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Improved post-harvest handling of lychee

A report for the Rural Industries Research and Development Corporation

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Foreword

Lychee is a seasonal, sub-tropical fruit that is considered to be a delicacy in many parts of Asia, especially amongst Chinese communities. Asia is potentially a lucrative market for Australian lychee growers because Australian production is out-of-season with respect to Asian production, and the Australian season coincides with the Chinese New Year, when demand for lychee is extremely high; and the fruit is prized more highly in Asia than it is in Australia. Prices paid for fruit exported from Australia are typically 40 % higher than those paid for fruit destined for Australia's domestic market. Nonetheless, Australia exports only 8 % of its lychee to Asia, and only 20 % of its fruit in total. The reason for this is that the fruit has only a short storage-life, which prevents anything other than the best quality fruit from being exported, and then only by the fastest and most expensive means of transport. The Australian Lychee Industry is seeking ways to increases its access to Asian markets.

The aim of the project is to increase the size of the Asian market for Australian lychee, by developing practical, safe, reliable and cost-effective protocols for increasing the quality and storage-life of the fruit. It is anticipated that such a protocol would allow further growth in lychee exports

CSIRO Plant Industry developed the project in collaboration with the Australian Lychee Industry, through its representative body, the Australian Lychee Growers Association (ALGA), the Rural Industries Research and Development Corporation (RIRDC) and the Queensland Fruit and Vegetable Growers (QFVG). It addresses those factors that affect fruit deterioration in the chain of production and processing from the pre-harvest care of trees through to the consumer. Previous research in this area has largely involved the piecemeal assessment of practices that have proven to be successful with the handling of other crops. The results from this research have either been too ambiguous or too impractical for widespread adoption by industry. The approach taken in the new project differs from earlier approaches in two ways. Firstly, it seeks to develop a rigorous protocol for the handling of lychee based on the specific physiological requirements of the fruit. Secondly, it attempts to integrate all levels of production and processing with respect to the final turnout of the fruit.

This project was funded from industry revenue that is matched by funds provided by the Australian Government.

This report is an addition to RIRDC's diverse range of over 900 research publications, forms part of our new plant products R&D program, which aims to facilitate the development of new industries based on plants or plant products that have commercial potential for Australia.

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Simon Hearn
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Executive Summary

The major achievements of this project have been to:

- Quantify the benefits of a number of processes involved in the postharvest handling of lychee. In doing this a number of options for improving these processes, from harvest to turnout have been identified.
- Determine the optimal time for lychee harvesting based on the water relations of the tree have been described. The potential to rehydrate fruit after harvest has been demonstrated though the risk of uptake of contaminants needs to be considered.
- The optimal method of cooling fruit has been quantified in terms of colour and turgor retention and rot development.
- The relative importance of storage temperature at different periods after packaging has been assessed revealing that greatest care is being taken when fruit are most resilient to temperature fluctuations.
- A range of options for controlling rots using heat treatments, food additives and biological agents has been identified. From these this work simple protocols for assessing the impact of packing lines have been developed.
- A model that describes heating and cooling of lychee fruit in water and air has been developed that can be used to predict responses to a range of treatments such as in the use of hot water to control rot development.

Most of these results will require further development before they can be integrated into existing postharvest processes for lychee.

This project aimed to increase the access of Australian lychee fruit to the Asian markets by improving post harvest handling from farm to consumer. It was managed through a steering committee comprised of growers, researchers and funding body representatives to which results were reported on a regular basis and in turn provided directions for the annual research priorities.

There were major changes in the proposed research program as a result of the decisions made by the steering committee resulting in the inclusion of investigations into the use of high temperature and acid treatments to preserve and accentuate the external appearance of the fruit. The steering committee also decided that project should assess storage over a two week period followed by transfer to 22^{o}C to replicate in shop conditions. The inclusion of the assessment of heat and acid treatments precluded detailed investigations of packaging materials and delayed other studies so that integration of the combined optimised treatments could not be assessed.

Prior to the commencement of this project it was generally recognised the lychees should be harvested prior to the extremes of daily temperature that occur around late morning and early afternoon. By using fruit water potential it has been shown that there is rapid loss of turgor early morning (~ 8am) with a recovery occurring in the afternoon (~ 4pm). It was estimated that this loss of turgor could be equivalent of 3-5% of fruit weight. Harvesting at an inappropriate time therefore can represent a substantial reduction in harvested fruit fresh weight. Browning of the fruit has been shown to occur when 10% of harvested fresh weight is lost through desiccation. Since weight loss of fruit after packaging is continuous the harvesting of fruit at inappropriate times will reduce the period until skin browning occurs. However, the current research did demonstrate the potential to rehydrate fruit after harvest. The capacity to rehydrate fruit reduced during the first hour following harvest. It is unclear whether rehydration can be used commercially as the duration from harvest till delivery to the packing facility may exceed 60 min. The risk of contamination also needs to be considered as it is unclear how the fruit takes up water.

It was also shown that fruit harvested when under mature developed fewer rots than fruit that would be considered mature or over mature. There were no significant differences in the deterioration of the mature and over mature fruit. However, was potentially a large reduction in yield loss due to harvesting under mature fruit as there was progressive 20% increase in harvest weight between each of these stages of fruit development. This research component of the project was limited and sensory implications of harvesting under mature and over mature fruit were not considered

Postharvest changes in the fruit of the lychee cultivars "Kwai May Pink" and "Wai Chee" were affected by the storage temperature and the method of cooling (air-cooling or water-cooling). There was evidence of chilling injury at 2 °C, with the fruit stored at 2 °C having poorer colour characteristics (lower *L*, lower *chroma* and higher *hue angle*) and greater water loss than the fruit held at 5 °C. The fruit held at 5 °C tended to have better colour retention, lower water loss and less rot development than fruit held at 10 or 15 °C, but temperatures of 5 or 10 °C were satisfactory for the storage of fruit for approximately two weeks. Air-cooled fruit had better colour retention and less rot development than water-cooled fruit, but lost more water. In a separate trial the effects of storing fruit at combinations 5, 10 and 15^{o}C during three consecutive 80h periods were assessed. These results indicated that having fruit stored at 5^{o}C during the third 80h period had the greatest effect on reducing rot development almost irrespective of whether the fruit had been held at 5,10 or 15 ^{o}C during the initial 80h period. The focus of the current cool chain handling of lychee is perverse, with considerable effort expended in cooling fruit immediately postharvest when the fruit are most resilient to temperature variation, and the retailing of fruit at room temperature when refrigeration is most needed.

The temperature of cartons containing fruit was monitored in a number of shipments using local transport companies engaged in transporting fruit to the Sydney. The temperature of the fruit at arrival ranged from around 20^{o}C to almost 0^{o}C. Lychees are frequently part of mixed loads of produce and are therefore not in a position to dictate refrigeration temperatures. The effects of varying temperatures during successive 80h periods after harvest indicated that the temperature during the early post harvest period is less critical than later during storage, but free water may arise from condensation during temperature changes that may promote rot development. The use of the CSIRO packaging developed for use with cauliflower that maintains high humidity while minimising the risk of free water on the fruit should be considered for use with lychee. The potential of minimising temperature fluctuations by ensuring fruit are pre-cooling to 5^{o}C prior to packing and then after packing, wrapping pallets with temperature regulating blankets to minimise temperature fluctuations during transport could also be worthy investigation.

The most effective means of controlling rots besides refrigeration was application of the now unregistered treatment involving a 52^{o}C benomyl solution. Our project showed that a substantial part of this benefit for rot control is derived from the use of 52^{o}C but the tolerances to achieve a benefit are very precise. Treating fruit for similar times with 54^{o}C water increased rots while treatment at 48^{o}C showed no benefits over the untreated controls. Previously there had not been wide adoption of the benomyl treatment using water baths presumably because of the thresholds for damage and benefit were not clearly described and were not matched to engineering thresholds. We demonstrated that similar benefits to water baths could be achieved using spray systems that are already used on conveyor belts to hot water treat other tropical fruit such as mango. Use of water on a conveyor system could also have the benefit of disinfesting the packaging line to some extent. Discussions with the industry indicated that a 1 min treatment of fruit was currently impractical for current high volume packaging lines. Further investigations are needed to determine whether higher temperatures for shorter periods may have equivalent benefits while allowing increased through put. Alternatively an improved engineering solution may exist.

A number of chemical products and biological agents already registered for the preservation of other crops or food products were shown to reduce the level of rots in lychee. These included acetic and lactic acid, potassium silicate, and *Trichoderma*. It should be noted that the now abandoned benomyl treatment only provides mild anti-fungal protection when applied at ambient temperatures. Further

research is needed to determine the effects of hot water treatment and these alternative treatments are additive.

It was also shown that field application of these alternative chemicals and biological agents could modify the microflora on the surface of fruit but no postharvest benefit could be demonstrated. It should be noted that these field sprays were ceased 2 weeks prior to harvest. This maybe unnecessary as these products are registered in other crops as postharvest dips and food additives. The now demonstrated ability of lychee to take up water after harvest suggests that any chemical treatment to control rots must be benign to avoid contamination.

Substantial resources were diverted to the investigation of the use of high temperatures and acid treatments to preserve the lychee skin colour. This, to a large extent, mimicked the overseas treatment of lychee with SO_2 but did not have problem of sulphur residues. Treatment of fruit with acid alone changed fruit colour but the effect gave the fruit a patchy appearance. Pre-treating the fruit with hot water made the acid effect more uniform. The heat and acid treatment created artificially bright coloured fruit that tended to be softer and more prone to rots than the untreated controls. There are no registered treatments to control the accelerated rot development resulting from these treatments. The colour of the fruit was not fixed and fruit gradually browned but the discolouration was different that evident in control fruit. Treatment of fruit this manner separates the appearance of the fruit from the eating quality. This treatment is not recommended since it could easily lead to attractive fruit that were unsuitable for consumption.

A single small-scale trial of a single packing line was investigated to determine the effects on postharvest rot development**.** Fruit were sampled at various stages along a commercial lychee packing line, stored at 5 °C for six weeks then assessed for rot coverage. The least infected fruit was sampled immediately prior to the packing line. The most infected fruit was that sampled at the end of the packing line, after the fruit had been hand-destalked, sorted and hydrocooled. This is the first assessment of commercial lychee packing. More studies are needed to work out ways in which handling practices might be improved to reduce the risk of contamination.

While the above combined investigations have shown improved means to storage and transporting of fruit they have not addressed the means to improve the shelf life of fruit in commercial outlets. Fruit in commercial outlets are currently left exposed on bench tops and loose their characteristic appearance in less than a day. The use of coatings to reduce water loss in trials subsequent to the current project and, or the incorporation of CSIRO packaging to maintain high humidity but minimise the risk of free water on the fruit surface hold promise. Development of any of these technologies needs to integrated with range of strategies to improve the postharvest handling of lychee presented here.

Adoption of the outcomes form this report will provide substantial improvements in the postharvest handling of lychee that will be further enhanced with the development of improved packaging.

1. Achievements and future directions

1.1 Achievements

The main achievement of the Postharvest Handling Project was to quantify the benefits of a range of postharvest handling procedures. A great number of techniques have been shown to increase the storage life or shelf life of lychee over the past 60 years but very little attention has been paid to the relative worth of these techniques. Without a measure of worth it is impossible to know which techniques should or should not be included in the postharvest handling line.

We have shown that refrigeration is the most effective means of slowing rot development followed, in order, by synthetic fungicides, hot water treatment and a range of soft anti-fungal options (Chapters 3,4,5, and 7).

We have also shown that refrigeration at 10 °C is little different from refrigeration at 5 °C in terms of pericarp colour retention and rot development (Chapters 3 and 4) unless long term storage is the goal, in which case the lower temperature is the preferred option Another way of stating this is to say that a range of temperatures suffices for the short term storage of lychee. It should be noted that long term storage of fruit at 2oC did cause the fruit to prematurely darken excessively.

A low sensitivity to variations in temperature during the immediate postharvest period might have been part of the reason for the poorer turnout of water-cooled fruit compared with air-cooled fruit (Chapter 3). This is to say that the disadvantages of immersion outweighed the limited advantages of the water-cooled fruit achieving a lower temperature sooner (Chapters 2 and 3).

There were a number of other achievements from the Project, including the following list of firsts:

- The first modelling of heat transfer processes in lychee. The models gave excellent descriptions of heat transfer for individual fruit in water and good descriptions of heat transfer in air (Chapter 2).

- The first measurements of the diurnal changes in fruit water potential (Chapter 6), from which it can be said that, in general, industry picks fruit too late into the morning and is oblivious to the potential of picking fruit late in the afternoon. More attention to the hydration state of fruit on trees might lead to less postharvest browning.

- The first demonstration that fruit can be rehydrated after harvest (Chapter 6). Rehydration may be another means of reducing postharvest browning.

- The first demonstration that a hot water spray is an effective means of delivering hot water treatments to lychee and that the preferred treatment temperatures and times derived from hot water dip experiments are probably transferable to the spray system (Chapter 7).

- The first demonstration that the density of lychee seeds varies with fruit maturity. The variation is probably related to the accumulation of seed oil, which might be of commercial interest.

As science and technology stands at the moment, the quality of retailed lychee could be vastly improved with a postharvest handling system that includes no more than sorting, a hot water spray, packing fruit into sealed punnets and storing fruit at 10 °C through to the point of sale. What is lacking at the moment is a commitment by all parties to the process to a high quality product.

1.2 Recommendations for future research

The postharvest handling of lychee would further benefit from research in the following areas:-

- An acceptable packaging for consumers and wholesalers of lychee needs to be determined. The current packaging of cardboard cartons with perforated bags is designed to allow excess water carried on fruit after hydrocooling to escape. It provides little benefit for the fruit once in shop where fruit are directly exposed to the air. An obvious candidate is the CSIRO packing developed for the export of cauliflower that maintains very high relative humidity in boxes while minimising the risk of free water on the contained produce. Early forms of this packaging were tested in previous lychee postharvest project by QDPI with RIRDC support and found to out perform the bags available at that time.

- The use of punnets needs to be investigated as they could provide a barrier to water loss under retail conditions and have the potential to improve shelf life for longer than the current 1 day. The use of modified atmosphere to further inhibit rot development has previously been demonstrated in lychee but needs to be confirmed

- The use of fruit coatings to reduce water loss and reduce rot development needs to be investigated. Since the completion of the current research program preliminary investigations have shown that simple oil and wax treatments can allow fruit to be directly exposed to ambient for up to three days with minimal colour change and reduced water loss. However, fruit tended to darken after a week at 5^{o}C. Coatings may allow customers to select fruit avoiding the potential inhibitions associated with pre-packaging. Formulation of these coatings still needs to be refined

- The potential for minimising rots by field application of new generations of fungicides needs to be considered to minimise the risk of postharvest rots. The candidate food additives and biological agents identified in the current project could also be further investigated to determine whether continuation of applications closer to harvest date than 2 weeks can provide any post harvest benefits for rot control.

- The engineering problems associated with the incorporation of hot water treatments into current packaging lines need to be evaluated and the pyramiding of the identified food additives and biological agents with the hot water treatment should be evaluated.

- It needs to be confirmed that the observed benefits of 5^{o}C storage of lychee fruit wrapped in vitafilm is not a reflection of the physical behaviour of the packaging material but associated with the physiological responses of the lychee fruit.

- The capacity of cheap temperature regulating blankets such as aluminium laminated polybubble wrap to moderate temperature fluctuations arising from mixed loads of produce including lychee during transport to market could be evaluated.

- The tissues receiving the moisture taken up postharvest by immersed fruit needs to be determined to assess the food safety risk associated with this phenomenon.

- While it has been established that hydrocooling increases the risk of rot development it has also been shown that fruit are initially more resilient to warmer temperatures than after several days storage. This could lead to the interpretation that fruit could be packed warm then chilled in transport. The risk of free water forming on fruit as a result of condensation forming needs to be assessed.

2. Temperature changes in lychee and the air inside lychee cartons

2.1 Overview

The iterative heat transfer model by Wang *et al*. (2001) was applied to lychee by assuming that lychee has the physical and thermal characteristics of cherry. Simulations from the model were compared measured changes in the core temperature of probed fruit undergoing water- or air-cooling. The correspondence between the simulated changes and measured changes were good, but better for the water-cooled than the air-cooled fruit.

The core temperature of the water-cooled fruit took 10 minutes to cool from 28 °C to 5 °C in 2 °C water when the fruit were uniformly 28 °C at the time of immersion. The core temperature of the air-cooled fruit took 3 hours to cool from 22 °C to 5 °C in 2 °C still air when the fruit were initially uniformly 22 °C.

In a simulation of the re-warming of fruit in 35 °C still air, a 30 mm diameter fruit with an initial temperature of 5 °C throughout, took 10, 19 and 31 minutes for the core temperature to rise by 5, 10 and 15 °C, respectively.

The air temperature monitored in cartons of fruit road freighted from Childers, Nambour or Brisbane to Sydney fluctuated about the general trend lines by only a few degrees. The cartons were loaded warm but had air temperatures of 10 °C or less by the time of arrival.

The air temperature in cartons of chilled fruit air freighted from Brisbane to Sydney fluctuated little during flight. However, large increases in carton air temperature occurred during transport (by car) to the airport and during handling at the airports.

2.2 Introduction

Refrigeration is fundamental to the storage of lychee (Ray 1998, Johnson *et al*. 2002) but there is little information on the thermal properties of the fruit.

Fruit can be water-cooled rapidly. Ketsa and Leelawatana (1992) chilled "Hong Huay" (syn. "Tai So") from 26 °C to 5 °C in *ca* 18 minutes in 3-5 °C water; Bagshaw *et al*. (1994) chilled "Bengal" and "Kwai May Pink" from 25-27 °C to 6 °C in *ca* 13-15 minutes and from 18-21 °C to 6 °C in *ca* 11 minutes in 3 °C water; and Pornchaloempong *et al*. (1997) hydrocooled "Mauritius" (syn. "Tai So") from 25-27 °C to 3 °C in 12-15 minutes in 0-1 °C water.

Forced-air-cooling can also be quick. Ledger (1986) made a general claim (no data presented) that fruit packed loose in side-vented cartons could be forced-air-cooled in 3-4 hours. In terms of specific examples, "Hong Huay" (syn. "Tai So") packed loose in side-vented cartons were chilled from 26 °C to 6 °C in *ca* 70 minutes using 3-5 °C air moving at 2 m s^{-1} (Ketsa and Leelawatana 1992); and "Mauritius" (syn. "Tai So") packed in commercial shipping cartons were chilled from 25-27 °C to 3 °C in ca 1 hour using 3 °C air and a 2.5 cm static pressure difference. However, Bagshaw et al. (1994) stated (no data) that the forced-air-cooling of fruit packed into plastic bags (not loose as in the examples given above) takes at least 12 hours.

Room-cooling (still air) is the slowest means of chilling fruit. Pornchaloempong *et al*. (1997) found that fruit packed loose in commercial shipping cartons and placed in a cool room varying between 0-4 °C took *ca* 7 hours to reach 5 °C.

Less work has been done on the re-warming of fruit following refrigeration. Bagshaw *et al*. (1994) found that the pulp temperature of fruit chilled to *ca* 5 °C increased by 12 °C in 10 minutes when placed in a single layer at 28 °C, or by 1-2 °C in 10 minutes if the chilled fruit remained packed in a plastic bag inside a carton.

The heating and cooling of fruit clearly depends on the way in which fruit is handled. For this reason, and also the high cost of research, there is a need to develop a model of heat transfer processes for lychee. Here we make a start with respect to the processes relating to individual fruit. We compare some of the outputs from the model with the temperature changes in probed fruit.

Practical modelling also requires knowledge of the temperature environment fruit are likely to experience. We provide carton air temperature profiles for fruit air and road freighted within Australia.

2.3 Materials and methods

Heat transfer simulations

Approximate heat transfer to or from spherical fruit was simulated using iterations of finite difference equations, after Wang *et al*. (2001), using additional information from Churchill (1983), Dincer (1997) and Holdsworth (1997).

Surface temperature (T_1):

$$T_{1\,j+1} = [zhT_m + k_f T_{2\,j}] / [zh + k_f] \quad \text{Eq. 1}$$

where, $h = h_f$ for forced convection

$h = h_n$ for natural convection

Intermediate temperatures (T_2 to T_{n-1}):

$$T_{i+1\,j+1} = T_{i+1\,j} + a_f t[\{(T_{i\,j} - 2T_{i+1\,j} + T_{i+2\,j}) / z^2\} + \{(T_{i\,j} - T_{i+2\,j}) / (z(r - iz))\}] \quad \text{Eq. 2}$$

Centre temperature (T_n):

$$T_{n\,j+1} = T_{n\,j} + 6a_f t[(T_{n-1\,j} - T_{n\,j}) / z^2] \quad \text{Eq. 3}$$

Supplementary equations:

$h_f = 0.37k[2ur/v]^{0.6} / (2r)$

$h_n = Nk / (2r)$

$N = 2 + [0.589R^{0.25} / \{1 + (0.469 / P)^{(9/16)}\}^{(4/9)}]$

$R = \text{modulus}\ [g\beta(2r)^3(T_m - T_{1\,j}) / (va)]$

$\beta = 1 / [T_m + 273.15]$ for air; tabulated values for water

$P = v / a$

Symbols:

a	thermal diffusivity of air or water ($m^2\ s^{-1}$)
a_f	thermal diffusivity of fruit ($m^2\ s^{-1}$)
β	volumetric thermal expansion coefficient for gas ($°K^{-1}$)
g	acceleration due to gravity ($m\ s^{-2}$)
h_f	forced convection heat transfer coefficient ($W\ m^{-2}\ °C^{-1}$)
h_n	natural convection heat transfer coefficient ($W\ m^{-2}\ °C^{-1}$)
i	sphere number with sphere 1 at the surface of the fruit and 'sphere' n at the centre
j	time step from commencement of treatment
k_f	thermal conductivity of fruit ($W\ m^{-1}\ °C^{-1}$)
k	thermal conductivity of air or water ($W\ m^{-1}\ °C^{-1}$)
n	number of equally spaced concentric spheres from surface to centre of fruit
N	Nusselt number

P Prandtl number
r radius of fruit (m)
R Rayleigh number
t time between each step (s)
$T_{i\,j}$ temperature on sphere i^{th} at the j^{th} time step
T_m medium (air or water) temperature (°C)
u medium speed (m s^{-1})
v kinematic viscosity of air or water (m^2 s^{-1})
z radial distance between each sphere

Thermal measurements of fruit

Changes in fruit temperature of "Kwai May Pink" were measured as follows. A hole was drilled through the pedicel and seed to the centre of the fruit. A thermocouple was inserted such that the junction of the two metals was at the centre of the fruit. The opening of the hole was then covered with Vaseline to prevent the movement of air or water from the surrounding medium into the hole. Temperature was electronically recorded using a DT500 Datataker (Data Electronics (Aust) Pty. Ltd, Brisbane).

Fruit were air-cooled by placement on a plastic coated grill in an incubator. The incubator had a drawing fan but the air currents were slight. Fruit were water-cooled in a water bath with a circulating water pump.

Carton air temperatures

Changes in consignment temperatures were measured by placing a temperature logger (Gemini Data Loggers, TinyTag Plus IP68-TGP-0017) temperature loggers inside 5 L commercial cartons (no vents) packed with a single layer of 250 g punnets of fruit. Temperatures were recorded every 5 minutes.

2.4 Results

Cooling lychee

The closest validation of the model possible was to compare the temperature changes in the water-cooled fruit with a simulation that assumed a moderate water speed. The reason for this is that in moderately circulating water the internal thermal resistance of the fruit is much greater than the surface thermal resistance and dominates the heat transfer process (Wang *et al*. 2001). For example, for a 30 mm diameter fruit with a thermal conductivity of 0.511 W m^{-1} $°C^{-1}$, equivalent to that of cherry (Wang *et al*. 2001), in a 2 °C water bath moving at 0.2 m s^{-1}, the ratio of internal to external thermal resistance (the Biot number) is 28. In a practical sense this means that the rate of change in the core temperature of water-cooling fruit varies little across a range of moderate water speeds.

There was good correspondence between the model of 0.2 m s^{-1} forced-water convection and the measured changes in the core temperature of the fruit cooling from 28 to 2 °C in 2 °C water (Fig. 1*a*). The largest discrepancies were at the earliest and latest stages of cooling, but these were relatively small. In line with the above arguments with respect to the Biot number, increasing the water speed from 0.2 to 0.5 m s^{-1} had little effect on the output, with the simulated core temperatures after five and ten minutes only 0.4 and 0.2 °C lower, respectively, at the higher water speed. The core temperature of the probed fruit reached 10 °C 6 minutes after immersion in 2 °C water and 5 °C after 10 minutes.

An estimate of the slowest water-cooling from 28 to 2 °C in 2 °C water was made using the model of natural convection (Fig. 2.1*a*). The simulated core temperatures were only slightly higher than the measured temperatures.

Fruit were air-cooled from 22 to 2 °C in 2 °C air (Fig. 2.1*b*). It took approximately 90 minutes to draw the core temperature of the fruit down to 10 °C and 180 minutes to 5 °C. This compared with 6 and 10 minutes, respectively, for the water-cooled fruit that had a 6 °C higher initial temperature (Fig. 2.1a).

A simulation of 22 to 2 °C air-cooling was run assuming natural convection, because the air currents within the incubator were slight. After the fruit were placed in the incubator there was a decline in the air temperature of the incubator over many hours, so the simulation was based on the median air temperature during half hour intervals. The median temperatures during the first and tenth half hour intervals were 3.7 and 2.1 °C, respectively. There were also spatial temperature variations within the incubator, with one fruit equilibrating to 2.4 °C and the other to 1.7 °C, but these were not factored into the simulation. The simulation overestimated the rate of cooling (Fig. 2.1*b*) with the simulated fruit reaching a core temperature of 10 °C approximately 40% sooner than the probed fruit, and 5 °C approximately 30% sooner.

Re-warming

The model of heat transfer under natural convection in air was also used to estimate the maximum time required for the return of chilled fruit to ambient temperature. The current storage temperature recommendation in Australia is 5 °C (Menzel *et al*. 2002) and severe weather conditions at the time of harvest would include ambient temperatures around 35 °C. These two temperatures were used in the model. It took 10 minutes for the core temperature of 30 mm diameter fruit to rise from 5 to 10 °C; 19 minutes to 15 °C; 31 minutes to 20 °C; 50 minutes to 25 °C; and 85 minutes to 30 °C.

Carton air temperatures

The fruit to be road freighted to Sydney were packed and then stored between 10 and 20 °C until the pulp temperature of the fruit was less than 20 °C. The fruit was then taken by car to the road freighting terminals. The loggers all recorded temperatures greater than 20 °C at the time of loading into the refrigerated trucks, indicating some rewarming of the freight. Air temperatures within the cartons declined overall during transit, and were 10 °C or less by the time the trucks reached Sydney (Fig. 2.3*a*). The reasons for the fluctuations during transit are not entirely clear: the fruit from Nambour was transferred to another truck in Brisbane; the fruit from Childers might also have been transferred in Brisbane, and to a truck with a different thermostat setting; and other consignments of fruit might have been collected *en route*.

The fruit to be air freighted were chilled to various temperatures at the CSIRO Plant Industry laboratory at Indooroopilly before being taken to the Brisbane terminal by car. Considerable rewarming of the freight often occurred in transit to the terminal and during handling at both airports (Fig.2.3*b*). In contrast, during the flight the air temperatures inside the cartons varied little.

2.5 Discussion

There was good correspondence between the model simulations and the measured changes in fruit temperature. The correspondence was better for water-cooling than for air-cooling, but the extent to which this was a limitation of the model is unclear because the critical environmental parameters were less defined for the air-cooled treatments, and the thermal properties of lychee (thermal conductivity, thermal diffusivity) are unknown, but assumed to be similar to cherry for the purposes of the simulations. Wang *et al*. (2001) found that the model gave good predictions of temperature changes in apples during hot air or hot water treatments, and good predictions for cherries in hot water.

The model did not include a function for physiological heat generation, but the rates of respiration for ripe lychee fruit are low. The highest reported rate is 195 mg CO_2 kg^{-1} h^{-1} by Zhang and Quantick (2000) for “Huaizhi” (syn. “Wai Chee”) equivalent to the generation of approximately 2.1 kJ kg^{-1} h^{-1}

(Kader 2000). If all the energy were liberated as heat (in practice approximately 50 % is coupled to ATP production) and all the heat retained by the fruit, and if it is assumed that lychee has the specific heat of cherry (3.6 kJ kg^{-1} h^{-1}; Wang *et al*. 2000), then the fruit would rise in temperature by only 0.6 °C h^{-1}.

The measured rates of change in temperature, for example, 10 minutes to chill the core temperature of lychee to 5 °C by 2 °C water-cooling or 3 hours by 2 °C air-cooling, were similar to those recorded by others (Ketsa and Leelawatana 1992; Bagshaw *et al*. 1994; Pornchaloempong *et al*. 1997).

A simulation of the re-warming of lychee in still air showed that individual fruit can take well over an hour to return to room temperature. Rates would be slower for bags of fruit (Bagshaw *et al*. 1994). The essential point is that consignments of fruit have considerable capacity to buffer external changes in temperature.

The measured changes in carton air temperatures during commercial transport would have reflected the combined influences of the heat transfer characteristics of the carton and carton contents where the temperature logger was housed, of the accompanying items of freight, and of the air within the freight container. The fluctuations in air temperature within our cartons would have been greater than within standard commercial cartons of lychee because our cartons contained a relatively low volume of fruit and high volume of air.

Our road consignments were packed warm and chilled during transit. Chilling was slow, but this was expected given that the fruit within the containers were packed in cartons and the cartons stacked on pallets (Bagshaw *et al*. 1994). Overall, the temperature fluctuations recorded by the temperature logger were relatively small and infrequent. On arrival in Sydney the carton air temperatures were approximately 10 °C or less.

With respect to the air freight, the fluctuations in carton air temperatures during flight were small. However, there were large increases in temperature both in transporting the cartons by car to the airport and during handling at the airports.

The fluctuations in temperature of the fruit within the cartons during transport were not measured but were presumably less than those of the air.

Fig. 2.1. Means (solid lines) ± standard errors (dotted lines) of core temperatures of fruit measured during (*a*) water-cooling (5 fruit) or (*b*) air-cooling (2 fruit). Also, simulations of the core temperatures during cooling assuming either (*a*) natural convection (i.e. the convection generated by the temperature difference between the fruit and the surrounding medium; dashed-dotted line) or (b) forced convection (dashed line). The simulations assume that lychee has the thermal properties of cherry as presented by Wang *et al*. (2001).

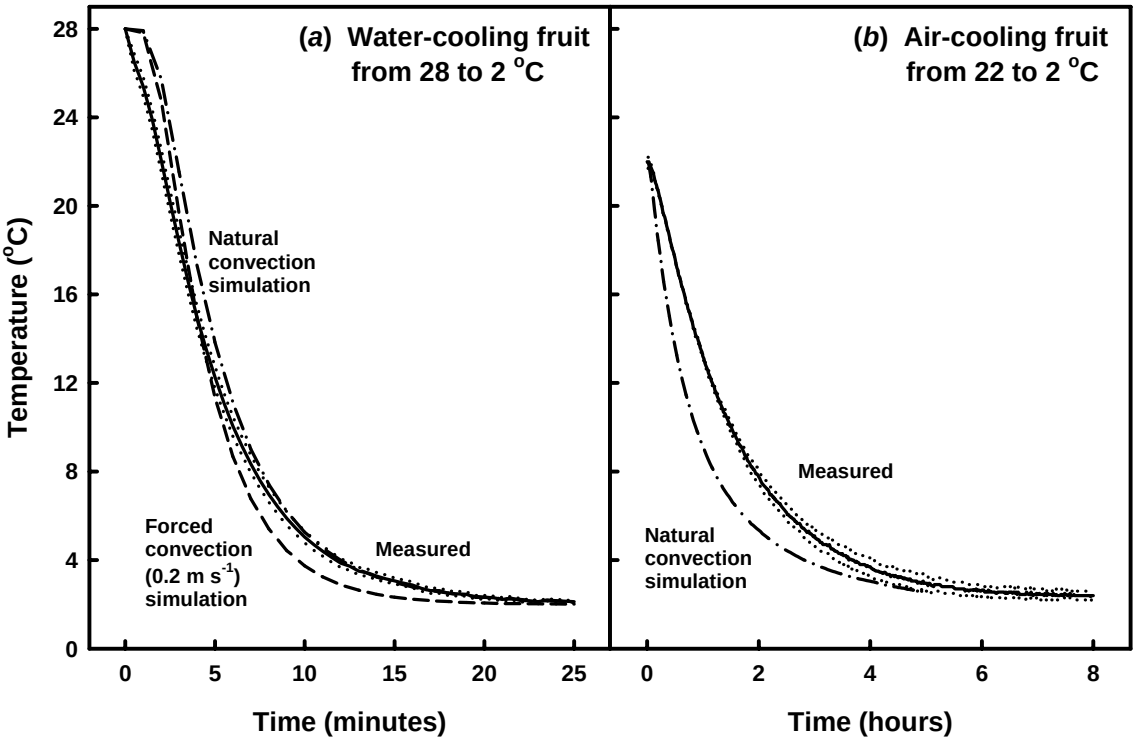


Fig. 2.2. Simulation of the change in core temperature of a 30 mm diameter lychee transferred from 5 to 35 °C under conditions of natural-air convection. The fruit is assumed to have the same thermal properties as cherry as presented by Wang *et al*. (2001).

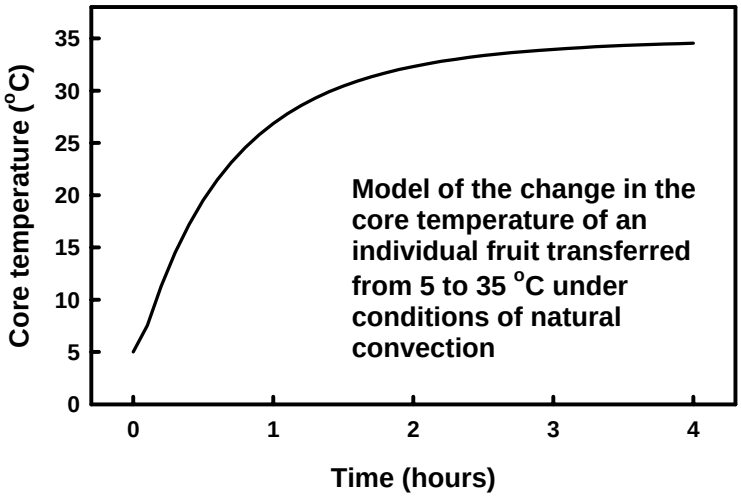
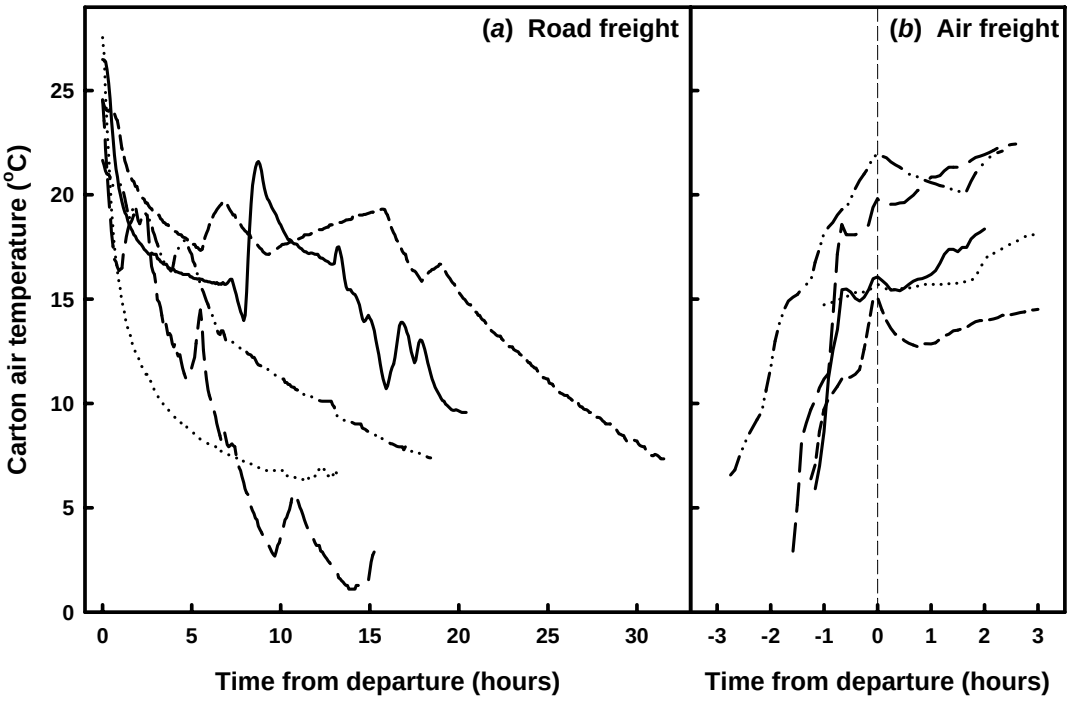


Fig. 2 3. (*a*) Carton air temperatures during road freight to Sydney. 0 hours represents the departure time from Childers (solid line, January 24, 1999), Nambour (short dashed line, February 13, 1999) or Brisbane (dotted line, January 30, 1999; dashed dotted dotted line, February 25, 1999; long dashed line, March 9, 1999). (*b*) Carton air temperature from the time of removal from the storage room in Indooroopilly, to delivery at the Brisbane airport (first shoulder of each curve), to flight departure (at 0 hours), to arrival and unloading at Sydney airport. Solid line, January 26, 1999; dotted line, February 1, 1999; short dashed line, February 16, 1999; dashed dotted dotted line, February 25, 1999; long dashed line, March 8, 1999. The maximum temperatures at the Brisbane and Sydney airports on the respective dates were: 28.4 and 27.2 °C; 26.6 and 22.8 °C; 31.2 and 28.4 °C; 27.5 and 23.3 °C; and 28.5 and 23.3 °C.



3. Effects of storage temperature and cooling methods on the storage life of lychee (*Litchi chinensis* Sonn.) fruit

3.1 Overview

Postharvest changes in the fruit of the lychee cultivars "Kwai May Pink" and "Wai Chee" were affected by the storage temperature and the method of cooling (air-cooling or water-cooling). There was evidence of chilling injury at 2 °C, with the fruit stored at 2 °C having poorer colour characteristics (lower *L*, lower *chroma* and higher *hue angle*) and greater water loss than the fruit held at 5 °C. The fruit held at 5 °C tended to have better colour retention, lower water loss and less rot development than fruit held at 10 or 15 °C, but temperatures of 5 or 10 °C were satisfactory for the storage of fruit for approximately two weeks. Air-cooled fruit had better colour retention and less rot development than water-cooled fruit, but lost more water.

3.2 Introduction

Lychee fruit are best stored refrigerated (Mukerjee 1956; Campbell 1959; Choudhury and Banerjee 1959; Akamine 1960; Datta *et al*. 1963; Akamine and Goo 1977; Tongdee *et al*. 1982; Paull and Chen 1987; Huang and Wang 1990; Schutte *et al*. 1990; Fontes *et al*. 1999; Johnson *et al*. 2002).

The optimum temperature for the storage is unclear and depends on the criteria used to define fruit quality. Campbell (1959) found that fruit of "Bengal" and "Brewster" stored at 1.5 °C maintained flavour and had less decay than fruit stored at 7 °C or higher temperatures. However, after 17 days of storage, the fruit at 7 °C had superior pericarp (skin) colour than fruit at 1.5 °C, which was perhaps an indication of chilling injury at the lower temperature.

Tongdee *et al.* (1982), Huang and Wang (1990 abstract alone) and Mitra *et al*. (1996) have also reported possible chilling injury to refrigerated lychee. "Haak Yip" (syn. "Fay Zee Sui") stored for 40 days at 7 °C had superior pericarp colour to fruit stored at 10, 5 or 0 °C (Tongdee *et al.* 1982). The colour ranking was 7 > 5 > 10 > 0 °C. The ranking for the prevalence of rots was 10 > 7 > 0 > 5 °C. "Hei Ye" (syn. "Fay Zee Sui") stored at 5 °C had superior colour to fruit stored at 2 or 0 °C and superior rot control at 2 °C than at the other temperatures (Huang and Wang 1990); and "Bombai" kept better at 4 °C than 0 °C (Mitra *et al*. 1996) .

Loosely synthesising these results, the optimum storage temperature for the retention of pericarp colour appears to be between 5 and 10 °C, while that for the control of rot development is between 2 and 5 °C. This said, however, Kremer-Kohne and Lonsdale (1991) found that "Mauritius" (syn. "Tai So") browned more slowly after storage at 2 °C than at 6 °C; and Zhang and Quantick (2000) that "Huaizhi" (syn. "Wai Chee") browned more slowly at 1 °C than at 5 °C.

Given the limited and inconsistent information available, and that little of it relates to Australia's mayor current commercial cultivars, we chose to re-examine the question of the optimum storage temperature of lychee with respect to "Kwai May Pink" and "Wai Chee".

The way in which fruit are cooled is also an issue in Australia at present. Fruit can be cooled more quickly by water cooling than by air cooling (see Chapter 2) but the benefits are ambiguous. Ketsa and Leelawatana (1992) found that hydrocooled "Hong Huay" (syn. "Tai So") fruit were less susceptible to browning than control fruit or forced air cooled fruit; Pornchaloempong *et al*. (1997) found a similar effect with "Mauritius" (syn. "Tai So") as well as no significant difference in the prevalence of decay amongst the different treatments; but Coates (1994) reported significantly higher

decay in hydrocooled than control fruit for "Kwai May Pink". Given this ambiguity, we combined an air versus water-cooled comparison with our study of the effects of various temperatures on the storage of "Kwai May Pink" and "Wai Chee" fruit.

3.3 Materials and methods

Experiments were conducted on a commercial property at Whitebridge (25.2 °S 152.3 °E) near Childers in southern Queensland. On January 28, 2000, fruit were picked from seven trees of the lychee cv. Kwai May Pink. The fruit from each tree were sorted into eight groups of ten and one group of eight. All groups were weighed. Four of the groups were weighed, placed into four punnets, one group per punnet, and double-wrapped in vitafilm. One punnet was then placed into each of four incubators running at 2, 5, 10 and 15 °C. The fruit in these punnets represented the air-cooled fruit, with seven replicates (i.e. one punnet of fruit from each of seven trees) per treatment.

The remaining four groups of ten fruit were immersed in 2, 5, 10 or 15 °C water for 70 minutes. After immersion, the groups were blotted dry, packed into punnets and double-wrapped in vitafilm. Fruit immersed in 2, 5, 10 and 15 °C water were placed in 2, 5, 10 and 15 °C incubators, respectively. These fruit represented the water-cooled fruit, again with seven replicates per treatment.

The group of eight was used to assess the initial colour and turgor of the fruit. Measurements of *L*, *chroma* and *hue angle* were made with a Minolta Chroma Meter (CR-200). Two measurements were made per fruit, from opposite sides of the fruit, perpendicular to both the suture line and the pedicel. Turgor was measured in terms of the change in displacement of a Mitutoyo (ID-C1012MB) penetrometer probe between 10 and 30 seconds after the placement of the probe on the fruit at the same location as for the colour measurements.

The fruit placed in the incubators were rated over three days, from February 15-17, 2000, 18-20 days after the commencement of the experiment. The colour and turgor of the fruit were measured as above; the groups were weighed; and every fruit was assessed for the number and area of visible rots. Rot area was calculated by assuming that the length and breadth of each rot represented the major and minor axes of an ellipse. The total rot area per fruit was the sum of the areas of the individual rots. Relative rot coverage was calculated as the ratio of total rot area to the total surface area of the fruit. The latter was calculated by measuring the length, breadth and width of the fruit, and by assuming that the fruit were shaped like irregular ellipsoids (Lang 1991).

The experiment was repeated on February 4, 2000, with cv. Wai Chee. The fruit were rated from February 25-27, 2000, 21-23 days after the commencement of the experiment.

Variation in the number of rots per fruit was analyzed using a generalized linear model fitted to the data by assuming a Poisson distribution and a log link function (McCullagh and Nelder 1989). Analysis of variance (ANOVA) was used for all other variables. All the analyses were made in Genstat (Payne 1993) with a 0.01 significance threshold.

3.4 Results

Kwai May Pink

Fruit stored at lower temperatures tended have fewer rots at the time of assessment (Fig 3.1*a*). At temperatures less than 15 °C air-cooled fruit had fewer rots than water-cooled fruit (Fig. 3.1*a*). These results were manifested in the analysis of deviance as a significant temperature effect and a significant temperature x cooling method (air versus water) interaction.

In the ANOVA of relative rot coverage there was a significant temperature x cooling method interaction. This essentially meant there was more rot coverage on fruit stored at 15 °C than at other

temperatures, and that the air-cooled fruit at 15 °C were more severely affected than the water-cooled fruit at 15 °C (Fig. 3.1*b*).

Rates of water loss were significantly lower at 5 °C than at other temperatures, and significantly lower for water-cooled fruit than for air-cooled fruit (ANOVA; Fig. 3.1*c*). However, the difference between cooling methods might not have been real in that the water-cooled fruit were weighed prior to immersion and water uptake during immersion might have occurred. Also, although blotted prior to packing, the water-cooled fruit were still packed slightly wet.

The differences in the rates of water loss were reflected in the fruit turgor measurements, with the fruit at 5 °C being more turgid than fruit at other temperatures, and the water-cooled fruit being more turgid than the air-cooled fruit (ANOVA; Fig. 3.1*d*). There was evidence of fruit rehydration of the water-cooled fruit in the penetrometer readings in that the turgor of the 5 °C water-cooled fruit at assessment was significantly greater (i.e. had a lower value) than that of (non-immersed) fruit at harvest (0.030 ± 0.002 versus 0.044 ± 0.003 mm displacement, respectively; ANOVA).

The colour characteristics of the fruit on the day of harvest were: L = 44.1 ± 0.5, *chroma* = 36.9 ± 0.2 and *hue angle* = 38.4 ± 0.9. From harvest to assessment, the values of L and *chroma* either declined or remained the same, while the *hue angle* either increased or remained the same (ANOVA; Figs 1*e*-*g*). At assessment, there were significant temperature effects with respect to L, *chroma* and *hue angle*; significant cooling method effects with respect to L and *hue angle*; and a significant temperature x cooling method interaction with respect to *hue angle*. The value of L for fruit stored at 2 °C was significantly lower than the value of L for fruit stored at 5 or 10 °C, but not significantly different from the value at 15 °C (Fig. 3.1*e*). L was significantly higher for air-cooled than water-cooled fruit (Fig. 3.1*e*). The value of *chroma* at 5 °C was significantly higher than for the other temperatures (Fig. 3.1*f*). For the air-cooled fruit the *hue angle* was significantly lower at 5 and 10 °C than at the other two temperatures, while for the water-cooled fruit *hue angle* at 2 °C was significantly higher than at the other three temperatures (Fig. 3.1*g*).

The reported colour quality at the time of assessment is somewhat exaggerated because of the deliberate avoidance of rots.

Wai Chee

The total number of rots per fruit decreased with temperature (Fig. 3.1*h*). All the differences were significant except between 2 and 5 °C (analysis of deviance). The relative rot coverage at 15 °C was significantly higher than at lower temperatures (ANOVA; Fig. 3.1*i*). In contrast to Kwai May Pink, there was no significant temperature x cooling method interaction for either rot number or relative rots.

With respect to rates of water loss, there were significant temperature, cooling method and interaction effects (ANOVA). In short, fruit stored at 5 °C lost water more slowly than fruit at other temperatures, and the water-cooled fruit tended to lose water more slowly than the air-cooled fruit (Fig. 3.1*j*). This was reflected to some extent in the turgor measurements, with the fruit at 5 °C being more turgid than the fruit at other temperatures, but there was no significant difference between cooling methods (ANOVA; Fig. 3.1*k*). The turgor at harvest (0.041 ± 0.003 mm displacement) was greater than or equal to that of all the treatments at assessment.

The colour characteristics of the fruit on the day of harvest were: L = 35.6 ± 0.3, *chroma* = 32.1 ± 0.6 and *hue angle* = 26.3 ± 0.6. From harvest to assessment, the values of L and *chroma* either declined or remained the same, while the *hue angle* either increased or remained the same (ANOVA; Figs 1*l*-*n*). At assessment there was only a significant storage temperature effect, with the values of L and *hue*

angle for the fruit stored at 2 °C significantly poorer than those for the fruit at other temperatures, and the value of *chroma* significantly better at 5 °C than at either 2 or 15 °C.

Overall, the results for Wai Chee were very similar to those for Kwai May Pink.

3.5 Discussion

The subtle discolouration we observed in the pericarp of both "Kwai May Pink" and "Wai Chee" when stored at 2 °C (Figs 3.1*e*,*f*,*g*,*l*,*m*,*n*) was probably an indication of chilling injury. The way in which the low temperature affected the cells is unclear, but there might have been an increase in membrane permeability resulting in reduced colour expression of the anthocyanins and/or the generation of brown pigments (Holcroft and Mitcham 1996).

Both cultivars kept better at 5 °C than at the other three temperatures in terms of pericarp colour retention, though there was little difference between the fruit held at 5 or 10 °C (Figs 3.1*e*,*f*,*g*,*l*,*m*,*n*). This result and the observation that the *L*, *chroma* and *hue angle* values after storage at these two temperatures were similar to the values at harvest indicate that there may be a moderate range of acceptable commercial refrigeration temperatures.

Less water was lost at 5 °C than at the other temperatures (Figs 3.1*c*,*j*). That water loss was very similar at both 2 and 10 °C (Figs 3.1*c*,*j*), but the fruit at 2 °C had poorer colour characteristics (Figs 3.1*e*,*f*,*g*,*l*,*m*,*n*), indicates that the chilling effect speculated above was related to more than just membrane permeability to water.

As expected, the fruit that lost more water were less turgid (Figs 3.1*c*,*d*,*j*,*k*). Interestingly, the 5 °C water-cooled "Kwai May Pink" were more turgid at assessment than at harvest. Pornchaloempong *et al*. (1997) speculated that hydrocooling might lead to rehydration of the fruit, but our results are the first supporting evidence.

Chilling injury can lead to advanced rates of rot development when the chilled fruit are returned to room temperature (Tongdee *et al*. 1982; Huang and Wang 1990). Severe chilling can also result in advanced rates of rot development during storage (Campbell 1959; Huang and Wang 1990). The fruit we stored at 2 and 5 °C had little rot development at the time of assessment (means and standard errors of percent rot coverage: "Kwai May Pink" in air, 0.04 ± 0.03 at 2 °C and 0.002 ± 0.002 at 5 °C; and in water, 0.4 ± 0.2 at both 2 and 5 °C; "Wai Chee" in air, 0.003 ± 0.002 at 2 °C and 0.08 ± 0.06 at 5 °C; and in water, 0 at 2 °C and 0.16 ± 0.07 at 5 °C) and difference between treatments are hard to resolve.

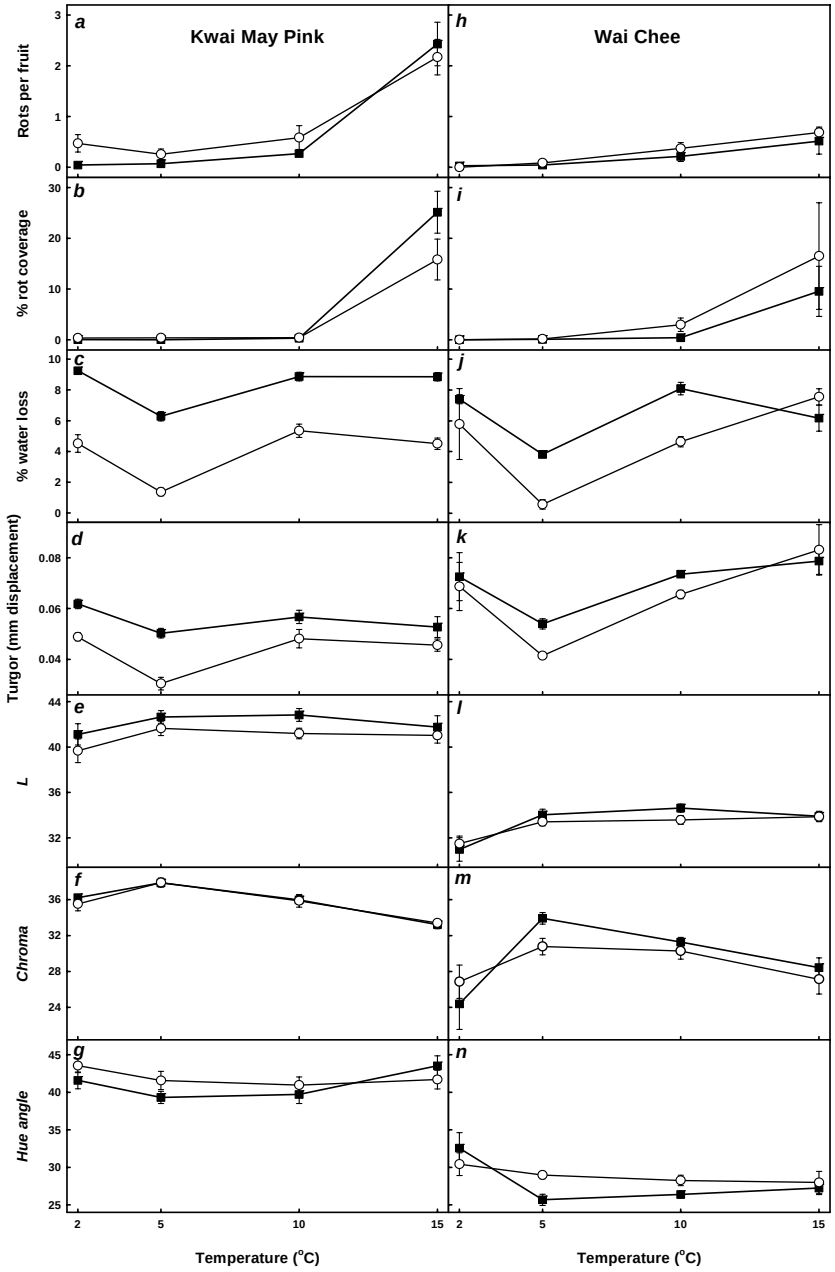
For both cultivars and both cooling methods rot coverage at the time of assessment was greater at 15 than at 10 than at 5 °C (Figs 3.1*b*,*i*). This is entirely consistent with the temperature dependence of rot development (Johnson *et al*. 2002).

The fruit stored at 5 °C tended to retain colour better than fruit stored10 °C and have a lower incidence of rots, but the differences were small, and both temperatures were satisfactory for the storage of fruit for approximately two weeks.

Overall the air-cooled fruit had superior colour (Figs 3.1*e*,*f*,*g*,*l*,*m*,*n*), fewer rots (Figs 3.1*a*,*h*) and less rot coverage (Figs 3.1*b*,*i*) than the water-cooled fruit at the time of assessment, but a poorer hydration state (Figs 3.1*c*,*d*,*j*,*k*). Why the water-cooled fruit were generally of inferior quality is not clear. Possible reasons include the packing of the water-cooled fruit with free water which might have facilitated the growth of pathogens; inoculation of the water-cooled fruit by dipping the fruit in contaminated water baths; or biophysical effects relating to the higher water potential of the fruit. Coates (1995) also found some evidence that water-cooled fruit were of poorer quality than air-cooled fruit: water-cooled fruit had a higher incidence of rots in one experiment and poorer pericarp colour in

another. In the latter experiment, the detrimental effects of water-cooling were mitigated to some extent by the addition of sodium hypochlorite (a disinfectant) to the water bath.

Fig. 3.1. Postharvest fruit characteristics of "Kwai May Pink", left column, and "Wai Chee", right column, after storage at 2, 5, 10 or 15 °C for 18-20 and 21-23 days, respectively. The results are given as means and standard errors of seven replicates, each replicate being the average value of ten fruit in a punnet. Open circles represent the water-cooled fruit, closed squares the air cooled fruit. (*a*) and (*h*) are the number of visible rot colonies per fruit. (*b*) and (*i*) are the percentages of the surfaces of the fruit covered by visible rots. (*c*) and (*j*) are the percentages of water loss with respect to the fresh weight of the fruit at harvest. (d) and (k) are distance measures of fruit compression under a weighted probe. The remaining graphs represent pericarp colour characteristics as measured by a chromameter



4. Effects of variations in storage temperature on the shelf-life of lychee (*Litchi chinensis* Sonn.) fruit

4.1 Overview

A full factorial experiment of three storage temperatures (5, 10 and 15 °C) against three successive intervals was designed to determine the effects of variations in storage temperature on the subsequent shelf life of "Kwai May Pink" fruit at 22 °C. The experiment was compromised somewhat by a failure of the 5 °C incubator during the second interval.

Fruit stored at 5 °C had slower rot development and colour decline than fruit stored at 10 or 15 °C. Differences in temperature during the first interval had less effect on shelf life than differences during the third interval, and a first interval by third interval interaction was also observed. The results are consistent with a decline in cell integrity with storage time leading to a greater susceptibility to temperature dependent spoilage, but more work is needed to resolve the matter.

4.2 Introduction

Previous work on lychee has looked at the effects of constant storage temperatures on storage life (Mukerjee 1956; Choudhury and Banerjee 1959; Akamine 1960; Datta *et al*. 1963; Akamine and Goo 1977; Tongdee *et al*. 1982; Paull and Chen 1987; Schutte *et al*. 1990; Fontes *et al*. 1999; Johnson *et al*. 2002) and shelf life (Huang and Wang 1990). Here we examined at the effects of variations in temperature during storage on the subsequent shelf life at 22 ºC of "Kwai May Pink".

4.3 Materials and methods

On March 6, 2001 55 kg of commercially harvested and packed fruit of "Kwai May Pink" were collected from Brooklet (28.7 °S 153.5 °E) and taken by car to the CSIRO Long Pocket Laboratories in Brisbane. The best fruit from the consignment were separated out and individually placed in MEA chippettes (cylindrical polypropylene containers 45 mm diameter x 24 mm deep). Each chippette with its single fruit was then double-wrapped in 14 μm Bunzl vitafilm (PVC). Fourteen of the wrapped chippettes were then placed on each of 81 trays. The trays were equally divided between three incubators operating at 5, 10 and 15 °C. Within each incubator nine trays were placed on each of three shelves. One assessor was assigned responsibility for the top shelves of the cabinets, another to the middle shelves and a third to the bottom shelves.

The experiment involved the refrigerated storage of fruit for ten days followed by the shelving of fruit at 22 °C. The storage period was divided into three successive intervals of 80 hours. At each shelf height one tray of fruit was subjected to each of the 27 interval by temperature combinations by transferring trays of fruit between incubators at the end of the first and second 80 hour intervals.

After the storage period all the incubators were reset to 22 °C. Two fruit from each tray were assessed at days 10, 12, 14, 16, 19, 21 and 23 for both rot coverage and colour. Rot coverage was estimated by measuring the length and breadth of each rot and by assuming that these measurements represented the lengths of the major and minor axes of an ellipse. The total rot area for a given fruit was the sum of all the individual rot areas. Rot coverage was then the ratio of the total rot area divided by the total surface area of the fruit. The latter was estimated by measuring the length, breadth and width of the fruit and by assuming that these measurements represented the lengths of the principal axes of an irregular ellipsoid (Lang 1991). Colour was measured in terms of *L*, *chroma* and *hue angle* using a

Minolta chroma meter (CR 200) with two colour measurement taken per fruit, from opposite sides of the fruit approximately perpendicular to both the suture line and the longitudinal axis.

The experiment was compromised to some extent by a failure of the 5 °C incubator some time during the second 80 hours. The temperature in the incubator drifted upwards to at least 28 °C, but the duration of the failure was not known. The failure did not affect the balance of the experiment, so the analyses of variance planned in the original design of the experiment still could be undertaken. All analyses were carried out in Genstat (Payne 1993).

4.4 Results

Lychee is a perishable fruit. Overall in our experiment the fruit reached 50 % rot coverage at approximately 15.6 days postharvest, equivalent to 5.6 days of shelving at 22 °C. From day 10 to day 16 the value of *L* had decreased by 6 %, *chroma* had decreased by 26 % and the *hue angle* had increased by 14 %, all indicators of pericarp colour decline.

In Chapter 3 rot development and colour decline increased with increasing storage temperature from 5 to 15 °C. This result was mirrored here in the shelf life following storage (Fig. 4. 1). In addition, there was a greater separation of storage temperature effects during the third interval than during the first interval. This was manifested in the analysis of variance as a 2.1 fold higher temperature effect mean square for the third interval relative to the first. And further evidence of unequal influences of temperature across the different intervals in a first interval by third interval temperature interaction ($P = 0.04$).

4.5 Discussion

Storage of "Kwai May Pink" fruit at 5 °C was more effective at slowing rot development and colour decline during subsequent shelving at 22 °C than storage at 10 or 15 °C (Fig.4.1). The result is consistent with the work of Huang and Wang (1990; abstract alone; no statistics presented) who found that fruit of "Hei Ye" (syn. "Fay Zee Sui") could be stored longer at 5 °C than at 0, 2 or 20 °C when assessed against a one day shelf life at 20 °C minimum.

The work presented here generally parallels that reported in Chapter 3 where storage at 5 °C was more effective at slowing rot development and colour decline *during storage* than storage at 10 or 15 °C.

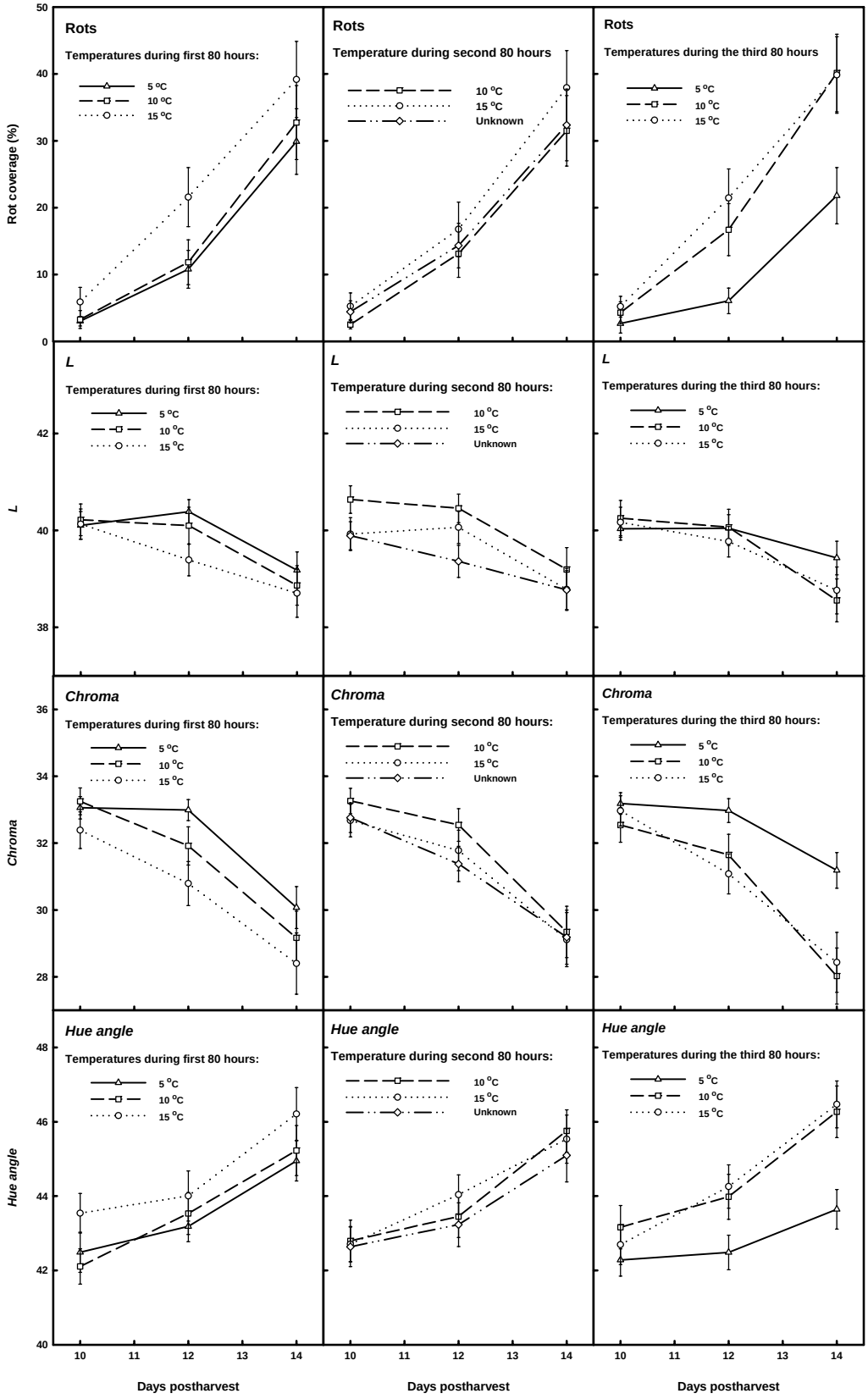
The importance of storage temperature on subsequent shelf life seemed to increase with increasing time postharvest. For example, it made little difference whether the fruit were stored at 5 or 10 °C during the first 80 hours postharvest, but considerable difference during the third 80 hours postharvest (Fig. 4.1). This is consistent with a loss of cell integrity over time (Jiang and Fu 1999) resulting in an increased susceptibility to spoilage. Other interpretations are possible, however. For example, the fruit at 5 °C during the third interval presumably took longer to warm to the shelving temperature of 22 °C than the fruit at 10 or 15 °C, although the difference would have been relatively short compared with the overall length of the third interval (see Chapter 2).

If the cell integrity interpretation is correct then the current cool chain handling of lychee is perverse, with considerable effort expended in cooling fruit immediately postharvest when the fruit are most resilient to temperature variation, and the retailing of fruit at room temperature when refrigeration is most needed. If fruit are losing cell integrity quickly then there may be an advantage in getting fruit off farm on the day of harvest, although this would need to be weighed against potential disadvantage (e.g. overnight storage in a cold room may make 'stung' fruit easier to detect). Chilling fruit to 5 °C on farm may be an unnecessary expense unless large fluctuations in ambient temperatures are expected (as may be the case with air freight). In Chapter 2 it was shown that road freight from Brisbane to Sydney consistently arrived with carton air temperatures of 10 °C or less, and close to the low temperature asymptote. If these temperatures are representative of most of the freight time then

current road freight conditions are probably generally acceptable. The major challenge is to extend the cool chain to the wholesale and retail markets. From Chapter 3, 5 °C is close to the biological optimum temperature for holding fruit from harvest to the consumer, but 10 °C might be closer to the economic optimum once refrigeration costs are balanced against storage/shelf life gains, unless extended periods of storage are involved.

This is only the first attempt to evaluate the effects of temperature variations on shelf life, and more work is needed to resolve the issues raised here.

Fig. 4.1. Effects of various temperature regimes during 10 days of postharvest storage on the rot development and changes in the pericarp colour characteristics of "Kwai May Pink" during simulated shelving at 22 ºC. The data is presented as the means and standard errors of 54 fruit.



5. Postharvest dips and preharvest sprays for the control of rots

5.1 Overview

A range of postharvest dips was investigated for the control of rots on the lychee cultivars "Kwai May Pink" and "Wai Chee". After treatment the fruit were packed into polyethylene punnets then double wrapped in vitafilm. The synthetic fungicides benomyl (as Benlate 1 g L^{-1} at 52 °C for 2 minutes) and prochloraz (as Octave at 0.1 or 1 g L^{-1}) were the most effective treatments. A 2 minute dip in 52 °C water was also effective, but less so than the synthetic fungicides. Solutions of acetic (0.05, 0.5 or 5 mL L^{-1}), lactic (0.0568, 0.568 or 5.68 mL L^{-1}) and propionic (0.05, 0.5 or 5 mL L^{-1}) acids, potassium silicate (0.5, 5 or 50 mL L^{-1}) and *Trichoderma* (0.1, 1 or 10 g L^{-1}) were all less effective again, and showed only weak rot control.

In general, fruit with fewer rots had better pericarp colour, but the correlations were not strong. The packaged fruit lost, on average, about 0.1 % of fresh weight per day.

Three experiments into the use of acetic acid, potassium silicate and *Trichoderma* as preharvest sprays for the postharvest control of rots were also conducted, but none of the treatments had a significantly lower incidence of rots at the time of assessment than the controls. However, fewer microbes were recovered from treated fruit at harvest, and the *Trichoderma* treated fruit had superior pericarp colour at the time of assessment.

5.2 Introduction

A large number of micro-organisms is responsible for the postharvest rot of lychee (Sittigul *et al*. 1994; Coates 1995; Johnson *et al*. 2002) and a variety of postharvest dips have been investigated for their control. Summaries of many of the investigations can be found in recent postharvest reviews by Revathy and Narasimham (1997) and Ray (1998).

The synthetic fungicide benomyl is the best characterised of the dips (Swarts and Anderson 1980; Scott *et al*. 1982; Bhullar *et al*. 1983; Brown *et al*. 1984; Huang and Scott 1985; Lonsdale and Kremer-Köhne 1990; Schutte *et al*. 1990; Wong *et al*. 1990; Wong *et al*. 1991; Johnson *et al*. 2002) and generally one of the most effective. However, no synthetic fungicide is registered for postharvest use on lychee in Australia.

Our interest was to find an environmentally soft alternative to synthetic fungicides.

Benomyl is usually used as a 50-52 °C dip, and there is some evidence that temperature pasteurization of the pericarp is part of the reason for the treatment's effectiveness (Swarts and Anderson 1980; Scott *et al*. 1982; Huang and Scott 1985). Consequently, one of the alternatives we chose to investigate was a straight hot water dip.

Our second approach was to modify the surface environment of the pericarp to make it hostile for the growth of pathogens. We did this in a number of ways by dipping fruit in weak concentrations of food acids or potassium silicate (an alkali) or in a light suspension of the parasitic fungus *Trichoderma*.

As points of reference for the effectiveness of these treatments we ran parallel treatments with the synthetic fungicides 52 °C benomyl and ambient temperature prochloraz.

Possible alternatives or adjuncts to postharvest dips are preharvest sprays. McMillan (1994) and Crane *et al*. (1997) showed that preharvest sprays of benomyl, mancozeb and tebuconazole reduced

the incidence of anthracnose on lychee fruit in Florida orchards, but that preharvest sprays of copper hydroxide were largely ineffective. However, Crane *et al*. (1997) also showed that the preharvest spray program had little bearing on the postharvest development of anthracnose on fruit with no visible symptoms of anthracnose at harvest.

To examine the matter further we applied preharvest sprays of food acids or potassium silicate or *Trichoderma* and monitored the effects on microbial load and postharvest rot development.

5.3 Materials and methods

Postharvest dips

On February 2, 2000, 200 ripe fruit were collected from each of seven trees of the cultivar "Kwai May Pink" at Whitebridge (25.2 °S 152.3 °E). The 200 fruit were divided into 20 groups of 10, with one group allocated to each of 20 dip treatments (Table 5.1). There were thus seven replicate groups per treatment.

The dip solutions were prepared as 5 L lots in 10 L plastic buckets on the day of treatment. Water for the hot water and hot benomyl treatments was heated in stainless steel pots over gas burners. Each group of ten fruit was weighed and then placed in an open-weave plastic mesh bag for dipping. The seven replicates were immersed simultaneously and dipped for 2 minutes.

After dipping, the groups of 10 fruit were placed in separate polyethylene punnets. Each punnet was then double-wrapped in 14 μm Bunzl vitafilm (PVC). The punnets were stored in an incubator at 5 °C until March 2-6, 2000 when the fruit were assessed.

Assessment involved the measurement of group fresh weight and the surface area, colour, turgor and rot coverage of individual fruit. Surface area was estimated by measuring the length, breadth and width of each fruit, assuming that these measurements represented the axes of an irregular ellipsoid (Lang 1991). Measurements of colour (*L*, *chroma* and *hue angle*) were made with a Minolta Chroma Meter (CR 200). Two measurements were made per fruit, from opposite sides of the fruit, perpendicular to both the suture line and the pedicel. Turgor was measured in terms of the change in displacement of a weighted contact point placed on the surface of the fruit for between 10 and 30 seconds. Two 25mm long spindle extensions were screwed together with a 10g washer clamped between the spindles. A 2mm drill bit was inverted and glued into one end of the spindle extensions and was used as the contact point. The male end of the spindle extensions was screwed into a Mitutoyo (ID-C1012MB) Digital Electronic Indicator Gauge, which was used to measure displacement. The gauge was then clamped to a Chatillon evelvated stage. Fruit were placed onto the stage and the stage was raised until the fruit displaced the contact by 0.50mm. A 50g brass weight was then placed onto the washer on the spindle extension and the degree of displacement was recorded at 10 and 30 seconds. Displacement readings were taken on the fruit at the same location as for the colour measurements. Rots were measured in two ways: the number of rots per fruit and rot coverage. Rot coverage was calculated by summing the individual rot areas on the surface of the fruit and expressing the sum as a fraction of the total surface area. Each rot area was estimated by measuring the length and breadth of the rot, assuming that these measurements represented the major and minor axes of an ellipse.

The experiment was repeated with the cultivar "Wai Chee" on February 3, 2000. The fruit were assessed on March 15-24, 2000.

Preharvest sprays

Preharvest spray trials were undertaken at Kennedy (18.1 °S 145.6 °E), Mareeba (16.6°S 145.3 °E) and Tabacum (17.1 °S 145.2 °E) using either water, 5 mL L^{-1} acetic acid, 5 mL L^{-1} potassium silicate

and 1 g L^{-1} *Trichoderma* (TRI-D25, JH Biotech, *Trichoderma koningii* $3x10^7$ g^{-1}, *Trichoderma* harzianum $2x10^7$ g^{-1}) Seven replicates of 3-4 m high "Kwai May Pink" trees were sprayed at Kennedy, six replicates of 4-5 m "Kwai May Pink" at Mareeba, and seven replicates of 2-3 m "Fay Zee Sui" at Tabacum. The trees were sprayed on four occasions at approximately 10 day intervals leading up to harvest, with the last spray approximately 10 days prior to harvest. At harvest, nine fruit per tree were individually packaged by placing each fruit inside a cylindrical polypropylene cup then double-wrapping the cup and fruit in vitafilm. In addition, nine more fruit from each of the water sprayed (control) trees were dipped in 52 °C water for two minutes before being air dried and packaged as above. The fruit were stored between 5-25 °C for several weeks before being assessed.

The fruit from Kennedy were assessed in terms of colour (*L*, *chroma* and *hue angle*) and rot coverage. Rot coverage was estimated using a six point visual scale with 1 = no visible rot; 2 = >0 to 25 % surface coverage; 3 = >25 to 50 % surface coverage; 4 = >50 to 75 % surface coverage; 5 = >75 to <100 % surface coverage; and 6 = 100 % surface coverage. The fruit from Mareeba and Tabacum were only assessed in terms of rot coverage by ranking the fruit from least to most infected.

For the Kennedy trial alone an estimate was made of the microbial load at harvest.

Analyses

The designs of the postharvest dips experiments were unbalanced in that the number of concentrations for each active ingredient tested varied from one to three, so the results were analysed by analysis of deviance and Pearson correlation analysis. Analysis of variance or Spearman rank correlation analysis was used for the results of the preharvest spray trials. Analyses were undertaken in Genstat (Payne 1993).

5.4 Results

Postharvest dips

For "Kwai May Pink" there was clear separation of the treatments in terms of the control of rots. Benomyl at 52 °C was the most effective treatment. The synthetic fungicides (benomyl and 1 g L^{-1} Octave) were more effective than 52 °C water alone or the highest concentration of potassium silicate; the latter two treatments more effective than the highest concentrations of the food acids; and the food acids slightly more effective than the ambient water control ($P < 0.05$; Table 1, especially rot coverage).

For "Wai Chee" the results were similar with benomyl again the most effective treatment for the control of rots; the synthetic fungicides more effective than 52 °C water; and 52 °C water more effective than ambient water ($P < 0.05$; Table 5.2). There were some differences, however. For example, 52 °C water was more effective at rot control than all the potassium silicate treatments; there was less evidence of a general decrease in rot coverage with increasing food acid and potassium silicate concentrations; and there were some erratic patterns in the acetic acid and *Trichoderma* series.

With respect to colour characteristics (*L*, *chroma* and *hue angle*) trends were less clear (Tables 5.1, 5.2). The benomyl treatments are best not interpreted because of poor dissolution of the product and consequently conspicuous residues on the surfaces of the fruit. The fruit of both "Kwai May Pink" and "Wai Chee" treated with 1 g L^{-1} Octave had better colour characteristics (higher *L*, higher *chroma*, and lower *hue angle*) than the controls ($P < 0.05$) and most of the other treatments. The 52 °C water apparently affected the cultivars differently with the 52 °C water treated "Kwai May Pink" having better *chroma* but poorer *L* and *hue angle* than the control fruit, and the 52 °C water treated "Wai Chee" having generally better colour characteristic than the control fruit, but only substantially better with respect to chroma. Fruit treated with food acids and *Trichoderma* generally (but not exclusively)

had better colour than the controls, while the fruit treated with potassium silicate were much the same as the controls.

Across the 140 punnets used in the "Kwai May Pink" experiment (20 treatments by 7 replicates) there were significant correlations ($P < 0.05$) between rot coverage and *L* ($r = -0.29$) and rot coverage and *chroma* ($r = -0.33$). In the "Wai Chee" experiment rot coverage was significantly correlated ($P < 0.05$) with *L* ($r = -0.46$), *chroma* (r = -0.59) and *hue angle* ($r = 0.26$). In short, rot development was broadly related to colour decline.

With respect to weight loss and fruit turgor there were few compelling differences between treatments (Tables 5.1,5.2). The mean rate of weight loss for the "Kwai May Pink" experiment was 0.11 % of initial fresh weight per day. For "Wai Chee" it was 0.08 % of initial fresh weight per day.

Preharvest sprays

Preharvest sprays of acetic acid, potassium silicate or *Trichoderma* at Kennedy reduced the fruit load of microbes that would grow on malt extract agar plates, but the variance was high (Fig.5. 1; $P = 0.2$).

In terms of the postharvest development of rots only the heat treated control fruit had significantly less rot coverage at the time of assessment than the control fruit ($P < 0.05$ at Kennedy (Fig5.. 2) and Tabacum; $P = 0.06$ at Mareeba).

The fruit from Kennedy were also for colour at the time of assessment. The heat treated control fruit had better colour characteristics (*L*, *chroma* and *hue*) than the control fruit (Table5. 3; $P < 0.05$) in line with the slower development of rots, outlined above. Interestingly, the *Trichoderma* treated fruit also had a significantly better *L* than the control fruit (Table 5.3; $P < 0.05$) so at least one of the preharvest treatments might have had a positive effect on fruit quality.

5.5 Discussion

The 2 minute 52 °C water postharvest dip was a class above the food acid, potassium silicate and *Trichoderma* postharvest dips and preharvest sprays for the postharvest control of rots (Table 1; Fig. 2), but not as effective as the synthetic fungicides (benomyl and prochloraz). The gap between the hot water treatment and the fungicides might be bridged to some extent by further refinement of the hot water treatment and by the dissolution of "soft" chemicals (e.g. a food acid, as examined here, or bicarbonate (Smilanick *et al*. 1999) or some other alternative) in the water.

In general, fruit with fewer rots had better pericarp colour, but the correlations were not strong, especially for the "Kwai May Pink" experiment. One potential source of complication for the relationships might have been infiltration of the dips into the protoplasms of the pericarp cells. Colour expression in the pericarp is pH dependent, with low pH (< 3) promoting the coloured form of the anthocyanin pigment and higher pH (> 3) the colourless form (Holcroft and Mitcham 1996). Thus the food acids might have subtly enhanced pericarp colour while the potassium silicate (alkaline) might have drained it.

Our preharvest spray trials were essentially pilot studies and showed some promise in modifying the microflora of the fruit (Fig. 5.1) and perhaps improving fruit quality (Table 3). The reported effects are generally similar to, but less dramatic than, the effects of synthetic fungicides reported elsewhere (McMillan 1994; Crane *et al*. 1997). No study on lychee has yet shown preharvest sprays to improve the postharvest life of fruit unblemished at harvest, but studies on other crops (e.g. mango; Prusky *et al*. 2002) have shown that pathogen loads at harvest affect postharvest rates of infection. Further work is needed to resolve the usefulness of preharvest sprays alone and in conjunction with postharvest treatments for the control of pathogen loads and postharvest rot development on lychee.

Further work on *Trichoderma* in particular is probably warranted. As a preharvest spray it caused a (non-significant) reduction in microbial counts (Fig. 5.1) and a significant improvement in colour (Table 5.3); and as a postharvest dip it caused some slowing of rot development (Tables 5.1,5.2) even though not recommended for use under refrigerated conditions. In addition, work on rambutan (Sivakumar *et al*. 2001) , in the same family as lychee and producing a similar fruit, has shown that *Trichoderma* is a strong antagonist of *Botryodiplodia theobromae* (stem end rot), *Colletotrichum gloeosporioides* (anthracnose) and *Gliocephalotrichum microchlamydosporum* (brown spot).

In conclusion, hot water is the best non-synthetic fungicide treatment for the control of rots in lychee to date but might be best used in conjunction with other "soft" treatments.

Table 5.1. Effects of various post-harvest dips on the fruit quality of the lychee cultivar "Kwai May Pink" stored for 4-5 weeks at 5 °C. Fruit were dipped on the day of harvest.

	Number of rots per fruit		Percent coverage of surface area by rots		*L*		*Chroma*		*Hue angl*		Penetrometer (microns of deflection)		Weight loss (g m^{-2} (surface area) day^{-1})	
	Mean	Std err	Mean	Std err	Mean	Std err	Mean	Std err	Mean	Std err	Mean	Std err	Mean	Std err
Lactic acid														
0.0568 mL L^{-1}	1.2	0.3	4.9	2.2	41.2	0.7	34.73	0.3	43.24	0.8	99	4	6.5	1.0
0.568 mL L^{-}	1.1	0.4	1.5	0.9	42.7	0.4	6.036	0.3	1.441	0.5	79	4	8.0	1.4
5.68 mL L^{-}	0.7	0.2	2.1	1.2	42.1	0.4	.2	0.4	.7	0.8	72	5	6.5	0.4
Propionic acid														
0.05 mL L^{-1}	1.1	0.3	2.9	1.2	42.0	0.9	35.93	0.6	42.34	0.6	102	10	7.5	1.7
0.5 mL L^{-}	0.9	0.3	1.5	0.8	42.1	0.5	4.736	0.5	3.240	0.4	76	6	8.2	0.4
5 mL L^{-}	0.7	0.3	1.1	0.8	42.1	0.5	.4	0.5	.7	0.8	68	8	7.3	1.5
Acetic acid														
0.05 mL L^{-1}	1.1	0.3	4.8	3.0	40.8	0.5	34.73	0.5	42.04	0.8	85	9	7.6	1.0
0.5 mL L^{-1}	1.1	0.4	2.3	0.8	42.1	0.5	5.935	0.6	2.341	1.0	99	8	7.0	1.7
5 mL L^{-1}	0.6	0.2	2.0	1.1	41.6	0.7	.4	0.5	.2	0.9	90	12	5.5	0.2
Trichoderma														
0.1 g L^{-1}	1.0	0.2	2.6	1.0	41.8	0.5	36.13	0.5	42.94	1.3	105	9	4.5	0.3
1 g L^{-1}	0.9	0.3	3.6	1.4	41.8	0.4	4.335	0.6	3.041	1.3	82	11	9.5	0.8
10 g L^{-1}	0.7	0.2	2.9	1.4	41.4	0.4	.1	0.3	.6	0.7	79	10	8.1	1.1
Potassium silicate														
0.5 mL L^{-1}	1.1	0.2	4.2	2.3	42.2	0.5	35.03	0.6	43.54	1.0	85	8	5.9	0.4
5 mL L^{-1}	0.7	0.3	1.5	0.6	41.3	0.4	3.833	0.6	4.543	0.7	85	8	8.7	0.6
50 mL L^{-1}	0.4	0.1	0.7	0.2	41.4	0.4	.9	0.4	.8	0.7	76	5	6.7	0.4
Octave														
0.1 g L^{-1}	0.3	0.2	1.6	0.8	41.5	0.4	35.73	0.5	42.94	0.7	71	6	8.2	0.6
1 g L^{-1}	0.2	0.1	0.4	0.3	42.6	0.8	6.5	0.4	1.9	0.8	66	6	5.1	0.2
Benlate														
1 g L^{-1} (52 °C)	0.0	0.0	0.0	0.0	41.9	0.5	35.2	0.2	45.9	0.7	68	4	7.4	0.4
Water														
52 °C	0.3	0.1	0.8	0.4	39.9	0.4	35.73	0.5	46.54	0.6	86	6	6.5	0.4
Ambient (control)	1.1	0.3	3.0	1.4	41.2	0.6	4.2	0.2	3.8	0.9	90	7	6.5	0.3

Table 5.2. Effects of various post-harvest dips on the fruit quality of the lychee cultivar "Wai Chee" stored for 6-7 weeks at 5 °C. Fruit were dipped on the day of harvest.

	Number of rots per fruit		Per cent coverage of surface area by rots		*L*		*Chroma*		*Hue angl*		Penetrometer (microns of deflection)		Weight loss (g m^{-2} (surface area) day^{-1})	
	Mean	Std err	Mean	Std err	Mean	Std err	Mean	Std err	Mean	Std err	Mean	Std err	Mean	Std err
Lactic acid														
0.0568 mL L^{-1}	1.7	0.3	10.9	3.3	32.8	0.3	28.3	1.0	30.6	0.7	82	4	4.8	0.3
0.568 mL L^{-}	1.3	0.1	21.5	5.8	32.9	0.5	26.5	1.1	30.4	0.7	76	8	6.6	0.5
5.68 mL L^{-}	1.5	0.4	11.6	3.2	33.3	0.4	27.0	0.9	31.6	0.8	71	9	5.5	0.3
Propionic acid														
0.05 mL L^{-1}	1.4	0.3	9.9	3.2	32.7	0.6	28.62	1.0	30.32	0.6	70	7	4.7	0.2
0.5 mL L^{-}	1.2	0.1	11.41	6.3	33.5	0.4	8.926	0.9	9.932	0.8	67	8	4.6	0.5
5 mL L^{-}	1.5	0.1	5.2	3.8	33.6	0.4	.3	0.7	.2	1.0	77	7	5.7	0.2
Acetic acid														
0.05 mL L^{-1}	1.8	0.2	11.15	3.3	33.1	0.6	28.62	1.0	31.42	0.3	65	7	4.6	0.7
0.5 mL L^{-1}	1.2	0.2	.7	1.8	33.8	0.4	9.127	0.9	9.531	0.8	70	4	4.6	0.3
5 mL L^{-1}	1.2	0.1	13.6	2.8	33.3	0.4	.2	0.6	.2	1.0	74	6	6.3	0.4
Trichoderma														
0.1 g L^{-1}	1.9	0.3	10.71	2.5	32.7	0.5	26.92	0.6	33.33	0.6	70	10	3.8	0.2
1 g L^{-1}	1.5	0.1	7.54.	4.3	33.3	0.4	6.429	1.4	4.230	1.8	71	8	6.0	0.2
10 g L^{-1}	1.1	0.2	5	1.7	33.7	0.5	.2	1.0	.9	0.7	62	7	4.3	0.2
Potassium silicate														
0.5 mL L^{-1}	1.1	0.1	16.31	4.1	33.3	0.7	26.02	0.8	34.93	1.2	70	8	5.6	0.2
5 mL L^{-1}	1.6	0.3	3.916	2.9	32.6	0.5	7.823	1.3	3.031	1.1	81	7	3.9	0.2
50 mL L^{-1}	1.7	0.3	.1	3.4	32.6	0.6	.9	0.8	.4	0.5	74	10	4.7	0.4
Octave														
0.1 g L^{-1}	0.8	0.1	8.4	2.3	32.133.8	0.4	28.12	0.9	32.23	0.7	73	7	4.8	0.2
1 g L^{-1}	0.5	0.1	6.1	3.1		0.4	9.2	1.1	2.0	0.8	80	6	5.8	0.3
Benlate														
1 g L^{-1} (52 °C)	0.2	0.03	0.9	0.5	35.7	0.5	27.9	1.0	32.4	0.5	78	4	6.7	0.5
Water														
52 °C	0.6	0.1	9.4	3.2	33.3	0.3	28.32	0.9	34.23	1.0	74	7	5.9	0.4
Ambient (control)	2.2	0.3	20.5	4.6	32.9	0.5	6.3	0.7	4.8	0.7	78	6	5.0	0.2

Table 5.3. Colour characteristics of fruit subjected to various preharvest spray treatments at Kennedy and 42 days of postharvest storage. The values represent the means and standard errors of the mean colour characteristics of fruit from seven trees. The means for each tree were based on two colour scans of nine fruit.

	L		Chroma		Hue angle	
	mean	std err	mean	std err	mean	std err
Control (water)	35.9	0.4	25.1	0.7	47.7	0.5
Control with 2 min. 52 °C water postharvest dip	39.0	0.4	30.3	0.5	46.4	0.4
Acetic acid	36.6	0.4	25.5	0.6	48.5	0.5
Potassium silicate	35.9	0.4	25.1	0.7	47.4	0.5
Trichoderma	37.1	0.4	26.4	0.6	48.2	0.6

Fig. 5.1. Effects of preharvest sprays at Kennedy on the microflora of lychee fruit at harvest. Total filamentous fungi counts were measured from plates that were inoculated with 100 microlitre suspensions, subsampled from washings of 5 fruit per tree in 100ml of phosphate buffer solution Columns and bars represent the means and standard errors, respectively, of the counts from five plates. Values are means of seven trees

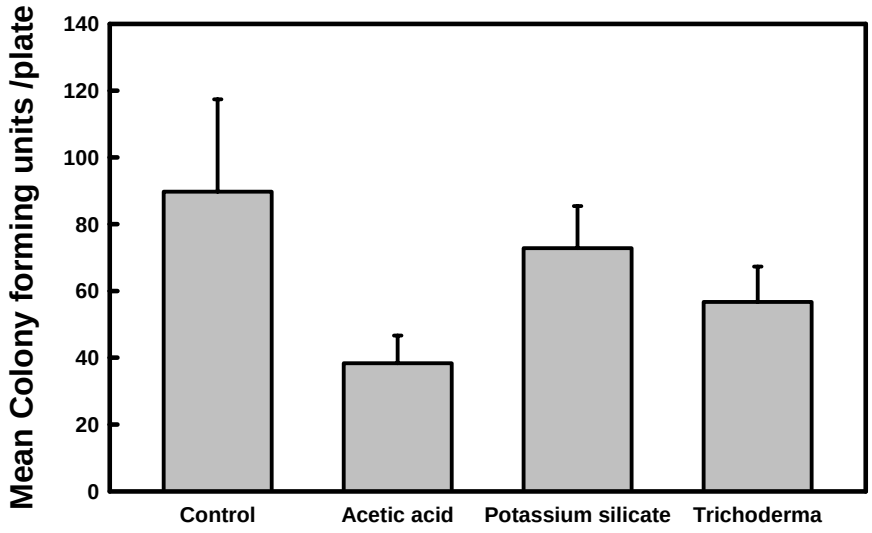
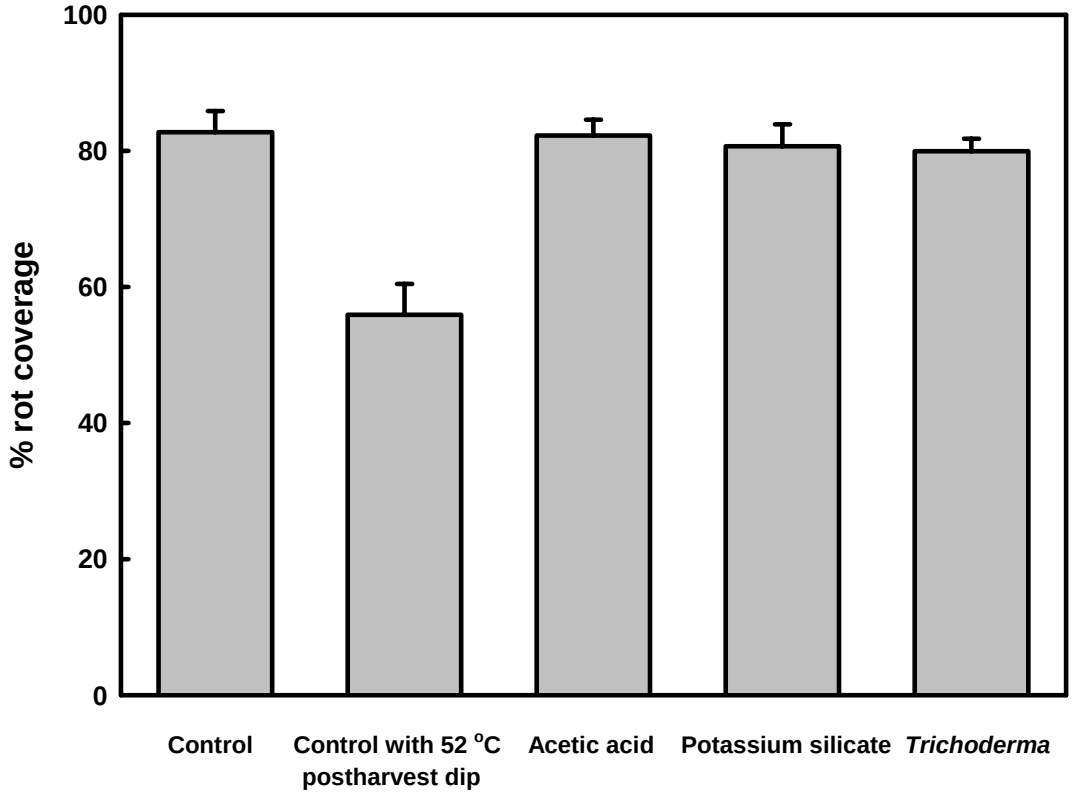


Fig. 5.2. Effects of preharvest sprays and a postharvest 52 °C water dip at Kennedy on the postharvest development of rots. The columns and bars represent the means and standard errors, respectively, of the mean rot coverage of nine fruit from each of seven trees. Rot coverage was assessed visually using six classes: 1 = 0 % coverage; 2 = >0 to 25 % coverage; 3 = >25 to 50 % coverage; 4 = >50 to 75 % coverage; 5 = >75 to <100 % coverage; and 6 = 100 % coverage. The mid-points of the classes were used to calculate the means.



6. Water relations of lychee fruit

6.1 Overview

A pressure bomb was used to explore the water relations of lychee fruit. Mature fruit on trees at Sarina Beach in north Queensland underwent diurnal variations in water potential of approximately 1 MPa, with very low water potentials between 10 a.m. and 3 p.m. solar time. The daily temperature maxima were in the low 30s °C.

The water potentials of leaves on cut branches were consistently lower than those of the fruit. The average difference was approximately 0.35 MPa.

Fruit could be rehydrated after harvest by dipping the fruit in water. The extent of rehydration depended on the delay between harvest and immersion, with less rehydration the longer the delay.

Further work is needed before recommendations on harvest times and rehydration protocols can be made.

6.2 Introduction

Little is known of the water relations of lychee fruit. The fruit commonly brown within a day of harvest if exposed to dry air currents. Complete browning requires the loss of greater than 10 % of the harvested fresh weight of the fruit (Ward 2000) presumably mostly as water given that respiratory losses are small (<1 % of fresh weight as CO_2 day^{-1}). This accords with micrographs of the pericarp surface that show a thin cuticle (1-3 μm) breached by microcracks (Underhill and Critchley 1992).

Packaging and refrigeration successfully slow the rate of water loss by reducing the water holding capacity of the surrounding air, slowing rates of diffusion and providing a physical barrier to air currents. In Chapter 5 fruit packed into polyethylene 250 g strawberry punnets and double-wrapped in PVC film lost on average <1 % of fresh weight per week.

In addition Pornchaloempong *et al*. (1997) found that fruit packed on the panicle browned more quickly than loose fruit, presumably because the panicle accentuated the rate of water loss from the fruit, though weight changes were not measured.

Here we take a different approach to the study of lychee water relations by using a pressure bomb (Scholander *et al*. 1965; Tyree 1997) to estimate the water potential of lychee fruit. The method is to place a fruit inside a pressure chamber with an attached panicle branch exserted through a rubber seal in the lid. Pressure is then applied until sap appears at the cut surface of the panicle branch. At this point the applied pressure (positive) is deemed to balance the water potential (negative). In fact, what the balance point represents is not clear because the lychee fruit is comprised of several different tissue types, including three parts pericarp, aril and seed that are essentially separate from each other. Nonetheless, we will show that the balance point can be used to provide practical insights into the physiological behaviour of lychee at harvest.

6.3 Materials and methods

Diurnal changes in fruit water potential

Diurnal changes in the water potential of fruit from one tree of "Tai So" and one tree of "Kwai May Pink" were monitored at Sarina Beach (21.4 °S 149.3 °E) on the 8th and 13th of December 2000, respectively. Water potentials were measured using a pressure bomb (Scholander *et al*. 1965) by

leaving a 3 cm length of panicle branch attached to the fruit that was exserted through the lid of the bomb so that the balance point could be observed.

The “Kwai May Pink” tree was 5 m in height, the “Tai So” tree 6 m in height. The fruit were sampled 1.5 m above the ground. At each sampling time three fruit of “Kwai May Pink” and four fruit (two from each of two panicles) of “Tai So” were harvest for bombing by cutting the panicle branches with a sharp knife. At the same time air temperature and relative humidity measurements were taken with a Vaisala HM 34 temperature-humidity probe (Helsinki, Finland).

Water potential in relation to water loss

On March 8, 2001 three fruit of “Kwai May Pink” were harvested into water at Yandina (26.33 °S 152.57 °E), still attached to 3 cm of panicle branch, and transported in water to Brisbane. One fruit was removed from the water, blotted dry and weighed. The balance point of the fruit was then determined with a pressure bomb. The pressure in the bomb was then increased to 1.5 MPa for 90 minutes to express sap from the fruit. After 90 minutes the pressure was released and the new balance point was determined and the fruit were reweighed. The procedure was repeated with the other two fruit on the same day.

Leaf and fruit water potentials in cut branches

On April 26, 2000 at Brooklet (28.7 °S 153.5 °E) several fruiting branches were cut from “Kwai May Pink” trees one vegetative flush behind the panicle. The branches were allowed to slowly dry over 24 h. At intervals, one leaf and one fruit were simultaneously cut from the same branch and bombed for the balance points. The order of bombing (leaf then fruit; fruit then leaf) was alternated with successive intervals. The leaf or fruit bombed second was kept in a plastic bag until the bomb was free.

Fruit rehydration

On December 11, 2000 at Sarina Beach (21.4 °S 149.3 °E) 35 fruit of “Kwai May Pink” were harvested at noon. Five of the fruit were harvested into water, the others into a plastic bag. At intervals of 5, 15, 30 and 60 minutes five fruit were transferred from the plastic bag into water. After 1 h of immersion the fruit were bombed for the balance points. With each group of five immersed fruit two dry fruit from the plastic bag were also bombed.

6.4 Results

Diurnal changes in fruit water potential

“Tai So” and “Kwai May Pink” had similar diurnal variations in fruit water potential (Fig. 6.1). The offset in the curves may have been related to aspect as the “Kwai May Pink” tree was growing on the western slope of a gully, and received more morning and less afternoon direct sunlight, than the “Tai So” tree, which was growing on the eastern slope.

Water potential in relation to water loss

The three fruit picked into water all had initial balance points of zero. The water potentials after 90 minutes of sap expression at 1.5 MPa were -1.35, -1.35 and -1.3 MPa corresponding with fully hydrated fresh weight losses of 3.9, 3.8 and 4.9 %, respectively. If these results reflect the water relations of fruit on trees then the diurnal variations in fruit water potential shown in Fig. 1 corresponded with a 3-4 % diurnal variation in fresh weight, given that the diurnal variation in potential for “Kwai May Pink” varied from -0.35 to -1.35 MPa and “Tai So” from -0.39 to -1.45 MPa,

and assuming that the change in the fruit water content per unit change in water potential increased with decreasing water potential (Nabil and Coudret 1995).

Leaf and fruit water potentials in cut branches

The leaves on cut branches drying on benches in a laboratory had water potentials *ca* 0.35 MPa lower than fruit on the same branches (Fig. 6.2).

Fruit rehydration

Fruit harvested directly into water were close to full hydration (0 MPa water potential) when bombed 60 minutes later (Fig. 6.3). With increases in the lag between harvest and immersion the extent of rehydration decreased. Even so, all the dipped fruit, even the fruit experiencing a 60 minute lag between harvest and immersion, had much higher water potentials than the non-dipped controls. The control fruit, kept inside a plastic bag, showed no significant change in water potential over two hours (linear regression $P < 0.05$).

6.5 Discussion

Current industry practice in Australia is generally to harvest fruit from dawn until 10 a.m., although some growers work beyond these limits, both earlier (under lights) and later. Picking stops at 10 a.m. because it is believed that the fruit become soft and warm in the middle of the day and more prone to postharvest spoilage (Menzel *et al*. 2002). However, at Sarina Beach the fruit of both "Kwai May Pink" and "Tai So" showed a rapid decline in water potential from dawn and were close to the minimum value by 10 a.m. (Fig.6.1). The minimum water potential appeared to correspond with a 3-4 % weight loss, presumably as water, from the fruit. In this regard, Kumcha (1998) showed that potted plants of "Wai Chee" with a pre-dawn leaf water potential of -0.3 MPa showed significant contraction of near mature fruit during the day. It is not clear from which tissues the water was lost, but loss from the pericarp would mean that fruit picked in the middle of the day would be more prone to browning than fruit picked at dawn because browning commences with the loss of only a few percent of the harvested pericarp fresh weight (Jiang and Fu 1999).

The diurnal patterns reported here for "Kwai May Pink" and "Tai So" fruit were very similar to the diurnal patterns reported for "Bengal" leaves at Alstonville on December 17, 1990 by Batten *et al*. (1994). Both reports show a rapid dehydration of fruit from dawn until 10 a.m. and a rapid rehydration of fruit from 3 p.m., although the leaves achieved lower minimum water potentials. Batten *et al*. (1994) also showed that leaves of droughted plants had lower potentials throughout the day than irrigated plants. Presumably the same would be true of the fruit. Thus, maintaining a good water supply up until harvest may improve fruit quality. Kumcha (1998) emphasised the importance of water management by showing that irrigated plants had a lower incidence of fruit splitting than plants where the irrigation was interrupted by a short period of drought during the last stages of fruit, then resumed.

The water potentials of leaves on cut branches were consistently lower than those of the fruit (Fig. 6.2). One interpretation of this is that transpiration from the fruit was slower than that of the leaves, and that some of the water loss from the fruit was caused by back flow to the leaves and stem. Such a back flow might have been part of the reason for the higher rates of browning reported by Pornchaloempong *et al*. (1997) for fruit packed on the panicle compared with fruit packed loose.

The diurnal variations in fruit water potential indicate good hydraulic connections with the rest of the plant. These connections open the commercial possibility of rehydrating wilted fruit after harvest (Fig. 6.3) with the potential benefit of slowing the rate of postharvest browning. Inadvertent rehydration is probably already occurring to some extent within the lychee industry through the practices of hydrocooling (Pornchaloempong *et al*. 1997), fungicidal dipping (Hargreaves 1983) and

dip disinfestation (e.g. with dimethoate solutions; Menzel *et al*. 2002). If so, rehydration may be affecting the movement of dip solutes into the fruit, with implications for the way in which fungicidal/pesticidal doses are calculated and residues determined.

Given the decline in rehydration potential with an increase in the time between harvest and immersion, perhaps caused by increasing embolism and collapse of the xylem elements around the harvest cut, and the impracticality of harvesting into water, a repeatable commercial rehydration procedure with an acceptable outcome would need to be developed. In the interim the best recommendation for those considering rehydration would be to wet fruit down in the orchard at harvest, minimise the time between harvest and delivery of the fruit to the packing shed, and immersing the fruit on arrival at the packing shed. Immersion has the potential risk of increasing the rate of rot development. Means of managing the risk are dealt with elsewhere in other chapters.

That immersion can cause rehydration has implications for the way in which residue analyses are conducted and reported as it is unclear whther the moisture is being taken up by the skin alone or by all tissues.

For those not considering rehydration it is difficult to give recommendations because we only have a limited database, and this only for very hot summer days, and because lychee is grown over such a wide range of climates. For Sarina Beach on the days on which the diurnal variations in water potential were reported fruit were perhaps best harvested between before 8 a.m. and after 4 p.m., as a compromise between fruit turgor and being able to see the fruit to harvest. What is best for Brooklet, where the harvest extends into the mild weather of early autumn, is unclear.

Fig. 6.1. Diurnal variations in the water potential of lychee fruit on trees at Sarina Beach. The open circles represent "Tai So" on December 8, 2000 with a maximum temperature of 34 °C and a midday (minimum) humidity of 40 %. Each open circle and associated bar is the mean ± standard error of four fruit. The closed circles represent Kwai May Pink on December 13, 2000 with a maximum temperature of 32 °C and a midday (minimum) humidity of 50 %. Each closed circle and associated bar is the mean ± standard error of three fruit.

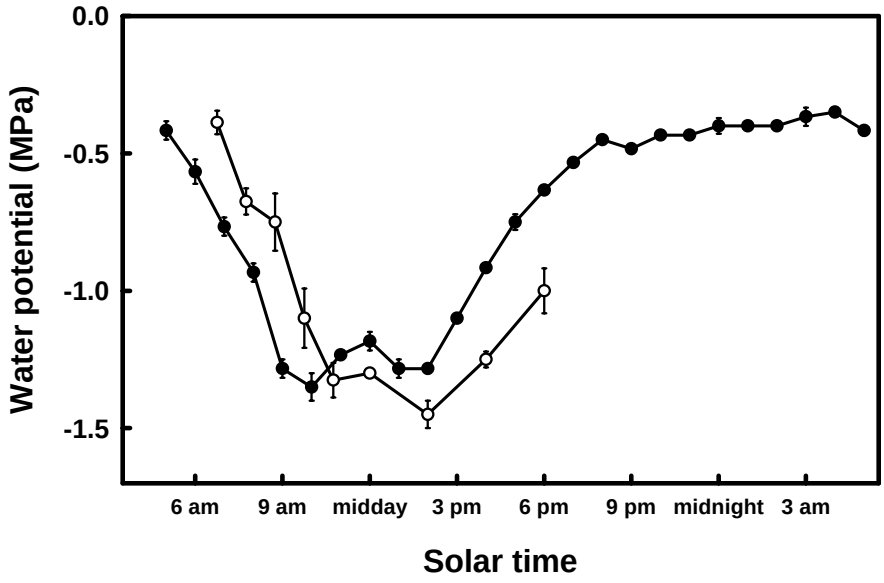


Fig. 6.2. Fruit and leaf water potentials on detached branches of "Kwai May Pink".

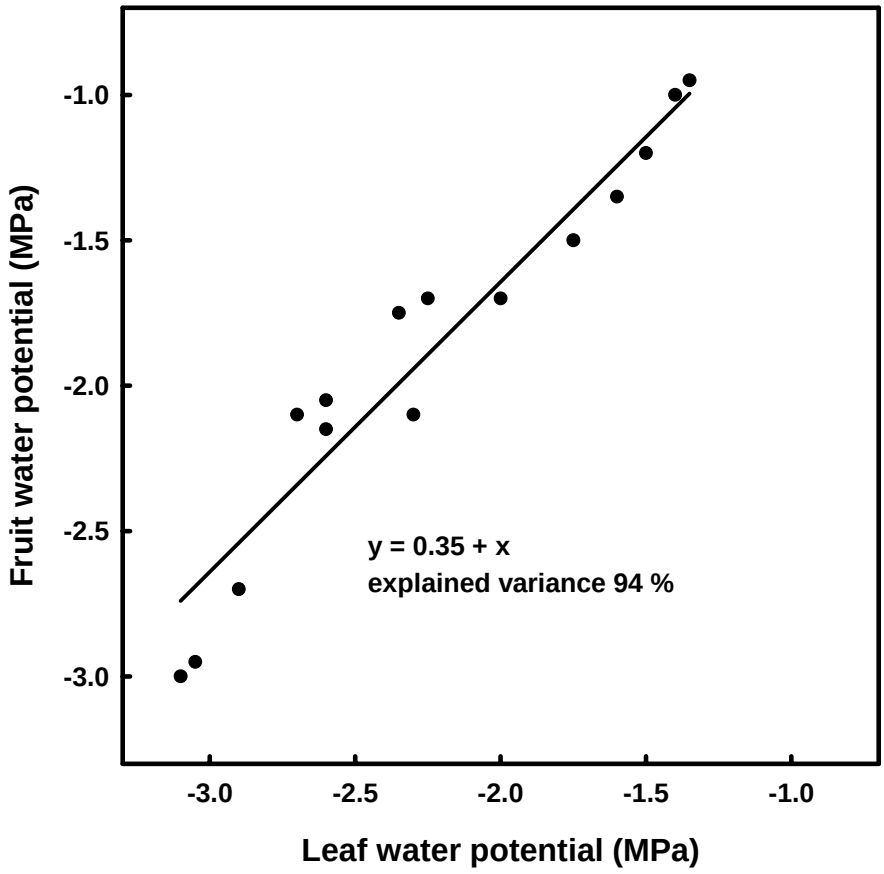
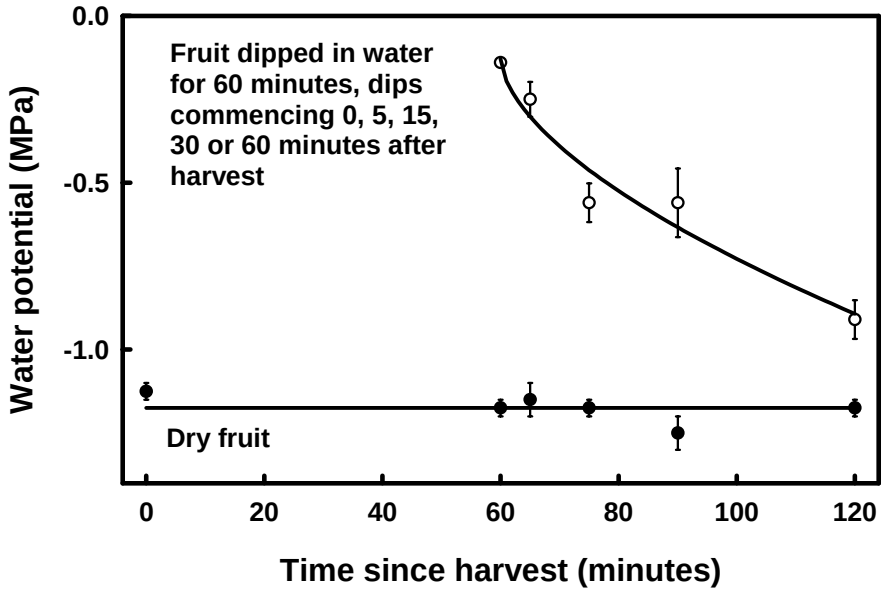


Fig. 6.3. The extent of fruit rehydration following immersion in water 0, 5, 15, 30 or 60 minutes after harvest.



7. Hot water treatments for the control of rots on harvested lychee (*Litchi chinensis* Sonn.) fruit

7.1 Overview

Lychee is a perishable stonefruit with an edible aril surrounded by a coloured pericarp. The fruit is highly susceptible to desiccation browning, but rates of water loss can be greatly reduced by packing fruit into sealed punnets. The problem then is to control rot development. Synthetic fungicides are effective, but none is registered for postharvest use on lychee in Australia, and there are concerns about the impacts on people's health and the environment. We examined the use of hot water treatments to control rot development. Specifically, the benefits of 2 or 5 minute dips at 48, 50 or 52 °C in one experiment, and 1, 2, 3, 4 or 5 minute dips at 52 °C in another. We also compared the benefits of a 1 minute 52 °C hot water dip with a 1 minute 52 °C hot water spray.

The most effective hot water dip was 1 minute at 52 °C, which slowed the rate of rot development by approximately 15 %. The hot water spray was equally effective as the hot water dip. On the basis of comparisons with other studies, a hot water spray was about half as effective as a hot benomyl dip.

The hot water treatments caused immediate effects on pericarp colour, with a positive linear correlation between dip time at 52 °C and chroma. Work with other crops has shown that heat treatments slow rot development by both a direct effect on the rots and by inducing protective heat shock responses in the plant cells. Such work needs to be pursued in lychee.

A model was used to simulate the temperature profiles within a 30 mm diameter spherical fruit during a 1 minute dip at 52 °C. At the end of the dip there was a steep temperature decline from the surface to the center of the fruit, consistent with a heat pasteurization effect largely restricted to the pericarp. The temperature differences within the fruit immediately following dipping had essentially equilibrated after five minutes of cooling at 22 °C.

7.2 Introduction

Lychee is an aromatic stonefruit with a large seed, an edible aril and a thin, tough, corklike pericarp. The aril is a translucent cream or white with a succulent texture and a floral, sweet taste. The pericarp of the mature fruit varies from green with a blush of pink through to a deep, uniform plum, depending on variety. The fruit is highly prized, especially in South-East Asia, but is also highly perishable, which limits its marketability.

Lychee is especially prone to dehydration. In the first instance dehydration only causes cosmetic injury with most of the initial water loss being from the pericarp, causing it to lose its fresh colour and to turn a dull brown. Eventually, however, the aril also loses water and the fruit becomes flaccid and bland (Underhill and Critchley 1993a; Underhill and Simon 1993).

The problem of dehydration can be overcome by the use of packaging designed to maintain high humidity around the fruit, but such packaging brings with it an increased risk of rot development (Scott *et al*. 1982). Refrigeration is the most effective means of reducing the risk (Ray 1998; Johnson *et al*. 2002), but the benefits of refrigeration can be enhanced by the use of supplementary treatments.

Synthetic fungicides are effective adjuncts to refrigeration (Ray 1998), but few are registered (none for postharvest use in Australia), those that are registered are expensive, and there are increasing concerns

about the ways in which synthetic fungicides might damage people's health and the environment. Here we examine the use of hot water treatments as soft alternatives to synthetic fungicides.

Swarts and Anderson (1980), Scott *et al*. (1982) and Huang and Scott (1985) showed that short hot water dips could significantly slow the rate of rot development, but the assessments were such as to give little indication of the potential magnitude of the effect. In contrast, we provide mathematical descriptions of the change in surface rot coverage over time for fruit treated to different hot water temperatures and dip durations, and quantify the effects of hot water treatments on rates of rot development based on the parameters of the fitted equations.

Hot water treatments are thought to not only retard pathogen development but to also affect the susceptibility of fruit to infection (Shirra *et al*. 2000). In citrus, the heat causes softening and movement of waxes on the surface of the fruit and changes the physiological state of the peripheral plant cells (Shirra *et al*. 2000). We use colour scans of the pericarp and scanning electron microscopy of the pericarp cuticle in an effort to detect immediate responses by the fruit to heat treatments.

Lastly, we compare hot water dips with hot water sprays of equal temperature and duration because sprays are the preferred mode of delivery of heat treatments in a number of horticultural industries (e.g. hot fungicide solutions in the Australian mango industry). Although dips and sprays are likely to have different heat transfer characteristics (the surrounding medium is water in the case of dips but a combination of air and water for sprays), heat transfer from water to fruit is rapid, so there may be little difference between treatments.

7.3 Materials and methods

Fruit

Lychee (cv. "Kwai May Pink") were harvested from commercial orchards at Yandina (26.5 °S), south-east Queensland (dip temperature and dip time experiments) and Bungundarra (23 °S), central Queensland (spray versus dip experiment). The fruit were picked into water to fully hydrate the fruit prior to the experiments so that fruit with a standard hydration state were used for all experiments. To confirm that full hydration was achieved, a pressure bomb was used to determine the water potential of six fruit per experiment. Fruit were processed on farm in a mobile laboratory (Yandina) or a farm shed (Bungundarra).

Dip temperature experiment

On February 9, 2001, 50 ripe fruit were packed into each of 14 open-weave plastic mesh bags, then immersed in a 22 °C water bath until treated. Two bags of fruit were randomly assigned to each of seven treatments. Control fruit were simply removed from the water bath. The other fruit were dipped in 48, 50 or 52 °C water for 2 or 5 minutes. All fruit were air-dried at 22 °C for approximately 10 minutes after immersion. Five fruit from each treatment were set aside for dissection, whereby a 10 x 2 mm strip was excised from the pericarp of each fruit. The excised pericarp was placed into a perforated cryotube and stored under liquid nitrogen for later examination by scanning electron microscopy (SEM, see below). Five other fruit were colour scanned (*L*, *a*, *b*, *chroma* and *hue angle* relative to a white tile) using a Minolta chroma meter (C-R 200), with two colour measurement taken per fruit, from opposite sides of the fruit approximately perpendicular to both the suture line and the longitudinal axis. The remaining 90 fruit were placed singly into MEA chippettes (cylindrical polypropylene containers 45 mm diameter x 24 mm deep) and double-wrapped in 14 μm Bunzl vitafilm (PVC). All the fruit were then transported (90 minutes at 15 °C) to Brisbane, stored in a 5 °C cold room for 7 days to simulate storage conditions, then transferred to a 22 °C incubator to simulate retail shelving conditions. From the eighth day postharvest, 9 fruit randomly selected from each treatment were permanently removed from the incubator at 2 to 7 day intervals until all the fruit had been exhausted. The selected fruit were weighed and colour scanned, as above. Mitutoyo digital

calipers were then used to measure the length and breadth of visible surface fungal colonies. The areas of the colonies were calculated by assuming that each grew as an ellipse. The total colonized area on each fruit was the sum of the individual colony areas. The total surface area of each fruit was estimated from measurements of the length, breadth and width of the fruit, assuming that the fruit was an irregular ellipsoid (Lang 1991). The percent rot coverage was calculated from the ratio of total colonized area to total surface area.

Dip time experiment

On February 7, 2001, 50 ripe fruit were packed into each of 12 onion bags. Two bags were assigned to each of the six dip time treatments (0, 1, 2, 3, 4 and 5 minute dips in 52 °C water). Prior to dipping, 5 fruit from each treatment were colour scanned, as above. The ten bags to be heat-treated were simultaneously immersed then removed at the appropriate intervals. After dipping, the fruit were air-dried for approximately 10 minutes. The fruit colour scanned prior to dipping were scanned again after dipping, then discarded. Pericarp excisions were taken from 5 fruit from each treatment, as above. The remaining 90 fruit were individually double-wrapped in chippettes with vitafilm. The fruit were then transported (90 minutes at 15 °C) to Brisbane, stored in a 5 °C cold room for 7 days to simulate storage conditions, then transferred to a 22 °C to simulate retail shelving conditions. From the eighth day the fruit were monitored for fresh weight, colour and rot coverage as in the previous experiment.

Spray versus dip experiment

On January 8, 2001, 72 fruit were harvested and divided into three groups. One group was treated to an ambient water spray (29 °C) for 1 minute using a purpose built mango hot water machine with 15 Tee Jet 11002 sprinklers per square metre, each delivering 360 mL per minute in a 110° fan. The second group was run through the machine at 52 °C for 1 minute. The third group was subjected to a 1 minute 52 °C hot water dip using water decanted from the hot water spray machine. The 24 fruit for the hot water dip were placed singly into 24 plastic mesh bags, and simultaneously immersed in the hot water. Six fruit from each group had a 10 x 2 mm segment of the pericarp excised and stored in liquid nitrogen for later examination by SEM. The remaining 18 fruit from each group were packed dry into chippettes and individually double-wrapped in vitafilm. The fruit were then stored on farm at 5 °C for 3 days before being transported (8 hours at 15 °C) by road to Brisbane, where the fruit were stored in a 5 °C cold room until the fruit were assessed for rots and colour, as described above, on February 26.

Scanning electron microscopy (SEM)

Specimens were prepared for scanning electron microscopy (SEM) by freeze-drying. The cryotubes containing the specimens were transferred to slots in a brass block, which had been precooled in liquid nitrogen. The block and specimens were transferred to a vacuum chamber at -35 °C in a freeze-drying unit. The specimens were held under vacuum for 48 hours for sublimation at -35 °C. After sublimation specimens were raised to room temperature over 24 hours before the vacuum was finally released. The specimens were mounted and either coated with gold or platinum before being examined at 300x magnification using a JOEL6400F SEM at 3 kV. Ten electronic images were taken systematically from each specimen, with the first image taken 2mm from one end and the subsequent 9 images taken at 0.5 mm intervals. The transects of images approximately spanned the width of two of the pyramidal segments of the pericarp surface. Each images was divided into 100 equal sized cells using a 10 x 10 grid overlay, and the dominant surface type (see Plate 1) for each cell was recorded. Two-way analysis of variance was carried out on the proportions surface type.

Heat transfer simulations

Approximate heat transfer to or from spherical fruit was simulated using iterations of finite difference equations, after Wang *et al*. (2001), using additional information from Churchill (1983), Dincer (1997) and Holdsworth (1997). Forced convection was assumed for heat transfer during hot water treatment, and natural convection for the cooling of fruit in air following treatment.

Surface temperature (T_1):

$$T_{1\,j+1} = [zhT_m + k_f T_{2\,j}] / [zh + k_f] \quad \text{Eq. 1}$$

where, $h = h_f$ for forced convection

$h = h_n$ for natural convection

Intermediate temperatures (T_2 to T_{n-1}):

$$T_{i+1\,j+1} = T_{i+1\,j} + a_f t[\{(T_{i\,j} - 2T_{i+1\,j} + T_{i+2\,j}) / z^2\} + \{(T_{i\,j} - T_{i+2\,j}) / (z(r - iz))\}] \quad \text{Eq. 2}$$

Centre temperature (T_n):

$$T_{n\,j+1} = T_{n\,j} + 6a_f t[(T_{n-1\,j} - T_{n\,j}) / z^2] \quad \text{Eq. 3}$$

Supplementary equations:

$h_f = 0.37k[2ur/v]^{0.6} / (2r)$

$h_n = Nk / (2r)$

$N = 2 + [0.589R^{0.25} / \{1 + (0.469 / P)^{(9/16)}\}^{(4/9)}]$

$R = \text{modulus } [g\beta(2r)^3(T_m - T_{1\,j}) / (va)]$

$\beta = 1 / [T_m + 273.15]$ for air; tabulated values for water

$P = v / a$

Symbols:

a	thermal diffusivity of air or water ($m^2\ s^{-1}$)
a_f	thermal diffusivity of fruit ($m^2\ s^{-1}$)
β	volumetric thermal expansion coefficient for gas ($°K^{-1}$)
g	acceleration due to gravity ($m\ s^{-2}$)
h_f	forced convection heat transfer coefficient ($W\ m^{-2}\ °C^{-1}$)
h_n	natural convection heat transfer coefficient ($W\ m^{-2}\ °C^{-1}$)
i	sphere number with sphere 1 at the surface of the fruit and 'sphere' n at the centre
j	time step from commencement of treatment
k_f	thermal conductivity of fruit ($W\ m^{-1}\ °C^{-1}$)
k	thermal conductivity of air or water ($W\ m^{-1}\ °C^{-1}$)
n	number of equally spaced concentric spheres from surface to centre of fruit
N	Nusselt number
P	Prandtl number
r	radius of fruit (m)
R	Rayleigh number
t	time between each step (s)
$T_{i\,j}$	temperature on sphere i at the j^{th} time step
T_m	medium (air or water) temperature (°C)
u	medium speed ($m\ s^{-1}$)
v	kinematic viscosity of air or water ($m^2\ s^{-1}$)
z	radial distance between each sphere

7.4 Results

Dip temperature

All fruit were picked into water and kept immersed at 22 °C for approximately one hour prior to sorting to fully hydrate the fruit. After sorting the control fruit were returned to the 22 °C water bath while the remaining fruit were dipped in 48, 50 or 52 °C water for 2 or 5 minutes. The fruit dipped in 48, 50 or 52 °C water for 2 minutes had significantly slower rates of rot development than the control fruit (ANOVA $P < 0.05$; Fig. 1). The rates of rot development amongst the three 2 minute hot water treatments were not significantly different (ANOVA $P < 0.05$), but did decline with increasing temperature (Fig. 1). The fruit treated to 52 °C for 2 minutes had significantly slower colour decline (slower initial decline in *L*; slower decrease in *chroma*; slower increase in *hue angle*) than both the control fruit and the fruit treated to 48 °C for 2 minutes (ANOVA $P < 0.05$; Fig. 2).

The rate of rot development on fruit dipped in 48 °C water for 5 minutes was not significantly different from that on the control fruit (ANOVA $P < 0.05$; Fig. 1) but the increase in the *hue angle* was significantly faster (ANOVA $P < 0.05$; Fig. 2). The fruit treated to 50 or 52 °C for 5 minutes had dramatically faster rates of rot development and colour decline than the controls (ANOVAs $P < 0.05$; Figs 7.1 and 7.2).

Dip time

Fully hydrated fruit were dipped in 52 °C water for 0, 1, 2, 3, 4 or 5 minutes. The hot water dips had an immediate physiological impact on the fruit in that there was a significant positive correlation between the difference in *chroma* before and after dipping and the dip time (t-Test $P < 0.05$; Fig. 7.3) and a similar positive correlation with the change in *a* ($\Delta a = 1.03 + 0.43$(dip time in minutes), $r^2 = 0.3$, t-Test $P < 0.05$; data not shown).

The fruit dipped for 1 minute had a significantly slower rate of rot development than the controls (ANOVA $P < 0.05$; Fig. 7.4), with the dipped fruit reaching 50 % rot coverage on day 23.5 (0.5 s.e.) postharvest compared with day 20.5 (0.3 s.e.) for the control fruit. The difference in the time taken to reach 50 % rot coverage represents a 13 % slower rate of rot development based on total postharvest time, or an 18 % slower rate based on shelving time (time from transfer from 5 to 22 °C), or a 17 % slower rate based on postharvest degree-days (Σ[days at a given temperature x temperature in °C]).

Fruit dipped for 2 minutes also had a significantly slower rate of rot development than the controls, while the fruit dipped for 3, 4 or 5 minutes had significantly faster rates (ANOVA $P < 0.05$; Fig.7.4). Overall for the experiment, the rate of rot development was positively correlated with the rate of colour decline, as expressed in terms of *L* (using a restricted data set to mitigate the influence of fungal reflection), *chroma* and *hue angle* (Fig. 7.5).

Consistency between dip temperature and dip time experiments

The control, 52 °C 2 minute and 52 °C 5 minute fruit reached 50 % rot coverage on days 19.6 (0.3 s.e.), 22.6 (0.7 s.e.) and 15 (0.1 s.e.), respectively, for the dip temperature experiment and 20.5 (0.3 s.e.), 22.3 (0.4 s.e.) and 14.1 (0.2 s.e.) for the dip time experiment. The overall rate of water loss was approximately 0.4 % of fresh weight per day for both experiments.

Hot water spray versus hot water dip

The 1 minute 52 °C spray was equally effective at slowing rot development as the 1 minute 52 °C dip (Table 7.1). An approximate comparison of rates was made by assuming that early rots spread exponentially, such that the rate was proportional to ln[1 + % rot coverage]. On this basis, the hot

water treated fruit had 19 % slower rates of rot development, very similar to the proportional effect of the 1 minute 52 °C treatment from the dip time experiment (18 % difference based on shelving time), although the absolute rates of rot development at 5 °C (spray versus dip experiment) were 75-80 % slower than at 22 °C (dip time experiment).

The fruit of the two hot water treatments had similar colour characteristics, and were superior to the control fruit with respect to *L* and *chroma* (Table 7.1).

Pericarp topography

The hot water treatments produced no significant changes (Two-way ANOVAs, proportions of surface types by treatments, $P > 0.05$) to the overall surface features of the pericarp in the dip temperature (control and 2 minute dips only), dip time or the dip versus spray experiments. The grouped percentages and standard errors of classes 1 to 5 (Plate 7.1) for the dip temperature experiment were 6 ± 1, 6 ± 2, 15 ± 4, 56 ± 3 and 17 ± 3 (n = 12; 3 specimens per treatment); the dip time experiment 7 ± 1, 21 ± 4, 28 ± 2, 30 ± 4 and 14 ± 4 (n = 16; 2 or 3 specimens per treatment); and the spray versus dip experiment 5 ± 2, 5 ± 1, 36 ± 5, 42 ± 5 and 12 ± 2 (n = 9; 3 specimens per treatment). There were significant differences in surface characteristics between all three experiments (Two way ANOVA, proportions of surface types by experiments, $P < 0.05$).

Class 1 surfaces represent either ruptures of the epidermis or rapid changes in focal length, as might occur at the meeting of two pyramidal segments (Underhill and Simons 1993). Ruptures may be artifacts of the SEM preparation, which involved dehydration of the pericarp, or natural micro-cracks. The convex features evident in Class 3 have diameters similar to those of epidermal cells in transverse section (Underhill and Simons 1993, Kumcha 1998) and presumably represent the end surfaces of such cells. Our images were taken at a higher magnification than those of Underhill and Simons (1993) and consequently it is impossible to distinguish Class 2 from Class 3 cells in their micrographs. Otherwise the fruit from the two studies seem to have had the same range of surfaces types.

Simulations of heat transfer

Our most effective hot water dip for fruit with an initial temperature of 22 °C was 1 minute at 52 °C (Fig. 7.4). The heat transfer during and immediately following this treatment was simulated using the model outlined above. There was a rapid rise in the surface temperature of the fruit during the initial stages of the hot dip, but the rise was increasingly damped as the surface temperature approached that of the water (Fig. 7.6). At the end of the dip there was a strong temperature gradient from the surface (51 °C) to the core (22.2 °C) of the fruit (Fig.7.7). Importantly, the temperatures at the end of the dip 1 mm below the surface of the fruit, in the mid to lower part of the pericarp (Underhill and Critchley 1992), and 2 mm below the surface, in the lower part of the pericarp or the upper part of the aril, were 46.8 and 42.5 °C, respectively. Thus the treatment did not expose the aril to extreme temperatures.

After cooling for 5 minutes in air at 22 °C the fruit had largely equilibrated to 35-35.7 °C (Fig. 7.7). Heat losses through evaporation from the wet fruit surface were not incorporated in the model, nor were radiant heat loss and heat generation through respiration.

Ideally fruit would be packed into sealed punnets after heat treatment to minimize subsequent contamination, but in packing warm fruit there is a risk of condensation and accelerated spoilage. Consequently we repeated the simulation assuming that the fruit had been pre-chilled to 5 °C, the approximate optimal storage temperature for lychee (Huang and Wang 1990), prior to treatment. The surface temperature at the end of the treatment was 50.5 °C; the temperatures 1 and 2 mm below the surface of the fruit were 43.9 and 37.2 °C, respectively; while the core temperature was 5.4 °C (Fig.7.7). After 5 minutes of equilibration at 22 °C the temperatures within the fruit varied from 27.3 to 28 °C. It would seem from these results that the temperature/duration dose would need to be reconsidered for pre-chilled fruit given that the near surface temperatures of the pre-chilled fruit at the

end of the hot water dip were lower than those of the non-chilled fruit. The post-dip equilibration temperature was approximately 8 °C lower for the pre-chilled fruit, but still relatively warm.

7.5 Discussion

Scott *et al*. (1982) found that the most effective hot water dips for maintaining the appearance of the lychee cultivar "Bengal" were 2 minutes at 52 °C and 1 minute at 56 °C. They also found that the most effective hot benomyl dips were for similar times at similar temperatures. In contrast, the most effective hot water dip for "Kwai May Pink" was 1 minute at 52 °C (Figure 7.3), and the most effective hot benomyl dip 0.5 minutes at 52 °C (Wong *et al*. 1991). "Bengal" has a thicker pericarp than "Kwai May Pink" and this may account for some of the varietal difference.

It should be noted, however, that while we found a significant slowing of rot development on "Kwai May Pink" with a 2 minute 52 °C dip (Figs 7.1, 7.4) Johnson *et al*. (2002) found no such effect with the same treatment. Also, Paull *et al*. (1995) reported improvements in the appearance and water retention of "Kwai Mei" (syn. "Tai So") fruit treated to a 10 minute dip at 50 °C followed by a 15 minute wash in cold running water, in contrast to "Kwai May Pink" dipped for 5 minutes at 50 °C (Figs 1, 2) and "Kwai May Pink" and "Wai Chee" dipped in 50 °C benomyl for 5 minutes and "Tai So" dipped in 50 °C benomyl for 8 minutes (Wong *et al.* 1991) which all showed colour loss and rot development greater than controls. Neither we nor Wong *et al.* (1991) used a post-dip cold water wash, and this might explain some of the discrepancy in that a simulation of our 5 minute 50 °C water dip/subsequent 22 °C air cooling (fruit traits and medium movement as per Fig. 7.6) indicated a surface temperature of 43 °C 5 minutes after the hot water treatment.

The optimal temperature and duration for the hot water dip for "Kwai May Pink" is still unclear (Figs 7.1, 7.4); temperatures greater than 52 °C and durations less than 1 minute need to be investigated. In addition, on the basis of our simulations (Figs 7.6, 7.7), work needs to be carried out on both chilled and non-chilled fruit because chilled fruit would seem to require more extreme treatment owing to surface and near surface temperature buffering from within the fruit. Various means of controlling condensation also need to be explored.

We reanalyzed the most effective hot benomyl treatments from Wong *et al.* (1991) and Johnson *et al.* (2002) using a logarithmic transform (ln[1 + % rot coverage]) to calculate rates of rot development. On the basis of these analyses, the varieties "Bengal", "Tai So", "Kwai May Pink" and "Wai Chee" had approximately 65, 50, 30 and 25 % slower rates of rot development than control fruit. Wong *et al*. (1991) noted that the varieties "Bengal" and "Tai So" have thicker pericarps than "Kwai May Pink" and "Wai Chee". It may be, then, that pericarp thickness is related to the effectiveness of the hot benomyl treatments, but how is unclear.

Our best hot water treatment on "Kwai May Pink" gave between a 13-19 % reduction in the rot development rate, depending on the experiment and how the calculations were made. Thus hot water treatment was about half as effective as hot benomyl. The synthetic fungicides imazalil, iprodione and prochloraz have not been shown to be consistently any more effective than hot benomyl (Brown *et al*. 1984; Kremer-Kohne and Lonsdale 1991; Coates 1995; Johnson *et al*. 2002).

There are few comparisons of the effectiveness of hot water treatments relative to synthetic fungicides for other species, usually with a very limited range of hot water treatments, and often with mixed results. For example, McGuire and Campbell (1993) found that a 3 minute 53 °C dip was approximately as effective as a cool imazalil (2000 mg/L) dip for the control of anthracnose on Tommy Atkins mangoes, and that the benefits of the two treatments were largely additive. In contrast, they found that the same hot water treatment was ineffective on Keitt mangoes, and that imazalil was less effective on Keitt than Tommy Atkins. Our estimate of the relative effectiveness of hot water dips for lychee is within the range for other crops.

The way in which hot water treatment serves to slow rot development is not well understood. There are direct effects on fungal growth, with reports from other crops of damage to mycelia and retarded spore germination and rot development (Shirra *et al*. 2000). There may also be indirect effects through elicited plant responses (Shirra *et al*. 2000) given that the hot water dips caused an immediate intensification of *chroma* (Fig.7.3) consistent with some form of plant cell disturbance. In a more extreme experiment, Underhill and Critchley (1993b) dipped fruit in 60 °C water for 10 minutes, and found immediate browning of the pericarp cells.

In addition, heat treatments often cause epicuticular waxes to melt and flow, covering surface cracks and stomata, thereby reducing the number of infection pathways, and mummifying pathogens (Shirra *et al*. 2000). However, the cuticle of lychee is thin (Underhill and Critchley 1992) and uneven (Underhill and Simons 1993; Plate 1) and there was little evidence that the heat treatments in our experiments caused substantial changes to the surface topography of the fruit. More positively, the results do highlight the potential of surface coatings (e.g. chitosan/L-glutamic acid; Zhang and Quantick 1997) for reducing rates of water loss, browning and surface decay.

Over the course of storage/simulated shelving the change in the colour of our fruit was marked by decreases in *L* and *chroma* (e.g. Fig.7.5) and *a* and *b* (data not shown) and by an increase in the *hue angle* (e.g. Fig.7.5), which is to say that the cheerful pink-red tended to a dull, flat brown. These seem to be the general trends in postharvest colour decline for lychee (Huang and Wang 1990; Huang *et al*. 1990; Ilangantileke *et al*. 1994; Jacobi *et al*. 1993; McGuire and Baldwin 1998; Underhill and Critchley 1994; Wong *et al*. 1991) except for sulfur treated fruit that are initially bleached by the sulfuring but which recover colour as the colourless anthocyanin-sulfite complexes dissociate (Underhill *et al*. 1992) and ethephon treated fruit that continue to ripen postharvest (Sadhu and Chattopadhyay 1989; lychee normally does not ripen after harvest). However, there may be subtle counter trends, especially during early storage. For example, there are reports of small but significant increases in *L* and *b* for "Tai So" during 3 weeks of storage at 5 °C (McLauchlan *et al*. 1992) and in *a* for "Wai Chee" (Underhill and Critchley 1994) during the first few hours of storage at 5 °C.

Long-term changes in fruit colour are related to the physiology of aging and to a range of external factors affecting the integrity of the pericarp cells. For example, Jiang and Fu (1999) monitored fruit stored at different relative humidities over several days for colour, water loss, membrane permeability (a guide to integrity) and polyphenol oxidase activity (PPO, enzyme related to the oxidation of anthocyanin pigments and other cell components). The degree of browning was positively correlated with water loss and membrane permeability with respect to the two factors, relative humidity and storage time. In contrast, PPO activity was positively correlated with the degree of browning on any given day, but declined with increasing storage time.

Cell integrity is important because intracellular partitioning is fundamental to colour expression. The anthocyanins pigments are located in the vacuoles of the cells in the outer layers of the pericarp (Underhill and Critchley 1993a), but only express colour at low pH. The tonoplast tends to maintain plant vacuoles at a pH lower than that of the cytoplasm (Ratajczak and Wilkins 2000) so that an increase in the permeability of the tonoplast may result in pH dependent decolourization. Furthermore, enzymes likely to oxidize anthocyanins and other cell components and generate brown pigments tend to be localized and sequestered away from many potential substrates (e.g. PPO is typically found in chloroplasts or other plastids; Underhill and Critchley 1995).

Loss of cell integrity may have both senescent and non-senescent causes. Heat was certainly a non-senescent cause for some of our treatments in that fruit dipped for 5 minutes at 48 °C had a more rapid decline in hue than the control fruit (Fig.7.2) and this was unrelated to differential rot development (Fig. 7.1). A similar result was reported by Jacobi *et al.* (1993) where a hot water vapour treatment of "Kwai May Pink", involving a 60 minute ramp up to a core temperature plateau of 45 °C for 31 minutes, caused a significant increase in browning relative to the controls but no significant difference in rot development. Consequently, the enhancement of rot development after treatment for 5 minutes

at 50 °C and 3, 4 or 5 minutes at 52 °C (Figs 7.1, 7.4) may have been related to the greater availability of substrates from damaged cells.

Infection might have been another non-senescent cause. In some of our experiments, heat treatments that slowed rot development also slowed colour decline (Fig. 7.5; Table 7.1) but this does not necessarily mean that the two processes were directly related (e.g. the heat treatments might have induced a membrane stabilization response).

Dehydration also affects cell integrity, as illustrated in the Jiang and Fu (1999) work summarized above. Differences in rates of water loss between treatments could not be resolved from our experiments. However, the nature of the packaging we used would have affected the rates of colour decline because it allowed rates of water loss equivalent to approximately 0.4 % of fruit fresh weight per day at 22 °C (dip time and dip temperature experiments), and dehydration related browning of the pericarp appears to begin with only a few percent loss of fresh weight (Underhill and Critchley 1994). The rates of water loss at 5 °C would have been lower, but we do not have estimates from our experiments.

Our packaging might also have affected the rate of senescence, and consequently the rate of senescence related loss of cell integrity. Scott *et al.* (1982) found that packaging fruit into polythene bags caused concentrations of CO_2 and ethylene to increase within the bags, and concentrations of O_2 to decrease. Modified atmospheres with 3-5 % CO_2 and 3-5 % O_2 (cf. 0.03 % CO_2 and 21 % O_2 for air) slow the rate of fruit deterioration (Jiang and Fu 1999) while postharvest applications of ethylene (as ethephon) caused fruit to ripen (Sadhu and Chattopadhyay 1989).

In terms of industry adoption of hot water treatments, the major shortcomings are scientific not industrial. Hot water spray units are easily incorporated into packing lines, with a spray cabinet suspended above a conventional roller conveyor, a water trap beneath and a circulation line through a small heater. Something similar to this is already used commercially in Israel (Lichter *et al*. 2000), although the treatment is a combination of hot water brushing (i.e. scouring the fruit surface whilst spraying with 55 °C water) followed by an HCl/prochloraz dip. Our purpose is different. To maintain the fresh, natural colour of the fruit, the fruit should be treated gently and handled as little as possible. Straight hot water treatments achieve a large proportion of the anti-fungal benefits of synthetic fungicides, and the gap might be further narrowed with the judicious use of other soft fungal inhibitors, such as dissolved bicarbonate in the hot water stream (Smilanick *et al*. 1999) and nitrous oxide in sealed punnets (Qadir and Hashinaga 2001). Such an approach would allay community concerns about the health and environmental risks of synthetic fungicides, and may be more cost effective.

Plate 7.1. Pericarp surface of fruit dipped in 52 °C water for 5 minutes. The rectangles delineate the five classes of surface types used to describe the topography. Class 1 is a microcrack (a rupture of the epicarp) or fissure of the wax, while classes 2 to 5 represent increasing waxiness. The bar in the top right hand corner represents a length of 100 μm.

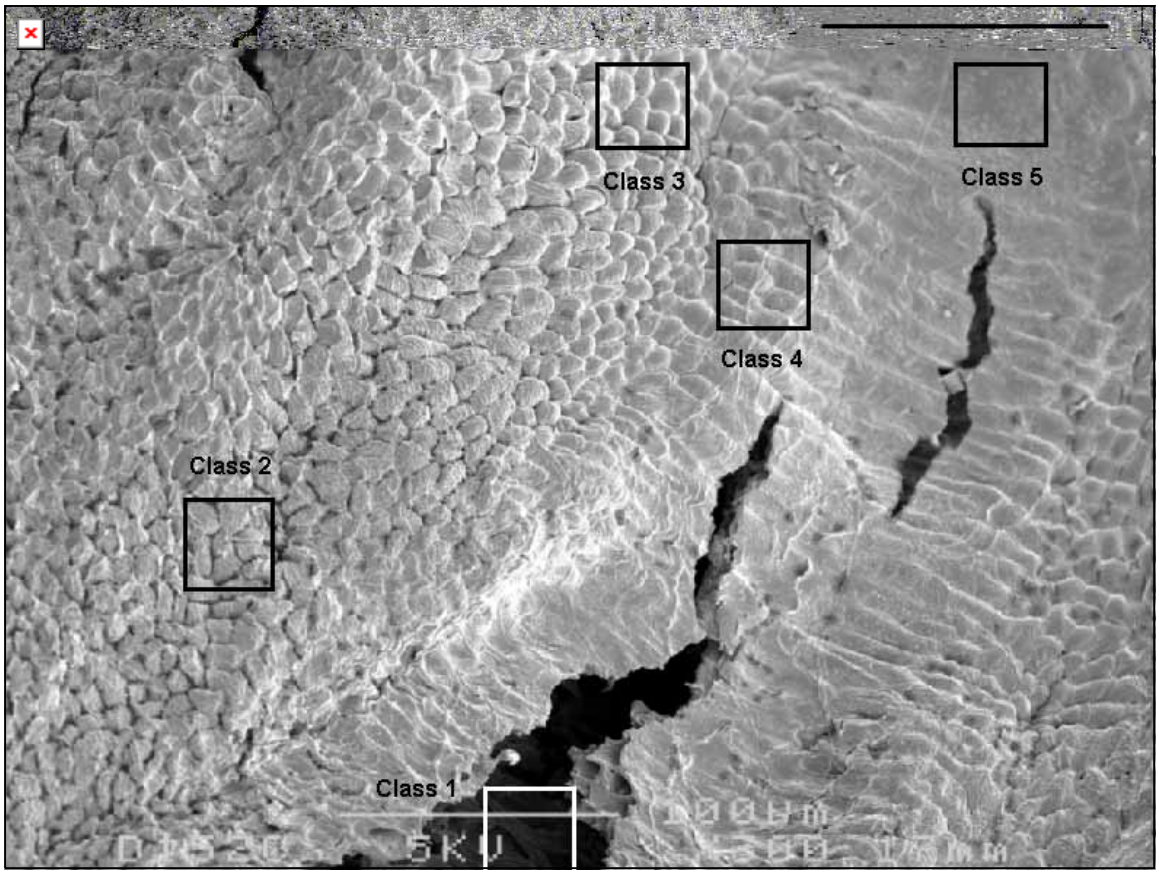


Table 7.1. Effects of hot water spray and hot water dip on rot development and pericarp colour. Control fruit were sprayed with water at 29 °C for 1 minute on the day of harvest, while the hot water treatments were both of 52 °C water for 1 minute. The fruit were then stored for 49 days at 5 °C before being assessed. An asterisk indicates a significant treatment effect (ANOVA $P < 0.05$) but no significant difference between the hot water spray and the hot water dip.

	Rot coverage* (% surface area)	*L**	*Chroma**	*Hue angle*
Control	14 ± 2	41.8 ± 0.6	33.2 ± 0.8	42.6 ± 0.9
Hot water spray	8 ± 2	43.3 ± 0.4	36.3 ± 0.3	40.9 ± 0.6
Hot water dip	8 ± 1	43.5 ± 0.4	36.1 ± 0.5	42.1 ± 0.6

Fig. 7.1. Rot development on fruit dipped into 48, 50 or 52 °C water for 2 or 5 minutes and on non-heated controls. Fruit were stored at 5 °C for the first 7 days postharvest, then at 22 °C. The rates of rot development ranked by ANOVA ($P < 0.05$) were 52 °C 2 min. = 50 °C 2 min. = 48 °C 2 min. < control < 50 °C 5 min. = 52 °C 5 min. The rate of rot development for the 48 °C 5 minutes treatment was neither significantly faster than any of the 2 minute hot water treatments nor significantly slower than the control. Symbols signify means ± standard errors for the control fruit based on sample sizes of 9 (day 21 or less, and day 31) or 18 (days 28 and 32).

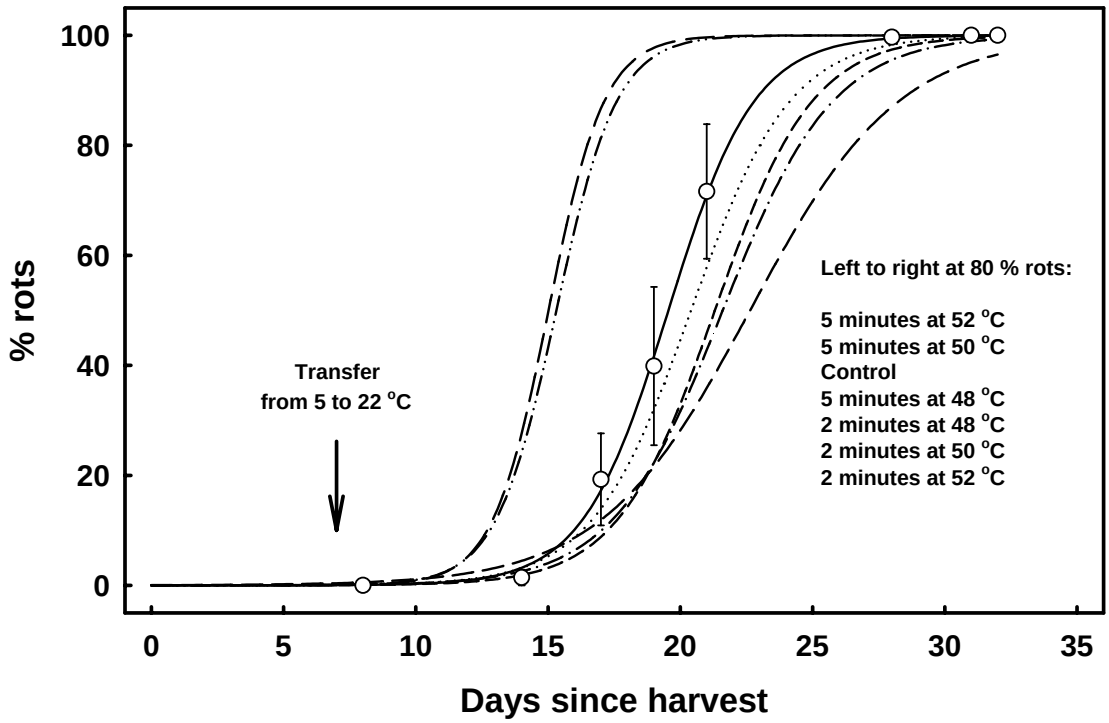


Fig. 7.2. Colour characteristics (*L*, *chroma* and *hue angle*) 19 days postharvest for fruit dipped into 48, 50 or 52 °C water for 2 or 5 minutes and for non-heated controls. Values are given as means + standard errors of 9 samples. Common letters mean no significant difference between treatments based on ANOVA ($P < 0.05$) of the entire time course of colour measurements from day 8 to day 32 postharvest (not just day 19).

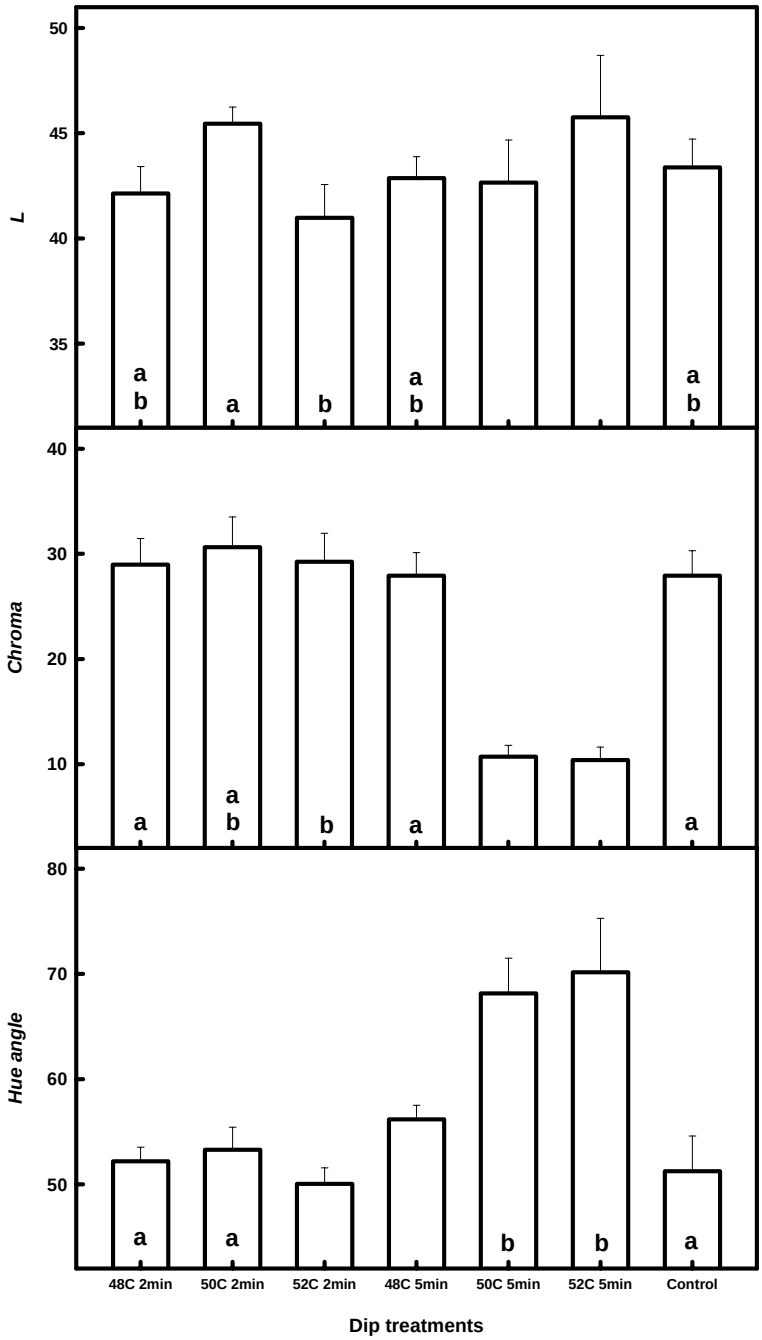


Fig. 7.3. Immediate effects of hot water dips on pericarp colour: *L*-value prior to dipping minus the *L*-value after; *chroma*-value prior to dipping minus the *chroma*-value after; and *hue angle*-value prior to dipping minus the *hue angle*-value after. Values are given as means ± standard errors of 5 samples. Only *chroma* was significantly dependent on dip time ($y = 0.41x + 0.73$, $r^2 = 0.33$, $P < 0.05$).

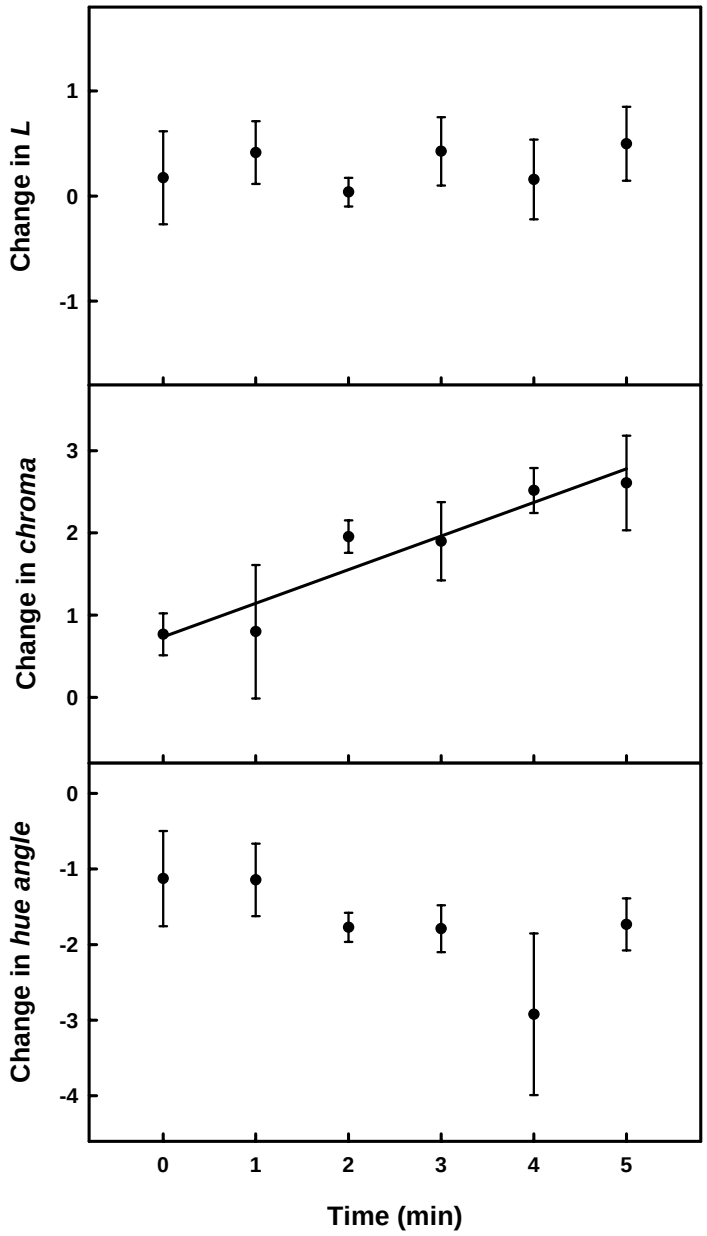


Fig.7.4. Rot development on fruit dipped into 52 °C water for **(a)** 0 (circles) and 1 (squares) minute and **(b)** 0, 1, 2, 3, 4 or 5 minutes. Fruit were stored at 5 °C for the first 7 days postharvest, then at 22 °C. The rates of rot development ranked by ANOVA ($P < 0.05$) were 1 min. = 2 min. < control < 3 min. < 4 min. = 5 min. Circles and squares and associated bars are means ± standard errors based on sample sizes of 9 (day 29 or less) or 36 (days 33).

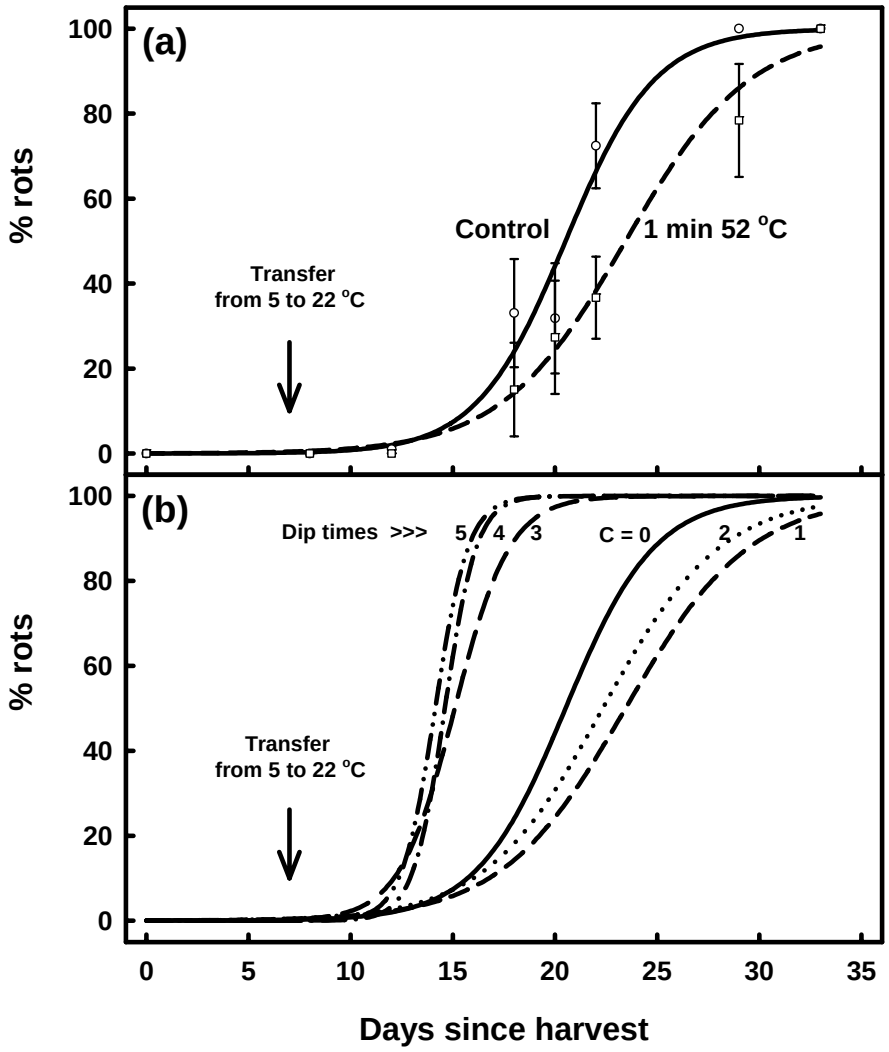


Fig. 7.5. Effects of 52 °C hot water dips on the day of harvest on subsequent colour loss. Fruit were stored at 5 °C for the first 7 days postharvest, then at 22 °C. **(a)** Trajectories of *L*-values with time for control fruit (open circles and solid lines; $y = 44 - 0.0004x^3$; $r^2 = 0.25$) and fruit dipped for 1 minute (closed circles and broken lines; $y = 44 - 0.0002x^3$; $r^2 = 0.10$). Symbols and associated bars are means ± standard errors based on sample sizes of 9 (day 29 or less) or 36 (days 33) and this applies to Figs 5b and 5c as well. **(b)** Trajectories of *chroma*-values with time for control fruit (circles and solid lines; $y = 38 - 0.027x^2$; $r^2 = 0.86$) and fruit dipped for 1 minute (squares and broken lines; $y = 38 - 0.024x^2$; $r^2 = 0.77$). **(c)** Trajectories of *hue angle*-values with time for control fruit (circles and solid lines; $\ln y = 3.7 + 0.015x$; $r^2 = 0.64$) and fruit dipped for 1 minute (squares and broken lines; $\ln y = 3.7 + 0.013x$; $r^2 = 0.54$). **(d)** Slopes of *L*-trajectories ($y = 44 - ax^3$) with respect to the maximum rate of rot development from Fig. 4b. Linear regression, $y = 0.000110 + 0.000025x$, $r^2 = 0.74$, sample size = 6. **(e)** Slope of *chroma*-trajectories ($y = 38 - ax^2$) against the maximum rot rates. Linear regression, $y = 0.0141 + 0.0011x$, $r^2 = 0.96$, sample size = 6. **(f)** Slope of *hue angle*-trajectories ($y = 38 - ax^2$) against the maximum rot rates. Linear regression, $y = 0.01075 + 0.00035x$, $r^2 = 0.93$, sample size = 6.

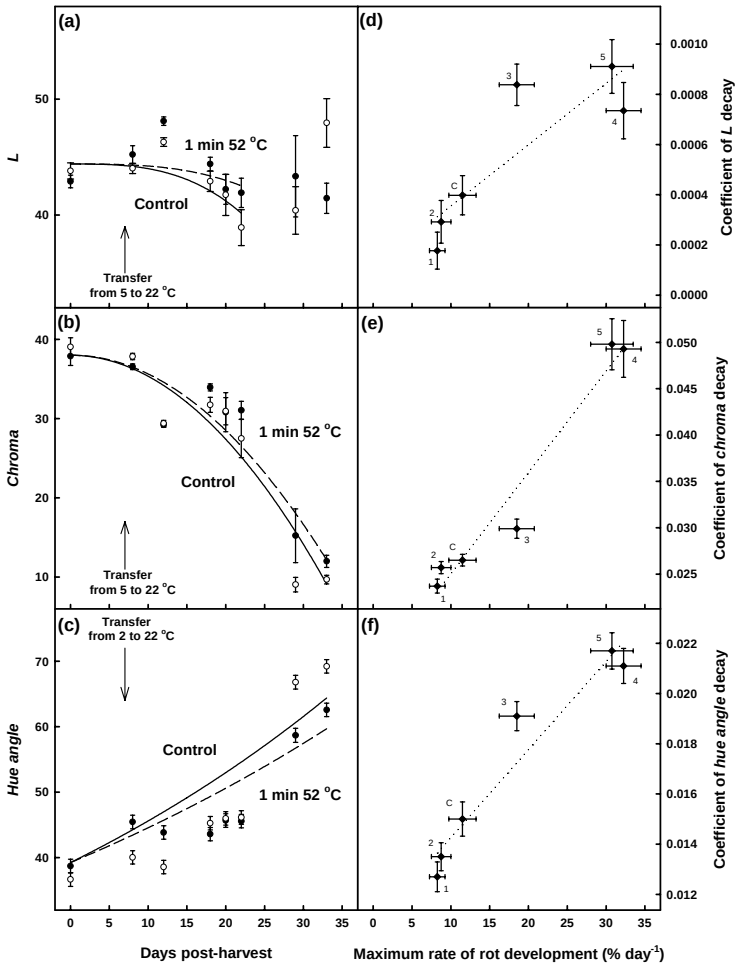


Fig.7.6. Simulations of the change in the surface temperature of a 30 mm diameter spherical lychee during and immediately following a 1 minute dip in 52 °C water. Following the dip the fruit were assumed to be motionless in 22 °C air with no forced air currents. The fruit had uniform initial temperature profiles of 5 or 22 °C. The simulations were based on the forced convection model outlined in the materials and methods for the 1 minute in 52 °C water, and the natural convection/radiation model for the subsequent period in air. The parameters for the simulation were: $a_{air} = 0.00002171$, $a_f = 0.000000139$, $c = 3643$, $g = 9.81$, $k_{air} = 0.02583$, $k_f = 0.511$, $k_{water} = 0.6454$, $\rho = 1010$, $r = 0.015$, $\sigma = 0.00000005669$, $u = 0.2$, $v_a = 0.00001546$, $v_w = 0.0000005328$. The parameters for water and air were interpolated from the tables in Dincer (1997). The water speed was estimated from the rate and amplitude of bag dipping. The fruit parameters were taken from Wang *et al.* (2001) assuming lychee to be comparable with cherry.

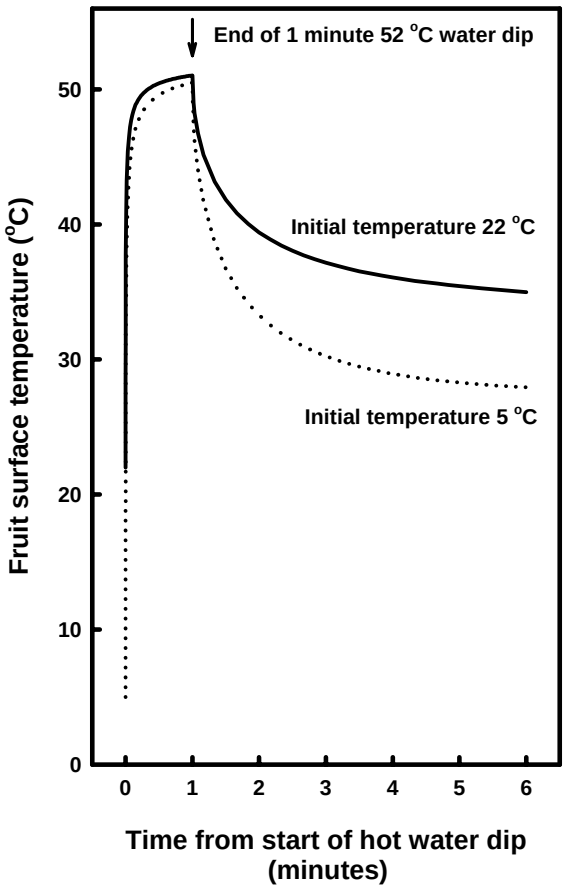
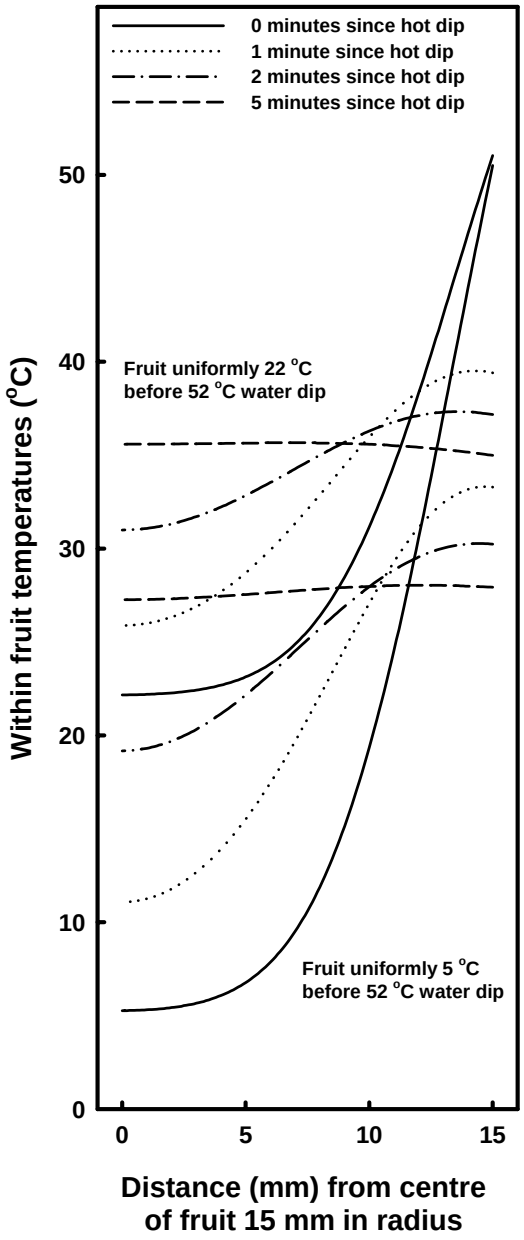


Fig.7.7. Temperature profiles at various times following the hot water dips for the fruit in the Fig. 6 simulation. Fruit with initial temperatures of 5 or 22 °C were dipped for 1 minute in 52 °C water and subsequently held still in 22 °C air with no forced-air currents.



8. Effect of fruit maturity on rot development in lychee

8.1 Overview

Fruit of "Wai Chee" were harvested and sorted into three levels of maturity on the bases of colour (from green/red through to deep plum) and pericarp topography (increasing smoothness) and designated 'unripe', 'ripe' and 'overripe'. The levels were separated by average fruit weight (17.3, 21.9 and 26 g) and by average fruit surface area (3114, 3632 and 3942 mm^2). After 43 days of storage, mostly at 5 °C, the 'unripe' fruit had significantly lower ($P < 0.05$) rot coverage than the 'ripe' or 'overripe' fruit (14.1, 30.1 and 34.2 %, respectively). In terms of rot coverage, the 'ripe' and 'overripe' fruit were not significantly different ($P > 0.05$).

8.2 Introduction

Sittigul *et al*. (1994) found that rot development on the lychee cultivar "Hong Huay" (syn. "Tai So") varied little across three maturity classes of fruit (31-60 %, 61-90 % and 91-100 % red pericarp). However, Pesis *et al*. (2002) found that red fruit of "Mauritius" (syn. "Tai So") harvested early in the season had less decay and better appearance and eating quality than red fruit harvested two to three weeks later.

The current recommendation for the harvest of "Tai So" in Australia is to pick the fruit when the 'colour changes from a bright red to a deep, dull red' and the 'spiky points partially flatten out' (Menzel *et al*. 2002) but in practice the fruit is often picked earlier. Given this, the work by Sittigul *et al*. (1994) is perhaps more pertinent in the Australian context than that of Pesis *et al*. (2002). Indeed, the range of the mean sugar to acid ratios in the Pesis *et al*. (2002) study was 60-125, which is very high by Australian standards whereby fruit are deemed to be mature at a ratio of *ca* 40 (Batten 1989; Underhill and Wong 1990).

For a perishable crop that matures in a narrow window, there are practical benefits in knowing the limits to harvest time in terms of managing labour and throughput. For this reason we ran a pilot study into the effects of fruit maturity on postharvest rot development. "Wai Chee" was chosen for study out of expediency. It was the only variety for which a large range of maturity levels could be found in the commercial orchards we visited.

8.3 Materials and methods

Three maturity levels were defined for "Wai Chee": 'unripe', where the fruit were small, had pointy protuberances and were red with patches of green; 'ripe', where the protuberances had largely flattened and the pericarp colour was red-purple; and 'overripe', where the protuberances were flatter still and the pericarp was a deep plum.

Thirty two fruit of each maturity were picked at Bungundarra (23 °S) on January 9, 2001. The fruit were singly placed in MEA chippettes (cylindrical polypropylene containers 45 mm diameter x 24 mm deep) and double-wrapped in 14 μm Bunzl vitafilm (PVC). The fruit were stored at 5 °C until February 21, 2001, except for 8 hours at 15 °C when the fruit were transported from Bungundarra to Brisbane.

Additional fruit were harvested with panicle branches attached for the determination of water potentials with a pressure bomb.

On February 21 the fruit were rated for fresh weight, fruit dimensions (length, breadth, width) and rot dimensions (length, breadth). The surface area of each fruit was estimated by assuming that the measured fruit dimensions were the lengths of the major axes of an irregular ellipsoid (Lang 1991). Each rot area was estimated by assuming that the length and breadth measurements were the major and minor axes of an ellipse. Percent rot coverage was based on the ratio of the total rot area per fruit to the total surface area of the fruit. The three maturity levels were compared by analysis of variance.

8.4 Results

The mean water potential of the fruit at the commencement of the experiment, based on 21 fruit, was 0.16 MPa with a standard error of 0.02 MPa. The remaining results are summarized in Table 8.1. The fruit of the three maturity levels were significantly different in size, both in terms of fresh weight and surface area ($P < 0.05$). At assessment the least mature fruit had significantly less rot coverage ($P < 0.05$) than the other fruit. There was not a significant difference in rot coverage between the two most mature classes of fruit ($P > 0.05$).

8.5 Discussion

The main finding was that fruit both ‘ripe’ and ‘overripe’ had similar rates of rot development. The ‘overripe’ fruit were almost 20 % larger than the ‘ripe’ fruit. If these results can be interpolated then the susceptibility to rot development varies little over a wide range of fruit maturities. Susceptibility to rots is, however, only one criterion of fruit quality, and other criteria, such as sugar and acid content (Batten 1989), flavour (Ong and Acree 1998) and fermentation products (Pesis *et al*. 2002), need to be investigated.

Another finding of note was that ‘unripe’ fruit were less susceptible to rot development than ‘ripe’ or ‘overripe’ fruit. The reason for the lower susceptibility is unclear. Underhill and Critchley (1992) found a progressive thinning of the pericarp cuticle during fruit development, so that ‘unripe’ fruit may have had a greater physical barrier to infection at the fruit surface than the ‘ripe’ or ‘overripe fruit, but there is a raft of other constitutive changes during fruit development (see Holcroft and Mitcham (1996) for examples) that might also affect susceptibility.

In the work there may have been interactions between fruit size and the packaging, the larger fruit, for example, possibly having greater relative direct contact with the vitafilm than the smaller fruit, but what effect these interactions might have had on the results is unclear.

Table 8.1. Fruit size and rot coverage for three maturity classes of "Wai Chee" after 43 days of postharvest storage, mostly at 5 °C. Thirty two fruit were selected for each class, but one fruit from the 'overripe' class was subsequently discovered to be 'stung' and was omitted from the analyses.

Maturity	Fresh weight (g)		Surface area (mm^2)		Rot coverage (%)	
	Mean	S.E.	Mean	S.E.	Mean	S.E.
'Unripe'	17.3	0.3	3114	42	14.1	3.4
'Ripe'	21.9	0.4	3632	52	30.1	4.7
'Overripe'	26	0.4	3942	42	34.2	5

9. Maturity indicators for lychee

9.1 Overview

Ripe and unripe fruit of the lychee cultivar "Kwai May Pink" were assessed for fresh weight, pericarp colour and smoothness, aril acidity and soluble solids (Brix), and seed density. There were significant correlations ($P < 0.01$) of seed density, fruit fresh weight, and pericarp colour (*L*, *chroma* and *hue angle*) with the Brix-acid ratio of the aril, the standard quantitative maturity index for lychee in Australia. The results are discussed in terms of the development of lychee fruit.

9.2 Introduction

The Brix-acid ratio is the standard quantitative maturity index for lychee in Australia (Batten 1989; Underhill and Wong 1990). However, it is very time consuming to calculate and not practical for large scale assessments of fruit quality. Here we examine the use of seed density as an alternative index with respect to "Kwai May Pink". Seed density is very easy to measure, requiring only the weight of the seed in air and the weight of the seed when suspended in a low density medium of known specific gravity.

The rationale is that viable seeds of lychee are somewhat oily; oils or fatty acids have a lower density than the other major seed components; and oil accumulation is likely to occur in the final stages of seed development. Therefore the seed density is expected to decrease as fruit mature.

Fresh weight and pericarp smoothness and colour were also measured to place the variation in the Brix-acid ratio and seed density in a broader context of fruit development.

9.3 Materials and methods

Thirty five fruit of "Kwai May Pink" were picked from a number of trees in a commercial orchard at Brooklet (28.7 °S 153.5 °E). The fruit were growing in shady positions in the lower parts of the tree canopies. The fruit were immediately ranked according to the smoothness of the pericarp, weighed and colour scanned with a Minolta Chroma Meter (C-R 200) in terms of *L*, *chroma* and *hue angle*. Two colour measurement taken per fruit, from opposite sides of the fruit, perpendicular to both the suture line and the longitudinal axis, and averaged.

The fruit were then transported to the CSIRO Longpocket Laboratory in Brisbane where each fruit was separated into pericarp (discarded), aril and seed. The aril was crushed to extract the juice. The Brix angle of the juice was measured with a refractometer and is a measure of the soluble solid content. The acidity of the juice was measured by titration against NaOH to an endpoint of pH 8.22, and converted to a malic acid equivalent by assuming a 1 M solution of NaOH neutralizes an equal volume of a 0.5 M malic acid solution.

The seed was weighed in air and again while suspended in a 95 % ethanol solution. Seed density (ρ_s) was estimated from these measurements as:

$$\rho_s = \rho_e \times w_a / (w_a - w_e)$$

where, ρ_e was the specific gravity of 95 % ethanol
w_a was the seed weight measured in air
w_e was the seed weight when suspended in 95 % ethanol

The strengths of relationships were assessed using Pearson's product moment correlation coefficient. Lines were fitted using principal component analysis.

9.4 Results

There were significant correlations ($P < 0.01$) of seed specific gravity, whole fruit fresh weight, *L*, *chroma* and *hue angle* against the Brix-acid ratio (Fig. 9.1). There was a weak, non-significant ($P = 0.46$) tendency for the smoother fruit to have a higher Brix-acid ratio (Fig.9.1).

9.5 Discussion

Seed density was strongly correlated with the Brix-acid ratio of the aril, but only accounted for 27 % of the Brix-acid ratio variance. Whether the relationship was linear or curvilinear is not clear.

Seed density is quick to measure. Thirty four seeds were assessed in the time taken for a single Brix-acid measurement.

Seed density has potential as a maturity index but there needs to be further work before it can be recommended as such, especially in terms of aril taste and the robustness of the technique over a range of within and between orchard environments.

The oil content of mature lychee seeds is not known. Assuming that the proportions of the non-oil components of lychee seed changed little over the range of maturities examined and that lychee oils have a specific gravity of approximately 0.9 then, using the two limits of the fitted line to the density against Brix-acid ratio relationship (Fig. 1), the oil content of the most mature seed was 10 % greater than that of the least mature seeds.

Unusual fatty acids have been found in high concentrations in other members of the Sapindaceae and may have commercial potential (Spitzer 1996). Knowing the percent oil content and fatty acid profiles of lychee seeds may lead to a commercial purpose for the high proportion of spoiled fruit currently discarded by industry.

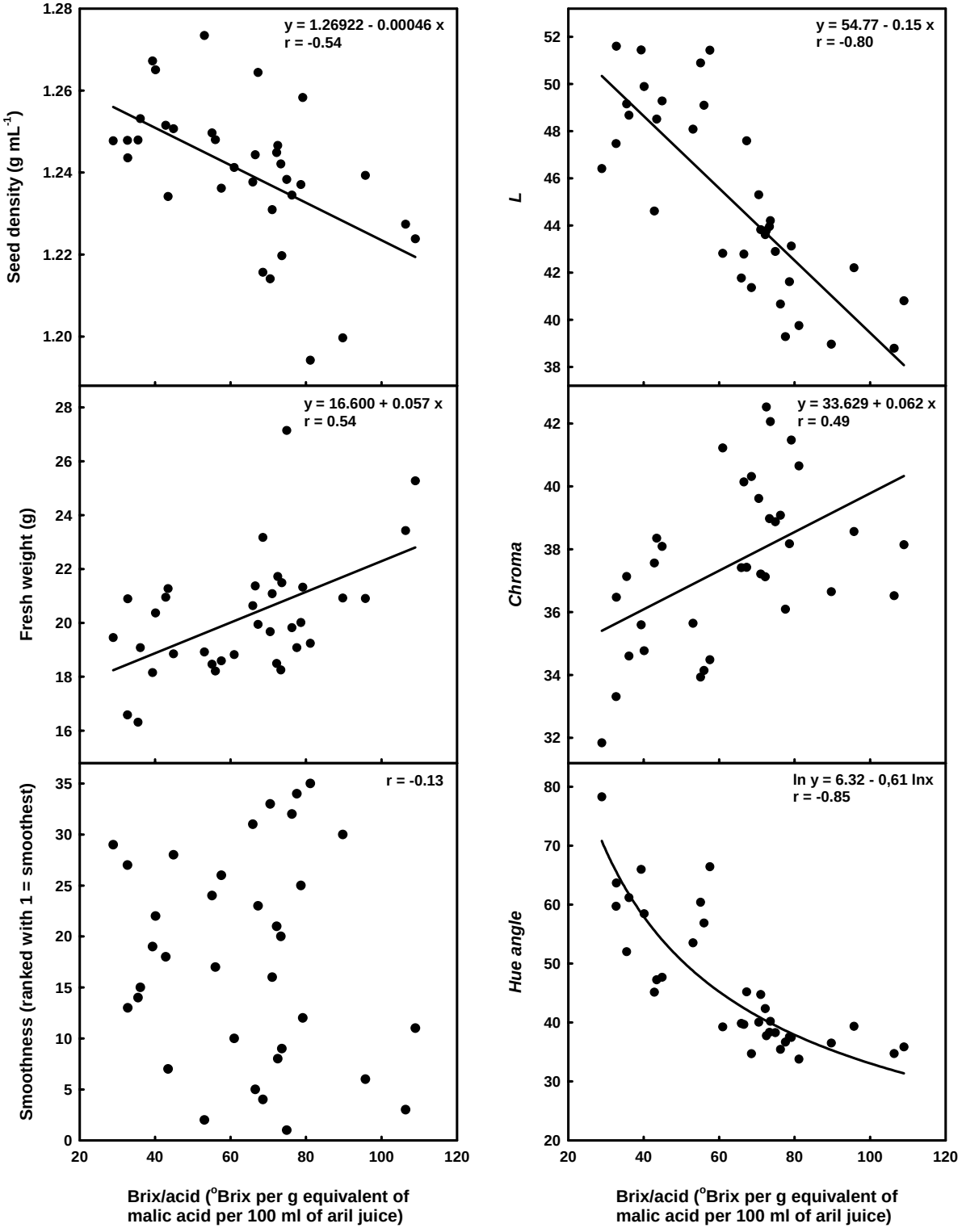
There were no ‘chicken tongue’ seeds (small and infertile) in our selection. Such seeds are likely to have different constitutions.

Fresh weight was as well correlated with the Brix-acid ratio as seed density (Fig.9.1) but more generally is a highly variable characteristic, affected by temperature and water stress (Kumcha 1998) and by cultural practices (Menzel *et al*. 2000), and is unlikely to be a good criterion for maturity in itself.

The best correlations were with fruit colour (Fig. 9.1) but as with fresh weight fruit coloration is highly dependent on the environment. The intensity and spectral quality of incoming solar radiation seems to be particularly important. There is little red colour development in the pericarp of fruit that is deeply shaded (Hu *et al*. 2001), but light shading gives rise to the reddest fruit (Tyas *et al*. 1998; Hu *et al*. 2001; Tomer *et al*. 2001). Anthocyanin are important determinants of the redness of the lychee pericarp (Sarni-Manchado *et al*. 2000) and anthocyanin production in other species has been shown to be affected by ultraviolet radiation and the ratio of red to far red irradiation (Schichijo *et al*. 1993; Brandt *et al*. 1995), as well as a number of other factors. The redness (*hue angle*) of the lychee pericarp has been correlated with the activity phenylalanine lyase (Hu *et al*. 2001), an enzyme involved in anthocyanin synthesis, but more work is needed on the role of radiation in the production and regulation of anthocyanin-related enzymes and in the turnover of anthocyanins.

Anthocyanins only accumulate in large quantities in the lychee pericarp late in fruit development (Underhill and Critchley 1992; Wang *et al*. 2001) but the regulation of the process is poorly understood.

Fig.9.1. A range of fruit characteristics expressed against the Brix-acid ratio, the standard quantitative maturity index for lychee in Australia. The sample size for the seed density graph was 34. For the other graphs the sample size was 35.



10. Effects of a commercial packing line on postharvest rot development

10.1 Overview

Fruit were sampled at various stages along a commercial lychee packing line, stored at 5 °C for six weeks then assessed for rot coverage. The least infected fruit was that which was sampled immediately prior to the packing line. The most infected fruit was that sampled at the end of the packing line, after the fruit had been hand-destalked, sorted and hydrocooled. This is the first assessment of a commercial lychee packing line. More studies are needed to work out ways in which handling practices might be improved to reduce the risk of contamination.

10.2 Introduction

We provide the first assessment of how various stages in a commercial lychee packing line affect the storage life of fruit. The line in question involved hand-destalking, sorting on a conveyor, hydrocooling and packing. Our criterion for assessment was the postharvest development of rots.

10.3 Materials and methods

Fruit from seven picking buckets were tracked through a commercial packing line and sampled at four stages: (1) directly from the bucket as it arrived in the shed; (2) immediately after destalking; (3) immediately after sorting and; (4) immediately after hydrocooling, which was immediately prior to packing.

For each bucket nine fruit were collected at each stage. Stung fruit were discarded and substituted with other fruit, otherwise the fruit were not sorted. Each fruit was placed in its own polypropylene cup (45 mm diameter x 24 mm deep) and double-wrapped in 14 μm Bunzl vitafilm (PVC). The fruit were then packed into commercial blueberry cartons and stored at 5 °C.

After six weeks of storage the fruit were rated on a five point scale of rot coverage: 1 = no rots; 2 = >0 to 25 % rots; 3 = >25 to 50 % rots; 4 = >50 to 75 % rots; 5 = > 75 to 100 % rots.

The results were analysed by two way analysis of variance (ANOVA), bucket by stage.

10.4 Results

After six weeks of storage there were significant differences (ANOVA $P < 0.05$) in the rot coverage of fruit according to the picking bucket that the fruit came from and the packing line stage the fruit were sampled at (Table 10.1). More technically, there were ‘bucket’, ‘stage’ and ‘bucket by stage interaction’ effects. Converting the ‘stage’ results from the five point scale to percent rot coverage, using the mid-points of the scale ranges, gave 15, 21, 18 and 22 % rot coverage for stages 1 to 4, respectively. In other words the least infected fruit was that sampled at the beginning of the packing line while the most infected fruit was that sampled at the end. Destalking (prior to stage 2) and hydrocooling (prior to stage 4) seemed to increase infection, but sorting (prior to stage 3) may have reduced it.

Table 10.1. The rot coverage of fruit from seven picking buckets and four handling stages along a commercial packing line assessed after six weeks of storage at 5 °C. Rot coverage was assessed using a five-point scale: 1 = no rots; 2 = >0 to 25 % rots; 3 = >25 to 50 % rots; 4 = >50 to 75 % rots; 5 = > 75 to 100 % rots. The results are taken from a two way ANOVA with nine fruit at each of the bucket by stage combinations.

Bucket	Mean	Stage	Mean
1	1.69	1	1.94
2	2.28	2	2.24
3	1.92	3	2.11
4	2.69	4	2.32
5	2.81		
6	1.89		
7	1.78		
Standard error of least square mean	0.11		0.08

10.5 Discussion

Ours was essentially a pilot study and mostly raises questions and begs further research.

Centralised hand-destalking caused an increase in infection (Table 10.1) but whether the increase could have been mitigated by harvesting the fruit individually instead of on the panicle is unknown.

Sorting seemed to reduce infection (Table10.1) which is consistent with the idea that broken fruit are more likely to rot

In Chapter 3 hydrocooling was shown to have a detrimental effect on the refrigerated storage of lychee, and this is consistent with what we observed here (Table10.1). It should be emphasised, however, that our results do not show that hydrocooling was necessarily a liability in the commercial context of the farm we studied. The commercial fruit was packed differently from the experimental fruit and air-freighted on the day of harvest, so it had a very different post-packing thermal history.

In assessing the worth of hydrocooling consideration needs to be given to whether any effects are caused by cooling *per se* or by rehydration of the fruit (Chapters 3 and 4) or by humidity levels within the packaging.

In general, packing lines might be improved by incorporating hot water pasteurization systems (Chapter 7) and minimal handling protocols, but further work is needed to clarify the matter.

11. Heat and acid treatments

11.1 Overview

The red pericarp of lychee fruit is prone to browning. We examined the potential of a range of hot water-acid treatments to stabilize the pericarp colour of "Kwai May Pink" and "Wai Chee". A pH 0 HCl dip alone was largely effective but unsatisfactory because of small patches of discoloured pericarp that probably resulted from uneven penetration by the acid. Pretreatments with hot water dips from 3 seconds at 80 °C to 6 seconds at 100 °C were all effective in giving even colouration. Of the pretreatments studied 3 seconds at 80 °C is to be preferred because it is likely to cause less damage to the fruit.

The colour is not fixed but subject to gradual browning. The browning of the treated fruit seems to be qualitatively different from that of the control fruit.

The worth of the technology is questionable. The colour of the treated fruit is unnatural and there are dangers that the treated fruit would have higher rates of water loss and rot development than untreated fruit. There is also a marketing danger in potentially passing a substandard product off onto the public.

11.2 Introduction

Lychee is prone to rapid postharvest browning of the pericarp. Brown fruit is less appealing than red fruit to consumers and therefore less marketable. For this reason hot water/acid treatments (Kaiser 1995; Tongdee *et al*. 1998; Tait and Kruger 1999; Lichter *et al*. 2000) are sometimes used to make the pericarp red colourfast.

The basic principles are simple. Anthocyanins, primarily located in the vacuoles of the cells in the outer layers of the pericarp (Underhill and Critchley 1993), are pigments that impart a range of reddish colours to the fruit. The coloured anthocyanins are in a pH dependent equilibrium with colourless chromenols, with the equilibrium favouring anthocyanins under acid conditions (Underhill and Critchley 1994; Kaiser 1995). Browning results from decompartmentalization of the pericarp cells, caused by aging or environmental stress, that probably results in a rise in the pH of the vacuole, with a consequent decolourization of anthocyanins, and the breakdown of various cell constituents to brown-coloured byproducts (Underhill and Critchley 1994; Kaiser 1995).

Acid treatment subverts this process by lowering the pH of the pericarp (Zauberman *et al*. 1991; Lichter *et al*. 2000) favouring the expression of anthocyanin colour (Ketsa and Leelawatana 1992; Underhill and Critchley 1994; Duvenage *et al*. 1995; Kaiser 1995; Tait and Kruger 1998; Tongdee *et al*. 1998; Tait and Kruger 1999; Lichter *et al*. 2000; Moran 2000). Pretreatments with hot water (Kaiser 1995; Tongdee *et al*. 1998; Tait and Kruger 1999) or hot water/scouring (Lichter *et al*. 2000; Moran 2000) seem to facilitate the penetration of acid, at least in some cultivars. In addition, the acid has been shown to reduce polyphenol oxidase activity (Zauberman *et al*. 1991; Lichter *et al*. 2000).

Pericarp structure varies between cultivars (Sarn-Manchado *et al*. 2000; Huang *et al*. 2001; Li *et al*. 2001) and hot water/acid treatments need to be tailored accordingly (Kaiser 1995; Tongdee *et al*. 1998; Tait and Kruger 1999).

No work has been done on the principal Australian cultivar "Kwai May Pink" and only a little work on the effects of heat treatment on electrolyte leakage for another Australian cultivar "Wai Chee" (syn. "Kim Cheng"; Tongdee *et al*. 1998). The pericarp of "Kwai May Pink" is light pink at maturity while that of "Wai Chee" is plum. The two cultivars are studied here both for the need for characterization and for the interest in the contrast.

We are particularly interested in the effects on colour and rot development. The previous work on colour has relied on visual assessment (Zauberman *et al*. 1991; Ketsa and Leelawatana 1992; Duvenage *et al*. 1995; Kaiser 1995; Tait and Kruger 1998; Tait and Kruger 1999; Lichter *et al*. 2000; Moran 2000) or the Hunter *a* value (an index of 'redness'; Underhill and Critchley 1994; Tongdee *et al*. 1998) or the absorbance at 527 nm of anthocyanin extracts (Ketsa and Leelawatana 1992) and there is a danger in such reports that the effects on pericarp colour have been oversimplified. The stability of the colour change also warrants greater scrutiny in that Ketsa and Leelawatana (1992) found that the absorbance at 527 nm of anthocyanin extracts from acid treated fruit declined over time.

Acid and hot water/acid treatments have been shown to slow postharvest rot development in some experiments (Tait and Kruger 1998; Tait and Kruger 1999) but Lichter *et al*. (2000), using a hot water pretreatment of a lower temperature and longer duration than other workers that was also coupled with scouring, found no inhibition. In the technology there is likely to be a balance between the pasteurization of the pericarp by the heat/acid treatments and the enrichment of the microbial environment caused by damage to the pericarp cells.

11.3 Materials and methods

One hundred and two fruit of "Kwai May Pink" were harvested from several trees in a commercial orchard at Brooklet (28.7 °S 153.5 °E) on March 11, 2000. The fruit were bulked and randomly sorted into 17 groups of 6 and colour scanned for *L*, *chroma* and *hue angle* using a Minolta Chroma Meter (CR 200) with two colour measurement taken per fruit, from opposite sides of the fruit approximately perpendicular to both the suture line and the longitudinal axis. Each fruit was placed into an open weaved plastic bag, one fruit per bag, and hydrocooled to 5 °C. The groups were then treated according to the list in Table 1. Water for the hot water treatments was placed into 30 L stainless steel pots and brought to temperature over a gas burner. Treatments were applied by immersing and agitating the bagged fruit in the heated water in the pots. Hydrochloric acid solutions of pH 0 or 1 were made up to 5 L in 10 L plastic buckets. Other buckets were half filled with water. The fruit treated with acid were dipped for 4 minutes, bagged. The fruit rinsed in water were dipped for 1 minute. For fruit both heat treated and acid treated or both acid treated and water rinsed the second treatment immediately followed the first. After treatment the fruit were blotted dry an individually placed into MEA chippettes (cylindrical polypropylene cups 45 mm diameter x 24 mm deep). Each chippette with its single fruit was then double-wrapped in 14 μm Bunzl vitafilm (PVC) and placed in a 5 °C incubator. The whole rigmarole was repeated for "Wai Chee" on the same day.

One day later all the fruit all the fruit were removed from the incubator, unwrapped and colour scanned for a second time. The fruit were then re-wrapped and returned to the incubator.

Thirty three days after harvest the "Wai Chee" were again removed, and assessed for colour, turgor and rot coverage. Turgor was measured in terms of the change in displacement of a Mitutoyo (ID-C1012MB) penetrometer probe between 10 and 30 seconds after the placement of the probe on the fruit at the same location as for the colour measurements. Rot coverage was calculated by summing the individual rot areas on the surface of the fruit and expressing the sum as a fraction of the total surface area. Each rot area was estimated by measuring the length and breadth of the rot, assuming that these measurements represented the major and minor axes of an ellipse. The surface area of the fruit was estimated by measuring the length, breadth and width, assuming that these measurements represented the axes of an irregular ellipsoid (Lang 1991). Forty days after harvest the "Kwai May Pink" were similarly assessed.

11.4 Results and discussion

Unless otherwise stated the treated fruit are discussed relative to the control fruit. The rot coverage data is summarized in Table 11.1, penetrometer readings in Table 11.2 and colour values in Table 11.3a and b.

Table 11.1. Effects of various hot water-acid treatments on lychee postharvest rot development. Fruit were treated on the day of harvest and subsequently stored at 5 °C. The fruit of "Kwai May Pink" were assessed 40 days postharvest, "Wai Chee" 33 days postharvest. For each treatment there was a sample size of six. Acid dips were for 4 minutes, water rinses for 1 minute.

Treatment	Rot coverage (%)			
	Kwai May Pink		Wai Chee	
	Mean	Std error	Mean	Std error
Control (no heat, no acid)	2.06	1.09	0.00	0.00
pH 0 dip	40.20	18.96	14.55	2.77
pH 0 dip followed by water rinse	2.79	1.28	4.55	0.92
pH 1 dip	2.08	1.98	6.43	2.52
pH 1 dip followed by water rinse	3.07	1.38	1.53	0.81
3 seconds 80 °C water dip followed by pH 0 dip	6.79	1.31	9.80	4.20
3 seconds 80 °C water dip followed by pH 1 dip	2.40	1.88	1.95	1.56
6 seconds 80 °C water dip followed by pH 0 dip	2.13	0.82	2.62	0.88
6 seconds 80 °C water dip followed by pH 1 dip	2.06	0.87	0.99	0.71
3 seconds 90 °C water dip followed by pH 0 dip	13.90	12.19	32.01	15.15
3 seconds 90 °C water dip followed by pH 1 dip	19.84	4.53	0.03	0.03
6 seconds 90 °C water dip followed by pH 0 dip	3.45	2.05	3.59	2.35
6 seconds 90 °C water dip followed by pH 1 dip	34.92	3.62	1.15	0.45
3 seconds 100 °C water dip followed by pH 0 dip	5.38	1.80	3.08	2.43
3 seconds 100 °C water dip followed by pH 1 dip	36.66	5.03	1.86	0.85
6 seconds 100 °C water dip followed by pH 0 dip	4.89	3.32	1.73	0.86
6 seconds 100 °C water dip followed by pH 1 dip	34.29	15.34	17.82	3.15

Table 11.2. Effects of various hot water-acid treatments on the relaxation of lychee fruit under a standard mechanical load. Fruit were treated on the day of harvest and subsequently stored at 5 °C. The fruit of "Kwai May Pink" were assessed 40 days postharvest, "Wai Chee" 33 days postharvest. For each treatment there was a sample size of six. Acid dips were for 4 minutes, water rinses for 1 minute.

Treatment	Penetrometer (microns deflection)			
	Kwai May Pink		Wai Chee	
	Mean	Std error	Mean	Std error
Control (no heat, no acid)	57	11	78	8
pH 0 dip	142	16	140	18
pH 0 dip followed by water rinse	148	13	90	14
pH 1 dip	65	8	95	19
pH 1 dip followed by water rinse	107	24	75	12
3 seconds 80 °C water dip followed by pH 0 dip	163	23	128	8
3 seconds 80 °C water dip followed by pH 1 dip	80	12	82	18
6 seconds 80 °C water dip followed by pH 0 dip	153	15	105	23
6 seconds 80 °C water dip followed by pH 1 dip	110	10	42	3
3 seconds 90 °C water dip followed by pH 0 dip	117	8	138	28
3 seconds 90 °C water dip followed by pH 1 dip	88	17	52	5
6 seconds 90 °C water dip followed by pH 0 dip	148	17	162	16
6 seconds 90 °C water dip followed by pH 1 dip	92	17	52	11
3 seconds 100 °C water dip followed by pH 0 dip	125	15	148	11
3 seconds 100 °C water dip followed by pH 1 dip	72	10	52	8
6 seconds 100 °C water dip followed by pH 0 dip	128	12	153	18
6 seconds 100 °C water dip followed by pH 1 dip	103	22	70	7

Table 11.3a. Effects of various hot water-acid treatments on the pericarp colour of lychee. Fruit were treated on the day of harvest and subsequently stored at 5 °C. Colour scans were taken on the day of harvest prior to treatment, then again 24 hours after treatment. The final scans for "Kwai May Pink" were taken 40 days postharvest. Two scans were taken on each fruit and averaged. There were six fruit per treatment. Acid dips were for 4 minutes, water rinses for 1 minute.

Treatment	Kwai May Pink					
	L		*Chroma*		*Hue angle*	
	Mean	Std error	Mean	Std error	Mean	Std error
Control (no heat, no acid)						
Harvest	44.0	0.9	38.7	0.4	41.3	1.9
24 hours postharvest	42.2	0.8	39.3	0.6	40.4	1.8
40 days postharvest	37.6	0.7	32.4	1.4	43.9	2.4
pH 0 dip						
Harvest	42.7	0.8	37.3	0.5	39.9	1.3
24 hours postharvest	47.9	0.9	38.3	0.2	41.0	1.5
40 days postharvest	45.1	0.8	28.9	1.0	55.3	1.3
pH 0 dip followed by water rinse						
Harvest	42.7	1.0	38.5	0.5	37.9	1.4
24 hours postharvest	40.3	0.8	29.3	0.9	42.3	1.8
40 days postharvest	36.1	0.7	21.3	0.5	55.5	1.3
pH 1 dip						
Harvest	45.4	0.6	37.3	0.5	45.6	1.6
24 hours postharvest	44.0	0.5	37.3	0.8	48.1	1.6
40 days postharvest	39.5	1.3	30.2	1.4	49.9	1.1
pH 1 dip followed by water rinse						
Harvest	43.3	0.6	37.7	0.5	39.8	1.2
24 hours postharvest	41.4	0.8	38.0	0.8	41.8	1.7
40 days postharvest	35.3	1.2	25.2	2.5	47.6	2.4
3 seconds 80 °C water dip followed by pH 0 dip						
Harvest	43.0	0.7	38.9	0.3	38.3	0.9
24 hours postharvest	47.5	1.1	42.9	0.8	40.7	1.4
40 days postharvest	47.6	1.6	36.2	0.7	53.9	2.5
3 seconds 80 °C water dip followed by pH 1 dip						
Harvest	42.4	0.5	37.9	0.6	38.4	0.9
24 hours postharvest	32.4	0.7	25.8	0.4	43.6	0.5
40 days postharvest	29.7	0.4	19.5	0.3	51.5	0.7
6 seconds 80 °C water dip followed by pH 0 dip						
Harvest	42.6	0.6	37.8	0.3	39.6	1.5
24 hours postharvest	47.5	0.7	41.1	0.3	41.4	1.3
40 days postharvest	47.8	1.4	34.7	0.7	54.7	2.0
6 seconds 80 °C water dip followed by pH 1 dip						
Harvest	42.8	0.4	38.0	0.3	39.2	0.9
24 hours postharvest	30.8	0.4	21.1	0.5	46.0	0.7
40 days postharvest	30.5	0.3	19.8	0.3	52.8	0.3
3 seconds 90 °C water dip followed by pH 0 dip						
Harvest	43.6	0.4	38.3	0.3	38.9	0.8
24 hours postharvest	48.0	0.6	40.1	0.8	40.8	1.2
40 days postharvest	46.9	1.7	31.7	1.7	55.5	1.3
3 seconds 90 °C water dip followed by pH 1 dip						
Harvest	44.9	0.7	38.2	0.5	41.7	1.0
24 hours postharvest	35.1	0.5	25.4	0.6	45.6	1.3
40 days postharvest	35.5	0.5	17.8	0.9	58.9	1.0
6 seconds 90 °C water dip followed by pH 0 dip						
Harvest	44.4	0.8	37.9	0.8	42.3	2.2
24 hours postharvest	49.7	0.6	40.0	0.2	45.1	1.7
40 days postharvest	49.2	1.4	33.4	0.9	59.8	1.8
6 seconds 90 °C water dip followed by pH 1 dip						
Harvest	42.9	0.8	38.1	0.4	39.8	1.3
24 hours postharvest	38.7	0.6	25.3	0.6	49.7	1.5
40 days postharvest	38.9	0.6	20.6	0.9	64.1	0.8
3 seconds 100 °C water dip followed by pH 0 dip						
Harvest	43.8	0.5	38.3	0.7	40.1	1.5
24 hours postharvest	49.2	0.8	40.1	0.4	41.2	1.5
40 days postharvest	47.9	1.3	36.0	0.2	52.8	2.1
3 seconds 100 °C water dip followed by pH 1 dip						
Harvest	43.2	0.6	37.8	0.4	40.0	0.9
24 hours postharvest	42.0	0.6	24.0	0.7	54.9	1.1
40 days postharvest	41.4	1.0	21.5	0.6	66.1	1.0
6 seconds 100 °C water dip followed by pH 0 dip						
Harvest	44.1	0.3	37.5	0.6	41.1	1.0
24 hours postharvest	49.3	0.8	41.0	0.5	42.2	1.5
40 days postharvest	49.6	1.0	35.5	0.3	54.2	1.7
6 seconds 100 °C water dip followed by pH 1 dip						
Harvest	43.7	0.4	37.5	0.3	41.2	0.8
24 hours postharvest	44.5	0.2	26.7	0.3	55.2	1.4
40 days postharvest	45.6	1.0	21.4	2.2	67.1	1.1

Table 11.3b Effects of various hot water-acid treatments on the pericarp colour of lychee. Fruit were treated on the day of harvest and subsequently stored at 5 °C. Colour scans were taken on the day of harvest prior to treatment, then again 24 hours after treatment. The final scans, for "Wai Chee" 33 days postharvest. Two scans were taken on each fruit and averaged. There were six fruit per treatment. Acid dips were for 4 minutes, water rinses for 1 minute.

Treatment	WAI CHEE					
	L		*Chroma*		*Hue angle*	
	Mean	Std error	Mean	Std error	Mean	Std error
Control (no heat, no acid)						
Harvest	34.1	0.8	33.7	1.1	25.3	0.5
24 hours postharvest	33.1	0.8	32.5	1.0	28.4	0.8
33 days postharvest	29.3	0.8	27.4	1.4	30.8	0.7
pH 0 dip						
Harvest	35.5	0.8	35.3	1.4	25.8	0.5
24 hours postharvest	39.4	0.9	42.6	0.4	25.5	0.6
33 days postharvest	42.9	1.1	33.3	2.9	34.6	3.3
pH 0 dip followed by water rinse						
Harvest	34.1	0.5	32.9	1.3	25.5	1.1
24 hours postharvest	36.1	0.9	34.0	2.0	24.9	0.8
33 days postharvest	39.8	1.3	21.7	1.2	54.1	1.5
pH 1 dip						
Harvest	33.9	0.5	34.0	1.0	25.1	0.3
24 hours postharvest	32.6	0.3	31.3	1.5	30.2	0.7
33 days postharvest	30.7	0.5	24.9	1.9	33.7	1.4
pH 1 dip followed by water rinse						
Harvest	34.0	0.6	35.4	1.1	25.2	0.9
24 hours postharvest	33.0	0.7	31.4	1.3	29.9	0.9
33 days postharvest	31.1	0.4	23.5	1.5	35.0	1.8
3 seconds 80 °C water dip followed by pH 0 dip						
Harvest	33.8	0.3	32.3	1.1	24.9	0.7
24 hours postharvest	36.9	0.5	43.3	0.5	25.0	0.4
33 days postharvest	39.0	0.6	35.9	1.3	30.1	0.9
3 seconds 80 °C water dip followed by pH 1 dip						
Harvest	33.6	0.6	32.8	1.1	25.2	0.5
24 hours postharvest	27.7	0.6	25.3	1.0	33.0	0.7
33 days postharvest	27.6	0.5	18.4	0.5	46.5	0.7
6 seconds 80 °C water dip followed by pH 0 dip						
Harvest	33.4	0.5	31.9	1.2	24.7	0.6
24 hours postharvest	36.6	0.6	43.3	0.6	25.8	0.5
33 days postharvest	39.5	1.1	36.6	2.0	33.4	3.4
6 seconds 80 °C water dip followed by pH 1 dip						
Harvest	33.1	0.3	32.0	1.0	24.8	0.6
24 hours postharvest	25.9	0.3	20.1	0.4	34.4	0.4
33 days postharvest	27.8	0.4	18.3	0.1	46.7	0.4
3 seconds 90 °C water dip followed by pH 0 dip						
Harvest	34.8	0.7	35.0	0.7	25.2	1.0
24 hours postharvest	41.0	1.5	46.4	0.5	27.7	1.1
33 days postharvest	39.9	1.6	26.5	2.8	39.2	1.9
3 seconds 90 °C water dip followed by pH 1 dip						
Harvest	34.1	0.6	31.8	1.0	27.5	1.3
24 hours postharvest	28.5	0.8	20.8	0.9	35.7	1.3
33 days postharvest	28.9	0.5	18.8	0.5	48.7	0.8
6 seconds 90 °C water dip followed by pH 0 dip						
Harvest	36.4	1.1	36.1	1.5	25.8	0.9
24 hours postharvest	37.4	0.9	43.0	0.9	25.9	0.7
33 days postharvest	43.4	1.8	38.2	0.7	33.6	1.6
6 seconds 90 °C water dip followed by pH 1 dip						
Harvest	33.6	0.9	32.4	1.2	24.7	0.7
24 hours postharvest	31.1	0.4	20.1	1.0	30.9	2.0
33 days postharvest	33.3	0.7	18.4	0.5	53.8	1.3
3 seconds 100 °C water dip followed by pH 0 dip						
Harvest	34.8	0.2	34.0	0.7	25.8	0.9
24 hours postharvest	39.3	0.6	45.1	0.5	26.7	0.4
33 days postharvest	41.9	1.0	40.8	1.1	31.1	0.4
3 seconds 100 °C water dip followed by pH 1 dip						
Harvest	34.1	0.7	33.5	0.7	24.7	0.6
24 hours postharvest	33.5	0.6	20.6	0.5	32.6	1.4
33 days postharvest	36.2	0.8	19.3	0.9	58.0	1.2
6 seconds 100 °C water dip followed by pH 0 dip						
Harvest	34.8	0.9	33.8	1.9	25.6	0.5
24 hours postharvest	40.4	1.2	45.8	1.0	27.7	0.6
33 days postharvest	42.0	1.6	39.9	1.0	34.0	1.3
6 seconds 100 °C water dip followed by pH 1 dip						
Harvest	35.1	0.5	34.0	0.6	27.4	1.2
24 hours postharvest	35.6	0.4	23.5	0.8	32.8	0.9
33 days postharvest	40.7	0.5	19.8	0.6	61.2	1.2

Control fruit

The fruit of "Kwai May Pink" were pink at harvest while those of "Wai Chee" were red to red purple. Across several weeks both cultivars showed the typical postharvest colour decline (browning), with decreases in *L* and *chroma* and an increase in *hue angle* (Chapter 7).

pH 0 dip

The pH 0 HCl dip promoted rot development, presumably by damaging the pericarp cells (at least), increasing the availability of substrates to the microbes. The penetrometer probe relaxed more deeply into the acid treated fruit, consistent with greater water loss or structural damage (e.g. to the cross-linkages in the cell wall). For both "Kwai May Pink" and "Wai Chee" the acid caused an immediate increase in the *L* value (brightness) of the fruit. The only other immediate change was an increase in the *chroma* (saturation of colour) of "Wai Chee". In terms of perception, the colour of "Kwai May Pink" had turned a burnt orange and the "Wai Chee" a loud majenta. The colours had a matte finish and were unnaturally even across the surface of the fruit except for small patches of discolouration. The discolouration may reflect uneven acid penetration: patches where there was sufficient acid to damage cells but insufficient acid to change the pH of the protoplasm to the extent needed for anthocyanin colour expression.

For "Kwai May Pink" *L* and *chroma* decreased over several weeks while the *hue angle* increased. For "Wai Chee" the trends were similar except that there was no decrease in *L* (perhaps even an increase). The general trends were broadly similar to those for the controls but the relative magnitudes of the changes were vastly different. On the one hand, the *L* values of the pH 0 treated fruit after several weeks of storage were still higher than those at harvest. On the other, the fruit were much "browner" (lower *chroma*, higher *hue angle*) than the controls. Taken altogether the quality of "brownness" was different between treated and untreated fruit, possibly with high concentration of both coloured anthocyanins and melanins in the former and low concentrations of coloured anthocyanins and high concentrations of melanins in the latter.

pH 0 dip followed by water rinse

The water rinse reduced the effect of the pH 0 dip on rot development and on the relaxation of the fruit under load. These results can be interpreted as meaning that the acid accumulated during the acid dip damaged the pH 0 dipped fruit beyond the dipping time, but the damage was attenuated by the water rinse owing to dilution of the accumulated acid.

The immediate effect of the pH 0/rinse treatment was to cause browning (lower *L*, lower *chroma* and higher *hue angle*) of the "Kwai May Pink" but slight colour enhancement of the "Wai Chee" (higher *L*, higher *chroma* and lower *hue angle*). A number of reasons can be advanced for the cultivar difference, but the anthocyanins of "Kwai May Pink" might have been more peripherally located than those of "Wai Chee" such that relatively more were decoloured by the treatment (the rinse raising the pH of the damaged peripheral cells) and there was relatively less acid enhancement of anthocyanins in deeper layers to compensate.

pH 1 dip and pH 1 dip followed by water rinse

The pH1 dip had little effect on the fruit, presumably because the acid was too weak to substantially disrupt the cell membranes or the membranes' homeostatic functions.

That the fruit of "Wai Chee" were much more infected than those of the controls perhaps just highlights the risk of contamination during handling.

Hot water treatments followed by pH 1 dips

The hot water treatments were clearly disturbing the pericarp cells in that the shortest and lowest temperature dips (3 seconds at 80 °C) caused browning of the pericarp (lower *L* and *chroma*, higher *hue angle*). Interestingly, with progressively more severe temperature treatments the *L* value progressively returned to, then surpassed, the control. Apparently the more severe heat treatments resulted in more severe damage, allowing more cell contents to be washed away, and allowing the weak acid to diffuse more freely through the protoplasm, with effects on the colour expression of the anthocyanins and reactions related to brown pigment development. On all colour criteria the best of the hot water-pH 1 treatments rated poorly against the pH 0 treatment alone.

For "Kwai May Pink" there was generally an increase in rot development with increases in both the temperature and duration of the water dip. "Wai Chee" was slightly different. As with "Kwai May Pink", there was an increase in rot development with an increase in the temperature of the 6 second dips. However, with the 3 second dips if there were any trend at all it would have been for minimum rot development at 90 °C. These results are consistent with the idea of a balance between the pasteurization effects of the hot water-acid treatments and the enrichment of the microbial environment caused by leakage from damaged cells.

In terms of the penetrometer readings, the treatments seem to have had little effect.

Hot water treatments followed by pH 0 dips

The hot water-pH 0 treatments all produced a general change in pericarp colour similar to that described for the pH 0 treated fruit except that there were no patches of discolouration, indicating better penetration of the acid. The magnitude of the immediate changes in *L* tended to be greater at higher temperatures, and more so for "Kwai May Pink" than for "Wai Chee". The cultivar difference may be related to the higher concentration of pigment in "Wai Chee". There was little evidence for other immediate colour trends in relation to the temperature and duration of the water dips.

In terms of the long term changes in colour during storage the value of *L* appeared stable for "Kwai May Pink" but tended to intensify for "Wai Chee". *Chroma* decreased. *Hue angle* increased. There were no other obvious trends.

There were no trends that could be confidently drawn from the rot data. There was a higher prevalence of rots on the treated fruit than on the controls.

As with the pH 0 treated fruit, the hot water-pH 0 treated fruit were softer than the control indicating higher water loss or structural damage.

Conclusion

If the technology were to be pursued the best recommendation at present would be for a 3 second 80 °C water dip followed by a pH 0 HCl dip as this probably achieves the desired effect with minimum damage to the fruit.

However, the colour of the treated fruit is unnatural and there are dangers that the treated fruit would have higher rates of water loss and rot development than untreated fruit. There is also a marketing danger in potentially passing a substandard product off onto the public.

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