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Postharvest Management on Quality Retention of Litchi during Storage

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ABSTRACT

The litchi (*Litchi chinensis* Sonn.) is a tropical to subtropical fruit. It is a popular export commodity due to its attractive skin colour and exotic flavour. The fruit has a rough indehiscent pericarp (skin) surrounding the succulent, edible aril and a seed in the centre. Pericarp browning, postharvest decay and micro-cracking are identified as major constraints affecting the commercial quality of litchi during storage, transportation or at the consumer shelf. Desiccation or moisture loss from the pericarp and mechanical injury due to improper postharvest handling practices during the fruit export chain ultimately result in browning. Micro-cracking was also observed preharvestly during fruit developmental stages, and postharvestly due to poor handling practices and packing line operations. The micro-cracks on the pericarp act as ports of entry for the invasion of postharvest pathogens during cold storage and transportation. Although pericarp browning caused by desiccation does not severely affect the sensory attributes of litchis, mechanical injury and postharvest decay can cause deleterious effects on the sensory attributes of litchi fruit. Pericarp browning and postharvest decay during storage and transportation are currently controlled by adopting sulphur dioxide fumigation in many litchi exporting countries. However, sulphur dioxide fumigation leaves undesirable residues, alters the fruit taste and results in health hazards for consumers and packhouse workers. This review summarises the latest developments in alternative treatments to replace sulphur dioxide fumigation in the litchi postharvest management chain to retain overall fruit quality.

Keywords: decay, fruit physiology, postharvest treatments, sulphur dioxide
Abbreviations: H_2O_2, hydrogen peroxide; **MAP**, modified atmosphere packaging; **PPO**, polyphenoloxidase; **POD**, peroxidase; **RH**, relative humidity; SO_2, sulphur dioxide; **SSC**, soluble solids concentration; **TA**, titratable acidity

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INTRODUCTION

The litchi (*Litchi chinensis* Sonn.) is a member of the family Sapindaceae, or soap berries, which includes longan and rambutan. It is a tropical to subtropical fruit that originated near southern China and northern Vietnam (Menzel 2001). The litchi fruit is formed in a panicle and the shape of the fruit differs from conical to spherical. The fruit has a rough indehiscent red pericarp (skin) due to the presence of anthocyanins surrounding the succulent, edible aril and a seed in the centre. A large number of cultivars are grown around the world. The protuberance type, texture and its arrangement are more reliable to identify the different cultivars than based on fruit shape, size or taste. The major cultivars in the world are mentioned in **Table 1**. The shapes of some cultivars are very distinctive, e.g. the round fruit of 'Kwai May Pink' can be differentiated from the egg-shaped 'Tai So' or the heart-shaped 'Haak Yip'. The fruit shoulders can be smooth or flat ('Wai Chee' and 'Kwai May Pink'), or uneven ('Souey Tung' and 'Bengal'). The apex or tip of the

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Table 1 Major litchi producing countries and major cultivars, in alphabetical order (Singh 1997; Mitra 2006).

Country	Major cultivars
Australia	Fay Zee Siu, Kwai May Pink, Salathiel, Souey Tung, Tai So and Wai Chee
China	Bah Lup, Baitang-ying, Fay Zee Siu, Haak Yip, Kwai May (Red), Lanzhu, No Mai Chee and Wai Chee
India	Bedana, China, Culcuttia, Late Bedana, Longia and Shahi
Indonesia	Local selection
Israel	Mauritius
Madagascar	Madras and Mauritius
Philippines	Sinco, Tai So and ULPB Red
South Africa	Mauritius, McLean's Red
Thailand	Chacapat, Haak Yip, Kom, Tai So, Wai Chee
USA	Brewster, Haak Yip, Kwai Wai, No Mai Chee, Shan Chi
Vietnam	Vaithieu

fruit can be round ('Kwai May Pink' and 'Wai Chee'), blunt ('Souey Tung' and 'Brewster') or pointed ('Bengal'). Typical colours include bright red ('Bengal'), dull red ('Wai Chee'), purple-red ('Haak Yip') or pink-red ('Brewster'). The skin can be thick ('Wai Chee', 'Bengal' and 'Kwai May Pink') or thin ('Haak Yip' and 'Souey Tung'). Skin segments at full maturity can be smooth ('Haak Yip'), swelling ('Wai Chee') or sharp-pointed ('Kwai May Red'), similar to the protuberances on each segment. Some cultivars ('Haak Yip' and 'Souey Tung') can be distinguished by the presence or absence of an obvious suture line. The texture, juiciness, taste and aroma of the flesh can aid description, e.g. 'Wai Chee' is watery, 'Kwai May Red' is firm, 'Kwai May Pink' is spicy and 'Bengal' is very sweet.

In terms of the consumer's view, a litchi peel is typically pinkish to bright red, depending on the type of cultivar, a sweet and sour blend of flavour and juicy, soft and crisp aril (Nakasone and Paull 1998). The daily vitamin C requirement for the average adult can be met by consuming 14-17 litchis (Wall 2006). The average ascorbic acid content of litchi is 27.8 mg/100 g. The consumption of a litchi fruit would meet 2-4% of the dietary reference intakes (DRI) for P, K, Mg, Fe, Zn and Mn and provide 22% of the DRI for Cu (Wall 2006).

The colour of the pericarp changes during maturity from green to reddish pink with decreasing chlorophyll content and increasing anthocyanin synthesis (Underhill and Critchley 1992). Litchi fruit is non-climacteric with relatively low levels of ethylene production after harvest. The fruit does not ripen after harvest and ethylene production remains constant at 1-3°C storage temperatures for 30 days (Chen *et al*. 1986). According to Jiang *et al*. (1986), a decline in the rate of respiration was observed during fruit development. In cv. 'Huaizi', a decrease in respiration was observed after harvest, followed by an increase. However, not much information is available on the rate of respiration in other cultivars.

Litchi is grown as a commercial crop in China, South Africa, Israel, Madagascar, Mauritius, Réunion, the United States (Hawaii and Florida), Australia, subtropical parts of India, Pakistan, the Philippines, Thailand, Taiwan, Indonesia, Vietnam and Brazil (Menzel 2001). China is the leading litchi producing country in the world with 950,000 tons of production of 40 export cultivars in 2002 (Lemmer 2002). China and Taiwan export approximately 12,000-15,000 tons of litchi to the major international markets, Hong Kong and Singapore (Mitra 2006). The European markets import approximately 20,000 tons of litchi, of which France imports 50% and the rest is imported mainly by Germany and the United Kingdom. The main litchi suppliers for Europe over Christmas and New Year are Madagascar and South Africa (Mitra 2006).

Pericarp browning (Huang and Scott 1985; Underhill 1992), desiccation (Underhill and Simons 1993), postharvest decay (Swarts and Anderson 1980) and micro-cracking (Li *et al*. 2001) were identified as major constrains that restrict the expansion of the industry in litchi exporting countries. The litchi industry commercially uses SO_2 fumigation to overcome these problems (Swarts 1985). In Israel and South Africa, SO_2 fumigated fruit is subjected to dipping in diluted HCl to restore the red colour following SO_2 bleaching; this practice has gained commercial acceptance (Zauberman *et al*. 1990, 1991).

One of the main concerns with SO_2 fumigation is that it leaves undesirable residues (Kremer-Köhne 1993). During recent years there were growing concerns regarding SO_2 residue levels present in the fruit, especially by importing countries such as those in Europe, the USA and Japan. At present, the strict standards enforced on fruit imports by the European Community permits a maximum concentration of sulphur residue levels of only 10 µg/g in the edible portion of the fruit (Ducamp-Collin 2004). The Food and Agriculture Organisation of the United Nations has developed CODEX quality standards for fresh litchi. According to the CODEX standards, mature fruit must have a predominantly

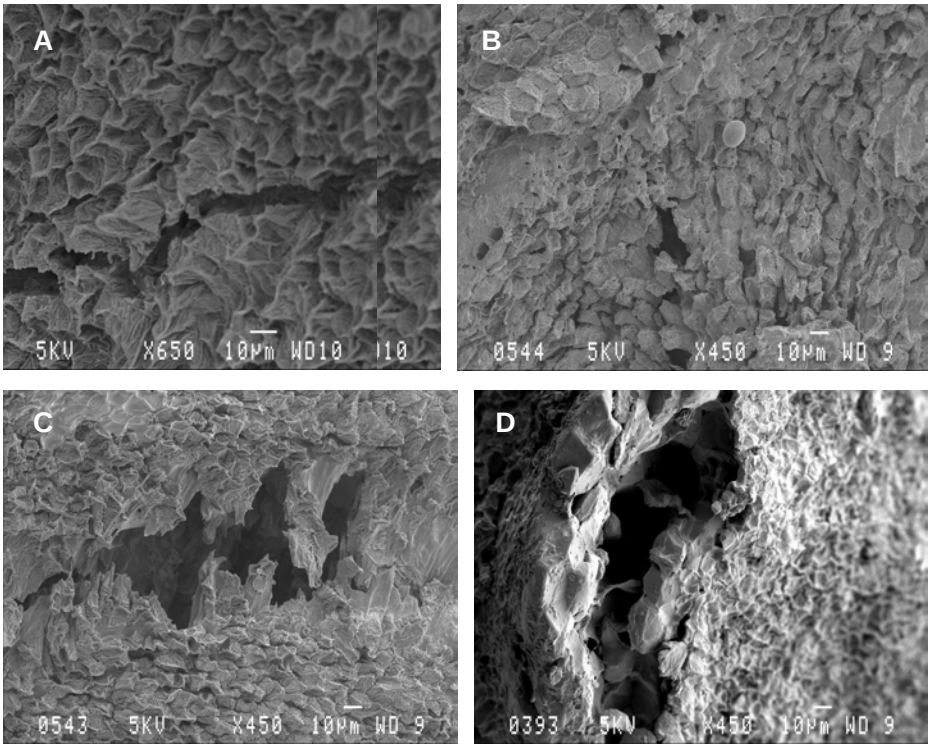

Fig. 1 (**A**) Micro-cracking at commercial maturity (**B**) micro-cracking during handling (**C**) "splitting' of pericarp when the fruit drops from 15 cm height during fruit separation processes (**D**) after SO_2 fumigation in litchi cv. 'Mauritius'.

red pericarp with only a small area of green; the diameter of the fruit must be larger than 20 mm for standard or second class (classes I and II) fruit; and 33 mm for "Extra" (superior) class fruit (Codex Stan 196). The soluble solid concentration (SSC) should be greater than 18% and the residue for sulphur in the flesh should not exceed 10 mg/kg (Mitra 2006).

Undesirable effects of sulphur dioxide fumigation on litchi fruit quality

Fumigation with SO_2 causes undesirable effects on fruit quality. The fruit taste is altered due to higher titratable acidity and lower pH resulting from direct penetration of SO_2 through the skin into the aril (Lonsdale and Kremer-Köhne 1991; Tongdee 1993). Evaluation of SO_2 fumigated fruit of different cultivars indicated a 12-14% mass loss during low temperature storage at 1°C (Lemmer *et al*. 2000; Sivakumar and Korsten 2006). It is also evident that commercial SO_2 fumigation intensified micro-cracking of the pericarp (Sivakumar *et al*. 2005), similar to observations on grapes by Zhang *et al*. (2003). SO_2 fumigation also results in health hazards for packhouse workers and consumers alike, causing allergic reactions and respiratory problems (Koeing *et al*. 1983).

The build-up of SO_2 residues in the pericarp and aril are dependent on different factors, such as damage to the pericarp RH and storage temperature. According to Lemmer *et al*. (2000), the SO_2 residue levels in the pericarp and aril (edible portion) of six cultivars ('Wai Chee', 'Fay Zee Siu', 'Kwai May Pink', 'Haak Yip', 'HLH Mauritius' and 'McLean's Red') were observed to be 1000-1400 ppm in the pericarp and 10-14 ppm in the aril soon after SO_2 fumigation and declined to 200-250 ppm and 8-12 ppm respecttively during low temperature storage at 1°C. The detected SO_2 residues varied between cultivars: higher values were recorded in cv. 'McLean's Red' than cv. 'Mauritius'. Furthermore, higher SO_2 residues were reported in the arils of fruit of cv. 'McLean's Red' and 'Mauritius' subjected to an acid dip treatment following SO_2 fumigation. Lemmer and Kruger (2000) also explained that peel injury caused by a low pH treatment could facilitate an increased diffusion rate into the aril, leaving less residues in the peel and consequently higher residues in the aril. Lemmer and Kruger (2000) further investigated the effect of Vapogard® prior to acid dip to reduce SO_2 residues in the pericarp and the aril of 'McLean's Red' and 'Mauritius' cultivars. However, no buffering effect due to the coating was detected in the residue levels in the pericarp or aril of both cultivars. Also, more mature fruit (higher SSC:TA ratio) were likely to have higher SO_2 residue ratios between the aril and pericarp due to the initiation of pericarp degradation as a result of the senescence process. These factors then lead to a higher SO_2 diffusion rate through the pericarp, resulting in higher residues in the aril. The storage temperature and RH also influenced the movement and absorption of SO_2 in the fruit; higher storage temperatures with low RH favoured the build-up of SO_2 residues in the aril (Lemmer and Kruger 2000). The time lapse between harvesting and fumigation also influenced the SO_2 residue build-up in the aril (Lemmer and Kruger 2000).

All these undesirable effects of SO_2 fumigation have necessitated the development of alternative postharvest treatments to maintain overall quality during storage and transportation. This review focuses on the published literature on developing alternative treatments that are safe, environmentally friendly and economically acceptable to replace or reduce SO_2 fumigation in the litchi postharvest management chain. It also focuses on retaining overall fruit quality by preventing pericarp browning, controlling fruit decay, and minimising desiccation and micro-cracking.

CONSTRAINTS IN LITCHI EXPORTS

Pericarp browning

Pericarp browning is related to water loss or desiccation from the pericarp (Scott *et al*. 1982). Wounding or mechanical injury, storage of fruit at undesirable low temperatures (chilling injury), pathogen or pest attack (Fitzell and Coates 1995) and senescence can result in browning of the pericarp. Browning caused by temperature stress, decay and senescence (Bagshaw *et al*. 1995) is evident as typical dark and water-soaked areas on the pericarp, whereas browning due to desiccation is differentiated by a pale-dry appearance of the pericarp. According to Huang *et al*. (1990) browning is initiated after harvest, and the pericarp becomes completely brown within 3 days at room temperature and 65-70% RH. Browning initiates from the protuberances of the pericarp and thereafter extends over the entire pericarp surface, until the pericarp eventually becomes dry and brittle (Underhill and Critchley 1995). Although pericarp browning does not affect the eating quality of the aril, it affects the cosmetic appearance of the fruit at the export market.

Intensive research has been conducted to work out the biochemical process underlying litchi browning. Underhill and Critchley (1994) suggested that the pH of the pericarp tissue plays a major role in the browning mechanism. The desiccation or moisture loss from the pericarp tends to increase the pericarp pH (4.15-4.52 over 48 h at 25°C and 60% RH; Underhill and Critchley 1994). Anthocyanins in the vacuoles of the pericarp cells are responsible for the red colour of litchi and is affected by pH change. At higher pH (>4), anthocyanin is converted to a colourless form, carbinol (Underhill and Critchley 1994). The fruit pH is the key factor that determines the ratio between the flavylium cation and the colourless carbinol form of the anthocyanin molecules. The other mechanism of litchi pericarp browning is mainly attributed to the oxidation process of phenolics and the degradation of anthocyanin (red pigment) by the enzymes polyphenol oxidase (PPO) or peroxidase (POD) (Huang *et al*. 1990; Zauberman *et al*. 1991; Underhill 1992; Zhang and Quantick 1997) and the formation of polymeric browning pigments (*o*-quinones). The PPO activity was observed to be low at maturity, whereas an increase in activity occurred during the first 2 days of storage, but no significant changes in anthocyanin content was observed during further storage (Underhill and Critchley 1992; Lin *et al*. 1998). Although the anthocyanin content did not show significant changes with respect to increased browning (Underhill and Critchley 1994), according to Zhang *et al*. (2001) the pericarp browning index increased while the anthocyanin content declined during storage. This observation was further supported by Zhang *et al*. (2000) who observed a decline in cyanidin-3-glucoside (major anthocyanin, representing 91.9% of the total anthocyanin) with increasing severity of browning during storage. Jiang and Fu (1999) reported a moisture loss and increased pH in the pericarp tissue directly related to the PPO activity, which was observed to increase at higher pH (7-7.4) and decrease at lower pH, whereas no activity was observed below pH 4.2 (Jiang *et al.* 1997). Underhill and Critchley (1994) concluded that the increase in pH from 4.15 to 4.52 during desiccation could stimulate PPO activity. The anthocyanins found predominantly in the epicarp and mesocarp of the pericarp and high PPO activity observed in these two layers led to the conclusion that the involvement of PPO activity in desiccation mediated browning (Underhill and Critchley 1995). In intact tissues, the PPO is separated from the substrate anthocyanin in the vacuole due to compartmentation. Water loss or dehydration causes rapid loss of membrane integrity, bringing the PPO in close contact with the substrate (-) epi-catechin to initiate the browning reaction (Jiang and Fu 1999; Sun *et al*. 2006). The loss of membrane integrity was observed to be associated with increased electrolyte leakage after harvest and during storage (Jiang and Fu 1999).

The browning mechanism of the litchi pericarp by PPO

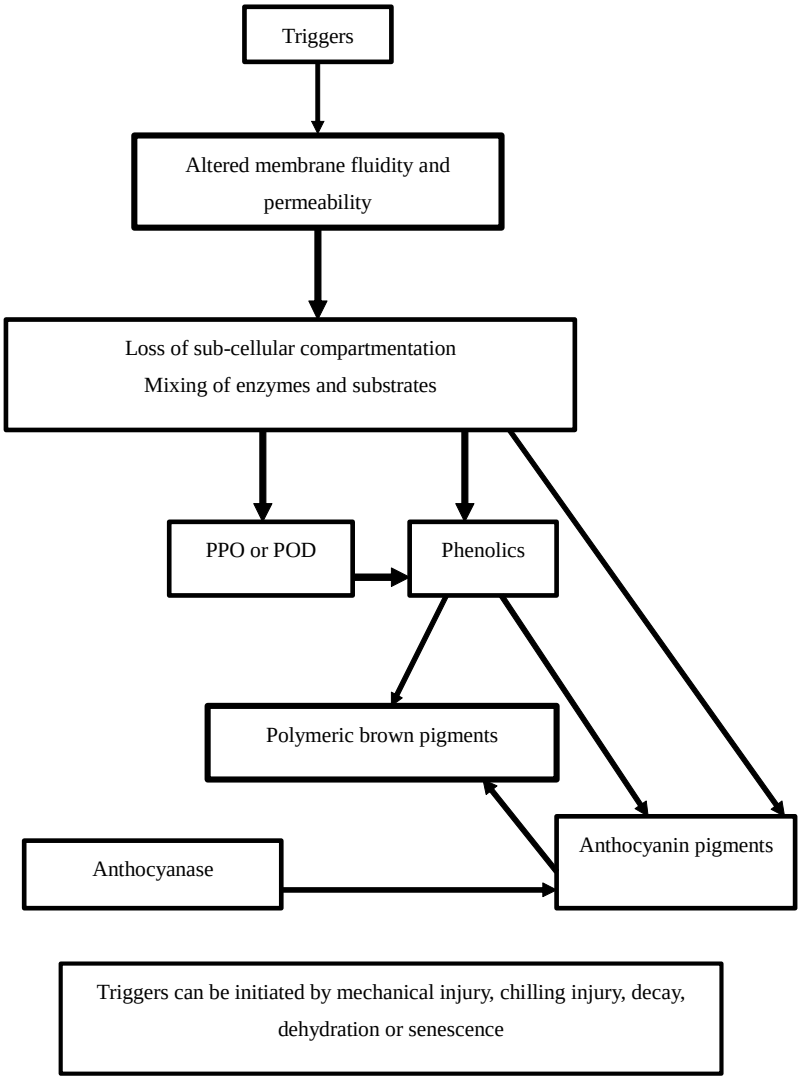

Fig. 2 A schematic diagram of enzymatic browning (based on Jiang *et al*. 2004). The pericarp cell pH is increased due to desiccation or water loss, which can stimulate the activity of the PPO and POD. During storage, desiccation and the senescence process result in loss of cellular compartmentation. Browning takes place when the phenolic substrate and the enzyme come in contact. Anthocyanins are hydrolysed by anthocyanase to anthocyanidins and PPO or POD oxidises the anthocyanidins to *o*-quinones (the browning pigment).

and POD is complex and indirect. After finding a higher anthocyanase activity (Zhang *et al.* 2001) in the litchi pericarp, Jiang *et al*. (2004) suggested from their findings that the anthocyanins are hydrolysed by anthocyanase to anthocyanidins and PPO and/or POD oxidises the anthocyanidins. High anthocyanase activity was observed in the litchi pericarp, suggesting the involvement of anthocyanase in pericarp browning, which could be related to the decrease in anthocyanin content in the pericarp during storage. The findings of Jiang *et al*. (2004) suggested that the anthocyanase-anthocyanin-PPO reactions take place in the pericarp cells. Zhang *et al*. (2005) suggested that, although high POD activity was observed in the litchi pericarp during storage, an inverse relationship existed between browning severity and anthocyanin concentration. It was further suggested that enzymatic browning could be caused by POD, and that degradation of anthocyanin could take place in the presence of hydrogen peroxide (H_2O_2) and simple phenols (guaiacol), possibly through the anthocyanase-anthocyanin-phenolic-H_2O_2 reaction (**Fig. 2**).

Micro-cracking and fruit cracking

Litchi micro-cracking was reported by Underhill and Simons (1993) who suggested that it is caused by desiccation (**Fig. 1A**). The cracking-resistant Chinese cv. 'Huaizi' showed a lower rate of desiccation than the cracking-susceptible cv. 'Nuomici'. Micro-cracking is also one of the causes of pericarp browning (Huang *et al.* 2004). According to Underhill and Simons (1993) the micro-cracks observed prior to harvest were observed to intensify during storage. Micro-cracking of the pericarp takes place at the initial stages of fruit development due to the rapid expansion of the aril (Huang and Xu 1983). According to Joubert (1986) the expanding aril exerts an increased stress or turgour pressure against the pre-grown pericarp, which is composed of three layers: exocarp, mesocarp and endocarp. Drought is another major cause of pericarp cracking during fruit development, which leads to a loss of pericarp extensibility (Li *et al*. 2001). The pericarp structure development was reported for Chinese (cv. 'Huaizhi' and 'Numici'; Huang *et al.* 2004) and South African cultivars (cv. 'Mauritius' and 'McLean's Red'; Sivakumar and Korsten 2005; **Figs. 1A-D**). Micro-cracking can also be caused due to handling or packing line operations (Sivakumar and Korsten 2004).

Litchi cultivars showed similar pericarp development, however, differences in the thickness of cuticle and spongy layers were observed between different cultivars (Huang *et al.* 2004). The spongy tissue responsible for gas exchange in the pericarp was thought to be responsible for water loss (Deng 1997). However, the findings of Huang *et al.* (2004) showed that cv. 'Huaizhi', which had a thicker, spongy layer, showed less desiccation. Huang *et al.* (2004) further showed that the cuticle accumulation pattern might help to explain the susceptibility or resistance to micro-cracking in different cultivars. Differences in wax deposit distribution were observed on the pericarp between the developmental stages of South African litchi cv. 'Mauritius' and 'McLean's Red'. Micro-cracking was also observed as a result of bad handling processes, and disruptions of the surface were observed in freshly harvested fruit (**Fig. 1A, 1B**). Fruit dropping during the separation process was observed to cause "splitting" damage in the pericarp (**Fig 1C**). Commercial SO_2 fumigation was observed to intensify micro-cracking in the pericarp (**Fig. 1D**; Sivakumar *et al*. 2005).

Fruit cracking also affects the cosmetic appearance of

Fig. 3 (**A**) SO_2 fumigated litchi fruits cv. 'Mauritius' after 24 h fumigation; (**B**) SO_2 fumigated litchi fruits cv. 'Mauritius' after 35 days cold storage; (**C**) Litchi fruits cv. 'McLean's Red' packed in modified atmosphere packaging after 30 days cold storage.

the fruit on the domestic or export market. It occurs during fruit development as a result of rapid expansion of the aril, exerting pressure on the pericarp, which has stopped forming new tissue. The degree of severity or damage, depending on the cultivar, is known to intensify with desiccation. The fluctuation of wet and dry periods at late fruit developmental stages can also aggravate fruit cracking. A relationship between fruit cracking and endogenous hormones or mineral nutrition (Ca, Mg and B) was reported by Qui *et al*. (1999) in cv. 'Nuomoci'. The contribution to cracking resistance by calcium is related to its structural role in the cell walls, and the availability of calcium during early fruit development is important for cracking resistance (Huang *et al*. 2005). 'Huaizhi' accumulated more calcium than its physiological needs, and the excess was stored as calcium oxalates, mainly in the epidermis. In contrast, 'Nuomoci' stored little calcium oxalate. The higher levels of structural calcium in 'Huaizhi' are due to higher calcium availability and more calcium-binding sites. Due to the higher concentrations of structural calcium and galacturonans, 'Huaizhi' showed a stronger pectic network, which enhanced cracking resistance. The structural calcium levels decreased in litchi pericarp from 22-52 days after anthesis. Cell expansion in the pericarp during this period resulted in the dilution of structural calcium (Huang *et al*. 2004), which eventually increased during aril expansion. This increase in structural calcium could be due to an increased availability of calcium or due to increased calcium-binding sites in the pectin (Huang *et al*. 2006). An increase in calcium-binding sites can be achieved by newly synthesised galacturonans incorporating into the cell walls, or by demethylesterification of available galacturon. However, changes in structural calcium were not paralleled by the changes of galacturonans, especially in the early stages of fruit development, indicating that calcium-binding sites were not the rate-limiting factor in structural calcium formation throughout fruit development (Huang *et al.* 2006). Peng *et al.* (2004) also reported that fruit cracking could be reduced by foliar application of brassinolide, a plant growth activator, before blossom. It could be recommended as a standard commercial practice, also to increase the commercial fruit value. The foliar brassinolide spray significantly affected the enzyme's activities, the calcium content of the fruit pericarp and reduced the fruit cracking. The brassinolide application was observed to increase the activity of pectin methyl esterase and polygalacturonase reflecting the rise of pectin metabolism, related to cell division, elongation and rapid fruit growth (Peng *et al*. 2004). The polygalacturonase resulted in monogalacturonic acid capable of binding Ca^{2+} and facilitating the formation of junction zones. The increase in calcium during early stages of fruit development provides a good basis of fruit pericarp development and the final increase in protopectin content in the pericarp guarantees good fruit pericarp quality (Peng *et al.* 2004).

Postharvest decay

Postharvest decay is one of the major obstacles in the postharvest fruit chain, reducing the commercial value of litchi fruit. A wide range of fungi can cause decay of litchi fruit (Holcroft and Mitcham 1996; Jiang *et al.* 2003). The main pathogen isolated from litchi was identified as *Peronophythora litchi* (Jiang *et al*. 2001). The predominant fungal genera associated with litchi in South Africa are *Phomopsis*, *Pestalotiopsis*, *Penicillium*, *Trichoderma*, *Alternaria*, *Botryosphaeria* and *Fusarium* spp. (de Jager *et al.* 2003). Many *Penicillium* spp. have been isolated pre- and postharvestly from litchi, of which *P. expansum* was reported as the major pathogenic species (Jacobs and Korsten 2004). After SO_2 fumigation, *Penicillium* spp. can become a major problem in the litchi export industry (de Jager and Korsten 2003). The SO_2 fumigation affects the natural eco-

logical balance and enhances decay due to saprophytic postharvest colonisation of *Penicillium* spp. (de Jager *et al.* 2003). Micro-cracks observed during fruit development and caused during postharvest handling (**Fig. 3A-C**) can provide a port of entry for decay pathogens that colonise the fruit surface (Sivakumar *et al.* 2005).

DEVELOPMENTS IN POSTHARVEST TECHNOLOGIES TO REPLACE SULPHUR DIOXIDE FUMIGATION

Currently, there is an ongoing search for alternative sulphur-free postharvest technologies to retain the overall quality of litchi fruit during transport and cold storage to satisfy the increasing consumer demand for high quality fruit, which are free of potentially harmful chemicals and microorganisms. The search for suitable alternatives for SO_2 fumigation was initiated in litchi growing countries in the 1990's. All the technologies developed are focused on preventing or minimising postharvest browning, desiccation and decay, thereby extending the storage life and retaining overall fruit quality.

Gamma Irradiation

Irradiation in combination with low temperature storage may be recommended as an alternative to SO_2 fumigation during short-term storage (less than 10 days; Ilangantileke *et al.* 1993). Irradiation treatment showed differential responses with respect to cultivar and dosage. According to Ilangantileke *et al*. (1993) irradiation up to 1 kGy dose, in combination with low temperature storage, maintained the market quality of Thai litchi by reducing the loss of red pericarp colour and decay. However, it failed to retain the overall fruit quality during prolonged cold storage. Further, irradiation is not commercially practiced in many countries for fresh commodities due to the psychological perception of consumers, regarding the safety of irradiated food for human consumption (Jiang *et al.* 2003). Since it is ineffective in retaining the quality attributes of litchi during long term storage exceeding 16 days, irradiation would not be practical to implement (Ilangantileke *et al*. 1993).

Postharvest dip treatments

Application of different postharvest treatments was investigated to increase the storage life of litchi fruit at low temperatures (2-5°C). Jiang and Chen (1995) recommended polyamines for the retention of red colour at low temperature storage for 30 days. Polyamines such as putrescine, spermine or spermidine (1 mmol/l) in combination with fungicides were reported to delay or reduce ethylene production, POD activity and also retain membrane integrity, which ensured the separation of enzyme and substrates. Jiang and Fu (1997) recommended the combined application of glutathione and citric acid to reduce the browning of litchi fruit. Although glutathione is safe for human health, the combination treatment with citric acid caused inhibition of PPO and higher residue levels of glutathione, detected especially in the inedible portion of the fruit. This application was merely effective in the control of browning in storage up to 4 days. Litchi fruit cv. 'Huaizhi' dipped in 1% HCl for 6 min and stored at 25°C and 80-90% RH showed the best fruit colour and minimal pericarp damage after 1 day storage (Jiang *et al.* 2004). According to Jiang *et al.* (2004), the HCl treatment inhibited PPO activity in the pericarp and maintained high anthocyanin content, retaining the red colour. The HCl treatment stabilised the pH change maintained the anthocyanin content in the pericarp tissues (Zauberman *et al*. 1991). HCl dip treatment inhibited anthocyanase activity in litchi cv. 'Guiwei' (Hu *et al.* 2005). Chitosan dip solutions at 1% showed beneficial effects on cv. 'Huaizhi' such as delaying changes in the contents of anthocyanin, flavonoid total phenolics, and reduced the PPO activity or inhibited the increase of POD activity, thereby reducing the severity of browning under low temperature storage (4°C) (Zhang and Quantick 1997). In cv. 'Mauritius', chitosan at 0.1% concentration reduced microbial decay and showed the anti-microbial properties of chitosan (Sivakumar *et al.* 2005). Zhang and Quantick (1997) hypothesised that the filmogenic chitosan coating around the fruit can modify its endogenous CO_2 and O_2 levels, which could result in a reduced supply of oxygen for the enzymatic oxidation reaction of the anthocyanin. Chitosan coating, integrated with acidification, formed an acid coat, which further stabilised the acidification of the epicarp during the dipping process (Joas *et al*. 2005). When the fruit were transferred from cold storage to market shelf conditions at ambient temperature (25°C), the litchi pericarp turned brown, losing its visual quality. Jiang *et al*. (2005) reported that application of 2% chitosan coating soon after cold storage extended the shelf life for 12 h at 25°C. Chitosan dipping after cold storage protected the fruit pericarp from browning and decay and retained the physico-chemical properties of the edible portion (Jiang *et al*. 2005).

Heat treatments

Litchi fruit exposed to steam treatment at 98°C for 30 s followed by hydrocooling in distilled water at pH 0 for 5 min preserved the red colour of the pericarp during storage. However, this technology failed to reach commercial acceptance since the steaming process affected the edible portion (aril) of the fruit (Kaiser 1998). This treatment was improved by reducing the steam treatment to 2 s, cooling in water at pH 0 and coating the fruit with Vapogard® (di-1-P menthene; Hygrotech Seed, Pty. Ltd., Pretoria, South Africa) (1%), an anti-transpirant, which retained the red colour of the pericarp without discolouration of the aril. Kaiser *et al.* (1995) suggested that co-pigmentation or complexing of anthocyanin might increase the stability of the pigment. However, Kaiser's treatment failed to show direct evidence of co-pigmentation and the observation on red colour retention could be due to the direct effect of pH (Holcroft and Mitcham 1996).

Vapour heat treatment at 45°C core temperature for 42 min was reported to maintain the quality of 'Tai So' and 'Wai Chee' litchi cultivars at 5°C for 4 weeks, retaining the appearance and increasing disease control (Jacobi *et al.* 1993). However, the success of the vapour heat treatment is cultivar dependent, which depends on the anatomical features of the pericarp such as thickness (Jacobi *et al.* 1993). In susceptible cultivars, such as 'Kwai May Pink', vapour heat treatment can cause a loss of membrane integrity, electrolyte leakage, PPO activation, pH fluctuation and pericarp browning (Wong *et al.* 1991). Taiwanese litchi cultivars were reported to respond well to vapour heat treatment suggesting that the cultivars were more heat tolerant (Jacobi *et al.* 1993).

Litchi fruit sprayed with hot water by brushing, followed by HCl and prochloraz® (N-propyl-N-[2-(2,4,6-trichlorophenoxy) ethyl] imidazole-1-carboxamide) dip treatments, maintained uniform red colour and excellent eating quality in terms of taste and flavour during storage for at least 35 days (Lichter *et al.* 2000). Hot water brushing at 25°C for 20 s was observed to reduce or inhibit PPO activity in the pericarp by uniformly exposing the fruit to the acid by a brushing action. However, the success of hot water brushing depends on fungicidal treatment. Although fungal growth is controlled at low temperatures, transfer of the fruit to market shelf temperature enhances colonisation by fungi. According to Lichter *et al*. (2000), hot water brushing does not provide antifungal protection to litchi fruit. The commercial application of hot water brushing remains a question until an alternative measure is found to replace the prochloraz dip to control decay at the market shelf. This is due to increasing concerns of health conscious consumers. Hot water spray is preferred over a hot water dip, although both methods are equally effective in retaining the red colour of the pericarp, but fungal rot is a major problem since

hot water does not provide additional protection (Olesen *et al*. 2004). However, a contradictory observation was reportted by Hu *et al*. (2005) on heat treatments of litchi cv. 'Guiwei'. Heat treatments increased anthocyanase activity in the pericarp with rapid discolouration and a subsequent decline in anthocyanin content. Furthermore, hot water dip treatments at 50°C for 2 min, or at 55°C for 1 min, caused deleterious effects on pericarp colour, quality parameters and surface structure, e.g. flattening of the highly ornamented pericarp surface, homogeneous with occasionally lifted wax plates due to melting of the wax layer (Sivakumar and Korsten 2006a).

Chemical control

Numerous fungicides including benomyl, iprodione, thiabenzdazole and prochloraz have been tested for the control of litchi postharvest diseases with variable levels of effectiveness (Korsten *et al*. 1993). However, increasing international concern over the indiscriminate use of fungicides on consumables and its subsequent detrimental effect on the environment has made chemical control less desirable. Due to strict regulations, especially in the European Union, the use of several chemicals is currently prohibited, and others have been withdrawn from the market. Over time, their continuous use can lead to the build-up of pathogen resistance. These chemicals, including SO_2 fumigation, usually tend to eliminate most microbial growth on the fruit surface, leaving a vacuum for decay-causing organisms.

Biocontrol agents

Due to the challenges associated with chemical disease control, postharvest decay control in litchi recently became more focused on the use of naturally occurring non-pathogenic bacteria or yeasts as antagonists. Application of antagonists to control postharvest diseases is more likely to be efficacious than in the field, because the storage environment around the fruit can be managed more easily to favour antagonist growth. The biocontrol agent *Bacillus subtilis* was found to be effective in controlling postharvest decay in litchi cvs. 'Madras' (Korsten *et al*. 1993) and 'Huaizhi' (Jiang *et al*. 2001) when kept at cold storage (5°C). The mode of action of this antagonist was reported as the antibiotic action of a cyclic polypeptide, iturin A (Gueldner *et al*. 1988; Jiang *et al*. 2001). The treatment with a cell-free suspension (extract) of the antagonist was effective in controlling fruit decay for a storage period of 30 days at 5°C. Although application of the antagonist did not alter the eating quality significantly, it caused moderate browning on the pericarp. The environment therefore still needs to be optimised to favour both antagonist survival and retention of fruit quality. More research is necessary on new biocontrol agents and their application as alternatives to chemical treatments in the litchi industry, in order to maintain a protective barrier, which does not allow fungal infection, without compromising fruit integrity.

Modified atmosphere storage

Modified atmosphere packaging (MAP) has the advantage of low cost and easy implementation at the commercial level (Flores *et al*. 2004). The successful use of MAP depends on the specific permeation properties of polymer films to O_2 and CO_2 to generate atmospheres desirable for the postharvest life of horticultural commodities. MAP technology provides two advantages for litchi: 1) it helps to reduce or prevent browning by maintaining a higher RH around the fruit inside the sealed plastic film, which prevents water loss due to transpiration, loss of membrane integrity, loss of electrolyte leakage and increased PPO activity (Paull and Chen 1987; Kader 1994; Lemmer and Kruger 2000; Persis *et al*. 2002); 2) it controls postharvest decay due to high CO_2 (>10%) or higher O_2 composition. Litchi fruit cv. 'Mauritius' subjected to hot water brushing treatment and followed by a 2 min HCl dip treatment (4%) amended with prochloraz (Lichter *et al*. 2000) and packed in laminated polyethylene bags (BoxiBag®, Atifon, Israel) with two types of perforations (micro and macro) showed higher CO_2, acetaldehyde and ethanol production in late harvested fruit than the early-season fruit in micro-perforated packaging at the end of storage (1.5°C for 4 weeks and 20°C for 3 days). This further indicated that fruit maturity in terms of late or early harvest is a critical factor that determines the success of MAP technology. The anaerobic respiration due to micro-perforation indicated the importance of selecting suitable films with specific permeance to create a desirable atmosphere around the fruit, in order to maintain superior overall quality. Tian *et al*. (2005) reported ethanol production by fruit in MAP (15-19% O_2 + 2-4% CO_2) during low temperature storage in cv. 'Heiye'. Combined applications were researched with MAP technology. Litchi fruit cv. 'McLean's Red' dipped in hot water at 55°C for 2 min, packed in Xtend® or BOPP (biorientated polypropylene) showed an increase in CO_2 composition around the fruit with a decrease in weight loss, fruit firmness and lower chroma with higher postharvest decay and browning during low temperature storage (Sivakumar and Korsten 2006). The loss of firmness was associated with water loss during hot water treatment. As stated by Wong *et al*. (1991), tolerance to high temperature depends on the cultivar and the morphological structure, especially the cuticular layer formation, pericarp thickness and the amount of wax deposits on the cuticle. The damage caused by hot water treatment on colour deterioration of the pericarp caused by PPO or POD activity cannot be compensated by the high RH or gas composition in the MAP. Different types of packaging (Xtend® or BOPP) or the same type of packaging (BOPP) with different perforations showed different gas compositions and RH around the litchi fruit, which affected their overall quality during long-term storage (Sivakumar and Korsten 2006a, 2006b). BOPP with 17% O_2, 6% CO_2 and ~90% RH around the early seasonal litchi fruit cv. 'Mauritius' reduced the rate of transpiration, and thereby prevented the browning related enzymatic mechanism, colour deterioration and weight loss, while retaining the overall fruit quality up to 34 days at 2°C and 2 days at 14°C (Sivakumar and Korsten 2006b). Furthermore, the sensory panellists did not detect ethanol or acetaldehyde related off-flavours in these fruits. Postharvest dip treatments with safe compounds (EDTA, 4-hexylresorcinol or phosphoric acid) were tested in combination with different types of BOPP packaging (Sivakumar and Korsten 2006b). The dip treatments affected the RH within the packaging, probably by absorbing the water as reported by Shirazi and Cameron (1992). The postharvest treatments affected the hue value of the pericarp, which turned yellowish red during long-term low temperature storage. Dip treatments slightly altered the eating quality but no decay was reported (Sivakumar and Korsten 2006b). **Fig. 3A-C** shows fruit quality in terms of colour with SO_2 treatments and MAP (BOPP). A negative impact on fruit quality can be encountered when the fruit in MAP is subjected to temperature fluctuations during shipping, handling or at the retail display (Sanz *et al*. 1999). Maintenance of an adequate temperature at 14°C is essential on the marketing shelf to retain the overall quality of litchi packed in MAP (Sivakumar and Korsten 2006b). The storage temperature varies among cultivars, e.g. 'Mauritius' and 'McLean's Red' at 2°C; 'Kwai May Pink' (or 'Gui Wei') and 'Wai Chee' (or 'Huai Zhi') at 5°C; 'Mauritius' grown in Israel at 1.5°C; 'Huaizhi' at 4°C and 'Heiye' at 3°C (Jiang *et al*. 2003). However, further research is needed to identify the best suitable biodegradable MAP with permeance that would obtain desirable O_2 and CO_2 levels and retain overall fruit quality for more than 30 days for specific export cultivars. This is a more convenient method for marketing and would be both safe and attractive for the consumer.

Controlled atmosphere storage

Litchi fruit cv. 'Huaizhi' stored at 1°C under controlled atmosphere (3-5% CO_2 and 3-5% O_2) at 90% RH showed good browning control, while retaining the fruit quality up to 30 days (Jiang and Fu 1999). Duan *et al.* (2004) suggested that litchi cv. 'Huaizhi' stored in pure O_2 (100% O_2 and 0% CO_2) for 6 days at 28°C showed significantly reduced pericarp browning. It is evident from their investigations that pure O_2 inhibited the activities of PPO and anthocyanase involved in the enzymatic browning mechanism. Therefore, pure O_2 atmosphere helps to prevent the degradation of anthocyanin by preventing the hydrolysis of sugar moieties from anthocyanin to anthocyanidin and the degradation of anthocyanidin by PPO to brown polymers. Duan *et al.* (2004) reported the presence of high levels of anthocyanins in the litchi pericarp by the end of 6 days' storage. The application of pure O_2 maintained high total soluble solids and titratable acidity in the aril (Duan *et al.* 2004). Application of high O_2 storage (70% O_2 + 0% CO_2) for one week followed by 5% O_2 + 5% CO_2 storage at 3°C and 95% RH for 14, 24 and 48 days showed significant reduction of decay, while browning increased after 14 days in cv. 'Heiye'. According to Tian *et al.* (2005), the anthocyanidin content in the pericarp decreased slowly when compared to the control and the ethanol content responsible for the off-flavours were reduced when the fruit were exposed to 70% O_2 for 1 week, followed by 5% O_2 +5% CO_2 at 5°C. Tian *et al.* (2005) also indicated the beneficial effects of higher O_2 in controlled atmosphere storage to limit the PPO and POD activities, maintain higher anthocyanin levels, prevent decay and retain good fruit quality. Superatmosphere O_2 at 50% showed a significant effect on inhibition of browning in cv. 'Hong Huay' for 8 days longer than the ambient temperature, but increased concentrations up to 70% did not show additional control of browning (Techavuthiporn *et al.* 2006). However, the effect of pure or higher O_2 concentrations during long-term storage on retention of overall quality in terms of storage life and disease development requires further investigation.

Treatment with 1-Methylcyclopropane (1-MCP)

Although litchi is a non-climacteric fruit, 1-MCP was observed to delay the activity of anthocyanase in litchi cv. 'Guiwei' (Hu *et al*. 2005). According to Prang *et al*. (2001), 1-MCP did affect ethylene production, respiratory rate, chemical composition, polyphenol oxidase and peroxidase activity.

Suggestions based on research to improve postharvest handling practices for quality retention of litchi

Postharvest handling strategies have to be improved throughout the system, i.e. from harvesting practices, time of harvest, pre-cooling, packing line operations and cold chain management, through to the end consumer. Most importantly, the cold chain has to be maintained in order to ensure superior fruit quality. Litchi has to be harvested prior to extreme day temperatures that occur from late morning to early afternoon. It is shown from the fruit water potential that a rapid loss of turgour occurs early in the morning (~8 am), with a recovery in the afternoon (~4 pm) (Olesen *et al.* 2003). The loss of turgour can affect the fruit weight (Olesen *et al.* 2003), with negative financial implications. Research also showed the potential to rehydrate the fruit after harvest to prevent or reduce the browning process. The capacity to rehydrate the fruit was observed to reduce during the first hour following harvest (Olesen *et al.* 2003). It remains a question whether rehydration can be used commercially, as the duration from harvest to delivery to the packhouse may take longer than 1 h. Litchi has to be pre-cooled immediately after harvest to remove the field heat and provide an effective cold chain management system during storage and transportation (Lin and Chaiang 1988; Ketsa and Leelawatana 1990). Hydrocooling at 0-2°C is recommended for litchi. However, fruit must be dried prior to packing after hydrocooling, as the presence of water droplets on the fruit surface can enhance decay development during storage and transportation. Forced air-cooling was also recommended, which will become effective when the cold room has humidifiers to maintain ~90% humidity to prevent desiccation during the forced air-cooling process. Maturity standards for harvesting of each cultivar must be adopted according to maturity standards developed, which depend on growth conditions and climatic factors. Ripeness standards in terms of SSC:TA also affect the postharvest performance with respect to different technologies. Selecting cultivars with good postharvest characters such as less browning or susceptibility for browning will be more practical and beneficial for the future.

CONCLUSIONS

Research on postharvest biology and technology of litchi has progressed and the relationship between physiological browning and enzyme mediated browning had been established. All the technologies mentioned above are focused on maintaining the overall fruit quality between 21-30 days. Due to increased production in litchi exporting countries, sea shipment was used as a convenient and economical mode of transportation to the export destinations. The transport time, including the voyage, storage and time spent at the retailers has extended the postharvest chain to more than 30 days. Since sea export consignments can exceed 30 days, further research is needed to improve the currently developed technologies to retain overall quality for longer storage periods.

The storage temperature and response to different gas compositions during modified or controlled atmosphere storage depends on cultivar, growth conditions and seasons (early or late). To replace fungicide treatments, protective packaging with high CO_2 in low temperature storage was recommended to control postharvest decay and insect infestation. However, since higher CO_2 concentrations can result in off-flavours due to acetaldehyde and ethanol (Persis *et al.* 2002) development in the aril, a 3-5% CO_2 concentration is recommended for litchi (Kader 1993). Higher humidity (~90%) also favours postharvest decay in sealed packaging and research on using biodegradable packaging as MAP will be more beneficial in the future. It is also important to evaluate the postharvest performance of the cultivars at different locations, since the growth conditions and climatic patterns can influence the overall fruit quality.

The effects of modified and controlled atmospheres, used on their own or in combination with postharvest treatments such as heat, acid, chemicals or biocontrol agents, are promising and should be further investigated. Furthermore, with the narrow spectrum of chemical applications currently available for use and taking their impact on the environment in consideration, treatments should be minimised, with the possible integration of new biocontrol agents.

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