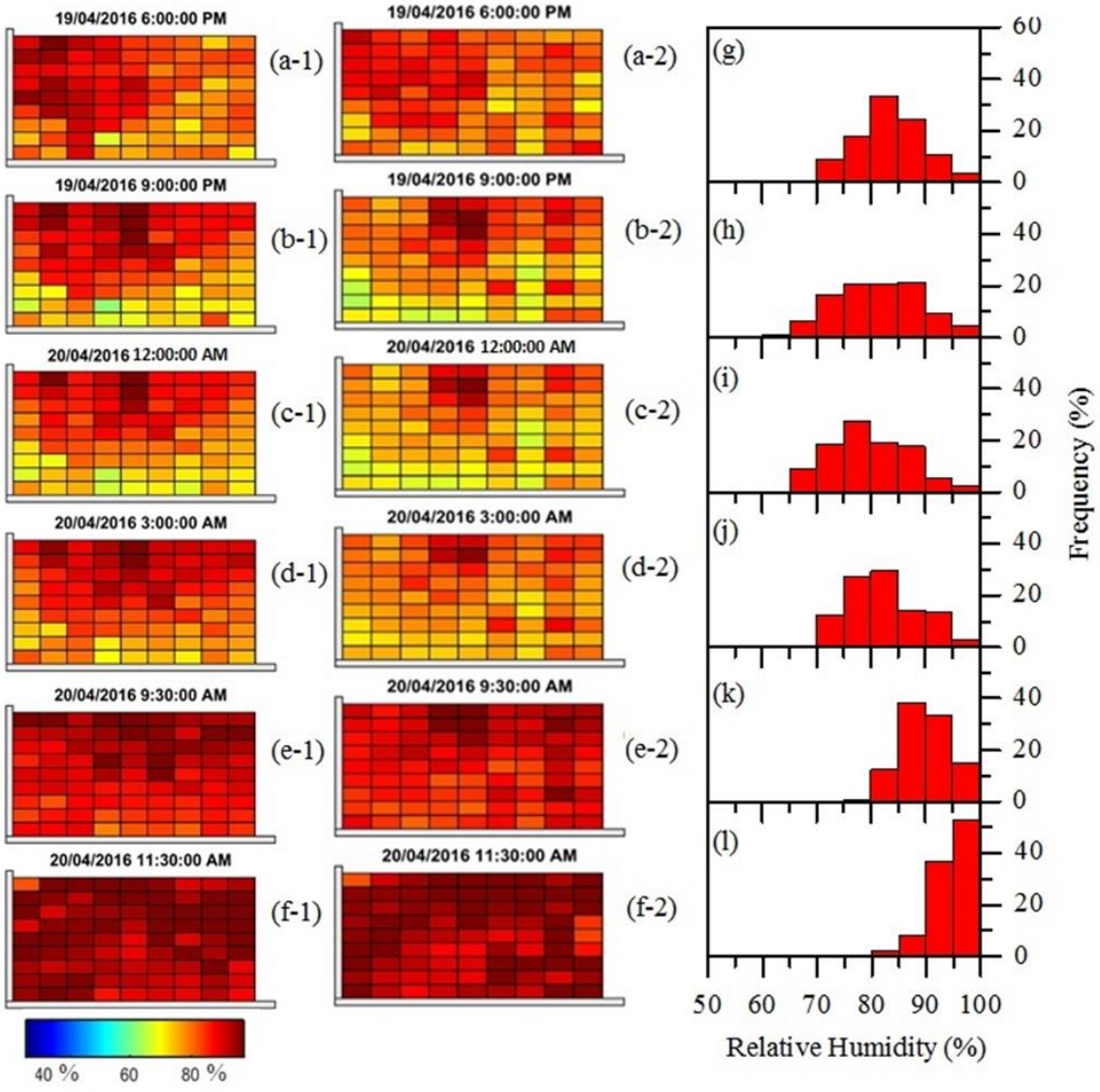


Figure 2.21: Spatial temporal RH variation of the middle of 320 kg ‘Hayward’ kiwifruit bins during commercial curing. The maps on the left labelled from (a-1) to (f-1) represent data for the primary row including interpolation (n = 72) and the maps on the right labelled from (a-2) to (f-2) represent data for the secondary row including interpolation (n = 74), while histograms report data from both rows (n = 146).

2.4.4.5 Weight loss impact as a result of curing

Fruit weight loss data were collected from all bins (n = 146) on both rows and fruit weight loss over the entire curing time (from 18 h to 27 h) for bags located on the top and in the middle of the bins (Tables 2.2 and 2.3). As explained, due to the uncontrollable experimental errors during measuring fruit weight bags at the orchard, the range of variability in the observations (-7.2 to 17.7%) was out of the normal scale for fruit weight loss and unrealistic, which indicated lack of reliability and accuracy of fruit weight loss data in this trial. The erroneous data stopped further analysis.

Table 2.1: Weight loss (%) of measured fruit on top (a) and in middle (b) of 320 kg 'Hayward' kiwifruit in the primary row (n = 72) during commercial curing.

(a)	**Fruit weight loss map**								
Bin height	**The primary row-top bags**								
9	-2.00	2.41	0.17	0.23	0.19	0.28	0.13	0.54	0.35
8	2.00	0.32	0.36	0.24	0.10	0.67	0.20	0.26	0.21
7	0.48	-1.58	0.38	0.42	0.38	0.30	0.43	0.15	0.60
6	1.49	-0.31	-1.14	0.36	0.40	0.35	0.20	0.19	0.23
5	0.20	-3.75	-	-	-0.80	0.30	0.28	0.13	0.25
4	7.25	1.40	-	-	0.35	0.52	0.27	0.55	0.24
3	0.49	1.50	0.38	0.46	0.51	-	0.31	0.42	0.22
2	0.30	-1.19	0.72	0.47	-	-	0.41	0.58	5.35
1	4.83	-2.03	7.22	0.43	-	-	0.34	0.31	0.20
(b)	**The primary row-middle bags**								
9	-0.15	4.90	0.35	0.23	-4.20	0.27	-0.42	0.18	0.05
8	0.65	0.28	0.36	0.31	0.04	0.29	-0.24	0.20	0.23
7	6.37	2.97	0.31	0.26	0.08	-0.32	-0.41	0.19	0.13
6	-0.14	-5.23	0.26	0.29	0.33	0.07	0.07	-0.05	-0.03
5	2.68	17.70	-	-	1.34	0.04	-0.18	0.23	0.16
4	2.99	2.37	-	-	0.20	0.29	-0.10	0.27	0.24
3	0.50	6.35	0.32	0.40	0.15	-	0.32	0.35	0.26
2	-0.07	3.42	0.73	0.45	-	-	0.31	-0.01	0.23
1	0.00	2.67	0.42	0.45	-	-	0.33	0.26	0.24
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	The columns of bins								

Table 2.2: Weight loss (%) of measured fruit on top (a) and in middle (b) of 320 kg ‘Hayward’ kiwifruit in the secondary row (n = 74) during commercial curing.

	Fruit weight loss map								
(a)	**The second row-top bags**								
9	0.46	-2.63	0.31	0.33	0.27	0.39	0.33	0.67	0.21
8	0.34	-4.99	-	-	0.22	0.53	0.33	0.35	0.27
7	-0.32	-5.49	-	-	0.31	0.35	0.23	0.17	0.27
6	0.54	10.35	0.44	0.18	0.44	0.30	-6.77	0.08	0.24
5	-	-6.40	0.39	0.24	0.39	0.38	0.38	0.27	0.18
4	0.47	0.90	0.43	0.13	0.37	0.47	0.16	0.13	0.28
3	0.85	0.40	0.25	0.38	0.56	0.36	0.44	-0.03	0.23
2	0.48	-0.88	0.11	-	0.44	0.29	0.17	0.19	0.21
1	0.09	4.41	0.42	-	0.54	0.13	0.03	-0.10	0.18
(b)	**The second row-middle bags**								
9	0.45	-7.18	5.19	0.28	0.08	0.31	0.32	-0.04	0.22
8	0.25	5.98	-	-	0.28	0.49	0.28	0.58	0.16
7	0.40	3.64	-	-	0.12	0.30	0.35	0.39	0.21
6	0.18	0.25	0.40	0.33	0.59	-0.06	0.37	0.13	0.56
5	-	6.85	0.28	0.15	0.36	0.35	-0.06	0.26	0.42
4	0.43	8.40	0.37	0.29	0.41	0.05	0.41	0.08	0.25
3	0.68	0.38	0.28	0.38	0.47	0.23	0.24	-0.05	-0.11
2	0.37	-2.21	0.43	-	0.35	-0.24	0.52	-0.19	0.02
1	0.44	5.18	0.43	-	2.76	0.10	0.37	-0.10	0.27
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	The columns of bins								

2.5 Curing trial three

2.5.1 Trial commentary

- The first primary stacked completed at 3:40 pm and the secondary row (an incomplete stack) started at 4:00 pm and was finished at 5:30 pm (Figure 2.22)

- In order to not disturb the usual harvest practices which occurred under high speed, normal operational activity was prioritised over experimental efforts. As a result, while attempts were made to measure each and every bin, not all bins harvested were monitored in each trial. In this trial, the decision was made that the experimental plan was too ambitious for the experiment time constraints and available resources. As a result, the instrumentation plan was changed from this trial and the following trials. Thus, the instrumentation was conducted for sets of 3 bins, in which all bins had their internal environmental conditions monitored, while one of every 3 bins also had two weight loss tracking sub-samples established (Figure 2.5)

- The commercial grower line harvested required 188 wooden bins in a day, of which 174 bins had monitoring of their temperature and RH conditions, and of these 174 bins, the position of 150 bins could be tracked, but the exact location of 24 bins in the stack was not clear, because the external labels to enable identification in the curing stack were lost during transportation. The possible reason was the labels hadn't been stapled properly to the wooden bins, due to time pressure to maintain the same speed during the packhouse operational activity to transport the fruit bins. In other trials, the self-adhesive labels could firmly and easily stick to the plastic bins without taking time

- The bins with missing labels were mainly sitting in the first fourth columns of the primary row

- The primary row was formed consisting of 142 bins that 104 of these bins were monitored

- 46 bins from the same grower were stacked in another row (the secondary row)

- 59 bins also had fruit weight loss monitored

- The bins from the same grower were packed in two packing runs on 11th May. The bins in the secondary row were packed in the morning at 9:45 am. The bins on the primary row had been tipped on the roller conveyor for packing process in the late evening at 9:30 pm on the same day. The curing time ranged from 40.7 h to 59 h on both rows

2.5.2 Fruit source

Fruit were collected from a commercial orchard located on Athenree Road about 15 km away from the packhouse on 9th May 2016. The filling time started at about noon (10:40 am) and carried on up to 5:10 pm in afternoon on the same day. Fruit were packed in two packing runs on 11th May 2016, the curing time was finished at 9:45 am for the secondary row, while the curing time was over at 9:30 pm for the primary row on the same day. The average temperature recorded by the local weather station was 15.1 °C and rainfall of 8.2 mm occurred during the three days when the trial was conducted (Figure 2.24).

2.5.3 Trial method specifics

For every three bins, the internal environmental conditions were monitored, while one of these 3 bins also had two weight loss tracking sub-samples established. The commercial grower line harvested required 188 wooden bins in a day, of which 150 bins had monitoring of temperature and RH conditions, 59 bins also had fruit weight loss monitored. The primary row (P) was established in the fourth bay of the curing area, consisting of 104 of bins while 46 bins from the same grower were cured in another row (L - the secondary row) in the third bay. There were three stacks of full plastic bins between them (Figure 2.22). It was a busy time at the packhouse during the trial as it was the peak harvest season for kiwifruit. Therefore, the two stacks were surrounded by different rows of wooden and plastic bins at different time points during the curing. The primary row consisted of up to 16 columns; all columns of bins stacked 9 except the last column of bin stacked 7) high and the second row had 5 columns; all columns of bins stacked 10 high except the last column of bin stacked 6.

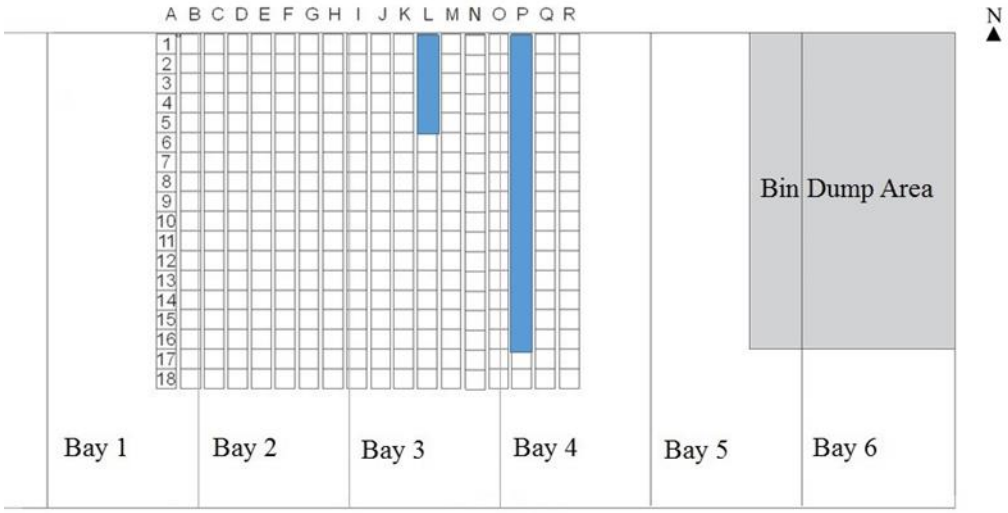


Figure 2.22: Illustration of an aerial view of bin stacking pattern for the third trial. The blue colour depicts the stacked bins for monitoring temperature and RH during curing.

2.5.4 Results

2.5.4.1 Time variability of curing

The bins were packed at two different packing time during the day, such that the curing time ranged from 40.7 to 59 hours (Figure 2.23). All bins of the second row were packed in the morning (9:45 am), while the primary row was packed in the late evening (9:30 pm) of the same day on 11th May 2016.

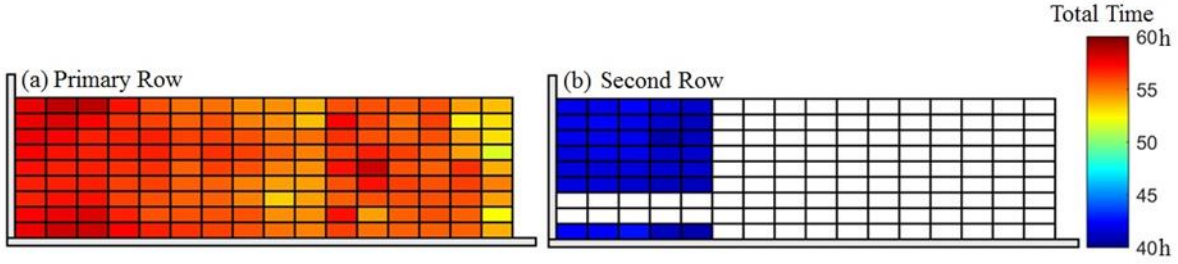


Figure 2.23: Duration of time in curing stack as influenced by position in stacked bins. Each block represents a single bin - a cross-sectional side view of the stack.

2.5.4.2 Ambient conditions during curing

Ambient temperature recorded by the local station was between 9.6-21.6 °C. The average temperature was 15 °C and showed a similar diurnal variation (Figure 2.24).

Ambient conditions during almost two and a half days of curing were reasonably stable, reflecting the diurnal cycles of temperature, from the midday of the second day until the end of the curing. The ambient temperature did not change, while RH under the canopy increased. The temperature range was between 12 to 21 °C. The average of temperature and RH under the canopy was 17.1 °C and 84%, respectively (Figure 2.25).

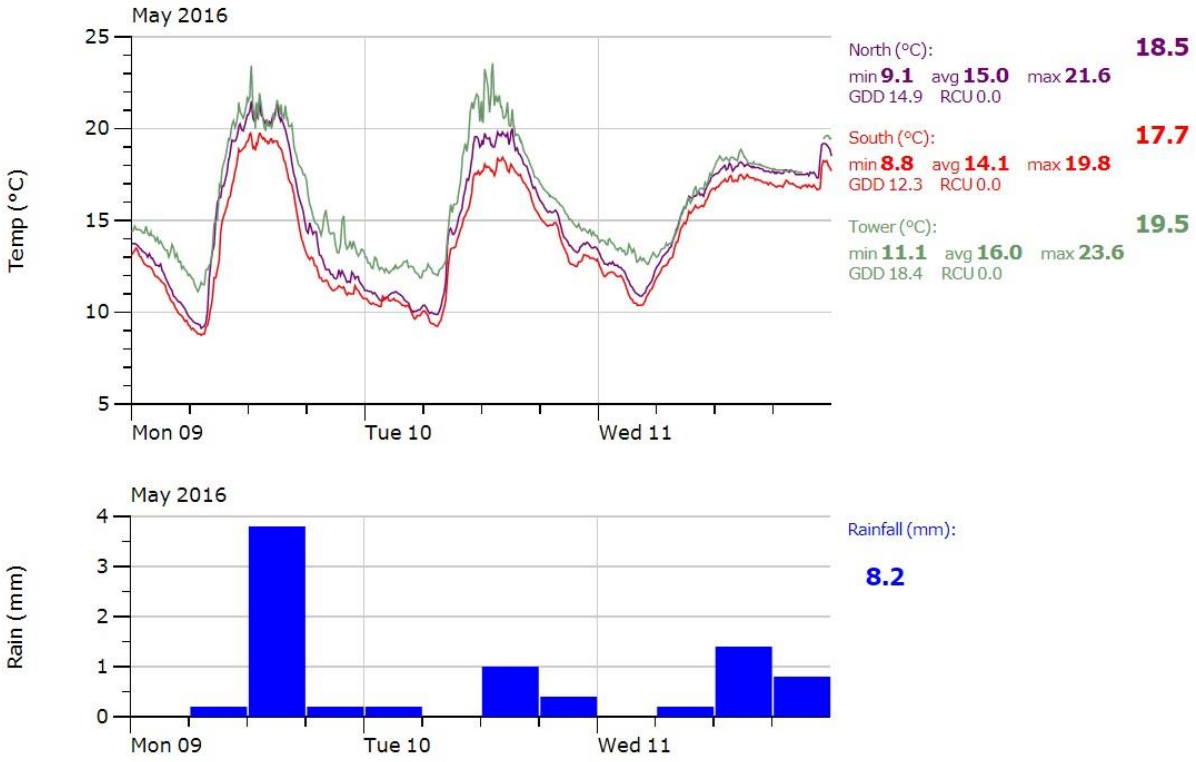


Figure 2.24: Temperature and precipitation data have been recorded at the local weather station for three days from 9th May to 11th May 2016.

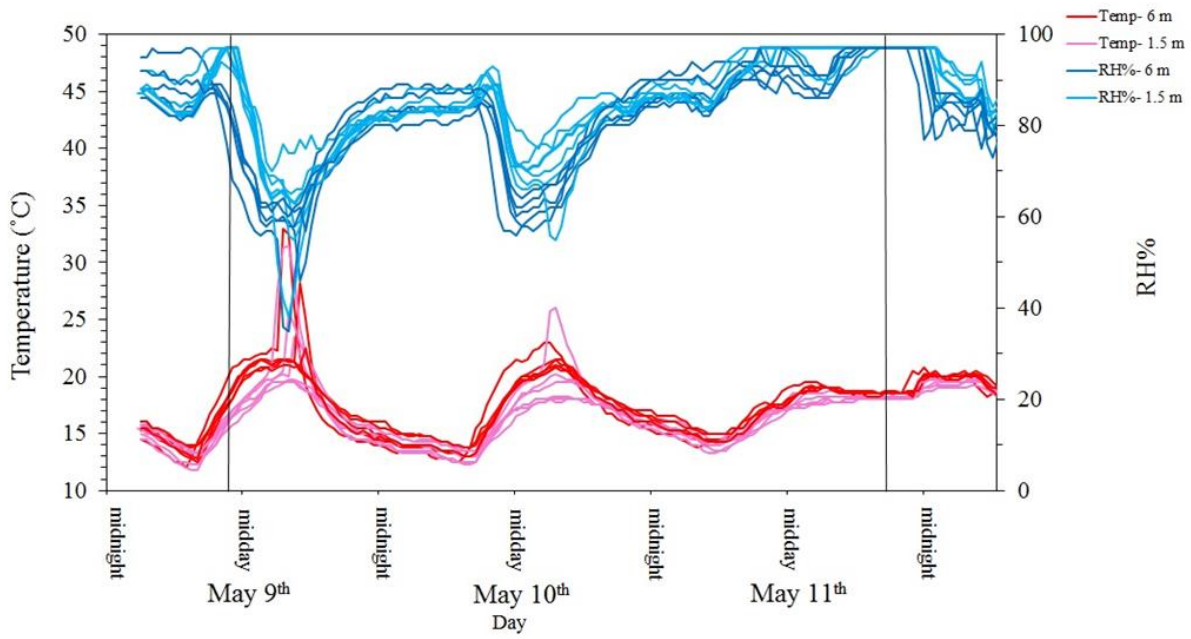


Figure 2.25: Ambient conditions under the canopy around the curing stack during the commercial kiwifruit curing, measured at 6 locations at 1.5 m and 6 m height. The black vertical lines represent the time scale of the curing.

2.5.4.3 Temperature during curing

The initial temperature profile immediately after forming both rows represented at-harvest temperature (Figure 2.26a). Fruit picked earlier in the day and closer to the wall were cooler (18-19 °C) than those picked in the heat of the afternoon until 3:40 pm (Figure 2.26a-1). Likewise, in the secondary row where fruit had been picked and stacked in the late afternoon, initial temperature was about 18-19.5 °C (Figure 2.26a-2). In general, the temperature variation in both curing stacks ranged from 17 to 22 °C at 5:30 pm after 7 h of filling time for the first bin of the primary row. Bins temperature dropped gradually in the whole stack. However, the temperature variability was the same (2.26 b-1, g). The same trend happened to environmental temperature after sunset. There was a 2 °C temperature difference between bins filled before noon and those which were loaded in afternoon and the difference can be seen until the midnight (Figure 2.26b), then the bins sitting at the bottom of the stack and also the bins loaded in morning and positioned in the middle of the stack showed lower temperatures compared to others (17 °C). Few bins in the middle and top locations of the stack harvest in the afternoon, showed the highest temperature 20 °C (Figure 2.26c-1). At this time point, the temperature variability in both rows became less and ranged from 16 to 20 °C (Figure 2.26h). On 10th May, at 10:00 am, the temperature in bins had decreased steadily (range of 15-19 °C) regardless of

a slight improvement of environmental conditions, due to the diurnal cycle (Figures 2.25 and 2.26d). On 11th May at 12:00 am, the temperature variability was still the same in the whole stack, while the effect of bin's position was still clear, with the warmest region (18.5 °C- approximately 10% of the stacked bins) was at the top location in the middle of the primary/secondary stacks and the rest of the bins had lower temperature between 1-2 °C equally in the whole stack, as temperature stratification (Figure 2.27a and f). After almost 54-59 h of curing of the primary stack, the range of temperature was about 16 to 19 °C in the whole stack. A significant proportion of the curing bins (approximately 70%) showed about 17.5 °C when the average of environmental temperature was about 18.5 °C (Figures 2.5 and 2.27e).

The temperature changes in the secondary row were the same with this difference as the bins that were located away from the north wall and picked in the late afternoon, and showed a lower temperature (18-18.5 °C). The temperature variability at the beginning of stacking was about 1.5 °C (Figure 2.26a-2). The right bottom corner of the stack away from the wall was the coldest zone of the whole stack (approximately 17 °C) and the temperature of the secondary row decreased gradually and then remained steady throughout the curing time (Figures 2.26 and 2.27). The secondary row was cured for at least 40.7 h.

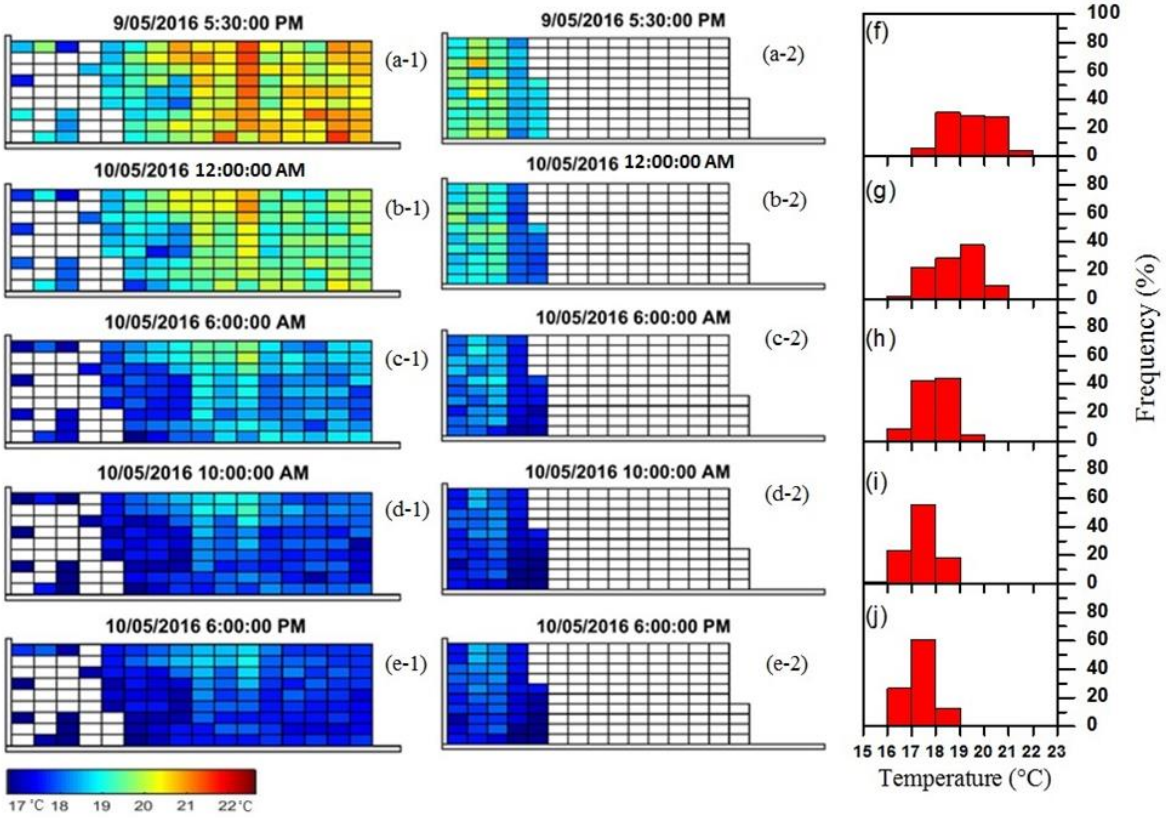


Figure 2.26: Spatial temporal temperature variation of the middle of 250 kg ‘Hayward’ kiwifruit bins. The maps on the left labelled from (a-1) to (e-1) represent data for the primary row including interpolation (n = 104) after the first 31 h of curing. The maps on the right labelled from (a-2) to (e-2) represent data for the secondary row including interpolation (n = 46) after the 26 h of curing, while histograms report data from both rows (n = 150).

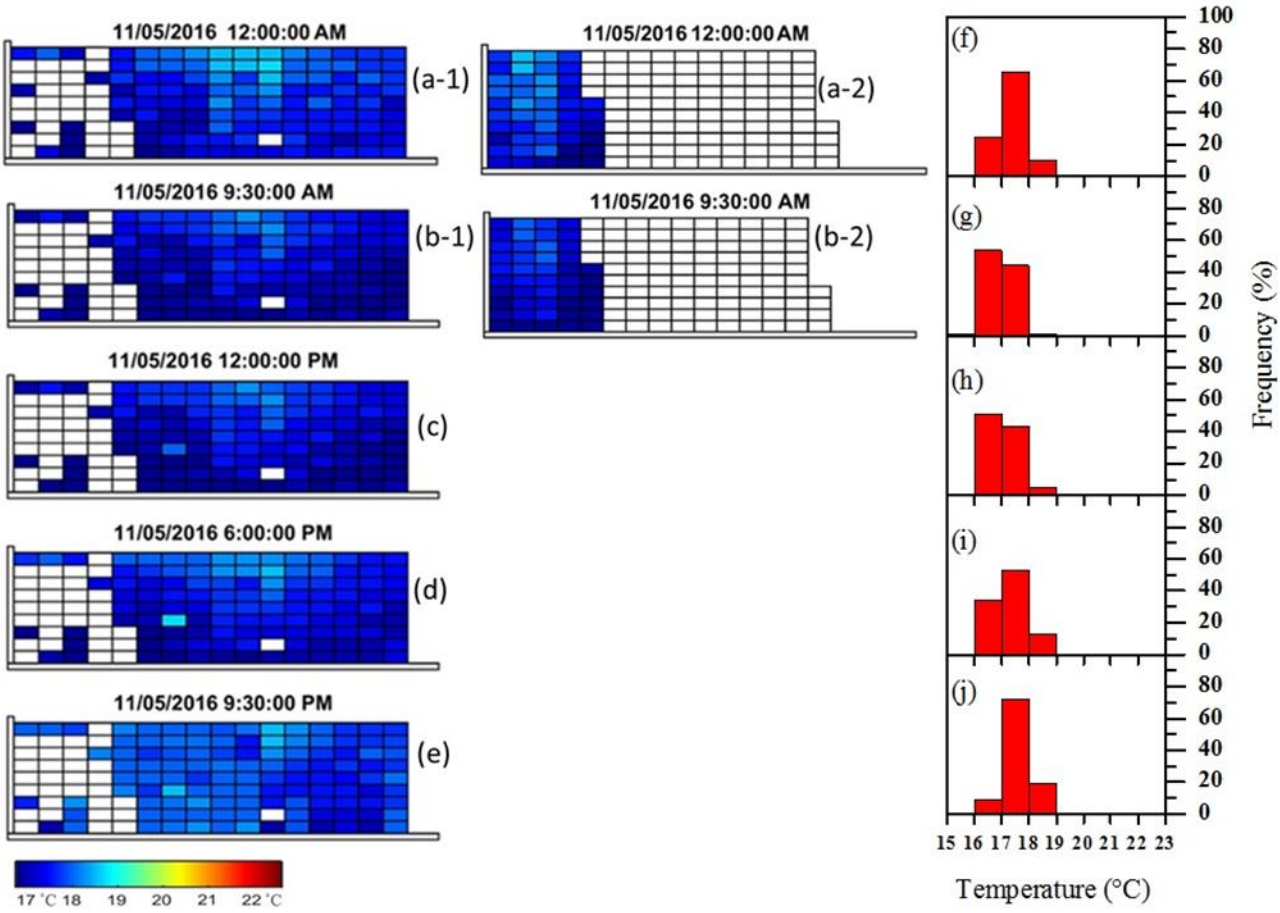


Figure 2.27: Spatial temporal temperature variation of the middle of 250 kg 'Hayward' kiwifruit bins after 59 h curing. The maps on the left labelled from (a-1) to (e) represent data for the primary row only including interpolation (n = 104) after 59 h curing. The maps on the right labelled from (a-2) to (b-2) represent data for the secondary row only including interpolation (n = 46) after at least 40.7 h curing, while histograms report data from both rows (n = 150).

2.5.4.4 Relative humidity during curing

RH conditions increased in the primary curing stack after about 7 h of filling (to a range of 80-97%) and it represented the picking time i.e. fruit were picking early in the morning about 10:00 am showed higher RH in the bins (Figure 2.28a). The conditions changed gradually over the night and decreased progressively until the next morning. However, the RH variability remained the same in the whole stack (Figure 2.28b, c, and d). When RH in the whole stack ranged from 75 to 97%) about 24 hours after filling, then it increased and became close to saturation point for 90% of the stacked bins at 6:00 pm on 10th May (Figure 2.29a). The condition remained intact until 3:00 am when RH started to reduce for a period of approximately 3 h (by 6:00 am) to the range of 80 to 97% (Figure 2.29c). The last two columns in the stack which were in the far end of the stack showed the lowest humidity conditions which

could be explained by the fact that it was located away from the wall and was exposed to airflow from the south side of the canopy. At the same time, environmental RH remained steady during the night and held this pattern until next morning. After 6:30 am on 11th May, RH increased to saturation point until the curing time was completed (9:30 pm) (Figure 2.29c-1, d-1, e, and f).

In the secondary row, the RH profile immediately after forming the stack showed no difference in the bins at different locations of the stack. But about 4 h later (9:30 pm), the last load of the bins which were picked in late afternoon had higher RH than other bins in the same row (Figure 2.28b-2). The effect of picking time was obvious, however, the time frame for building the secondary row was only 1 h 30 min. The secondary row was cured for at least 40.7 h. The humidity conditions in the secondary row showed a similar pattern like the primary row. Although the observed variation occurred in a smaller-scale (Figures 2.28 and 2.29). One possible explanation for this might be the second fruit stack was shorter than the primary one and it had only 5 columns, when it was surrounded tightly by the stack of plastic bins on both sides. Therefore there was a very low chance of direct airflow.

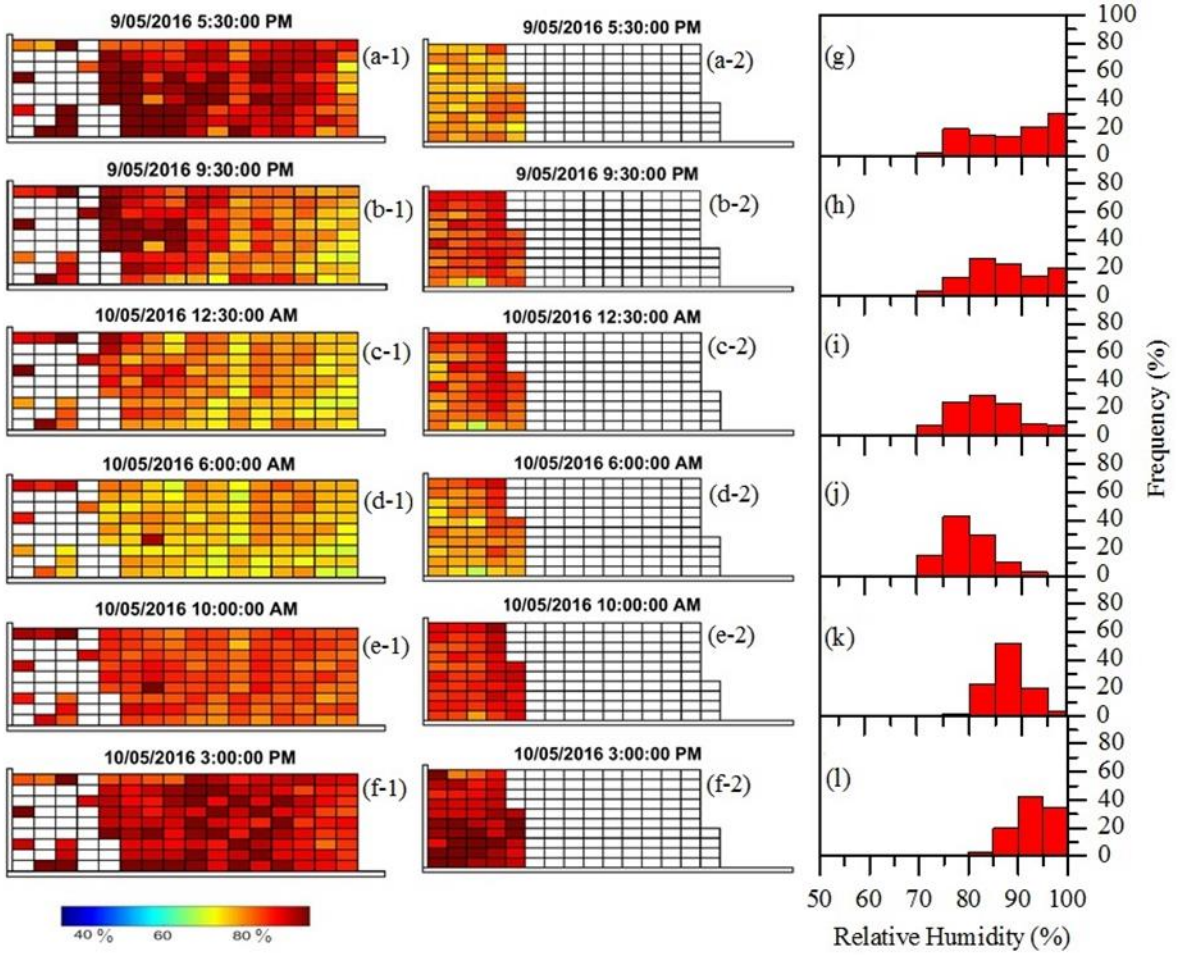


Figure 2.28: Spatial temporal RH variation of the middle of 250 kg 'Hayward' kiwifruit bins. The maps on the left labelled from (a-1) to (f-1) represent data for the primary row only including interpolation (n = 104) after the first 28 h of curing. The maps on the right labelled from (a-2) to (f-2) represent data for the secondary row including interpolation (n = 46) after the first 23 h of curing, while histograms report data from both rows (n = 150).

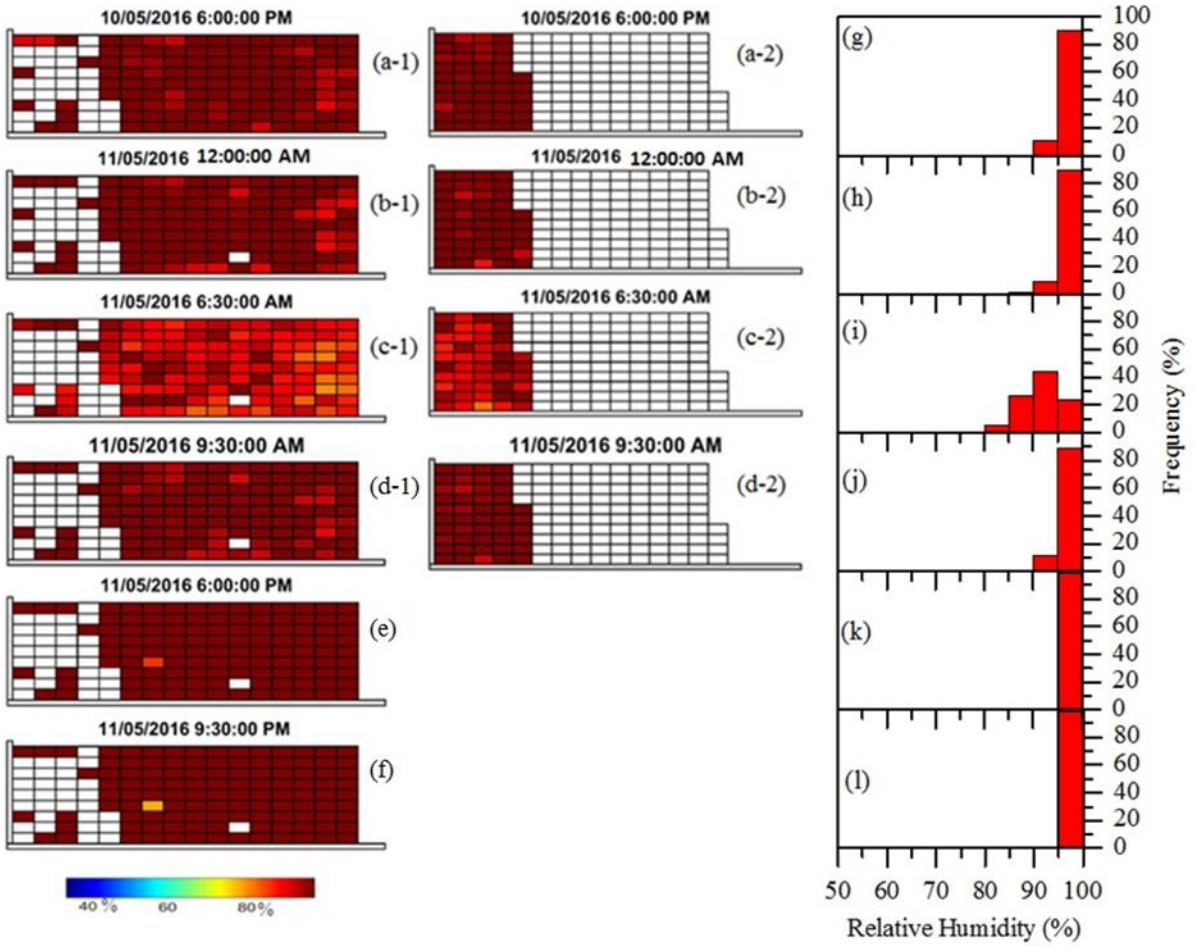


Figure 2.29: Spatial temporal RH variation of the middle of 250 kg 'Hayward' kiwifruit bins. The maps on the left labelled from (a-1) to (f) represent data for the primary row only including interpolation (n = 104) after 59 h curing. The maps on the right labelled from (a-2) to (d-2) represent data for the secondary row including interpolation (n = 46) after 40.7 h curing, while histograms report data from both rows (n = 150).

2.5.4.5 Weight loss impact as a result of curing

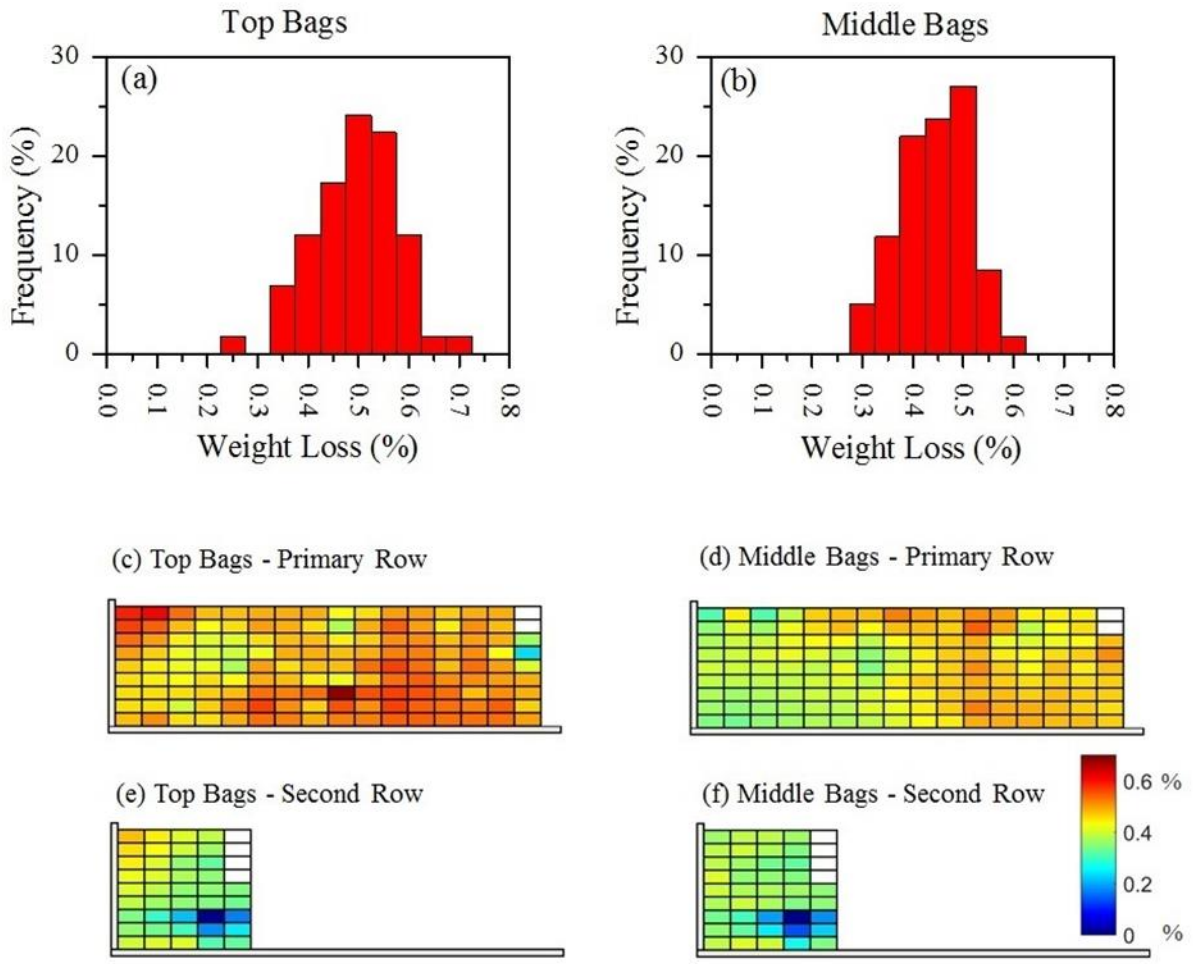


Figure 2.30: Weight loss of measured fruit on top (a, c, e) and in middle (b, d, f) of 250 kg 'Hayward' kiwifruit during commercial curing (n = 59).

Weight loss over the entire curing time for the bags located on the top of the bin showed a normal distribution (P-value = 0.95) averaging 0.46%, and a standard deviation of 0.08% (Figure 2.30a) and the distribution of the weight loss in the middle bags was also normal (P-value = 0.53; mean = 0.40%, SD = 0.06%) (Figure 2.30b). In general, weight loss was between 0.3-0.5% for about 90 percent of the bags during 40.7 (the second row) to 59 h (the primary row) curing.

2.6 Curing trial four

2.6.1 Trial commentary

The fourth trial started in rainy weather and shortly after the starting point, the trial was stopped, due to the bad weather conditions.

- The trial was conducted in a small-scale (n = 38 bins)

- The curing time was the shortest curing time among the trials (between 5 h 40 min to 7 h 15 min)

- At harvest time fruit were wet. The short distance between the orchard and the packhouse was beneficial under wet weather conditions

- The wet weather conditions at harvest influenced fruit weight loss measurement, therefore there were some erroneous fruit weight loss data

2.6.2 Fruit source

Fruit were collected from a commercial orchard located on Beach Road about 500 m away from the packhouse on 24th May 2016 at 12:40 pm. The filling time was about 1h 10 min (1:50 pm) when the filling stopped, because of rainy weather. The whole trial was conducted between 12:40 pm and 7:20 pm on 24th May 2016. The average temperature which was recorded by the local weather station was 12.8 °C and a rainfall of 25.8 mm occurred during the three days when the trial was conducted (Figure 2.33). On 24th May, the average daily temperature and rainfall were 13.8 °C and 4 mm, respectively. To avoid excessive moist on fruit loads, fruit were immediately delivered to the packhouse.

2.6.3 Trial method specifics

For each set of three bins all had their internal environmental conditions monitored, while one of these three bins also had two weight loss tracking sub-samples established. The plastic bins (38 bins) were stacked in one single row (K) in the third bay within the canopy (Figure 2.31). Fruit were wet at the initiation of curing, because of rainy weather conditions. Fruit weight loss was monitored in 13 bins.

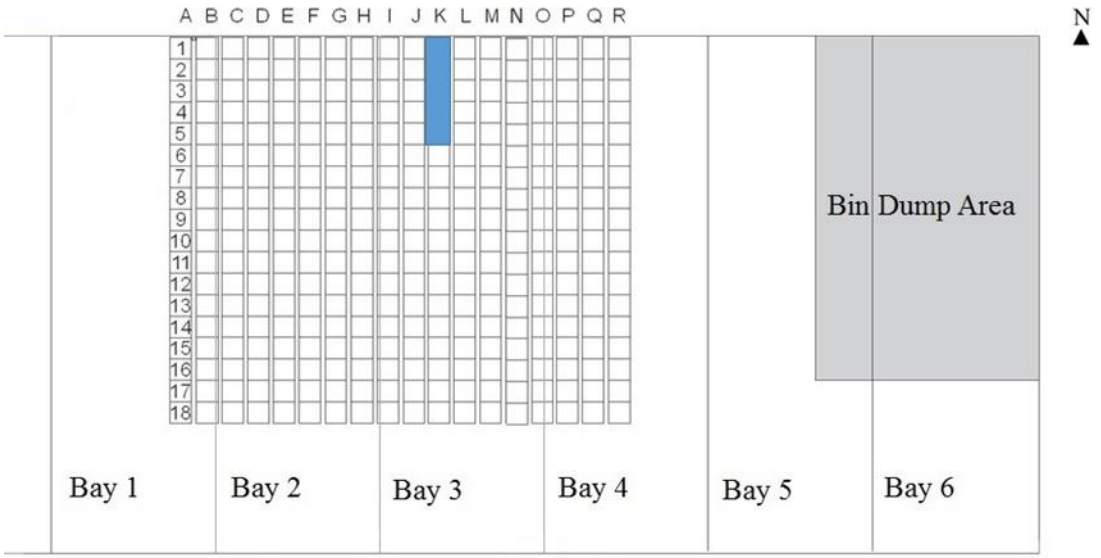


Figure 2.31: Illustration of an aerial view of bin stacking pattern for the fourth trial. The blue colour depicts the stacked bins for monitoring temperature and RH during curing.

2.6.4 Results

2.6.4.1 Time variability of curing

Thirty eight bins (n = 38) were picked and stacked in a single row. The shortest curing time was 5 h 40 min and the longest curing time was 7 h 15 min (Figure 2.32). In the third bay, all bins of the first load were stacked against the wall and the second load was adjacent to the first load in the same row further from the wall. The stack was formed by 5 columns, the height of stacked bins was 9 bins in each column except the last column consisting of only 2 bins.

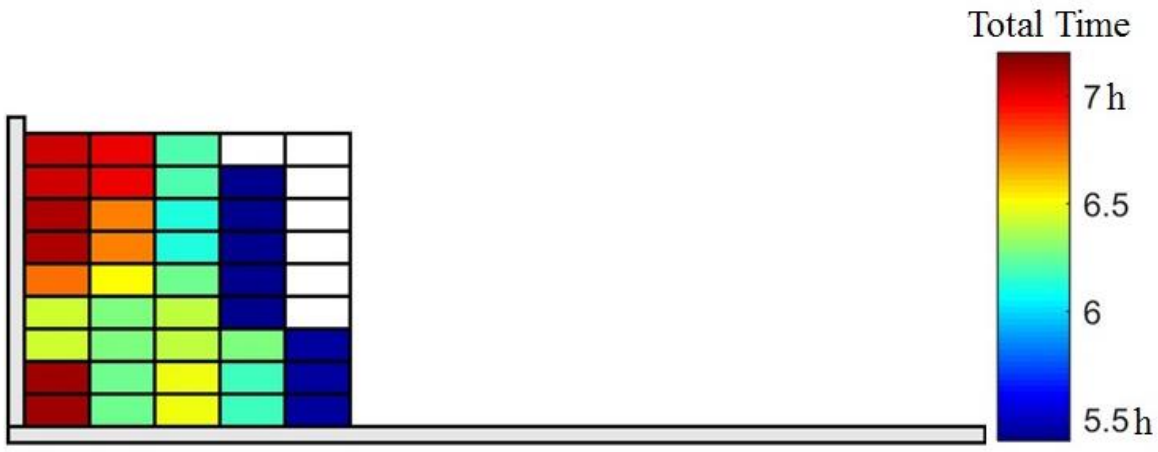


Figure 2.32: Duration of time in curing stack as influenced by position in stacked bins. Each block represents a single bin - a cross-sectional side view of the stack.

2.6.4.2 Ambient conditions during curing

Ambient temperature recorded by the local station was between 5.8-17.6 °C. The average temperature was 12.8 °C and average precipitation in depth was approximately 5 mm (Figure 2.33).

Ambient temperature under the canopy showed a steady state (average temperature was 15.4 °C) on 24th June, while RH dropped in a short time and then increased rapidly at noon when the rain started (the average RH was 78%) (Figure 2.34).

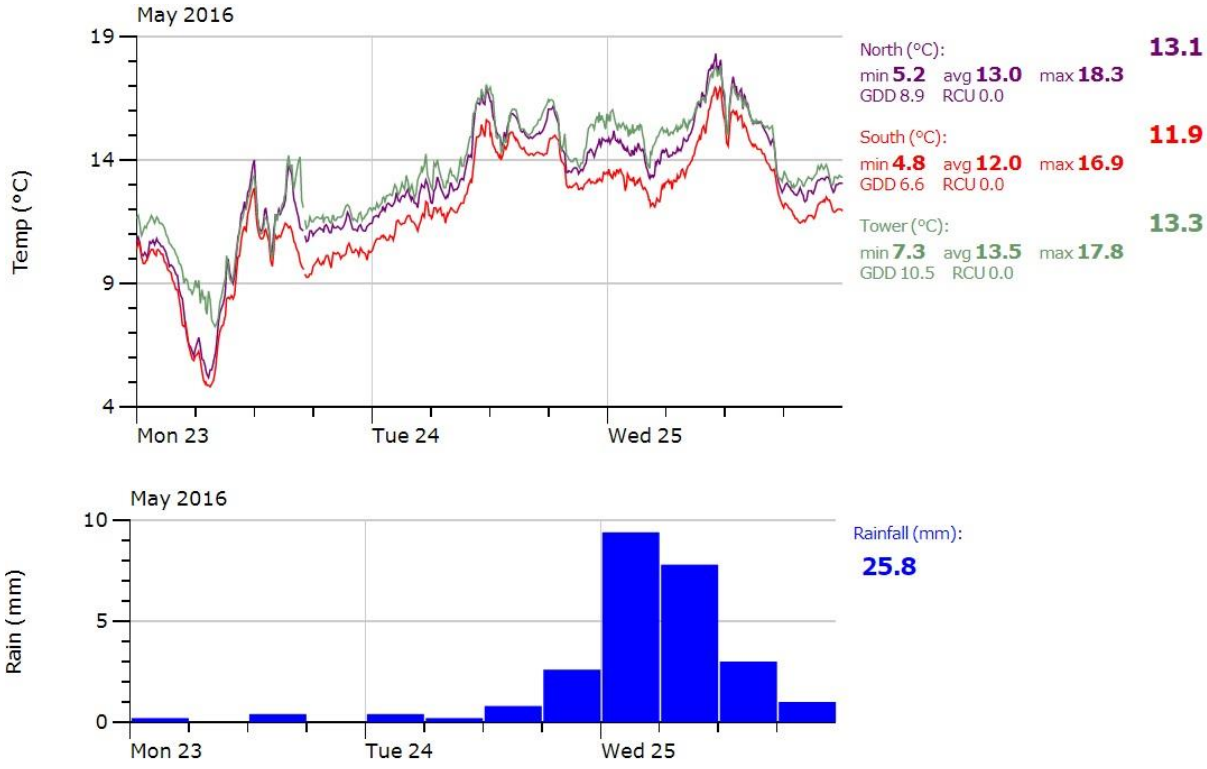


Figure 2.33: Temperature and precipitation data have been recorded at the local weather station for three days from 23rd May to 25th May 2016.

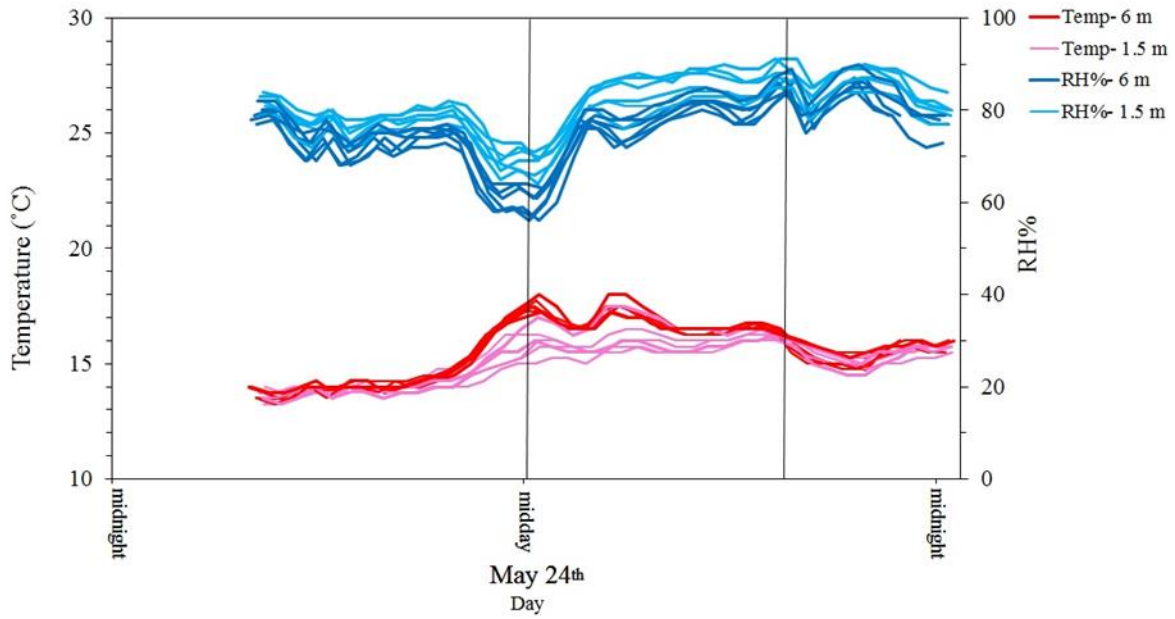


Figure 2.34: Ambient conditions under the canopy around the curing stack during the commercial kiwifruit curing, measured at 6 location at 1.5 m and 6 m height. The black vertical lines represent the time scale of the curing.

2.6.4.3 Temperature during curing

The initial temperature in the stacked bins demonstrated that harvest temperature with fruit picked earlier in the day and stacked closer to the wall were slightly cooler than those second load of fruit picked later, although the stack was formed about 1 h (Figure 2.35a). The temperature difference decreased and became almost equal in two loads during two hours of curing (Figure 2.35b and c). The temperature distributed evenly on both sides of the curing row (15-16 °C).

The effect of at-harvest temperature on the stack temperature heterogeneity was clear and ranged from 15 to 19 °C. However, the filling time was only about 1 hour (Figure 2.35a and d). At the end of the trial, there was an even temperature distribution in the whole stack regardless of the position in the curing stack.

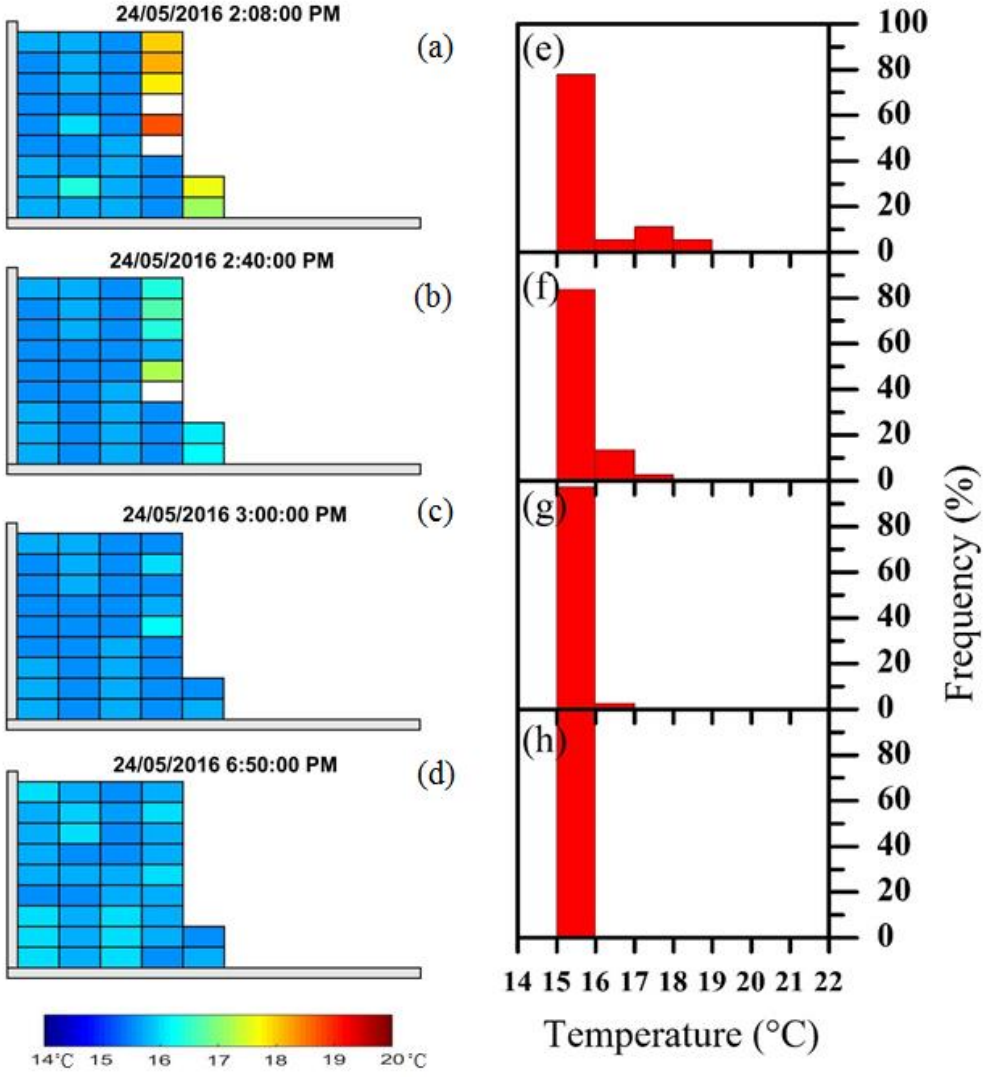


Figure 2.35: Spatial temperature variation of the middle of 320 kg 'Hayward' kiwifruit bins after 6 h curing. Maps (a-d) represent data for the row including interpolation (n = 38) and also histograms (e-h) represent the frequency of temperature value in the same row.

2.6.4.4 Relative humidity during curing

As expected humidity conditions increased in the middle of the bins after approximately 2 h of filling. This is shown in Figure 2.36b and c, where humidity increased towards near saturation RH conditions and remained steady until the end of curing. Comparing the temperature and humidity graphs show decreasing temperature was accompanied by a simultaneous increase in humidity within the bins (Figures 2.35 and 2.36). This observation could be explained by the fact that fruit were wet at picking time when it was raining, and the free water on the surface

of fruit increased the humidity to the saturation point in the middle of the bins shortly after curing and cooled down temperature in the last load of the stacked bins.

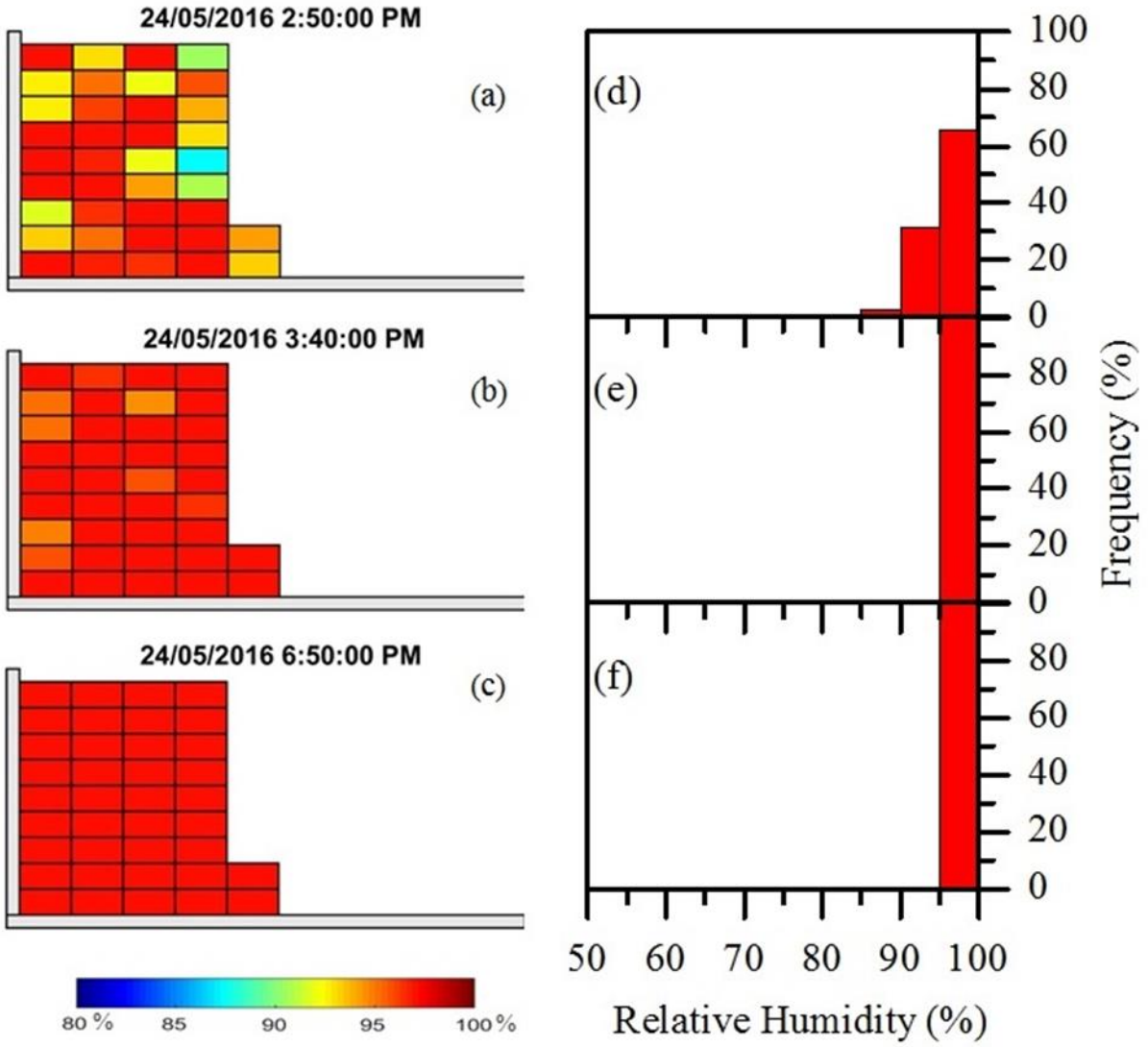


Figure 2.36: Spatial RH variation of the middle of 320 kg ‘Hayward’ kiwifruit bins after 6 h curing. Maps (a-c) represent data for the row including interpolation (n = 38) and also histograms (d-f) represent the frequency of RH in the same row.

2.6.4.5 Weight loss impact as a result of curing

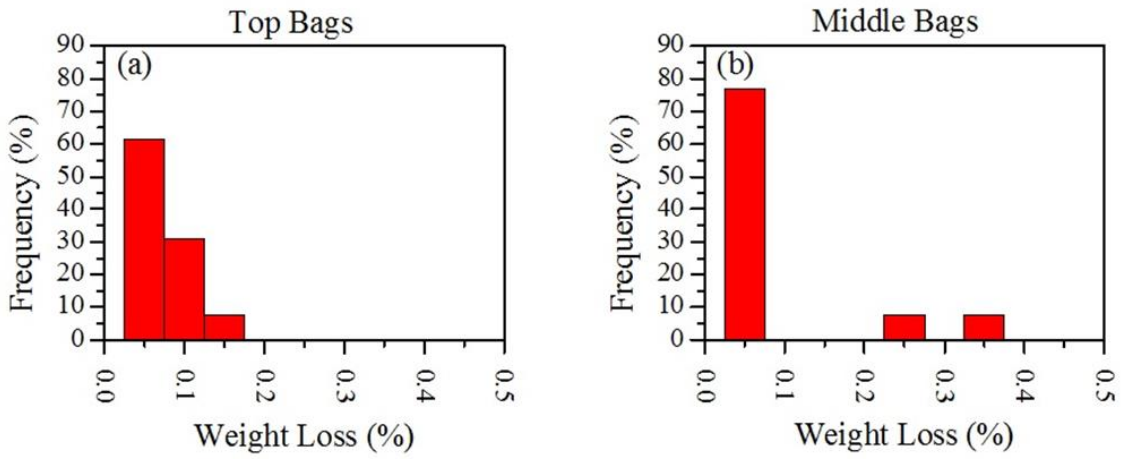


Figure 2.37: Weight loss of measured fruit on top (a) and in middle (b) of 320 kg 'Hayward' kiwifruit during commercial curing (n = 13).

Weight loss over the entire curing time for the bags located on the top of the bin didn't show a normal distribution (P = 0.004) averaging 0.03%, and a standard deviation of 0.04% (Figure 2.37a) and the distribution of the weight loss in the middle bags was not normal either (P<0.001; mean = 0.04%, SD = 0.1%) (Figure 2.37b). Thus, no fruit weight loss map has been provided for this trial.

Half of the collected data were negative and the rest were close to zero (Figure 2.37b). This can be explained by the fact that the fruit were wet at harvesting time and this increased the fruit turgor. Due to the small sample size, free water on fruit surface and short curing period, it is difficult to follow a similar pattern in fruit weight loss in the bins at various locations within the stack and make any conclusion.

2.7 Curing trial five

2.7.1 Trial commentary

- Harvest of the commercial block occurred over 2 days (14-15th June 2016) and hence is represented by two populations
- The commercial grower line harvested required 340 plastic bins in two days, and of these bins, 191 bins had monitoring of their temperature and RH conditions
- On 14th June, filling time started at 10:30 am and finished at 5:30 pm
- On 14th June, 129 bins of 148 harvested fruit bins had monitoring of temperature and RH conditions. And of these 129, 117 bins transported and stacked at the packhouse and 12 bins were picked, stacked and remained in the orchard's shed until the next day
- On 15th June, filling time started at 9:30 am and finished 12:00 pm, since there was no more logger available
- One hundred and ninety two (192) bins were picked on the second day (15th June 2016). 12 bins picked on 14th June were stacked with these 192 bins in the same row (the secondary row). 74 bins had monitoring of temperature and RH conditions in this row
- Almost all bins of the first day picked were stacked in a single row of bins (the primary row), with the second day's pick stacked in a second row (the secondary row)
- For each set of three bins all had their internal environmental conditions monitored, while one of these 3 bins also had two weight loss tracking sub-samples established i.e. 67 bins also had fruit weight loss monitored
- All bins from the same grower were packed in a single packing run when the curing time was finished at 11:30 am 17th June 2016. It means that the curing time ranged from 53 h to 76 h on both rows. The fifth trial had the highest number of bins and longest curing time among all trials

2.7.2 Fruit source

Fruit were collected from a commercial orchard located on Matahui Road about 12 Km away from the packhouse in 14th and 15th June 2016. The average temperature which was recorded by the local weather station was 10.4 °C and rainfall of 2.8 mm occurred during a week when the trial was conducted (Figure 2.40). The average temperature and rainfall were 10.2 °C and 1 mm, respectively between 14th and 17th June 2016 (the trial's time window).

2.7.3 Trial method specifics

For each set of three bins, all had their internal environmental conditions monitored, while one of these 3 bins also had two weight loss tracking sub-samples established. The commercial grower line harvested required 340 plastic bins in 2 days when the trial was conducted, of which 191 bins had monitoring of temperature and RH conditions, and of these 191, 67 bins also had fruit weight loss monitored. The trial was the largest one in this study, assuming a commercial packout of 90%, this batch represents approximately 21,000 trays equivalents of export quality fruit.

Two rows from the same grower were cured in the third bay at the packhouse. Each row consisted of up to 14 columns. All columns of bins stacked 10 except the last column of bin stacked 6 on row 'L'. In row 'J', the bins with the internal environmental conditions monitored were stacked up to column number 10. There was a stack of full wooden bins between two monitored stacks until 5:00 pm on 16th June. After that, there was an empty space between the two rows (Figure 2.38).

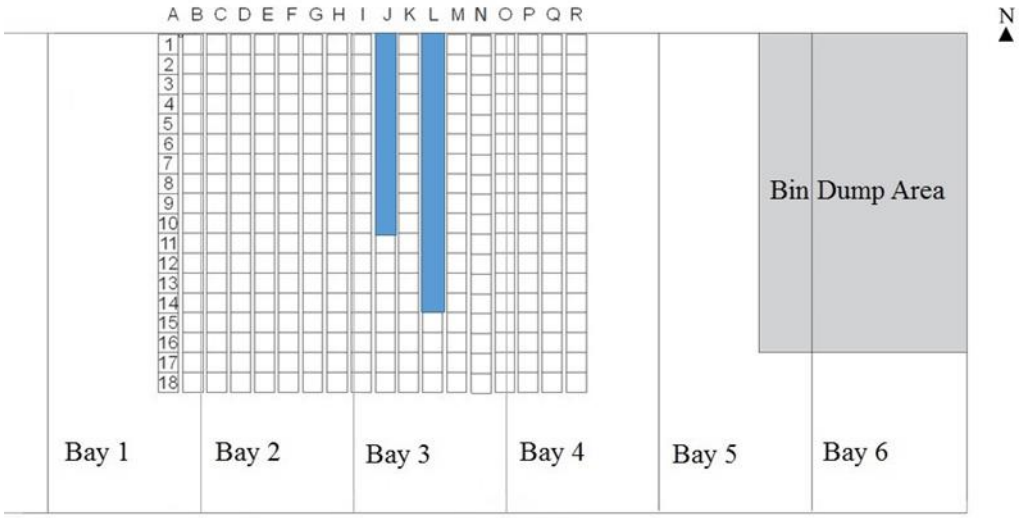


Figure 2.38: Illustration of an aerial view of bin stacking pattern for the fifth trial. The blue colour depicts the stacked bins for monitoring temperature and RH during curing.

2.7.4 Results

2.7.4.1 Time variability of curing

Harvest of the commercial block occurred over 2 days and hence is represented by two populations. One hundred and twenty nine (129) bins were monitored on the first day with the remaining 62 bins on the second day. In total, 191 bins were monitored in this trial. All bins were packed in a single packing run meaning that the curing time ranged from 53 to 76 hours. Almost all bins of the first day's pick were stacked in a single row of bins (the primary row, n = 117), with the second day's pick stacked in a second row (the secondary row, n = 74). A small number of bins (12) were picked on the first day and remained on the orchard undercover and stacked into the secondary row which can be clearly seen by the long time frame for these bins (Figure 2.39).

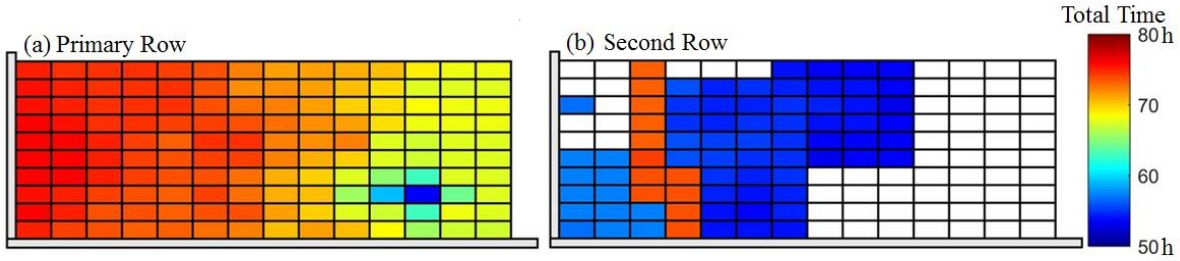


Figure 2.39: Duration of time in curing stack as influenced by position in stacked bins. Each block represents a single bin - a cross-sectional side view of the stack.

2.7.4.2 Ambient conditions during curing

Ambient temperature recorded by the local station was between 1.4-16.8 °C. The average temperature was 10.5 °C during the week when the trial was conducted. This shows a large difference in temperature during the week (Figure 2.40).

Ambient temperature remained relatively stable between 10-18 °C, with an obvious diurnal cycle during the first 2 days of curing. On the 3rd night of curing (16th June) temperatures dropped consistently more to a range of 4.5-7 °C for a period of approximately 6 h (Figure 2.41).

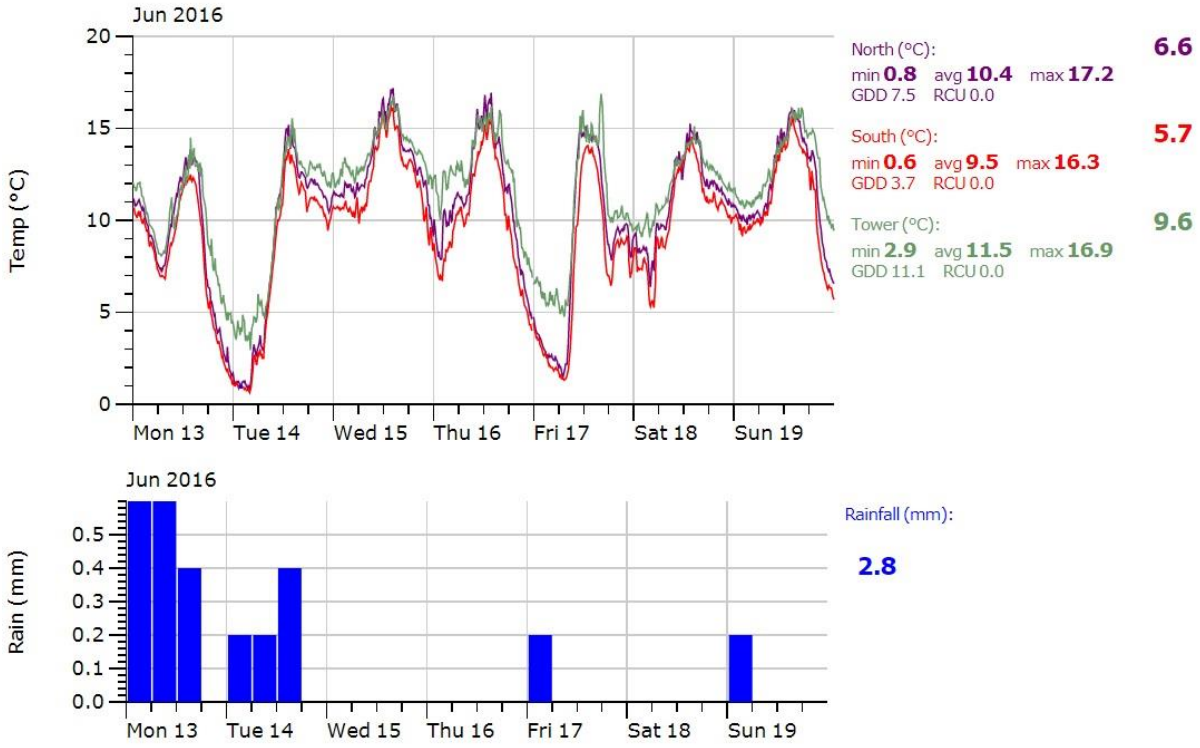


Figure 2.40: Temperature and precipitation data have been recorded at the local weather station for a week from 13th June to 19th June 2016.

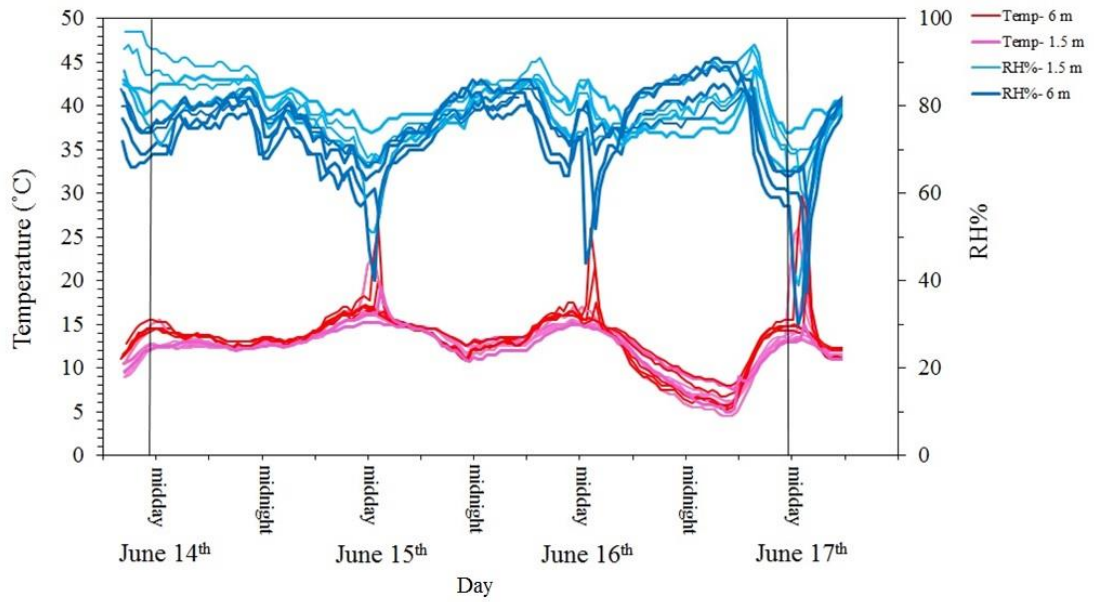


Figure 2.41: Ambient conditions under the canopy around the curing stack during commercial kiwifruit curing, measured at 6 locations at both 1.5 m and 6 m heights.

2.7.4.3 Temperature during curing

The initial temperature is reflective of the at-harvest temperature with fruit picked earlier in the day (and closer to the wall) cooler than those picked in the heat of the afternoon (Figure 2.42 a). Fruit packed early in the morning and on the first truck (by 10:45 am) averaged 9 °C; the fruit on the second truck that were picked by 1:35 pm averaged 13.9 °C. These differences in temperature remained over the first night (Figure 2.42b). By the end of the following day, the temperature variation in the curing stack reduced (to a range of 9-17 °C), due to warming of the coolest fruit, but the variation was still dominated by the picking time (Figure 2.42c).

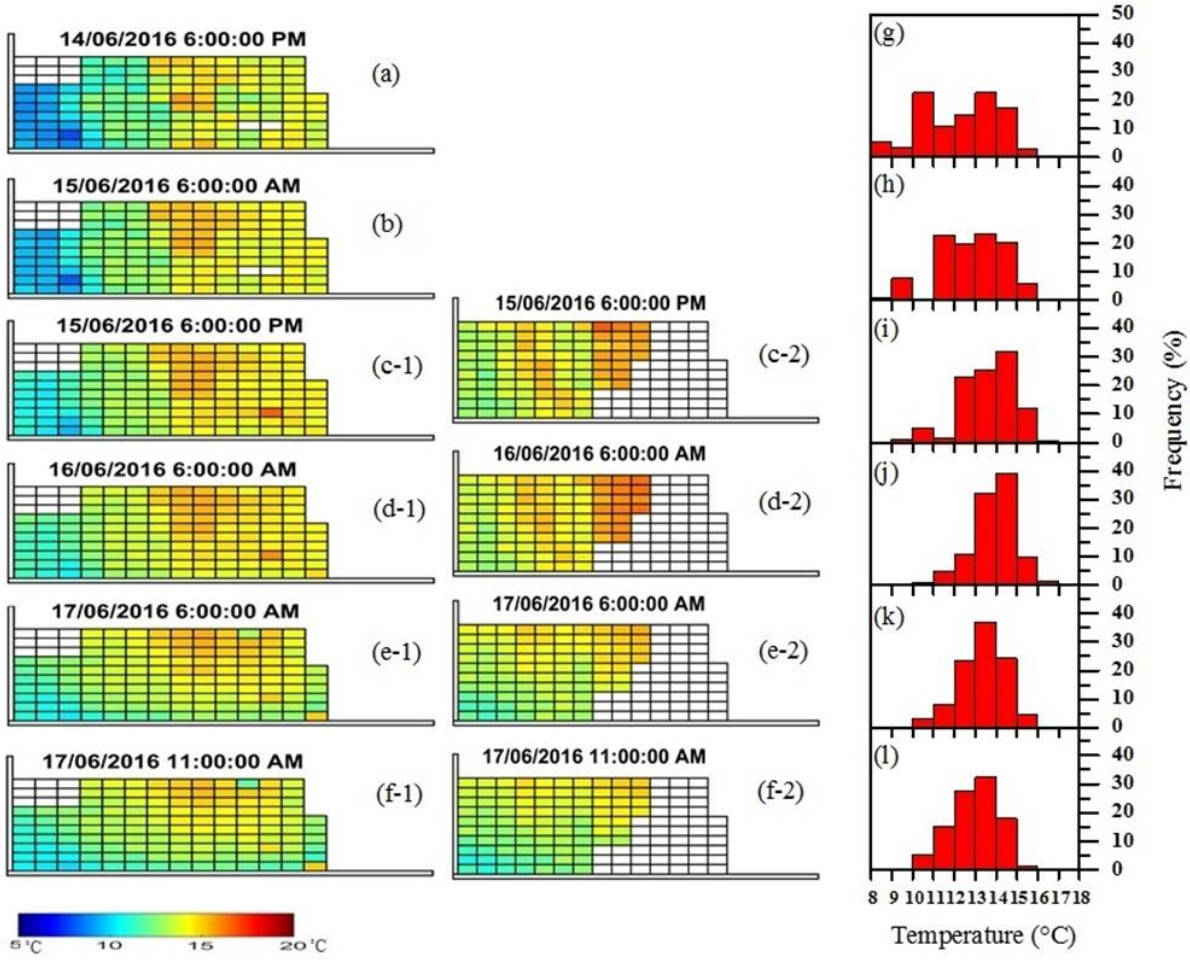


Figure 2.42: Spatial temporal temperature variation of the middle of 320 kg 'Hayward' kiwifruit bins during commercial curing. The maps on the left labelled from (a) to (f-1) represent the primary row only including interpolation (n = 117) after 73 h curing, the maps on the right labelled from (c-2) to (f-2) represent data for the secondary row including interpolation (n = 74) after at least 50 h curing, while the histograms report data from both rows (n = 191).

After the second night (Figure 2.42d-1) the temperature variability became even less, with the trend in variability beginning to be influenced by position in the curing stack. Those bins located at the bottom of the stack became cooler, with the warmest location of the curing stack moving to top locations in the middle of the stack. In the second row, the last three columns (8-10) of bins have been harvested at noon (11:30) had still the highest temperature (16.5 °C) (Figure 2.42d-2). The development of cooler bins at the bottom of the stack in both rows is to be expected in relatively stable air conditions, as temperature stratification that results in the coolest air at ground level could occur. It was most noticeable that this temperature stratification effect developed during the night hours of the 3rd day (Figure 2.42e), as a result of the fruit at the bottom of the stack or close to the wall cooling and due to being exposed to

cooler night air (Figure 2.41). By the end of the 3rd night, the vertical position in the curing stack dominated the effect on bin temperature (Figure 2.42f).

2.7.4.4 Relative humidity during curing

High humidity conditions were observed to develop in the middle of the bins after approximately 3 h of filling (data not shown, because of in complete stack). This can be observed in Figure 2.43a, where those picked later in the day are still developing towards high RH conditions at 6 pm of harvest day (on 14th or 15th May) and both stacks have a similar pattern and then increased to the saturation point in the following morning (Figure 2.43b). These near saturation RH conditions remained for the following 2 days until the more dramatic cooling period on 16th June occurred. Over this night period, humidity in the lower and more external bins was observed to significantly drop to as low as approximately 60% RH (Figure 2.43c) accompanying the drop in temperature observed at the same time (Figure 2.42e). The only plausible explanation for the simultaneous reduction in both temperature and RH conditions in these bins is the significant refresh of air inside the bin, suggesting that under these conditions there is an opportunity for air exchange to and from a bin. As temperatures increased towards the packaging time, the humidity again increased towards saturation (Figure 2.43d).

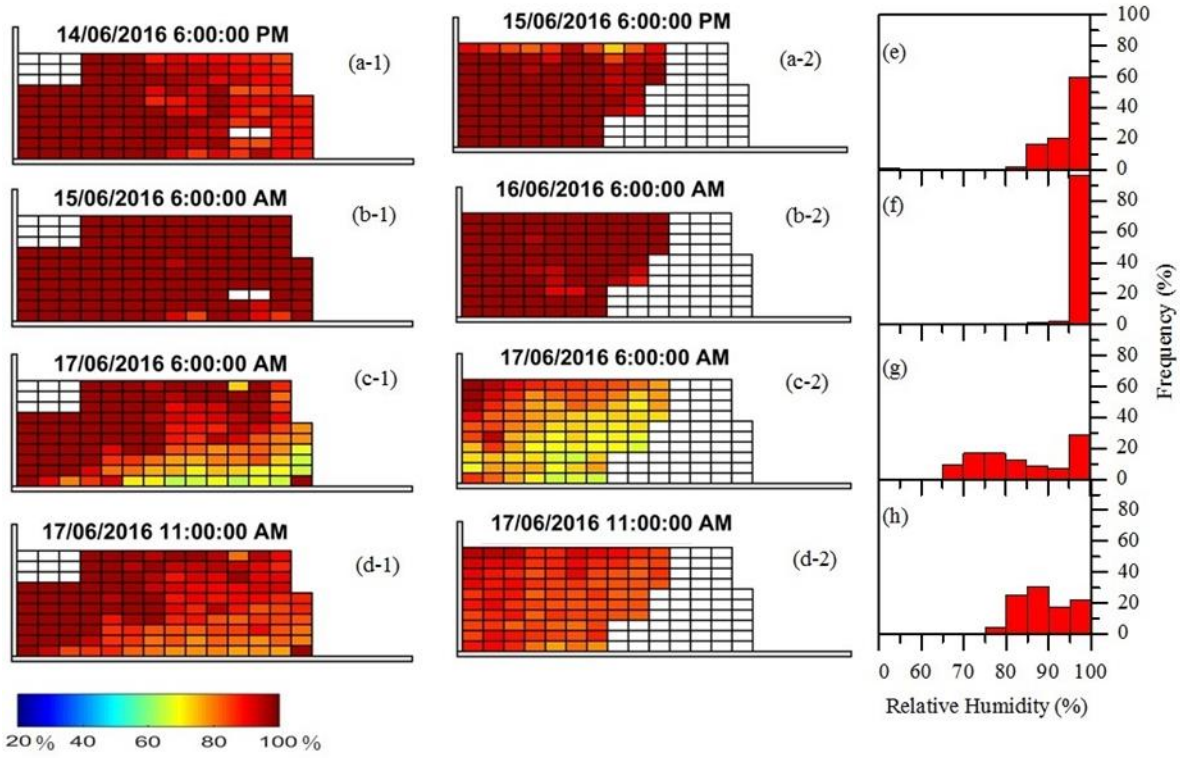


Figure 2.43: Spatial temporal RH variation of the middle of 320 kg 'Hayward' kiwifruit bins during commercial curing. The maps on the left labelled from (a-1) to (d-1) represent the primary row only including interpolation (n = 117) after 73 h curing, the maps on the right labelled from (a-2) to (d-2) represent data for the secondary row including interpolation (n = 74) after at least 50 h curing, while the histograms report data from both rows (n = 191).

2.7.4.5 Weight loss impact as a result of curing

Weight loss over the entire curing time for the bags located on the top of the bin represented a normal distribution (P = 0.53) averaging 0.48%, and a standard deviation of 0.06% (Figure 2.44a). However, the distribution of the weight loss experienced by bags located at the middle of the bins was far greater, although still normal (P = 0.07; mean = 0.32%; SD = 0.11%). In particular, a significant proportion of the bags (approximately 36%) had weight loss less than 0.35% (Figure 2.44b).

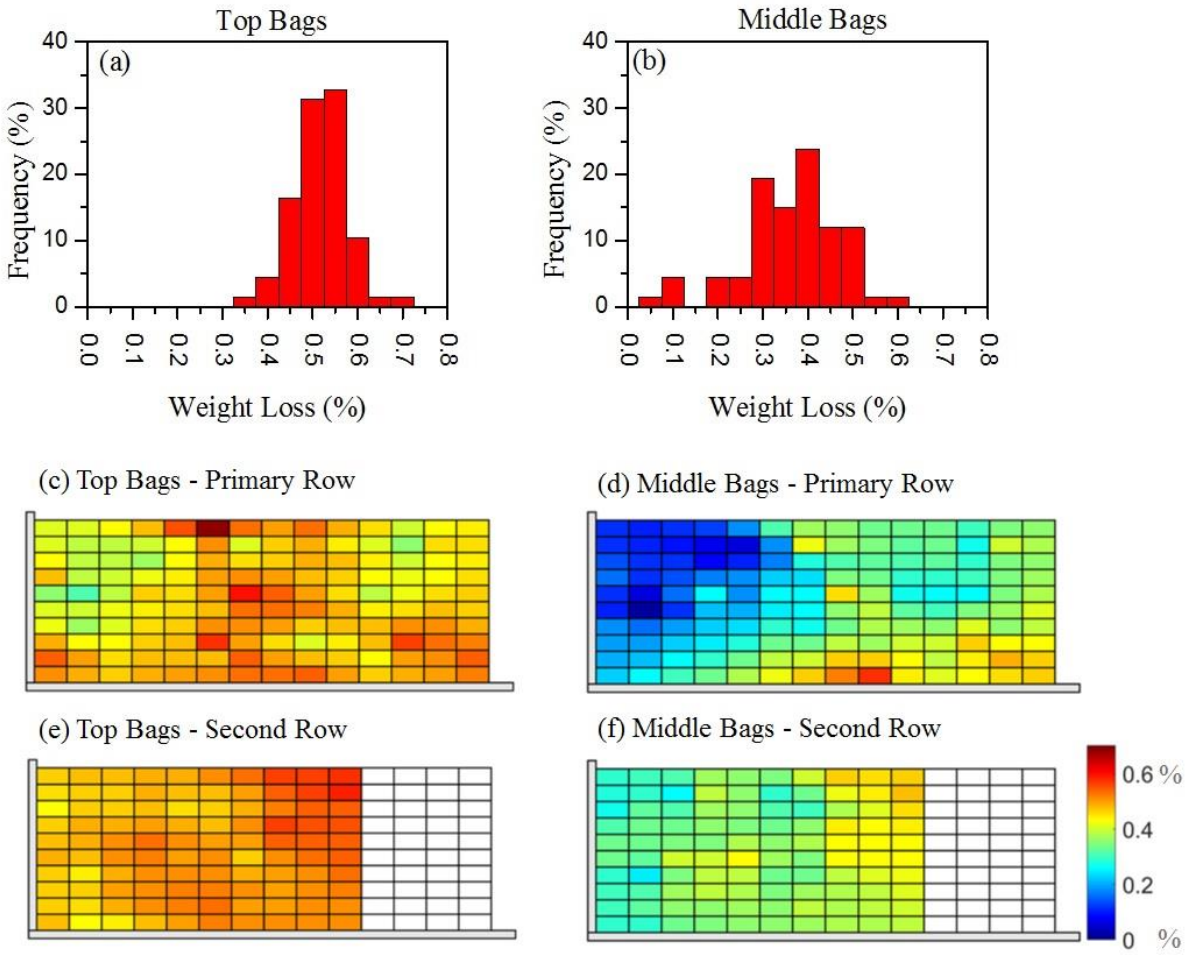


Figure 2.44: Weight loss of measured fruit on top (a, c) and in the middle (b, d) of 320 kg 'Hayward' kiwifruit during commercial curing. Maps (c-d) represent data for the primary row only including interpolation, while the histograms represent data for both rows (n = 67).

Those bags that lost less weight had a tendency to be closer to the physical wall and the earliest picked fruit. This suggests that this lower weight loss may be a result of either less air passing through the bins due to the lower exposure to environmental airflow, or the initial lower temperatures that fruit were picked at (Figure 2.42a). As would be expected those bins subjected to a period of low RH, in the lower rows of bins close to the outside of the stack, (Figure 2.43c) were found to have the highest weight loss from the fruit in these bins (Figure 2.44d).

2.8 Discussion

In this section, observations from the five commercial curing trials are summarized, with the discussion focused on generalisations and explanation for the spatial and temporal variability observed.

2.8.1 Initial picking temperature

The first section of the supply chain of kiwifruit begins at the orchard, with this curing section between the orchard and storage usually neglected.

Valentine and Goedhals-Gerber (2017) investigated the influence of fruit picking time on fruit temperature within the 48 h after harvest for apples. Over-heating of fruit was contributed to by factors such as the orchard distance from the packhouse, the number of picking teams, the efficiency of pickers, number of forklifts, truck availability and size, loading efficiency, general transportation and the conditions of precooling conditions in store. Picking time affected fruit quality by directly influencing fruit temperature (Valentine & Goedhals-Gerber, 2017).

In the industrial trials after approximately12 h (the 2nd trial), 20 h (the 3rd trial) and 32 h (the 5th trial) of filling time, the stack's temperature still reflected at-harvest temperature with fruit picked earlier in the day cooler than those picked in the heat of the afternoon (Figures 2.20, 2.26, 2.42a and b). This could occur due to the fact that fruit which were picked earlier have a lower initial temperature or there might be low airflow around the stack during curing to distribute heat more evenly throughout the stack. As illustrated in Figures 2.26 a and b, after sunset until midnight, the bin temperature dropped gradually with the environmental temperature (Figure 2.25), with an approximate 4-5 °C temperature difference between bins filled before noon and those loaded in the afternoon (Figure 2.26b). Bins that were picked earlier in the day had a lower temperature, while those bins harvested in the afternoon were the hottest and this resulted in temperature heterogeneity (17-22 °C) in the whole stack 7 h after filling. It took those afternoon-bins more time to cool down to the ambient temperature under the canopy (Figure 2.26a, b, c, and f).

This indicates the influence of at-harvest temperature on temperature variability in the stack during curing.

2.8.2 Ambient conditions during curing

Ambient conditions are part of exogenous factors which directly impact fresh produce quality by affecting respiration and transpiration rate in fruit. These environmental factors including temperature, RH- resulting WVPD and airflow (Sastry & Buffington, 1983; Becker & Fricke, 1996; Morandi *et al.*, 2010b; Paul & Pandey, 2014). Therefore, it is usual practice in handling of many horticulture produce to reduce the heat load to prevent weight loss.

At the packhouse, fruit stacks were subjected to natural ventilation during curing. In all trials, the ambient conditions remained stable during curing and reflected the diurnal cycle. When the average environmental temperature was 14.9 °C (ranged 1.5-26.9 °C), the range of environmental conditions under the canopy was between 4.5 and 22.3 °C in different trials (Figures 2.12, 2.19, 2.25, 2.34 and 2.41). The canopy conditions mimicked the diurnal cycle of the environment with minimal differences (Figures 2.11, 2.18, 2.24, 2.33 and 2.40). The minimum temperature under the canopy was approximately 3-4 °C higher than what recorded by the local weather station in the different trials. As expected, the surrounding air below the canopy reflected more rapidly the environmental fluctuations than monitored microclimate inside of fruit bins.

The impact of airflow as an environmental factor on bin temperature and RH have not been measured in this study, but should not be underestimated. Airflow limits temperature variability in the stack (Moureh & Flick, 2004). Moureh *et al.* (2009) reported the average air velocity magnitudes inside the pallets were directed by the airflow behaviour in the surrounding environment of the pallets. They observed airflow reduced heterogeneity inside the stacked bins and improved an even temperature distribution throughout the pallets.

During different trials, stable environmental conditions have been recorded under the canopy (Figures 2.11, 2.18, 2.24, 2.33 and 2.40), when the influence of at-harvest temperature on temperature variability in the stack has been observed (Section 2.8.1). Under this assumption that airflow reduces the spatial and temporal temperature viability in the stack. One reason that at-harvest temperature lasted between 12 h (the 2nd trial) and 32 h (the 5th trial) in different trials and led to temperature heterogeneity in the stack might be low airflow under the canopy in this period of time elapsed.

In trial 3 and trial 5, the effect of unquantified airflow on RH of the stack was observed. In the third trial, RH dropped in the whole stack during two nights between 9:30 pm (9th May) (70-100%) and 6:00 am (10th May) (70-95%) and also 12:30 am (11th May) (85-100%) and 6:30 am (11th May) (80-100%), when temperature decreased simultaneously only on first night (Figures 2.26, 2.27, 2.28 and 2.29). The recorded conditions under the canopy showed a normal diurnal decrease of temperature at night (17-13.2 °C) and the environmental RH conditions remained almost steady between 12:00 am to 6:00 am (80-90%). After this elapsed time, RH developed towards high RH conditions (80-100%) in the curing stack, while temperature profile in the stacked bins decreased slightly and remained almost motionless (16-19 °C). One plausible explanation for the repeated observed over two nights might be when the bin stack had a higher RH than the surrounding condition, the difference in pressure caused circulation to increase (out of and into the stack) and resulted in lower RH. Airflow changed RH within the bins (the bins microclimate) and caused a break in the high RH conditions in the bins. In the fifth trial, the same behaviour was observed over the night period, with humidity in the lower and more external bins dropping significantly to ≈ 60% RH (Figure 2.43c) accompanied by simultaneous temperature reduction (Figure 2.42e). Airflow under the canopy could also explain the simultaneous reduction in both temperature and RH in the bins in the fifth trial.

In the fourth trial, there was rain at harvest when the initial fruit weight measurements were conducted (Figure 2.33). The ambient conditions (15-18 °C, 78% RH) remained steady during the curing time (between 5 h 40 min to 7 h 15 min) with no airflow. Thus, the final measurement of fruit weight showed almost no weight loss (Figure 2.37). This occurred, due to the fruit being wet during harvest and transport and there was not adequate airflow to dry the free water (moisture) from the fruit skin.

Thus, this could indicate the effect of environmental conditions below the canopy on the range of conditions experienced by fruit during curing.

2.8.3 Logistical constraints and bin stacking issues

According to the literature, fruit should be cured for at least 48 h to control *Botrytis* (Bautista-Baños *et al.*, 1997; Lallu *et al.*, 1997). The aim of this study was to document examples of real practice in the industry. Consequently, the packhouse's schedule was not influenced for the duration of the work. Curing in the commercial packhouse was not regulated by any industry-

wide procedure and the priority was to use the available space efficiently and to ensure grading and packing continue with no interruption. Therefore, curing time, in particular, was influenced by packhouse workload and logistics. In this study, the curing time ranged from 5 h 40 min (4th trial) to 76 h (5th trial) in different trials.

The packhouse did not follow the First in, First out (FIFO) principle to help achieve uniform curing time for each grower line. The lack of uniformity in curing time could contribute to the variability between grower lines and impact fruit quality in subsequent storage (Lallu *et al.*, 1997).

It was observed that fruit were picked on the same day from the same orchard, cured for different hours. In trial 3 (Figures 2.26 and 2.27), the first bin row was formed in the early afternoon and cured for 59 h. The secondary bin row was stacked in the late afternoon and cured for 40.7 h. All the fruit bins came from the same grower.

Another factor was the effect of the north wall on the temperature of the adjacent bins in different trials. In trial 2, the bins were sitting at the bottom of the stack and close to the wall showed a lower temperature (15-17 °C) (Figure 2.20c). While the canopy temperature was relatively steady (12-14 °C) at night and the temperature of the stack was almost stable (15-21 °C). In trial 5, a similar observation has been recorded during the night hours of the 3rd day (Figure 2.42e), when the cooler spot of the stack (approximately 10 °C) was the bins at the bottom of the stack and close to the wall and the stack temperature range was (10-16 °C) and the environmental conditions were relatively stable (4.5-7 °C). The lack of air circulation near the wall meant that the cool, morning-picked fruit stacked near the wall tended to remain cool. A cold spot close to the wall was recognisable. The bin position in the stack plays a critical role in temperature variation. In the current study, the canopy was open to the environment except on the north side wall (Figure 2.7). In that dimension, there was likely less airflow, as there was no space between the wall and the bins in the stacks. Ideally, there should be at least 0.5 m gap between the stack and the wall in the packhouse with a similar structure (ventilated area with minimum three sides) (Lallu *et al.*, 1997). However, this design was not used during the experiment, probably because nowadays, rot incidence is not the main issue for NZ kiwifruit industry (Manning *et al.*, 2010). Therefore at the packhouse, they took the most advantage of available space under the canopy to avoid a backlog in the curing area. The bins set up quite close to the wall, while the space between the bins rows were between 0-20 cm which depended on available space in the canopy (Figure 2.6).

On the other hand, on the south side of the canopy, there was a large open space required for forklift maneuver. Therefore, the bins on the south side of the stack were exposed to more airflow underneath the canopy. On occasions when there was significant airflow through the system resulted in higher temperature and lower RH in this part of the stack (Figures 2.28, 2. 29, 2.42 and 2.43). The temperature difference between two sides of the row could be 2-3 °C (Figures 2.42e and 2.43c).

The bin position in terms of distance from the canopy floor also contributes to temperature variability. During the day time, the surface of the packhouse roof may get hot from solar radiation and consequently radiate the heat to the fruit beneath the roof or heat the air under the roof via convection. This could have an amplifying effect on the thermal stratification i.e. when the hot air naturally gets trapped under the roof. In the second trial, from midnight the bins at the bottom of the stack cooled to result in temperature differences of approximately 4-5 °C between the top (20.5 °C) and bottom (15-17 °C) of the stack at 6:00 am (Figures 2.20b-1 and c-1). However, the temperature variability (range 15-22 °C from 12:00 am to 6:00 am) in both rows slightly changed in the whole trial. One possible explanation for this phenomenon is a physical effect, or mechanical obstruction of the canopy's roof prevents heat transfer from the underside of the canopy to the outside, creating temperature stratification. Similarly, in trial 5, when this temperature stratification effect developed during the night hours of the 3rd (Figure 2.42e) day, as a result of the fruit at the bottom of the stack (approximately 10 °C).

The packhouse structure acts as a natural ventilation system with air inlets and outlets, the air naturally flows out. Airflow over the surface of the fruit effects moisture loss and heat transfer from the fruit, therefore impacting postharvest quality. It is imperative in the stacking arrangement to avoid excessive airflow on fruit bins. In the curing stack airflow at any moment could be considered unidirectional. It can pass directly throughout the whole canopy.

It was noted that the stack orientation in the packhouse was perpendicular to the length of the canopy. Thus, the runner space of the bins was perpendicular to the airflow coming from the west side of the packhouse (the prevailing wind direction). This bin arrangement possibly minimised airflow throughout the stack.

In this stacking arrangement, the runner space of the bin - which is the main path for air movement in the bin (Hellickson & Baskins, 2003) - was perpendicular to the airflow. Therefore, the thermal equilibrium between the bins and the surrounding air slowed down the (Hellickson & Baskins, 2003). As an example, in the third trial (Figure 2.26c-1), After

approximately 20 h curing, when the environmental temperature was between 12-13 °C at 6:00 am on 10th May (Figure 2.26c-1), the bins in the middle of the stack showed a temperature of approximately 20 °C.

This specific configuration may also explain the increase of RH to the saturation point (≥ 97%) in the bins which occurred 3-7 h after filling in different trials (Figures 2.21, 2.28 and 2.43).

Thus, this stack configuration may be beneficial, in terms of lower water loss, but it could have a negative effect on temperature variability in the stack.

2.8.4 Effect of bin design on environmental conditions in the bin

In this work, the conditions during curing were investigated for both wooden and plastic bins. There are no standard sizes for wooden bins and it usually depends on the packhouse (Harmandeep, 2010). The dimensions of the wooden bins in this study were 1200 × 1200 × 500 (h) mm, while the plastic bins were 1200 × 1200 × 600 (h) mm (the standard size). Thus, the plastic bins had 1.2 more capacity than wooden bins and when the bins were stacked vertically in the packhouse, their stack was higher in the stacked plastic bins compared to the wooden bins.

Wooden bins also absorb moisture which is withdrawn from the fruit and the surrounding air (Harmandeep, 2010), while plastic bins do not take up moisture (Table 2.3). The wooden bins used during trial 1 and 3 have almost solid walls but are ventilated by one narrow gap, which runs around all four sides (Figure 2.4a) with an open area of only about 1.5% (Waelti, 1992). Conversely, plastic bins are manufactured with vented walls and floor covering 7-11% of the total surface area. These differences in vent area mean that wooden bins are less likely to be influenced by ambient airflow than plastic bins. More airflow would be expected to result in a more uniform temperature distribution and decrease temperature variability in the stack (Vigneault *et al.*, 2009), and a more rapid response of fruit to the environmental changes.

In this study, however, it was not possible to directly compare RH establishment or within bin temperature variability as influenced by bin design, as different environmental conditions persisted in each trial. It may be worth considering investigating the possible influence of bin material and design in influencing temperature heterogeneity in the stack during curing.

Table 2.3: Comparison of differences between two typical bin designs in NZ kiwifruit packhouses (Harmandeep, 2010).

Wooden bin	**Plastic bin**
Absorption of moisture	Non absorption of moisture
Absorption of chemicals	Non absorption of chemicals
Porous i.e. poor sanitation	Non porous
Weathering	Resistant to weathering
Inadequate air circulation around	Better air circulation
Variable design	Standard industry design
Capacity 250 kg	Capacity 300-350 kg
Nails and splinters	No nails, rust, paint chips and splinters

2.8.5 Environmental conditions and weight loss

Temperature and RH are the environmental parameters that influence fruit transpiration (Montanaro *et al.*, 2011). Temperature and RH are the main factors which affect water vapour pressure (Somboonkaew & Terry, 2010).

It has been reported that the percentage of mass loss has a strong correlation with 'point-in-time' water status of the produce tissue (Morgan, 1984). Water movement in and out of the fruit could impact some fresh produce traits including fruit weight (Leonardi *et al.*, 2000).

Water loss in fresh products occurs when there is a difference between the products surface water vapour pressure and the surrounding environment. Water activity on fruit surface is 0.99 (Maguire, 1998). When fruit temperature is not the same as the surrounding air. There will be a driving force for water loss, due to the partial pressure on fruit surface. Fruit starts to humidify the surrounding air up to the saturation point (Maguire, 1998). Under saturated RH, there will be a very small or zero water vapour pressure deficit, but fruit may still lose water (Xanthopoulos *et al.*, 2017).

Under real conditions, RH reached the saturation point (≥ 97% measured) a few (3-7) hours after curing in different trials. This indicates there was a low WVPD in the near saturation

condition, resulted in low fruit water loss. In this study, water loss during curing determined primarily by measuring fruit weight loss ranged approximately between 0.3 and 0.5%.

In the industrial trial, despite the fact that the environmental conditions were different in each trial, in each case the environmental conditions remained relatively stable.

Under these environmental conditions, bins were stacked mainly in the middle bays (3 and 4) of the packhouse where the stacks were surrounded by empty or full bin rows. This stacking configuration (in the middle of the packhouse with minimal airflow), plus the stable environmental conditions, probably increased RH in the bins. An observation in the third trial could illustrate this situation - the secondary bin row consisted of 46 bins (5 columns; a short row) and was surrounded tightly by two rows of plastic bins on both sides during curing in the third bay (i.e. restricting airflow). RH was noted to increase more rapidly in this row (4 h) and remained higher in comparison with the primary row (Figures 2.28 and 2. 29). This is consistent with the argument that particular stacking configurations have important impacts on RH.

These conditions facilitated a rapid increase of RH in the bins in different trials, therefore it can be assumed that ΔpH_20 would then decrease to a low level that resulted in low water loss.

When the airflow travels throughout the stack, high RH in the bins could not prevent water loss, if the fruit temperature is not equilibrated with the air temperature. Under this condition, fruit weight loss would occur.

Bautista-Banos et al., (1997) previously reported a range of 0.46-1.07% weight loss for ‘Hayward’ curing at 10-15 °C for 3 days. In this study, only in the third and fifth trials had reliable data in terms of fruit weight loss data, because of the experimental conditions and the sample sizes. In these two trials, weight loss over the entire curing time for the sub-sample bags located on the top and in the middle of the bin ranged between (0.3-0.5%). In the third trial, the environmental temperature ranged between 12 and 21 °C, with 0.4-0.55% fruit weight loss during 2 days curing and in the fifth trial at ambient temperature between 10 and 18 °C, the fruit weight loss was 0.3-0.5% during 3 days curing. In general, fruit weight loss was low and the range was almost similar in these two trials, despite different curing conditions and different fruit maturity in each trial (Figures 2.15, 2.30, 2.37 and 2.44). However, the influence of at-harvest temperature and also the bin positioning on weight loss was noticed within each trial (Figures 2.30 and 2.44).

In this study, fruit at different maturity and seasonal timing were studied under different environmental conditions. Fruit weight loss measurements were taken, but no measures of fruit firmness (or other fruit quality characteristics) after curing or in subsequent storage were measured. In the next chapter, a number of curing conditions representing the range of likely curing conditions are created in the lab and investigated for the resulting effect on fruit quality after a long-term cold storage. In particular, the impact of curing conditions on fruit softening and SBD incidence is investigated.

2.9 Conclusion

Spatial-temporal variability in temperature, RH and resulting weight loss during commercial kiwifruit curing practices can be influenced by logistical constraints imparting time and spatial placement; initial picking temperature; ambient conditions (ambient temperature, RH) during curing.

Unknown factors that need further investigation include the packhouse structure, bin configuration and also airflow, bin design.

These results are particularly useful in a context of attempting to apply consistent or optimal curing treatments during industrial practice. They also suggest the potential for curing to cause variation between kiwifruit grower lines, which may possibly impact fruit quality in subsequent storage. Up until this study, there was a lack of certainty about what conditions fruit experience during curing, and how variable this may be through the curing stack. This work helps to document this gap in industry understanding.

CHAPTER 3

3 Part B-Effects of curing on ‘Hayward’ storage outcomes

3.1 Introduction

To clarify some terms; when the aim of holding fruit at ambient conditions prior to coolstore is to reduce chilling injury, then the process is generally known as ‘delayed cooling’. This is referred to as ‘conditioning’ when it occurs under both controlled temperature and RH and the purpose is for reducing chilling injury (see Chapter 1). However, in this chapter ‘curing’ will be used for all designed controlled temperature treatments and also the ambient conditions treatment prior to coolstorage to maintain consistent terminology and a common brand voice across the whole thesis.

Fruit firmness is strongly related to storage potential of kiwifruit and reduces the incidence of postharvest decay and fruit loss. Fruit firmness is associated with the decomposition of pectic substances, celluloses, and hemicelluloses in the middle lamella (Wills & Golding, 2016). At low temperatures, the rate of fruit softening decreases, because the lower degradation rate of pectins and hemi-celluloses in the cell wall maintain the water retention capacity (Paliyath *et al.*, 2012). However, the common storage temperature (0 °C) for ‘Hayward’ leads to chilling injury in long-term storage and causes fruit quality loss (Burdon & Lallu, 2011). It shows that environmental conditions at harvest and throughout the postharvest handling process could impact fruit softening. Curing, as a postharvest practice, is conducted immediately after harvest and prior to packing, cooling, and storage. The time of application and environmental conditions (temperature and RH) during this period could have profound effects on the fruit outcomes after storage by impacting fruit physiological state. As identified in the Literature Review (Section 1. 4. 2. 1), Factors including fruit maturity at harvest, acclimation, cooling rate, storage time and temperature have all been shown to influence SBD incidence and fruit softening in kiwifruit in long-term storage (Burdon; Lallu *et al.*, 1989; Burdon *et al.*, 2007; Yang *et al.*, 2013; Zhao *et al.*, 2015; Zhao, 2017).

Temperature variation resulting the variation of WVPD which is the main driving force for water loss could impact the ripening and softening rate (Taglienti *et al.*, 2009). Burdon *et al.* (2017) compared the pattern of ‘Hayward’ fruit softening on or off the vine (in storage) and also fruit response to different temperatures in the range of 0 to 16 °C for 1 week before being stored at 0 °C for up to 20 weeks. These authors observed that fruit at higher temperature 16

°C up to 6 d of conditioning period were consistently the firmest fruit throughout 20 weeks coolstore at (0 °C), while fruit conditioned at 8 °C for 6 d were the softest fruit after the prolonged storage. Hertog *et al. (2016)* investigated fruit softening in early harvested 'Hayward' from 14 growers. Fruit were treated with exogenous ethylene levels (0, 0.1, 10 and 200 μL L^{-1}) and stored under temperature conditions ranging from (0 to 10 °C) for 4 weeks, followed by an ethylene free period (6 w) in a range of (0 to 20 °C). Fruit softening increased at higher temperatures. The first phase of fruit softening was shortened by increasing temperature even when temperature increased by only 2 degrees from 0 °C and the second phase of softening took place immediately at higher temperatures. It has been observed that softening was more affected by treatment (inoculation or not) than by curing time (Dr. Jeremy Burdon, personal communication, PFR). Zhao *et al.* (2015) found that rapidly cooled fruit (3 d) were firmer after prolonged storage (120 d), although the rate of unmarketable fruit after storage was higher than delayed cooling (2 w), possibly due to SBD incidence. On the other hand, the incidence of rotten fruit was higher in gradually cooled fruit (Zhao *et al.*, 2015). Yang *et al.* (2012) found that the increase of antioxidant enzymes activity may be involved in the decrease of SBD symptoms during storage in gradual cooled 'Hongyang' kiwifruit (from 15 °C to 0 °C). They took the investigation further by doing a similar research on 'Hayward'. Yang *et al.* (2013) found that low-temperature conditioning at 12 °C, 90-95% RH for 3 d effectively reduced SBD and also suppressed fruit softening, respiration rate and ethylene production in stored fruit at 0 °C, 90-95% RH for 120 days. Gradual cooling also (from 15 °C to 0 °C) inhibited increases in membrane permeability, malondialdehyde content, ROS content including superoxide anion (O_2-) production rate and hydrogen peroxide (H_2O_2) and simultaneously, increased antioxidant enzymes activities. The effect of temperature conditioning to alleviate SBD incidence is possibly related to antioxidant system activities enhancement which scavenges oxygen species and maintains membrane integrity (Yang *et al.*, 2016). SBD incidence and its severity depend on temperature, its variability and also the duration of it. The SBD symptoms could be different among different cultivars (Burdon, unpublished data). Given that chilling stress is cumulative (Kader *et al.*, 1974; Vigneault *et al.*, 2009), temperature management before and after harvest will influence SBD incidence and its severity in store fruit and the symptoms could be visible only after prolonged storage when fruit firmness decreases to 'eating ripe' level (Burdon, 2018).

This phase of the study investigates the effect of curing condition on fruit quality (fruit firmness, SBD development, and rot incidence) throughout long-term storage. In particular,

fruit firmness and SBD development are measured since they are both critical in influencing fruit quality are measured. The results from the survey of real industrial conditions provided information about the spatial-temporal variability of temperature and RH in a fruit stack during curing at ambient conditions. The aim of this experiment is to provide more understanding of how curing conditions (temperature and time) may cause variability in fruit quality outcomes in terms of fruit softening, SBD incidence and fruit decay.

3.2 Materials and methods

3.2.1 Objectives

The environmental observations in the industrial trials (Chapter 2) under real conditions were applied to design a simulated curing (delayed cooling) conditions matrix and evaluate the effect of temperature variability on fruit quality outcomes (fruit firmness and SBD) and decay incidence during subsequent long-term storage. In five industrial trials, the environmental temperatures ranged between 10.2 and 18.2 °C when the temperature range in the kiwifruit stacked bins was from 8 to 26 °C and the average curing time was approximately 41.5 h. However, the curing time mainly depended on logistical constraints in the packhouse. Therefore in the present experiment, an attempt was made to mimic the industrial conditions, a matrix of practical curing temperatures (the ambient conditions (AMB), 10 °C and 20 °C), and times (2 and 4 d) was set up to understand the effects of these factors and their reaction during curing on kiwifruit quality destined for long storage periods (Table 3.1).

3.2.2 Fruit source

Kiwifruit (*Actinidia deliciosa* [A. Chev.] C. F. Liang and A. R. Ferguson var. *deliciosa* 'Hayward') used in this study were collected from three selected grower lines at commercial maturity on 7th June 2016 from Pukekohe, South Auckland. After harvest fruit were immediately transferred to MARC by a truck with no temperature control facility. Fruit were considered as late maturity fruit in terms of time in the harvest commercial season. This curing simulation experiment and related fruit quality measurements were conducted at the Postharvest laboratories of Plant and Food Research in Mt. Albert (MARC), Auckland.

3.2.3 Postharvest evaluation

Upon arrival at MARC, fruit were placed into 20 kg 47-L ventilated plastic crates (600 mm × 400 mm × 253 (h) mm) and were weighed before and after curing to measure fruit weight loss (%) and then stored at 0 °C. In the treatment where fruit were cooled immediately (IMD or control) fruit were packed in single layer trays with a wrap of polyethylene polyliner and stored at 0 °C directly. One RFID communicable temperature and RH logger (XSense HiTag, BT9, Israel) sensor was placed per crate to record temperature and RH in each crate during curing (delayed cooling) simulation.

Characteristics of fruit were determined both at harvest and after curing for 2 or 4 d on a sample of 30 fruit in each treatment for each orchard. Fruit assessed individually for SSC, firmness (see below for assessment details). DM was also measured on a sample of 30 fruit for each orchard at harvest time. Five trays were used for each treatment condition combination (temperature × time).

3.2.4 Curing (delayed cooling) simulation and storage time

Fruit were selected randomly from the bins and placed into 20 kg plastic crates and exposed to different curing regimes; 10 or 20 °C, 2-4 days and the ambient conditions (AMB), 4 days (Table 3.1).

Table 3.1: Curing regime and assessment times following storage time at 0 °C.

	0 day	2 days	4 days
Curing regime	Control IMD (0 °C)	- 10 °C 20 °C	AMB 10 °C 20 °C
Storage time (d)	100 125	125 + 7 (20 °C)	150 175

The ambient condition was achieved by storing the fruit crates under ambient conditions for 4 d in the loading bay at MARC which simulated the conditions in a commercial pack house (large covered structure with air-flow). Curing simulation at 10 and 20 °C was conducted in

two identical controlled temperature rooms using a standard refrigeration system (i.e. evaporator and fans) of 6.5 m × 2.8 m × 2.6 m and stacking the crates for 2 or 4 d in a completely randomized block design with a set of 24 crates (12 crates (experimental unit) for each treatment) arranged in a three columns by four rows by two layers array (Appendix A). One Xsense sensor was placed in the middle of each crate to record temperature and RH during curing (Figure 3.1b). Moreover, environmental loggers were set up at different locations of the curing room to monitor environmental temperature and RH (Figure 3.1a). Temperature and RH measurement was recorded at irregular intervals between 1 and 60 minutes for each and every logger inside of the crates and in environmental conditions. A layer of half-full crates was placed at the top of the fruit stack and covered by a layer of shade cloth to avoid direct airflow on the top layer fruit crates (Figure 3.1d). After curing fruit were placed in the fibreboard single layer trays (22 fruit per pack) with a wrap of polyethylene polyliners and stored at 0 °C 95 ± 5% RH up to 25 weeks (175 d). Fruit removed for fruit firmness, SBD and rot assessments after 100, 125, 125 + 7 d at 20 °C, 150 and 175 d of storage in 2016.

Figure 3.1: (a) Environmental X-sense logger in the curing room, (b) Measuring fruit crate before and after curing, (c) the fruit crate sack before curing, (d) the fruit crates stack has been covered with a layer of shade cloth.

3.2.5 Assessment methods

To assess fruit quality (fruit firmness and SBD development) after each storage time, fruit were held at 20 °C-12 h to acclimatize to room temperature before evaluation.

3.2.5.1 Fruit Firmness

A Fruit Texture Analyser (Güss, model GS14, South Africa) fitted with a 7.9-mm Effegi™ penetrometer probe was used to measure fruit firmness. First, the fruit skin and flesh was removed about 1 mm depth, then the probe ran into the flesh at 8 mm s^{-1} to a depth of 7.9 mm, and the firmness value was the maximum recorded force. At the equator of each fruit, fruit firmness was measured on two sides of fruit at 90° to each other, and the average of the data are presented in kilogram-force (kg_f). It was measured at harvest, after curing and in each storage time (100, 125, 125 + 7 at 20 °C, 150 and 175 d). Fruit firmness measurement was conducted on individual intact fruit of each treatment.

3.2.5.2 Soluble solids content

At harvest and immediately after curing, SSC was determined separately for the stylar and stem ends of the fruit and averaged by using a digital refractometer (‘Pocket’ PAL-1, 0-50%, Atago). A sample size of 30 fruit for each treatment at harvest time was used to measure SSC. Fruit were cut and juice squeezed from fruit equator using the proximal (stem end or stylar end) half of the fruit onto the prism of the refractometer and fruit soluble solids concentration (SSC) has been recorded as a percentage on the Brix scale.

3.2.5.3 Dry matter

At harvest, the percentage of DM content of the fruit was measured by drying out a 2-mm transverse slice of the fruit at 65 °C for 24 h. A sample size of 30 fruit for each orchard at harvest time was used to measure the average dry matter. It was presented as a percentage of the dry weight on fresh fruit weight.

3.2.5.4 SBD scoring

To assess SBD on fruit, three transverse slices were made along each fruit from the blossom end, and any visible sign of the disorder at the cut surfaces was recorded. The development of SBD was scored on a scale with four categories; fruit without any visible sign of SBD was recorded as sound fruit, any granular appearance in the outer pericarp was considered as trace and slight SBD, granular appearance with a broken or complete circular zone in the outer pericarp was moderate SBD, granular appearance on the whole surface of the outer pericarp accompanied with/without water soaking appearance in the inner or outer pericarp was categorised as severe SBD (Figure 3.2). Some water soaking could also be observed in the slight and moderate SBD, although it was restricted to only small scattered spots of graininess. The incidence of SBD was measured after each storage time for individual fruit. SBD measurement was conducted visually. It was calculated as a percentage of the whole fruit population.

Figure 3.2: Transverse slices of healthy 'Hayward' kiwifruit (left) and fruit with SBD symptoms (right)- graininess and progressive water soaked tissue under the skin and the outer pericarp.

3.2.5.5 Decay incidence

Decay incidence was visually detected on the fruit body or the stem end. No fungal isolation or identification was carried out in this experiment. The decay incidence was presented as a percentage of rotten fruit in the total fruit population.

3.2.5.6 Data analysis

Statistical analysis was done by using GenStat (17^{th} Edition, Lawes Agricultural Trust, Rothamsted Research, UK) software. Fruit firmness data were subjected to General ANOVA to test the effect of treatment, orchard and their interaction on fruit firmness at each storage time. The ANOVA table has been provided in Appendix B. Mixed Models (REML) were also used to determine significant differences between treatments. Curing regime was fitted as fixed effect, block (orchard) was fitted as a random effect to adjust the orchard effect. Moreover, the comparison of fruit firmness in different curing regimes were determined using Tukey's HSD (Honest Significant Difference) test at 5% significance level. The binomial distribution and the logistic (logit) link function were used to analyse the significance of SBD incidence (%) data and compare curing regime, orchard, and storage time effects on SBD incidence (%) proportion. The graphs were designed by using Microsoft Excel 2013 and Origin version 8.5 (OriginLab Corporation).

3.2.5.7 Experiment commentary

To meet the time constraints of this study, the difference between the partial pressure of water vapour (ΔpH_20) between environmental conditions and inside of the fruit crates has not been measured. However partial pressures could be used as an effective approach to determine the importance of factors that are involved in fruit water loss under each treatment.

3.3 Results

3.3.1 The designed curing condition profile

Environmental conditions (temperature and RH) during curing at either 10 °C or 20 °C or ambient conditions are shown in Figure 3.3a, b and c. A time-temperature and RH profile of

all fruit crates for each treatment (2 or 4 days) have also been represented to compare with the environmental conditions. Approximately 1.5 d (20 °C) and 2 d (10 °C and AMB) were required before the temperature in the centre of the crate approximately equilibrated to the conditions in the temperature controlled room. Initial RH in the crates at experiment initiation point was approximately 62% and this condition under 20 °C and AMB condition was higher than the environmental RH conditions which was expected, while it took approximately 24 h for the RH levels in the crates at 10 °C to equilibrate to environmental conditions and then gradually increased and followed the trend of environmental conditions. This time to come to equilibrium is defined by experimental configurations of the produce packaging system, in this case, 20 kg-plastic fruit crate (Section 3.2.3) which will have a major influence on the heat transfer and airflow. The average temperature and RH at the ambient condition for 4 d were 17.4 °C and 80% RH, respectively. The minimum and maximum temperatures in the ambient situation was 15.7 and 20.5 °C, respectively (Figure 3.3c), and the average temperature and RH in the middle of fruit crates over 4 d were 16.8 °C and 88%, respectively. In the 10 °C controlled room, the average temperature, and RH was 10 °C and 87% RH. The airflow into the curing room was 6.9 m s^{-1} during curing. The average temperature and RH in the middle of fruit crates at 10 °C 2 d were 12.4 °C and 79%, respectively and the average temperature and RH in the middle of fruit crates at 10 °C 4 d were 11.5 °C and 88%, respectively. The environmental loggers recorded 20 °C and 64% RH in the curing room. The airflow into the curing room was 6.7 m s^{-1} during curing. The average temperature and RH in the middle of fruit crates at 20 °C 2 d were 17.7 °C and 76%, respectively and the average temperature and RH in the middle of fruit crates at 20 °C 4 d were 18.9 and 82%, respectively.

Despite the fact that the aim was to mimic industrial conditions in this experiment, still there were inevitable differences in the experimental conditions, due to the dimensions of the curing room and the number, size and location of the experimental unit (crate) and the stack compared to the industrial trials condition (i.e. large picking bins). For instance, in the second industrial trial when the average environmental temperature and RH under the canopy were 16.4 °C and 74%, it took approximately 3 h for the first load of fruit bins to reach to 80% RH, the bins temperature were dominated by at-harvest temperature and then bin position in the stack. In terms of equilibrium to environmental conditions, after 12 h of filling when the surrounding temperature was about 12-14 °C (Figure 2.19). The bins temperature range hardly changed and still represented the initial temperature at harvest (Figure 2.20b). In addition, the bins in the top-middle of the stack that picked in the heat of the afternoon needed almost 17 h to cool down

approximately 5 °C when temperature in other locations of the stack didn't change in the same degree. Similarly, in the third trial, the temperature in bins decreased steadily (range of 15-19 °C) regardless of slight improvement of environmental conditions, due to the diurnal cycle (Figures 2.25 and 2.26d). Therefore, the observed temperature variability in the curing stack was dominated by at-harvest temperature and the effect of bin's position than environmental conditions.

In the ambient condition (60% initial RH) in this experiment, the fruit crates required approximately 12 h to reach 80 RH. It is probably related to a crate's volume which had about 12.5 or 16 times less volume or capacity than a wooden or plastic bin, respectively. Therefore, even a gentle airflow around the fruit stack was adequate to reduce RH in the middle of the stacked crates. In addition, under the relatively stable ambient conditions, fruit crates temperature gradually increased before equilibration to environmental conditions (17.4 °C) after approximately 2 d of curing and followed a similar pattern as environmental conditions. This phenomenon could be also explained by the experimental unit volume. Since the crate was smaller (a larger surface-to-volume ratio than fruit bin), after the initial equilibration point (for the thermal equilibration) to environmental conditions, the fruit response to environmental conditions changes occurred faster and temperature heterogeneity in the whole stack decreased. In the industrial trials after 12 h (the 2nd trial), 20 h (the 3rd trial) and 32 h (the 5th trial) of filling time, the stack's temperature was reflective of the at-harvest temperature with fruit picked earlier in the day cooler than those picked in the heat of the afternoon. In general, in the lab experiment, the temperature variation in curing stacks showed ranged from 10.3 to 16.8 °C at 10 °C, from 15.5 to 20.8 °C at 20 °C, and from14.8 to 18.8 °C at AMB., this is difficult to explain or follow the spatial and temporal variability in temperature according to the crate's position in the stack. This is possibly related to the stack's volume (1200 mm × 1200 mm × 1265 mm) which approximately was equal to the volume of two bins. Other than that, two fruit bins from each orchard were used to fill the crates for the relevant treatments, therefore initial (at-harvest) temperature which was observed to play a key role in bins temperature heterogeneity in the fruit stack in the real scenario at the packhouse was almost similar in the simulated curing condition regardless of the crate position in the stack.

The range of RH inside of the crates was from medium-low (60%) to high (97%) from the initiation point to the end of the experiment in different controlled rooms and AMB condition.

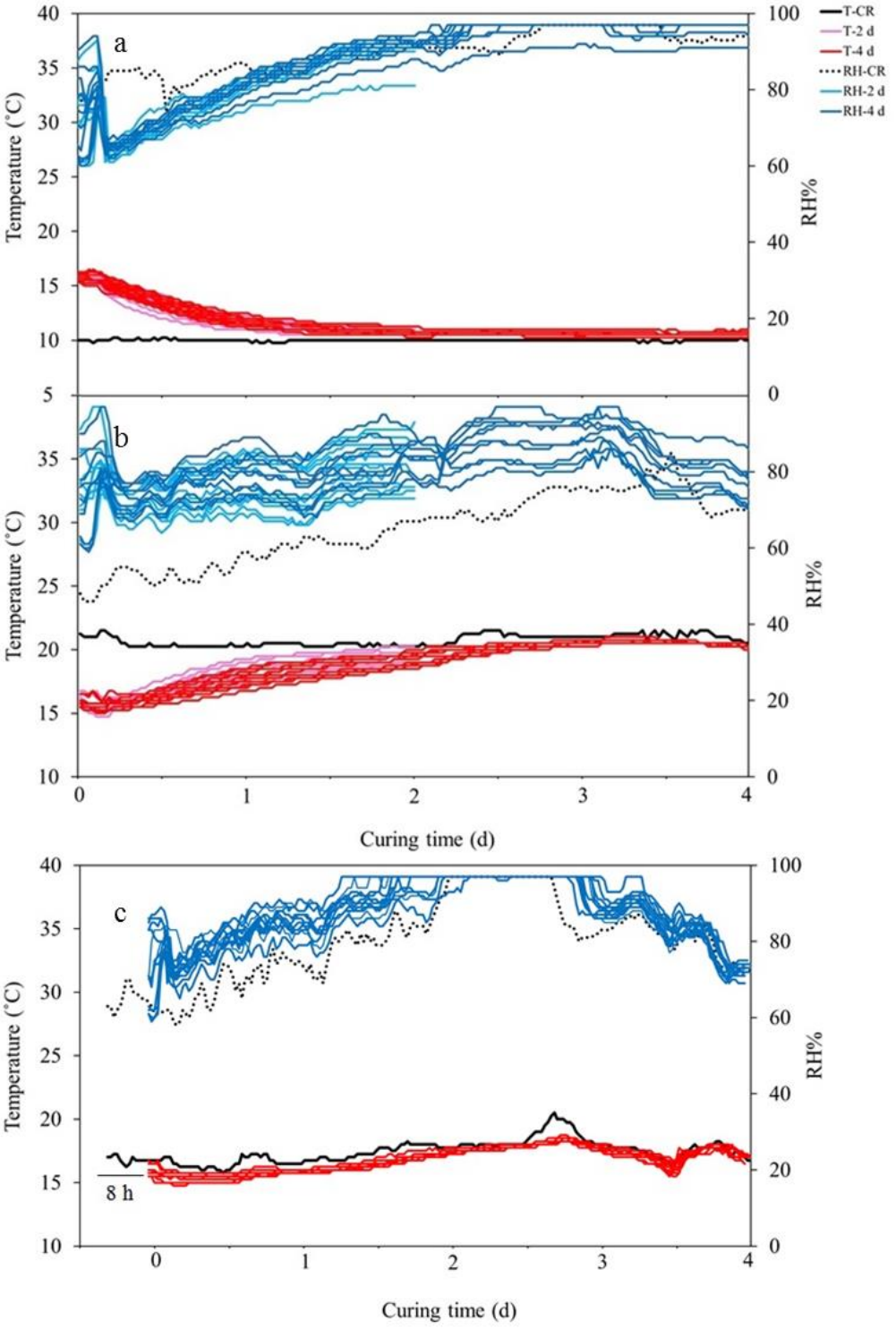


Figure 3.3: The environmental conditions profile in and outside of the crates in each simulated curing condition: (a) 10 °C, (b) 20 °C and (c) the ambient conditions before storing fruit at 0 °C. T-CR and RH-CR refer to the environmental temperature and RH profile, respectively at each controlled temperature room and ambient conditions up to 4 days. T-2 d and RH-2 d represent temperature and RH, respectively in each crate in each designed curing condition up to 2 days. T-4 d and RH-4 d represent the temperature and RH profiles, respectively inside each crate under proposed curing condition up to 4 days.

3.3.2 Fruit quality attributes at harvest

At commercial harvest, the orchard effect on initial firmness was observed with orchard 3 (O3) had the firmest fruit (and the lowest SSC) i.e. less mature fruit. Fruit from O1 was softer than that of O2 and O3, but SSC was not statistically significant (Table 3.2).

Table 3.2: Mean at-harvest fruit firmness and soluble solids content (%). Each value is the mean of 30 fruit per orchard (mean ± standard error (SE), n = 30). Different letters show statistically significant difference between the treatments.

Orchard	Fruit firmness (kg_f)		SSC (˚Brix)	
Orchard 1	6.2 ± 0.21	a	9.6 ± 0.23	ab
Orchard 2	6.9 ± 0.11	b	10 ± 0.18	b
Orchard 3	7.1 ± 0.11	b	9.1 ± 0.15	a

Table 3.3: Mean fruit firmness, soluble solids content and fruit weight loss (%) at harvest and after curing treatments. Each value is the mean of 30 fruit per replicate (3 replicates = orchards) (mean ± SE, n = 90). Each fruit weight loss value is mean of fruit weight loss of 12 crates (20 kg each) each treatment. Different letters show statistically significant difference between the treatments.

Curing regime	Fruit firmness (kg_f)		SSC (˚Brix)		Fruit weight loss%	
IMD 0 d	6.7 ± 0.10	c	9.6 ± 0.11	a	N/H	
10 ˚C 2 d	6.8 ± 0.12	c	9.9 ± 0.12	ab	0.3 ± 0.02	a
20 ˚C 2 d	6.9 ± 0.07	c	9.8 ± 0.11	ab	0.5 ± 0.02	b
10 ˚C 4 d	6.2 ± 0.10	a	10.4 ± 0.11	c	0.5 ± 0.01	bc
AMB 4 d	6.6 ± 0.11	bc	10 ± 0.12	ab	0.6 ± 0.01	c
20 ˚C 4 d	6.3 ± 0.11	ab	9.8 ± 0.12	ab	1 ± 0.05	d

As shown in Table 3.3, immediately after curing, fruit cured at 20 °C-2 d had the highest fruit firmness (6.9), and the lowest firmness was for fruit cured at 10 °C-4 d (6.2). After harvest, average DM% was 17.08% which was higher than the minimum at-harvest DM% threshold of 15.5%. Therefore, fruit were commercially acceptable. Fruit had on average: 9.6 °Brix. The highest SSC was observed at 10 °C-4 d (10.4 °Brix), and the least SSC for fruit cooled immediately after harvest (IMD; 9.6 °Brix). The New Zealand kiwifruit industry has considered 6.2% SSC as a minimum maturity index for harvesting 'Hayward' kiwifruit

(Snelgar *et al.*, 1993; Crisosto & Crisosto, 2001). Harvested fruit were well above commercial clearance standard.

The curing conditions did not cause any significant difference in SSC of fruit, other than curing at 10 °C-4 d which also had the lowest fruit firmness (6.2) (Table 3.3), this means that fruit were in more advanced ripening after curing at 10 °C-4 d.

3.3.3 Fruit weight loss during curing

In general, fruit weight loss increased with higher curing temperature and longer duration (Table 3.3). As expected, the lowest total weight loss (0.3%) was observed at 10 °C-2 d and the highest weight loss (1%) was in fruit cured at 20 °C-4 d. At AMB condition (17.4 °C, 80% RH, 4 d) total fruit weight loss was 0.6%. At each temperature treatment, fruit weight loss increased with the duration of treatment which is an expected response to environmental conditions (Table 3.3).

Weight loss observed in different commercial trials (the 3rd and the 5th trial) were in the same range of 0.3-0.5% after approximately 2-4 d (40.7 to 76 h) period (Figures 2.30 and 2.44). Likewise, in this experiment, fruit weight loss ranged from 0.3 to 1% under different curing conditions (Table 3.3). As expected, fruit weight loss at 10 °C-2 d (the lowest%) and 20 °C-4 d (the highest%) were significantly different between the treatments.

3.3.4 Effect of curing on fruit firmness after storage

Immediately after curing, the pattern of fruit firmness changes was not consistent with curing temperature and time (Table 3.3). However, the curing regime significantly influenced the fruit softening rate in subsequent storage (Table 3.5).

As expected, fruit firmness decreased with storage time at 0 °C. Curing temperature and duration had a significant effect on fruit firmness after subsequent storage ($p < 0.001$). Fruit exposed to the extreme curing regime (20 °C-4 d) were the firmest after different storage periods (100 d, 125 d, 125 d + 7 d (20 °C), 150 d and 175 d) and fruit were cured in the ambient condition (17.4 °C) for 4 d had the second highest firmness, and this pattern was consistent with different storage periods. After curing at ambient and 20 °C-4 d conditions, there was a

significant difference in fruit softening in the subsequent storage period compared to conditioned fruit in other curing regimes. Despite the fact that temperature and the duration of curing were extreme in the designed curing conditions, it was observed that the rate of softening during subsequent storage was reduced by curing at 20 °C-4 d and AMB (Tables 3.3 and 3.5). There was no significant difference in fruit firmness between immediately cooled fruit and fruit cured at 10 °C, after 125-175 d storage (Table 3.5). Fruit softening value after curing at 20 °C-2 d was between these two extremes, however, the pattern of changes was not always significantly different between 20 °C-2 d and other treatments at lower temperatures (10 °C and IMD) (Table 3.5).

Table 3.4: The relationship between the orchard and fruit firmness (kg_f) immediately after curing and during 175 d of storage (0 °C). Each value represents the mean ± SE of fruit firmness (kg_f) for each orchard at each assessment time, with 30 fruit per treatment at 0 d (immediately after curing) and 110 fruit per treatment at 100 d, 125 d, 125 d + 7 d (20 °C) and 220 fruit per treatment at 150 d, 175 d. Values in a column with the different letters group are significantly different at (p = 0.05).

Fruit firmness (kg_f)	**Storage time (d)**					
Orchard	**0 d**	**100 d**	**125 d**	**125 + 7 d (20 ˚C)**	**150 d**	**175 d**
Orchard 1	6.14 ± 0.08 a	1.11 ± 0.01 a	0.93 ± 0.01 a	0.80 ± 0.01 a	0.88 ± 0.01 a	0.80 ± 0.01 a
Orchard 2	6.66 ± 0.04 b	1.34 ± 0.01 b	1.25 ± 0.01 c	1.07 ± 0.01 b	1.21 ± 0.01 b	1.10 ± 0.01 b
Orchard 3	6.92 ± 0.05 c	1.13 ± 0.01 a	1.01 ± 0.01 b	0.77 ± 0.01 a	0.89 ± 0.01 a	0.78 ± 0.01 a

As explained, there was a significant difference in fruit firmness between O1 and O2 or O3 at commercial harvest (Table 3.2). O3 had the less mature fruit (the highest FF and lowest SSC). Immediately after curing, O3 still had the firmest fruit, but during storage, Fruit from O2 consistently had the highest firmness between the orchards and there was no significant in fruit firmness between O1 and O3 (Table 3.4). Based on at-harvest soluble solids content and fruit firmness changes throughout coolstorage, more mature fruit (O2, 10 °Brix) had a slower rate of softening during storage and had the firmest fruit. The significant effect of curing regime on fruit firmness during coolstorage has been observed, however, the consistent effect of the orchard on fruit firmness was greater (Tables 3.4, 3.5 and Appendix B).

Table 3.5: Mean fruit firmness (kg_f) at harvest and also the effect of curing regimes on fruit firmness during subsequent storage at 0 °C. Each value is the mean ± SE of fruit firmness of three orchards (n = 3), with 110 fruit per replicate per treatment at 100 d, 125 d, 125 d + 7 d (20 °C) and 220 fruit per replicate per treatment at 150 d, 175 d. Values in a row with the different letters are significantly different at (p = 0.05).

Fruit firmness (kg_f)	**Curing regime**					
Storage time (d)	IMD 0 d	10 °C 2 d	20 °C 2 d	10 °C 4 d	AMB 4 d	20 °C 4 d
100 d	1.16 ± 0.02 b	1.10 ± 0.02 ab	1.28 ± 0.02 c	1.08 ±0.02 a	1.32 ± 0.02 cd	1.39 ± 0.02 d
125 d	0.97 ± 0.01 a	1.00 ± 0.01 a	1.10 ± 0.02 b	1.00 ± 0.01 a	1.13 ± 0.02 b	1.20 ± 0.02 c
125 d + 7 d (20 °C)	0.84 ± 0.02 ab	0.80 ± 0.02 a	0.86 ± 0.02 b	0.85 ± 0.01 ab	0.97 ± 0.02 c	0.98 ± 0.01 c
150 d	0.90 ± 0.01 a	0.93 ± 0.01 a	1.00 ± 0.01 b	0.93 ± 0.01 a	1.05 ± 0.01 c	1.18 ± 0.01 d
175 d	0.82 ± 0.01 a	0.85 ± 0.01 ab	0.88 ± 0.01 b	0.83 ± 0.01 a	0.96 ± 0.01 c	1.04 ± 0.01 d

3.3.5 Effect of curing on SBD development during storage period

There was no trace of SBD incidence until 125 d of storage (5.2%) (Table 3.6). As expected SBD incidence increased with storage up to an average of 46.5% across all treatments at the end of storage (Table 3.6). Fruit exposed to 20 °C-4 d and the ambient condition displayed a lower incidence of SBD compared to other curing regimes. After 175 d of storage, SBD incidence at 20 °C-4 d and the ambient condition were 35.6% and 37.9%, respectively, whereas the highest incidence of SBD (57.9%) was observed in immediately cooled fruit and cured fruit at 10 °C-2 d (53.3%). There was a consistent pattern in the results at each assessment (Table 3.6). In general, fruit at 20 °C-4 d and AMB significantly represented the lowest SBD incidence and there was no significant difference between immediately cooled fruit and fruit cured fruit at 10 °C (Table 3.6).

There was a significant difference between the orchards in SBD incidence. O2 (12.9%) had the lowest SBD incidence. The results provided evidence that at-harvest fruit maturity probably had an influence on SBD incidence in subsequent storage. There was no significant difference between O2 (6.9) and O3 (7.1) related to at-harvest fruit firmness, but O2 had the highest SSC rate (10 °Brix) and O3 had the lowest rate of SSC (9.1°Brix) between the orchards at harvest and there were a significant difference between O2 and O3. Statistically, the difference between the orchards (three of them) was low in terms of SSC content which is used as a harvest fruit maturity (Table 3.2), but another maturity index i.e. dry matter also indicates that fruit from O2 were more mature (data not presented). O2 and O3 represented a significant difference in SBD incidence (%) after prolonged storage (Table 3.6). O3 with the highest firmness (7.1) and lowest SSC (9.1 °Brix) (less-advanced in ripening) at harvest, significantly had the highest SBD (41.7%) incidence after storage (Table 3.7). This means that less mature (lower SSC) fruit were more susceptible to SBD incidence. O3 had the shortest DAFB (days after full bloom) (188 d) between the orchards.

Table 3.6: Curing regime treatment influence on SBD incidence (%) during storage at 0 °C. Data represent mean of SBD incidence (%) of three replicate orchards (n = 3), with 110 fruit per replicate per treatment at 100 d, 125 d, 125 d + 7 d (20 °C) and 220 fruit per replicate per treatment at 150 d, 175 d. Mean column/row represents the pooled data from three orchards throughout four storage assessments. Values in a column/row with the different letters are significantly different at (p = 0.05).

SBD incidence (%)	**Storage time (d)**						
Curing regime	**100 d**	**125 d**	**125 d + 7 d (20 ˚C)**	**150 d**	**175 d**	**Mean**	**Total**
IMD 0 d	0	11.5%	25.5%	40.8%	57.9%	39% d	1980
10 ˚C 2 d	0	7.9%	31.2%	39.4%	53.3%	37.4% cd	1980
20 ˚C 2 d	0	3.3%	17.3%	23.9%	45.3%	26.5% b	1980
10 ˚C 4 d	0	5.5%	27.0%	33.5%	48.9%	32.9% c	1980
AMB 4 d	0	2.1%	8.5%	18.6%	37.9%	20.6% a	1980
20 ˚C 4 d	0	0.6%	12.1%	15.5%	35.6%	19.1% a	1980
Mean		5.2% a	20.3% b	28.6% c	46.5% d		
Total		1980	1980	3960	3960		11880

Table 3.7: The relationship between the orchard and SBD incidence (%) during 175 d of storage (0 °C). Each value represents the mean of SBD incidence (%) for each orchard throughout four storage assessment time (125 d to 175 d). Values in a column with the different letters group are significantly different at (p = 0.05).

Orchard	**SBD%**		**Total**
Orchard 1	33.2%	b	3960
Orchard 2	12.9%	a	3960
Orchard 3	41.7	c	3960

3.3.6 Effect of curing on rot incidence during storage period

In general, the percentage of rot incidence was low (0.1-0.5%) during the whole storage period (Table 3.8). No rot was seen on fruit up to 125 d of storage. Rot incidence increased to 0.9% after one week at 20 °C after 125 d of storage (Table 3.8). The curing conditions did not impact the rot incidence at different storage times. The counts of rot incidence were so low that no statistical analysis was possible.

Table 3.8: Effect of curing regimes on rot incidence (%) after subsequent storage at 0 °C. Data represent the mean of rot incidence (%) of three orchards (n = 3), with 110 fruit per replicate per treatment at 100 d, 125 d, 125 d + 7 d (20 °C) and 220 fruit per replicate per treatment at 150 d, 175 d.

Rot incidence%	**Storage time (d)**				
Curing regime	100 d	125 d	125 d +7 d (20 °C)	150 d	175 d
IMD 0 d	0	0	1.0	0.5	0.3
10 °C 2 d	0	0	1.0	0.0	0.2
20 °C 2 d	0	0	0.3	0.8	0.5
10 °C 4 d	0	0	1.7	0.8	0.6
AMB 4 d	0	0	1.7	0.6	0.6
20 °C 4 d	0	0.6	0.3	0.3	0.6
Rot incidence (%) after each storage period	**0**	**0.1**	**0.9**	**0.5**	**0.5**

Figure 3.4: Example of healthy ‘Hayward’ kiwifruit (left) and rotten fruit (the side rot) with severe SBD symptoms which had been extended throughout the whole pericarp (right).

3.4 Discussion

3.4.1 The effect of fruit weight loss during curing on fruit quality

Fruit weight loss after curing treatments was higher in higher temperature (lower RH) and after longer curing (Figure 3.3 and Table 3.3). Fruit exposed to higher temperatures for a longer time during curing (20 °C-4 d and AMB) had higher fruit firmness and lower SBD incidence after storage (Tables 3.5 and 3.6).

Bautista-Baños *et al.* (1995) reported a similar range of 0.4-1.1% weight loss for curing ‘Hayward’ at 10-20 °C up to 4 days. It has been reported that fruit weight loss during curing ‘Hayward’ at 10 °C, 2-4 d were 0.4% and 0.7%, respectively and at 20 °C, 2-4 d were 0.5% and 1% and there was a significant difference in fruit weight loss at different curing time for each temperature (Bautista-Baños *et al.*, 1995). In another experiment, fruit weight loss increased with the increase of curing temperature (0-20 °C) after curing (3 d) and coolstorage (6-12 w), regardless of fruit maturity. Fruit weight loss at 10-20 °C for 3 d ranged from 0.5 to 1.3%. Weight loss increased during both curing and subsequent coolstorage (Bautista-Baños *et al.*, 1997). In the latter research, fruit weight loss increased with increased curing temperature and subsequent storage (12 w). The range of fruit weight loss and increased fruit weight loss

with curing temperature and duration are in agreement with the results of the present study (Table 3.3).

The mechanism of curing has not been fully understood, although it is apparently associated with fruit water loss (Michailides & Elmer, 2000; Manning *et al.*, 2010). Manning *et al.* (2010) found that curing is not effective if no weight loss occurs. Water loss during storage has been shown to reduce chilling injury expression, although the effect was minor compared to the effects of storage temperature and duration (Burdon & Lallu, 2011).

The higher weight loss (1%) measured at 20 °C-4 d is related to the influence of higher temperature and lower RH (Table 3.3) in environmental conditions on water vapour pressure gradient between fruit and surrounding air. WVPD is the driving force for water loss which here has been initially measured by fruit weight loss in this experiment. Temperature and RH are the main factors which affect water vapour pressure (Somboonkaew & Terry, 2010). Higher temperature (accompanied by lower RH) increases the driving force for water loss.

3.4.2 The effect of curing condition on fruit quality

Curing effect to provide an adequate *Botrytis* control depends on the interaction of temperature × humidity × duration of environmental conditions (Pennycook & Manning, 1992). The critical environmental conditions during curing could trigger some fruit physiological responses that impact fruit quality during coolstorage, other than the fruit weight loss during curing. 'Hayward' kiwifruit should be cured in ambient conditions for 48-72 h (Lallu *et al.*, 1997). Previous research has demonstrated that combinations of time and temperature (specifically associated with kiwifruit chilling threshold temperatures) could impact either fruit softening and SBD incidence and there is a close relationship between these two critical fruit quality characteristics (Yang *et al.*, 2012; Yang *et al.*, 2013; Zhao, 2017; Gwanpua *et al.*, 2018).

In the current study, there was no trace of SBD incidence until 125 d of storage (Table 3.6). Zhao (2017) observed first SBD symptoms after 130 d of storage and it progressed rapidly towards the end of storage (172 d). Lallu (1997) observed when there was only 14% SBD incidence with slight severity after 20 weeks at 0 °C, SBD incidence increased to 76% with more than 30% of stored fruit displayed moderate and severe SBD after 24 weeks. In this study, SBD incidence increased up to 46.5% at the end of storage (Table 3.6).

Lallu (1997) also suggested that SBD incidence and severity are closely related to the rate of cooling. The results of this experiment indicate that immediate cooling (which is very rapid under coolstore conditions at MARC), had the highest rate (39%) of SBD incidence, while curing was significantly beneficial at higher temperatures (20 °C-AMB) for a longer period (4 d) to suppress SBD incidence (Table 3.6). After 175 d of storage, fruit exposed to 20 °C-4 d showed 35.6% SBD incidence, whereas SBD incidence increased up to 45.3% in fruit at 20 °C-2 d (Table 3-6).

The curing conditions did not cause any significant difference in the SSC of fruit, other than curing at 10 °C-4 d (10.4 °Brix) (Table 3-3). Bautista-Baños et al. (1995) also observed no significant changes in the total SSC of cured kiwifruit after curing at four temperature conditions (0-30 °C and 90-100% RH) for up to 6 days. At-harvest soluble solids content as fruit maturity index shows fruit from O2 were more mature (10 °Brix) had the lowest SBD incidence (12.9%) between the orchards. While fruit from O3 with less at-harvest maturity had the highest SBD incidence (41.7%) at the end of storage. This indicates the influence of orchard on fruit susceptibility to SBD incidence i.e. less mature fruit are more susceptible to SBD. Similarly. Koutsoflini *et al.* (2013) reported the incidence of SBD was higher in early harvested fruit (less mature), while mid- and late-harvested fruit showed a lower rate of SBD symptoms. SBD incidence was 78-82% in early mature fruit, while it was 11% at the mid harvested fruit and didn't show any increase along with fruit maturity progress. Sfakiotakis *et al.* (2005) observed that immature fruit were significantly more susceptible to SBD compared to late harvested fruit at −0.5 °C for 24 weeks. In contrast, Zhao (2017) reported a higher rate of SBD incidence in more mature fruit (late harvest).

Low temperature even for a short period could induce chilling injury in long-term storage, because chilling has a cumulative effect (Kader *et al.*, 1974; Vigneault *et al.*, 2009). SBD incidence and severity progressed consistently with the advancement of fruit ripening (softening) during storage time (Tables 3-5 and 3-6). Lallu (1997) reported up to 99% SBD incidence after 24 weeks storage at −0.5 °C in stored fruit of some orchards, while only 9% of the fruit were impacted by SBD at 2.5 °C for 24 weeks. Gwanpua *et al.* (2018) observed that initial storage of 'Hayward' at 0 °C following by 2 °C resulted in a lower proportion of soft fruit and reduced SBD incidence. Zhao (2017) also observed fruit were exposed to similar conditions (12 h-3 d at 0 °C), but stored at different storage temperature (0 °C or 2 °C), precooled fruit showed a different rate of SBD incidence. Rapidly cooled fruit displayed a higher number of SBD incidence in fruit compared to gradual cooling (Zhao, 2017). This was

in agreement with the results of this experiment under immediately cooling conditions here, however, cured fruit at 10 °C, 2-4 d had the second (37.4%) and the third (32.9%) highest SBD incidence, respectively (Table 3.6). The results at 10 °C, 2-4 d were not significantly different from immediately cooled fruit which contrasts with the above research. Yang *et al.* (2013) found that LTC, of 12 °C for 3 d effectively delayed and reduced SBD incidence. It has been suggested that gradual cooling and LTC could contribute to kiwifruit tolerances and acclimation to low temperature in subsequent coolstorage (Burdon & Lallu, 2011; Yang *et al.*, 2013; Zhao, 2017). The fruit response observed to curing at a lower temperature (10 °C, 2-4 d) did not fit into the acclimation hypothesis.

Bautista-Baños *et al.* (1997) suggested fruit firmness was influenced more by harvest date (fruit maturity) than environmental conditions during curing. There was a small difference in fruit firmness after curing and no consistent pattern of curing condition (10 °C-3 d) effect on fruit firmness during storage (6-12 w). They concluded that at-harvest fruit maturity probably had a greater influence on fruit firmness during storage than curing condition. This is in agreement with the result of fruit firmness immediately after curing in this study that fruit firmness immediately after curing did not show a clear and significant change (Table 3.3). However, in this experiment, fruit firmness changes showed a consistent pattern during storage (Table 3.5). In this study, it was observed that the orchard influenced fruit firmness from 100 d towards the end of the storage and the effect of the orchard on fruit softening after curing was more dominant than curing condition (Appendix B). O2 (10 °Brix at-harvest) had the firmest fruit through the storage, while fruit from O3 (9.1 °Brix at-harvest) were less-advanced in ripening had lower firmness during storage. At-harvest fruit firmness from O3 was significantly higher than O1, but there was no significant difference in fruit firmness between these two orchards during storage. It means that the rate of softening during storage in less mature fruit was higher than others (O2 and O1) and resulted in softer fruit. Zhao, 2017 reported that early harvest fruit (less mature) were firmer up to 100 d of storage, but become softer than late mature fruit in subsequent storage. Abdala *et al.* (1996) believed less mature 'Hayward' kiwifruit soften faster than mature fruit, because of the higher membrane permeability that occurs during maturity development and storage. Burdon *et al.* (2017) investigated the response of harvested 'Hayward' kiwifruit to different temperatures (0-16 °C) for one week. They observed fruit response was consistent with temperature conditioning, regardless of harvesting time (8 harvest time - early to late mature fruit), with fruit held at 10 °C were softer compared to other temperatures.

In another experiment, Bautista-Baños *et al.* (1995) reported fruit firmness decreased after curing at higher temperatures (0-30 °C) for a longer period. In addition, at lower temperatures, (0 or 10 °C) longer curing up to 6 d also caused a significant decrease in fruit firmness from 7.2 to 4.5 kg_f and 8.1 to 6.5 kg_f, respectively. This contrasts with the results of fruit firmness immediately after curing in this experiment. The observed results in the body of previous research agree with the result of the present study that curing at 20 °C-4 d and the ambient condition maintained fruit firmness in subsequent storage (Figure 3.5 and Table 3.5). Burdon *et al.* (2017) observed that fruit at higher temperature 16 °C up to 6 d of conditioning period were consistently the firmest fruit throughout 20 weeks coolstorage at (0 °C), while fruit conditioned at 8 °C for 6 d were the softest fruit after the prolonged storage (Figure 3.5). It was observed that stored fruit at 0 °C were firmer than fruit stored at other low temperatures. At higher temperature, i.e. 16 °C, fruit conditioned for 4 d tended to be the firmest after long-term storage (0 °C) compared to fruit conditioned fruit for 2 or 6 d at a similar temperature. This is in agreement with results of curing at low and high temperatures in this study. Immediately after curing, fruit were softer at 10 °C-4 d, but the difference in fruit firmness among treatments and immediately cooled fruit was statistically small (Table 3.3). Immediately cooled fruit and cured fruit at 10 °C consistently were softer than cured fruit at 20 °C throughout storage (Table 3.5). Burdon *et al.* (2017) suggested that when the temperature dropped from 16 °C to 10 or 8 °C during conditioning period, it may trigger fruit softening, but temperatures lower than 10 or 8 °C decreased the softening rate. They stated that this possibly occurred, due to the biochemical reactions rate or temperature-regulated effects on fruit softening.

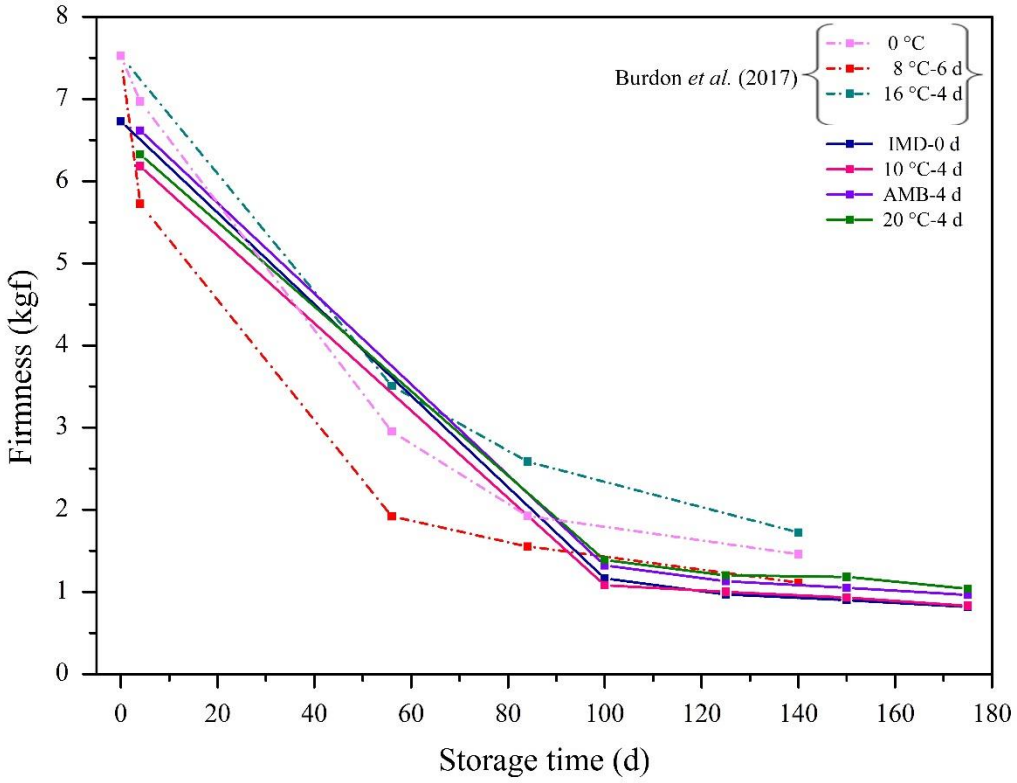


Figure 3.5: Comparison of 'Hayward' kiwifruit softening during storage for up to 140 d at 0 °C following holding at 8 °C-6 d or 16 °C-4 d and immediately stored fruit at 0 °C. Each value is the mean of 20 fruit (Burdon et al., 2017) with mean fruit firmness at harvest (IMD) and different curing regimes at 10 °C, 20 °C and AMB-4 d during subsequent storage 0 °C in the present experiment. Each value is the mean of fruit firmness of three orchards (n = 3), with 110 fruit per replicate per treatment at 100-125 d and 220 fruit per replicate per treatment at 150-175 d.

According to the results of this experiment, the interaction of curing period and temperature could impact the intensity of fruit response to low temperature storage. Similarly, the residual effect of curing conditions on fruit firmness at storage has been observed to be consistent and related to the interaction of curing period and temperature (Tables 3.5 and 3.6). This demonstrates there is a relationship between fruit softening and the incidence of SBD.

Fruit from O3 with lower maturity (9.1 °Brix) significantly had the highest SBD (41.7%) incidence and softer fruit during storage (Tables 3.2, 3.5 and 3.7), while O2 had more mature fruit (10°Brix) that consistently were firmer during storage with the least SBD incidence (12.9%) at the end of storage (Tables 3.2, 3.5 and 3.7). This demonstrates the influence of orchard and maturity advancement on fruit quality outcomes.

The results of this study have shown that curing at low temperature, but not chilling temperature (10 °C, 2-4 d) could significantly impact fruit softening throughout storage and

this softer fruit had a higher rate of SBD incidence compared to other curing temperature (20 °C and AMB). Moreover, there was no significant difference between the effect of curing at 10 °C, 2-4 d and immediately cooled fruit (0 °C) on fruit firmness and SBD incidence throughout the storage. The effect of curing at a lower temperature, regardless of curing duration, on fruit firmness and SBD incidence was similar to the effect of rapid cooling or immediate cooling methods which have been reported in different studies (Lallu & Webb, 1997; Burdon *et al.*, 2017; Zhao, 2017). Given that kiwifruit SBD incidence influences textural changes and leads to over-soft fruit, SBD incidence may have contributed to average firmness reduction. Zhao (2017) observed the SBD incidence in fast cooling fruit (0 °C, 12 h-3 d) which stored at 0 °C or 2 °C, resulted in softer fruit with a greater proportion of SBD incidence at 0 °C than 2 °C. However, differentiation between chilling-related softening and normal fruit softening was difficult. He suggested that fruit softened more rapidly at 0 °C, due to SBD incidence. After 150 d in storage, 'Hayward' kiwifruit that were stored continuously at 0 °C showed a sudden decline in fruit firmness, but not in the dual temperature treatments. The proportion of soft fruit was correlated with SBD incidence (Gwanpua *et al.*, 2018).

At higher temperature (20 °C), the curing duration played a critical role in fruit softening and the rate of SBD incidence in subsequent storage (Tables 3.5 and 3.6). There was a significant difference between cured fruit at 20 °C-2 d and 20 °C-4 d in terms of fruit softening and SBD incidence throughout storage (Tables 3.5 and 3.6). Fruit exposed to the extreme curing regimes (20 °C-4 d) were consistently firmer with lower SBD incidence after long-term storage (≥ 100 d) inwards (Tables 3.5 and 3.6). Yang *et al.* (2013) also found that low-temperature conditioning at 12 °C-3 d effectively reduced SBD incidence and also suppressed fruit softening in prolonged storage (120 d). This is in agreement with what was found in the current study. They concluded the effect of temperature conditioning to alleviate SBD incidence is related to membrane permeability (Yang *et al.*, 2013; Yang *et al.*, 2016).

These results validate the importance of the interaction between curing temperature and time on fruit softening and development of SBD incidence in prolonged storage outcomes and how these two environmental factors could have an overlapping and complementary effect on fruit quality.

Pennycook and Manning (1992) reported the effectiveness of curing to control rot at 14 °C increased in non-inoculated fruit as the duration increased up to 7 days. They suggested the interaction of environmental conditions (temperature × RH × the exposure time) is involved in

controlling rot incidence. In total, the rot incidence was low throughout the whole storage, regardless of curing condition and storage time. It was observed after long-term storage (≥ 125 d) along with SBD incidence.

Zhao *et al.* (2015) observed the rate of rotten fruit was lower in direct cooling fruit compared to gradual cooling (2 w) and the rot incidence was significantly higher only at the end of prolonged storage (0 °C). Lallu and Webb (1997) investigated the effects of precooling (9-12 h) on 'Hayward' kiwifruit quality after 20 weeks coolstorage (0 °C). The results demonstrated that precooled fruit were firmer, but they showed a higher incidence of the stem-end *Botrytis*, physiological pitting and SBD incidence when compared to non-precooled fruit (passive cooling). This is not in agreement with the results of this experiment (Table 3.8). In extended storage when the development of SBD symptoms expression in moderate or severe, it has been noted that chilling injured fruit are more susceptible to the enumeration of other disorders and diseases. In this case, the rot incidence is associated with chilling damage and it is called chilling injury-rot (Dr. Jeremy Burdon, personal communication, PFR). In other words, the rot incidence could be the consequence of tissue damage, due to SBD incidence (Figure 3.4). However, rot infection usually starts from the orchard at harvest time and spreads to other fruit in the postharvest chain (Wurms, 2005; Prusky & Gullino, 2010).

Bautista-Baños *et al.* (1997) found the interaction between harvest maturity and curing condition RH ranges caused a significant difference in the rate of rotten fruit in inoculated fruit which were cured at 10 °C-3 d. The rate of rotten fruit decreased in more mature fruit (late harvest) under highest RH (95-98%) condition during curing. What was found in the present study possibly fits into this theory that the rot incidence was low in all treatments in prolonged storage, because fruit that used for this experiment were late mature fruit. Other preharvest factors such as orchard management, environmental conditions in the season could explain the low level of rots expressed in this experiment.

3.5 Conclusion

Curing temperature and time combined with orchard variability and storage time influence 'Hayward' fruit quality in prolonged storage. The results show that the effect of orchard variation and fruit maturity should not be neglected on fruit softening and SBD incidence development. Less mature fruit are more susceptible to SBD incidence and fruit softening. The

results indicate that the SBD incidence was developed throughout storage. Both curing temperature and time influence the fruit responses in storage.

The effect of curing at low temperature (10 °C, 2-4 d) on fruit quality was similar to rapidly cooled fruit. At higher temperature (up to 20 °C), curing time could play a critical role to evaluate fruit quality in subsequent storage. Curing at higher environmental temperature between 17.4 °C (ambient condition for this experiment) to 20 °C, around the intermediate range (64-80%) RH up to 4 d preserved fruit quality better during prolonged storage by significantly slowing down fruit softening and SBD damage.

Possible mechanisms might be maintainance of cell wall structure and membrane integrity such as cell wall-modifying enzymes and antioxidant enzymes may be involved in the effects of curing on fruit storability in the prolonged storage. Nevertheless, additional research on assessment of some significant affective variables (such as ethylene production, fruit turgor, cell wall biochemical alterations, cell wall-modifying enzymes, and antioxidant enzyme activities) is needed to clarify the curing mechanism.

These experimental settings could represent how environmental conditions during curing and curing time result in variable storage performance in terms of fruit firmness and SBD incidence susceptibility of fruit batches which are destined for long-term storage. This research could provide further relevant information for the kiwifruit industry for strategic temperature management to maintain fruit quality in the supply chain. In the next chapter, the general discussion and conclusion of real industrial conditions and the effects of curing on ‘Hayward’ storage outcomes, i.e. temperature management and the response of fruit to environmental conditions and how the outputs of this study could be useful to the commercial handling of kiwifruit will be discussed.

CHAPTER 4

4 General discussion, conclusions, and future work

In this study, curing conditions in a real scenario and also the effect of the simulated curing conditions on fruit quality in subsequent storage has been investigated. In this chapter, the factors are involved in the obtained results and also the possible implications of the outputs of this study for the kiwifruit industry will be discussed.

4.1 Effect of temperature variability during curing on fruit weight loss

Curing is commercially applied to enhance produce resistance to pathogen invasion (Saltveit *et al.*, 2004) which could be conducted by delaying cooling for 48-72 h. Providing specified conditions of temperature and RH is necessary for an effective curing.

Temperature is the key factor on the water gradient between fruit and the air and the amount of moisture that the air can hold. For instance, under similar RH conditions (medium-high RH), 10 °C temperature differences could almost double the driving force for evaporation of water. The temperature variability could impact RH distribution (Hertog *et al.*, 2004).

If the small weight loss which occurs in respiration is not considered, then water loss is the major contributor to fruit weight loss (Maguire, 1998; Hertog *et al.*, 2004). The rate of water loss depends on WVPD which is directly influenced by temperature and RH (Hertog *et al.*, 2004). Therefore, the effect of temperature and RH on water loss could primarily be shown by measuring fruit weight loss. Considering that Manning et al., (2010) reported that effective and appropriate curing does not occur, if no weight loss occurs. Bautista-Baños *et al.* (1997) reported temperature and RH influenced fruit weight loss during curing that continued in subsequent storage.

This study collected data under real industry conditions to provide more understanding of what conditions may occur during full-scale curing. Temperature, humidity and weight loss of full-scale commercial bins of fruit from five orchards were monitored from harvest to packing. This effort filled a need for data in monitoring spatial-temporal variability of temperature that might occur within the system (the stacked bins) in the commercial condition. Understanding the sources of variability that may be imparted to a typical batch of kiwifruit during curing enables development and adoption of additional techniques for the purposes of preserving fruit quality

in long-term storage. Techniques that maintain quality and reduce storage loss could add more monetary value to the whole industry.

Under real conditions, RH could reach approximately the saturation point (≥ 97%) a few hours after the starting point of curing (3-7 h). In the simulated curing conditions, this took approximately 24 h for the RH levels in the crates at 10 °C to equilibrate to environmental conditions (80%) and then gradually increased and followed the trend of environmental conditions (≥ 97%) throughout curing (Figure 3.3).

Bautista-Baños *et al.* (1997) reported fruit weight loss was inversely proportional to environmental RH conditions during curing. In the industrial trials, the fruit weight loss was approximately between 0.3-0.5% over 2 to 3 d (Figures 2.30 and 2.44). Under the assumption that weight loss can be attributed to water loss. The low fruit weight loss data in the whole stack indicated that under saturated RH conditions (≥ 97%) in the bins, there was a very low driving force for water loss.

Despite the low range of fruit weight loss in industrial trials, an influence of at-harvest temperature and also the bin positioning on weight loss was observed within each trial (Figures 2.21 and 2.28).

Curing conditions leading to successful storage outcomes are regarded as dependent on water loss occurring within a certain range. Lallu and Webb (1997) found that when kiwifruit water loss was between 0.2 and 0.4% during curing, then rot incidence decreased in subsequent storage.

In the lab conditions, fruit weight loss ranged from 0.3 to 1% under different curing conditions (Table 3.3) having a weight loss of 0.6-1% in fruit exposed at > 17.4 °C (with > 64% RH) for 4 days. The fruit weight loss range doubled the range of fruit weight loss in the industrial trials. In the curing simulations, fruit with higher weight loss (0.6-1%) were consistently the firmest and had the lowest incidence of SBD after 100 d of storage (Tables 3.3, 3.5 and 3.6). As expected, fruit weight loss increased with an increased curing temperature and time.

In industrial trials, at-harvest temperature, the bin location in the stack and environmental conditions during curing and the combinations of these factors were the main factors to impact temperature gradients between the fruit bins and the surrounding environment.

The effect of at-harvest temperature on fluctuating pattern of fruit temperature within 48 h after harvest has been reported in apples (Valentine & Goedhals-Gerber, 2017). Fruit harvested earlier in the morning had a lower temperature than fruit picked in afternoon heat, during the hottest temperature of the day. Fruit picked in the afternoon required more time to equilibrate with the cooler ambient conditions during curing (Figure 2.25). In the industrial trials after 12 h (the 2nd trial), 20 h (the 3rd trial) and 32 h (the 5th trial) of filling time, the stack's temperature was still reflective of the at-harvest temperature with fruit picked earlier in the day cooler than those picked in the heat of the afternoon. In the third trial, temperature variability was approximately 5 °C in the stack 7 h after filling, due to the harvesting time (Figures 2.26a, f). Similar observations were recorded in other trials (Figures 2.20 and 2.42a and b).

The first picked fruit (lower temperature) showed a lower fruit weight loss during curing (Figures 2.30 and 2.44). This could be explained by this fact that at a lower temperature and the saturation point of RH, the driving force for water loss will be lower (Maguire, 1998). Given that weight loss can be attributed to water loss, the obtained fruit weight loss magnitude in the stack was the result of temperature variability in the stack.

The results of this study provide evidence that the temporal and spatial variability in temperature and RH within the stack could impact the fruit weight loss magnitude in the stack. Despite the low range of fruit weight loss.

The importance of maintaining the produce temperature and RH in the optimum level immediately after harvest to preserve fruit quality in subsequent storage has been reported in cherries (Schick & Toivonen, 2002).

Burdon et al. (2017) investigated the short-term effect of temperature (0-16 °C) on 'Hayward' fruit softening during two subsequent years. There were a significant difference in fruit softening in the first week of three weeks conditioning between 16 °C and other treatments. Fruit softening occurred faster at 8 and 12 °C than 16 °C, while fruit softening at 4 °C was slower than 8 and 12 °C in the first week of conditioning. They suggested when temperature decreases from 16 °C to approximately 10 °C in a short-term, this could impact fruit softening rate. Likewise, the results of the lab experiments in this study indicated there was a significant difference in fruit firmness in temperature variability between 17.4 (AMB)-10 °C, regardless of curing time (Table 3.5).

In the industrial survey, an approximately similar temperature range (8-17 °C) (Figure 2.42) to what Burdon et al (2017) reported in the above research was observed in the stack in the fifth trial (late harvest fruit). When the temperature variation was within the critical range and reminded approximately unchanged in this range during the curing (76 h). The temperature variation in the curing stack was mainly influenced by the picking time and the bin positioning (Figure 2.42).

In apple, the effect of picking time on fruit temperature profile which may impact fruit susceptibility to some postharvest disorders such as bruise and pitting in subsequent storage has been reported (Crouch, 2003).

According to the results of the lab experiment, in terms of the effect of curing condition on fruit quality and the temperature variability in the stack during the industrial trials. There is a possible opportunity for the observed temperature variability in the stack to contribute to storage outcomes, specifically in late harvest fruit, when the average environmental temperature usually is lower than 17.4 °C. Thus, further investigation is required to improve industrial curing practices to minimise the effect of temperature variability within and between the stacks. This could be particularly important for late harvest fruit outcomes which are typically destined for long-term storage.

The outputs of this phase of this study could add applicable information in kiwifruit curing practice and emphasises the importance of temperature management in initial postharvest handling procedure.

4.2 Effect of curing on fruit quality and the possible mechanisms

Fruit with firmness lower than 1 kg_f is below the standard for export in the NZ kiwifruit industry. The main reason for temperature management is to restrict kiwifruit softening (Macrae *et al.*, 1989; Lallu, 1997).

Low temperature storage (0 °C) retards fruit softening, but does not inhibit softening. Therefore, fruit softening as an integral part of fruit ripening continues even at low temperature (Satake *et al.*, 2002). Both physical and biochemical changes are involved in the softening process in kiwifruit.

Cell turgor as influenced by water loss is considered as a main physical factor and the relevant biochemical changes in the cell wall constitute the major biological factors (Li *et al.*, 2016). There are some physiological events, including cell wall swelling and the breakdown of the middle lamella which result in fruit softening to 'eating ripe' (0.6-0.8 kg_f) (Atkinson et al., 2011).

Low temperatures, even for a short period, could induce chilling injury in subsequent long-termstorage, because chilling temperature has a cumulative effect (Kader *et al.*, 1974; Vigneault *et al.*, 2009). One possible explanation for the results of curing at 10 °C and immediately cooled fruit might be the cumulative effect of chilling injury. When fruit were subjected to 10 °C during curing and subsequently exposed to 0 °C storage, the whole procedure may have acted as a signal and caused fruit responses to cold stress. Therefore, SBD incidence and severity progressed consistently with storage time (Table 3.5 and 3.6) and the interaction of temperature and time could impact the intensity of response. Stored 'Hayward' kiwifruit continuously at 0 °C showed a decline in fruit firmness after 150 d in storage, but not in dual temperature (2 °C exposed) treatments (Gwanpua *et al.*, 2018).

Given that kiwifruit SBD incidence influences textural changes and leads to over-soft fruit, SBD incidence may have contributed to average firmness reduction (Burdon & Lallu, 2011). The irreversible damage to cell membranes could accumulate, resulting in more chilling injury damage in subsequent storage. Zhao (2017) suggested that SBD development in kiwifruit negatively impacts fruit firmness. Gwanpua *et al.* (2018) also reported the proportion of soft fruit was correlated with SBD incidence. The results of SBD incidence and fruit softening in this experiment agreed with this (Tables 3-5 and 3-6).

One potential theory for curing at higher temperature suppressing SBD development is that the delay period enables fruit maturity to develop. At-harvest fruit maturity could impact fruit responses to the storage conditions, however, there is a conflict between the reported results (Koutsoflini *et al.*, 2013; Burdon *et al.*, 2017; Zhao, 2017). The stress caused by the act of harvesting itself, can trigger initiation of important enzymes required for regular ripening. An alternative fruit system where this has been studied in more depth is peach and nectarine (*Prunus persica).* Delayed storage (DS) of nectarines at 20 °C and 80% RH for 2 d prevented woolliness (chilling injury) in nectarine fruit stored for up to 6 weeks at 0 °C (Zhou *et al.*, 2000). Zhou *et al.* (2000) observed PG activity increased caused by delayed storage which was maintained during storage. The same treatment also resulted in a higher PG/PE activity ratio

of during shelf life at 20 °C. Zhou *et al.* (2000) believed the higher activity of PG after delayed storage was responsible for decreasing woolliness in subsequent storage. However, delayed storage were also softer than non-treated fruit after storage in nectarine (Zhou *et al.*, 2000). There are contradictory results in this experiment in regard to fruit softening after delayed cooling (curing), but both are in agreement in terms of lower chilling injury incidence after delayed cooling. Peace *et al.* (2005) observed endoPG activity, pectin-degrading enzyme, had a significant contribution to the development of mealiness in peach. These authors suggested endoPG genes are probably the first of the relevant genes for mealiness incidence. This shows there may be coordination between changes that normally occur on fruit softening and chilling injury incidence at low temperatures.

Schroder and Atkinson (2006) reported that the complicated process of softening started with pectin softening, solubilisation, and de-esterification, an increase in PME and increased cell wall swelling. PME causes dimethyl esterification of homogalacturonan (HG). This can either form Ca^{2+} bonds, which promote the development of the so-called 'egg box' structures that underlie the formation of pectin gels, or become a target for pectin-degrading enzymes such as PG and pectate lyases (PL) and pectin lyases. In the former case, PG activity will be reduced in pectin gel. It means that PE could involve in cell wall integrity (Sénéchal *et al.*, 2014). There is possibility that during curing at higher temperatures for a longer period (20 °C and AMB), a similar mechanism has been involved in maintaining cell wall integrity through PME acts on HG producing free carboxyl group (-COOH) could bound to Ca^{2+} bonds and leads to pectin gel which reduces PG activity, therefore preserves cell wall integrity. There will be further potential to investigate this hypothesis in kiwifruit curing at higher temperature.

Mworia *et al.* (2012) observed *Actinidia chinensis* 'Sanuki Gold' kiwifruit stored at 4 °C for 1 month softened significantly and lost more than 85% of harvest firmness without any traceable ethylene production. At low temperature, fruit softening accompanied by mRNA accumulation of PG and PL and an increase in expansin mRNA without ethylene production in intact fruit. Whereas stored fruit at the ambient conditions (25 °C) maintained 60% of harvest firmness and fruit firmness was four times higher than fruit held at 4 °C and did not show any accumulation of PG and PL mRNAs. Even repeated 1-methycyclopropene (1-MCP) treatment (12 h, twice a week) on fruit at 4 °C could not alter or modify the physiological changes that occurred, due to low temperature exposure (Figure 4.1). They indicated that low temperature modulates the ripening of kiwifruit in an ethylene-independent manner, suggesting kiwifruit softening and expression of cell wall-modifying enzymes can be induced by low temperature in an ethylene-

independent manner. The results of this study at higher and lower curing temperature possibly fit into this hypothesis, however further study needs to be conducted to understand the biochemical regulatory mechanisms of fruit softening responses to different curing conditions.

Figure 4.1: Expression of cell wall-degrading genes in 'Sanuki Gold' kiwifruit stored under room temperature 25 °C or low temperature 4 °C with or without repeated 1-MCP treatments. RT-Cont, stored at 25 °C; RTMCP, stored at 25 °C with repeated 1-MCP treatments; LT-Cont, stored at 4 °C; LT-MCP, stored at 4 °C with repeated 1-MCP treatments. Each sample lane was loaded with 5 lg of total RNA (Mworia et al., 2012).

Cellular membrane damage is typically an early chilling injury response (Rui *et al.*, 2010; Aghdam & Bodbodak, 2014). Chilling injury incidence in kiwifruit is associated with factors which impact the basic function of cell membrane (Lallu, 1997; Sfakiotakis *et al.*, 2005). The first impact of chilling injury on cell membrane is the transition phase from flexible liquid crystal to solid gel structure. At low temperatures, a series of events take place in cell membrane which starts with peroxidation of fatty acids, degradation of phospholipids and galactolipids and the increase of sterol/phospholipids ratio which decrease membrane fluidity. Therefore, chilling injury can be interpreted as an oxidative stress (Hodges *et al.*, 2004; Sevillano *et al.*, 2009; Yang *et al.*, 2012; Singh & Singh, 2013).

Yang et al. (2013) also found that low-temperature conditioning (LTC), of 12 °C for 3 d effectively delayed and reduced SBD incidence. These authors suggested the conditioning at 12 °C could alleviate SBD incidence, due to the antioxidant system activities enhancement.

The beneficial effect of temperature conditioning to alleviate SBD incidence is enhancing antioxidant system activity resulting in scavenging oxygen species and consequently maintaining membrane integrity (Yang *et al.*, 2016). Yang et al. (2013) found that LTC at 12 °C for 3 d effectively alleviated SBD incidence in kiwifruit and also suppressed fruit softening by increasing antioxidant enzymes activities. Gradual cooling also (from 15 to 0 °C) also inhibited progressive increases in membrane permeability and the production of reactive oxygen species (ROS), which are the cause of oxidative damage. Simultaneously, gradual cooling resulted in higher rate of antioxidant enzymes activities in comparison with the control. Consequently, the results observed in the present experiment supports the possibility of antioxidant enzymes involvement during curing at higher temperature for a longer period to maintain fruit firmness concomitantly by alleviating SBD incidence during prolonged storage. Higher antioxidant enzymes activities protect cell membrane from the accumulation of oxygen species and reduce the peroxidation of unsaturated fatty acids of the cell membrane. Therefore, cell membrane integrity will be maintained which leads to higher fruit quality.

The effect of curing at higher temperature on suppressing SBD development and maintaining fruit firmness could possibly be related to this hypothesis that the delayed storage enables fruit maturity to develop. In this experiment, the advancement of fruit maturity in fruit from O2 (highest at-harvest SSC °Brix) resulted in firmer fruit with lower SBD incidence (Tables 3-4 and 3-7).

It would be interesting to cure fruit at different harvest maturity and investigate cell wall-modifying enzymes (PG, PE and PG/PE activity) and mRNA levels, also antioxidant system activities and cell membrane response in fruit at different maturity levels which will be exposed to variable temperature in curing. Further work on biochemical and molecular changes at cellular level in response to curing condition will be necessary to determine the curing mechanisms and explain how this postharvest practice influences fruit quality and SBD incidence in prolonged storage.

4.3 Industry implications

The simulated curing results indicated that curing at ≥ 17.4 °C (with > 64% RH) for 4 d significantly reduced fruit softening and SBD incidence in storage in comparison with curing

at 10 °C or IMD. In terms of the possible implications of these results for the kiwifruit industry, a few points should be considered. In kiwifruit, curing occur by holding fruit in ambient conditions for 2-3 d immediately after harvest (Lallu *et al.*, 1997). In New Zealand, 'Hayward' kiwifruit harvest starts in late March and peaks the first three weeks of May. In the real conditions monitored, the average daily temperature under the canopy from late March to mid-May (Figures 2.12, 2.19 and 2.25) was close to the temperature range that showed the highest fruit quality outcome in the lab experiment. When the average temperature recorded by the local weather station was 15.7 °C (Figure 4.2).

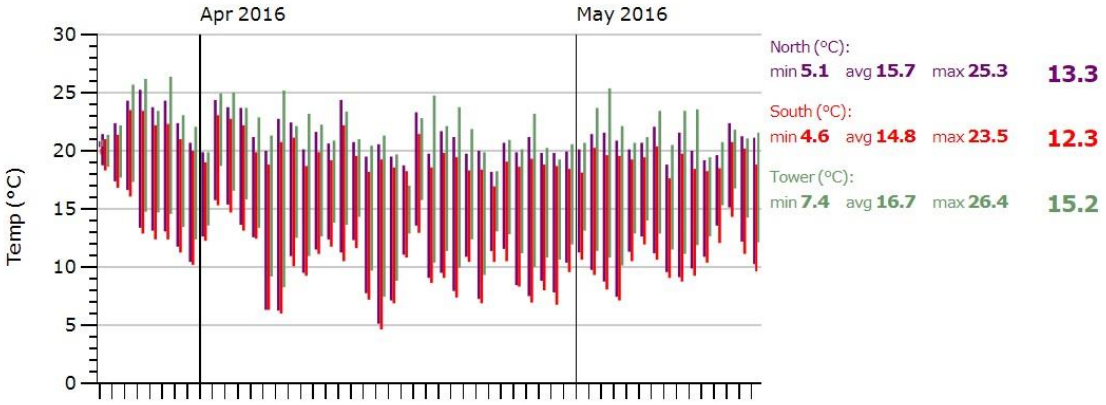


Figure 4.2: Temperature recorded by the local weather station from 23rd March to 15th May 2016.

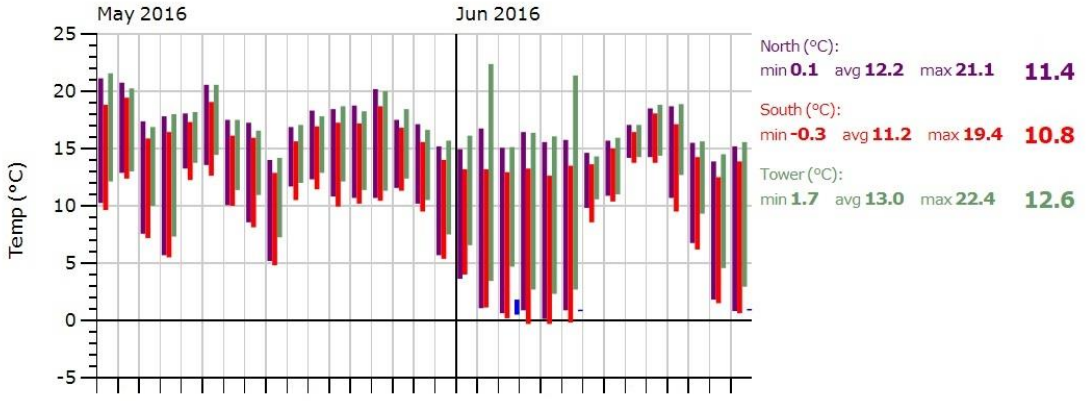


Figure 4.3: Temperature recorded by the local weather station from 15th May to 15th June 2016.

This suggests to achieve the industry situation during the months of March and mid-May that results in high fruit quality outcomes, curing may not need large monetary investments of controlled conditions at the packhouse. However, curing of late harvest fruit (late-May to mid-

June) will need to be conducted in a temperature controlled room. In Katikati, where the industrial trials were conducted, over this period (late-May to mid-June) the daily average high temperature decreases to approximately 17 °C and the daily low temperature drops to about 10.5 °C (Anonymous, 2017a).

During this period (late May to mid-June), when trial 4 and trial 5 were conducted (Figures 2.34 and 2.41) the daily temperature range under the canopy fluctuated between 4.5-18 °C. When the average temperature recorded by the local weather station (12.1 °C; Figure 4.3) was close to the temperature of the lab experiment (10 °C) that had low quality fruit outcome. It was possible to monitor the environmental conditions of the stack in more details in trial 5, because of the long curing duration (76 h). Ambient temperature remained between 10-18 °C during the first 2 days. In the lab experiment, a similar temperature variation (10.3 to 16.8 °C) was observed in the curing stack at 10 °C condition. This temperature range was also within the critical range which led to softer fruit, as reported by Burdon *et al.* (2017).

The results showed that the kiwifruit industry may benefit from curing late harvest fruit in controlled conditions, because the in-stack temperature variability of late-harvest fruit under a real scenario was in the critical range. This in-stack temperature range could possibly result in low fruit quality outcomes.

Managing environmental conditions during curing under controlled conditions is different from current conventional curing practice in the kiwifruit industry, and may take economic investment in establishing appropriate facilities. This practice needs specific approaches to be taken, to manage the available resources or improve the system, variable costs, depreciation, annual operation and maintenance costs, apart from the initial capital cost to establish facilities. This practice may also increase the handling costs, as handling bins when there is a doorway and the forklift egress in and out of the controlled room will become slower. Moreover, the forklift needs some space to manoeuvre inside of the room, therefore a sizeable part of the room must be left empty.

It is worthwhile to notice that under real conditions, RH increased to saturation (≥ 97% measured) a few (3-7) hours after starting curing. The recorded weight loss in different commercial trials (the 3rd and the 5th trial) ranged between 0.3 and 0.5% after approximately 2-3 d (Figures 2.30 and 2.44). Therefore, the recorded weight loss was low. While under controlled simulated curing conditions, fruit exposed to > 17.4 °C (with > 64% RH) for 4 days,

the average RH inside of the crates was 82% (20 °C-4 d) and 88% (AMB-4 d). The range of fruit weight loss was (0.6-1%), double that measured in the industry trials.

Applying curing at > 17.4 °C, (with > 64% RH) for 4 d under a controlled condition system, there would be a higher rate of fruit weight loss in the initial steps of supply chain in comparison with what has been already recorded in the industry. Since the curing should be applied under the intermediate range of RH (≈ 80%) in comparison with the saturated conditions (≥ 97%) which already has been observed in the industrial survey. Considering the subsequent fruit weight loss during storage, this could lead to shrivelled fruit at the end of storage. Kiwifruit are susceptible to shrivel when 4-5% of weight has been lost (Burdon & Lallu, 2011).

Total returns to growers is a function of the mass of harvested fruit, which is first measured prior to tipping the bin onto the roller conveyor at the front of the packing line. Hence any weight loss between harvest and the packing line (i.e. the period monitored in this study) equates to loss in financial return to growers. The value of increasing individual fruit weight by 1 g equates to approximately $875 per hectare for 'Hayward' (NZ Kiwifruit Growers, 2016). Thus, bin conditions from picking to grading are critical, not only to preserve fruit quality during long-term storage, but also for economic returns for growers.

Thus, curing under a controlled condition needs an optimal temperature and RH management practices to achieve the desired outcomes. Following the curing strategy at > 17.4 °C, (with > 64% RH) for 4 d would result in higher fruit weight loss (less returns for the growers), but with the trade-off of higher fruit quality at the end of storage, specifically for late harvest fruit.

The industrial survey demonstrated that at-harvest fruit temperature was a factor in imparting temperature variability in the whole stack, regardless of environmental conditions. The temperature variability throughout the stack was 5-8 °C, with the effect of the initial picking temperature lasting up to approximately 24 h after harvest. The bin position in the stack was another factor in temperature variation. The highest temperature was recorded at the top location of the stack, resulting in a temperature difference between 2 to 5 °C between layers.

An advantage of curing under the controlled conditions might be that the significant airflow required to maintain conditions would also help a better temperature distribution, and hence reduce spatial and temporal variability in the curing stack as well as keeping bins RH at an optimal level (≈ 80%).

The results of this study have potential implications for the kiwifruit industry. Environmental conditions during curing and the consequent spatial and temporal variability in the stack impact fruit weight loss. Applying curing under controlled conditions would allow reduction of condition variability, particularly for late harvest fruit. Controlling curing conditions could maintain fruit quality in kiwifruit batches destined for long-term storage by reducing environmental variability.

4.4 Future work

At the packhouse, the stack configuration could impact airflow around the stack and causes temperature heterogeneity in the stacked bins. Under real conditions in the packhouse, one of the possible reasons for the spatial and temporal variability in temperature and RH in the stack was non-uniformly distributed airflow. In the third trial, RH dropped in the whole stack during two nights, when temperature decreased simultaneously only on the first night (Figures 2.26, 2.27, 2.28 and 2.29). The recorded conditions under the canopy showed a normal diurnal decrease of temperature at night and the environmental RH remained almost steady between 12:00 am to 6:00 am (80-90%). After this elapsed time, RH developed towards high RH conditions (80-100%) in the curing stack, while temperature profile in the stacked bins decreased slightly and remained almost motionless (16-19 °C). There is an assumption that airflow through the stacks reduced RH within the bins and caused a break in the high RH conditions in the bins. Future experiments should adopt additional techniques to measure airflow rates under curing conditions and investigate airflow impacts on temperature heterogeneity and the subsequent RH in the whole stack.

In the industrial survey, it was not possible to directly compare how rapidly RH developed inside the bin designs (wooden or plastic) as environmental conditions were different in each trial. Slots in the floor and sides of bins amount to 7-11% of the total surface area of the plastic bins which increase the ventilation bins and double the rate of cooling in comparison with wooden bins (Waelti, 1992; Harmandeep, 2010; Anonymous, 2017c). Thus, future research could investigate the effect of packaging materials and ventilation design on temperature and humidity distribution within individual bins.

In the lab experiment, temperature was monitored in the controlled room and RH was a consequence rather than directly controlled. In early research, there were contradictory results

on the influence of RH on curing efficacy in terms of controlling rot (Pennycook & Manning, 1992; Bautista-Baños *et al.*, 1997; Retamales *et al.*, 1997). However, it has been recommended to cure kiwifruit in ambient conditions (10 to 20 °C, >88% RH) for 2-3 d at the packhouse (Bautista-Baños et al., 1997; Retamales et al., 1997). In the industrial trials, high humidity conditions (70-80% RH) were observed to develop consistently in the stacked bins after about 3 h of filling and became near saturation in the middle of the bins after approximately 6-7 h of filling, regardless of environmental conditions. If the ambient conditions under the canopy remained relatively stable during curing, RH inside the stacked bins remained consistently near saturation throughout curing. In the simulated curing conditions in the lab, at 10 °C and AMB conditions, the crates required approximately 2 d to become near saturation RH. At given temperatures, the average RH inside of the crates was relatively medium-high (≈ 80%) and the range was between 60-97%. The crates required a longer time to reach to the full saturation point at 10 °C and AMB compared to the observations in the industrial survey. During the lab work, at 20 °C, RH reached saturation only in a few crates after 2 d and lasted for approximately 6-7 h (Figure 3.3). It would be favourable to create conditions that occur in the industry in the lab simulations by establishing near saturation (≥ 97%) RH conditions. Bautista-Baños *et al.* (1997) reported less rot incidence in cured fruit at 10 °C, 89-95% RH for 3 d than at lower humidity conditions after 12 weeks of subsequent coolstorage. Bautista-Baños *et al.* (1997) also observed that fruit firmness was influenced by fruit maturity at harvest, but not by RH during curing. Earlier studies on the effects of environmental conditions on fruit quality have shown that higher RH reduces chilling injury incidence in sensitive tropical produce (Paull, 1999). These need more investigation to replicate the industry survey under controlled condition, higher RH, closer to the saturation point.

In early research, Lallu *et al.* (1997) reported that environmental conditions during curing have a greater impact on fruit quality than curing time. This work found that curing at 10 °C did not make a significant difference in fruit quality compared to immediate cooling. Even the duration of curing, whether it was for 2 or 4 days, had no effect. At higher temperature (20 °C), there was a significant difference between 2 d and 4 d of curing at the same temperature. Longer periods noticeably maintained fruit quality. In industry, curing could occur for less than 24 h or greater than 72 h. However, curing longer than this period (72 h) (trial 5) rarely could happen in the current industry practice. The curing time in the industry mainly depends on time and logistic constraints in the packhouse. It is well worth considering the effect of curing at higher temperature for a longer period (≥ 4 d) on fruit firmness which is normally expected to result

in softer fruit and also measure the SBD incidence changes. Since Burdon *et al.* (2017) also reported a better preservation of fruit quality after delayed cooling at 16 °C, 4-6 d than 2 d (Figure 3.5). The consistency of the results on the same cultivar in different seasons provides confidence to these results in terms of suggesting a new approach in the industrial curing.

In this study, the effect of the orchard on fruit quality was more dominant than the curing treatment. More mature fruit were firmer and had less susceptibility to SBD incidence after long-term storage. Burdon *et al.* (2017) reported at-harvest fruit maturity could result in a wide range of softening patterns in fruit from a single genotype. In contrast, Zhao (2017) reported the orchard effect on fruit quality, a higher proportion of soft fruit was observed in more mature fruit (late harvest). Therefore, it would be interesting to repeat this experiment across several growing seasons and fruit maturities to evaluate the consistency of the results under different environmental conditions and fruit physiological status in late season fruit.

The mechanism of curing has not been fully understood, although it is apparently associated with fruit water loss. Manning *et al.,* (2010) found that there is not an effective curing when no water loss occurs. The impact of temperature heterogeneity within the stacked bins was observed on fruit weight loss during curing in a real scenario. However, fruit weight was low (0.3-0.5%) during curing. It would be interesting to measure fruit weight loss throughout curing and subsequent storage to investing a possibility for a consistent trend for weight loss from curing conditions.

Physiological and biochemical changes in the cell wall constitute the major biological factors involved in fruit softening of kiwifruit. The results of the present study indicate that fruit exposed to extreme curing regimes (20 °C for 4 d) and ambient condition for 4 d were consistently the firmest after long-term storage (≥100 d) onwards (Table 3.5).

In tomatoes, the rates of softening measured using the non-invasive techniques depended on both temperature and the applied water vapour pressure deficit (Hertog *et al.*, 2004). Bautista-Baños *et al.* (1997) reported the interaction of maturity and the environmental RH conditions could impact fruit quality.

Further investigation is required to understand the effects of curing condition (humidity, temperature and its duration) on fruit quality in subsequent storage. Whether the fruit firmness results observed in this experiment in low and high temperature related to the biochemical process of cell wall breakdown or this is related to the physical process of water loss.

4.5 Recommendation to improve the experimental conditions in future

In the industry survey, the challenges for each trial have been represented in the relevant trial commentary subsection, but there are a few points which might be applicable to improve the experimental conditions to replicate in industry or laboratory contexts.

The XSense loggers used in this study were really practical and accurate and cost-effective in recoding environmental conditions in a few hundred bins under the time pressure of industry conditions. However, collecting the data from the related website for each trial was challenging. Moreover, the device was not set on for the NZ time zone, therefore the recoded time had to be changed to the NZ time zone manually for each use. It is recommended to communicate directly to the device manufacturer or the NZ authorized representative and ask about the required details before starting to use the device, since there might be no relevant information in the device manual. Another problem was the thin wire of the loggers easily tangle into knots and the aerial part of it might be broken, to avoid this and save time. This is better to put each logger in a mash and netlon bag, while the aerial part is out of the bag.

This is also quite worthwhile to measure fruit core temperature during curing. In this study, it was not possible to record fruit temperature and monitor fruit response to environmental conditions during curing, due to a technical issue.

In the lab experiment, it is also recommended to use fruit bins as a sample unit instead of fruit crates, if the facilities are available. As discussed, the industrial survey showed that at-harvest temperature is one of the key factors in the stack heterogeneity. While the crates were filled from the same bin, then there was no or a small difference between initial temperatures of crates to follow spatial and temporal variability of temperature and RH in the sample units during curing.

4.6 Conclusion

The industry survey of this study contributes to understanding about conditions during curing in the kiwifruit industry. The spatial placement; at-harvest fruit temperature; and ambient conditions combine to result in temperature and humidity heterogeneity in stacked bins during curing. This condition variability in the stack could influence fruit weight loss. RH increased to saturation ($\geq$ 97% measured) in a short period (3-7) hours after starting curing. Therefore,

fruit weight loss was low (0.3-0.5%), but the influence of at-harvest temperature and also the bin positioning on weight loss was observed within each trial.

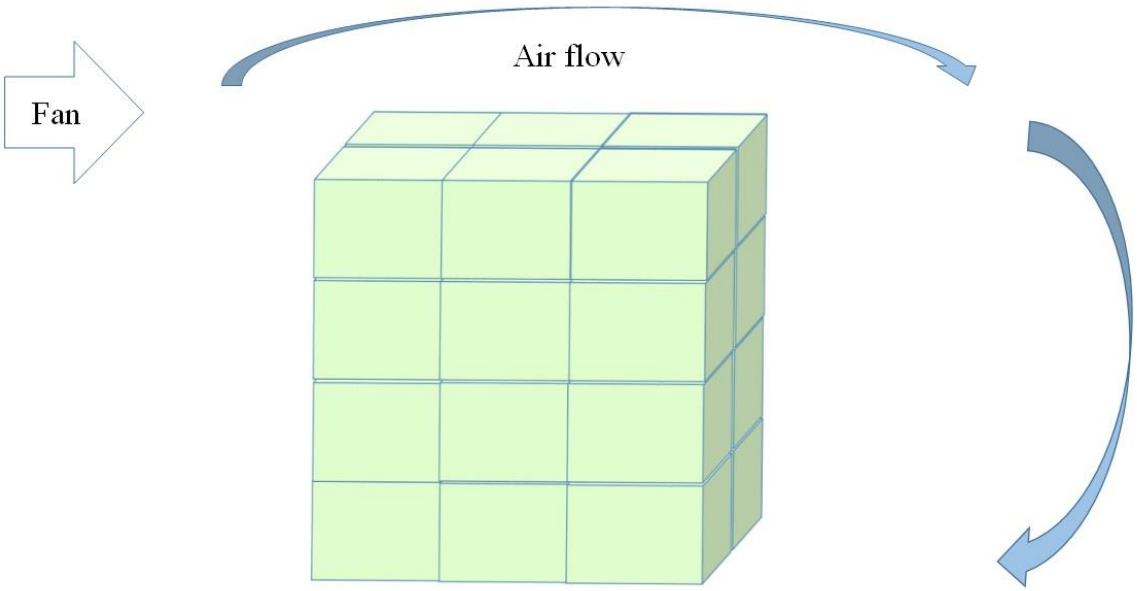
The results of the lab experiment support the hypothesis that curing conditions (temperature × time) could significantly impact fruit quality and cause differences in fruit performance throughout storage. Curing at higher environmental temperatures between 17.4 to 20 °C up to 4 d maintained fruit quality during prolonged storage by significantly inhibiting fruit softening and SBD development.

The link between the industry survey and the lab experiment determined deliberate contribution and the effect of temperature variability in initial steps of kiwifruit supply chain on storage outcomes.

These results suggest that curing at > 17.4 °C (with > 64 % RH) for 4 d could be applied by the industry from late March to mid-May (the peak of harvest time) with no need for huge investment to facilitate the packhouses. However, the curing of late harvest fruit needs to be conducted under controlled conditions to reduce the environmental variability in the stack. This strategy could reduce curing imparted variability and possibly impact fruit quality outcomes in long-term storage.

Appendices

Appendix A: Airflow in the designed curing room (10 °C and 20 °C, 2-4 days) and the crates stack's location.



Appendix B: Statistical Analysis

ANOVA table representing the sum of square (SS), mean square (MS) F and P value of factors (curing condition and orchard) that had an effect on fruit firmness during each storage time. P<0.001 represents a significant effect on fruit firmness.

	Factors	DF	SS	MS	F	P
a-100 d	Curing_Tmt	5	27.42622	5.48524	55.33	<.001
	Orchard	2	34.28186	17.14093	172.92	<.001
	Curing_Tmt.Orchard	10	5.26330	0.52633	5.31	<.001
	Residual	1930	191.31714	0.09913		
	Total	1947	254.75716			
b-125 d	Curing_Tmt	5	13.43259	2.68652	42.45	<.001
	Orchard	2	37.33067	18.66533	294.92	<.001
	Curing_Tmt.Orchard	10	1.84080	0.18408	2.91	0.001
	Residual	1962	124.17234	0.06329		
	Total	1979	176.77639			
c-125 d + 7 d (20 °C)	Curing_Tmt	5	8.81074	1.76215	30.50	<.001
	Orchard	2	35.54968	17.77484	307.65	<.001
	Curing_Tmt.Orchard	10	1.14985	0.11498	1.99	0.031
	Residual	1959	113.18272	0.05778		
	Total	1976	158.62655			
d-150 d	Curing_Tmt	5	36.29706	7.25941	127.25	<.001
	Orchard	2	94.83727	47.41863	831.17	<.001
	Curing_Tmt.Orchard	10	3.62511	0.36251	6.35	<.001
	Residual	3936	224.55124	0.05705		
	Total	3936	359.13049			
e-175 d	Curing_Tmt	5	24.50191	4.90038	93.28	<.001
	Orchard	2	82.71008	41.35504	787.23	<.001
	Curing_Tmt.Orchard	10	2.44019	0.24402	4.65	<.001
	Residual	3933	206.60909	0.05253		
	Total	3950	316.06292			

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