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Kernel brown centres in macadamia: a review

M. D. Le Lagadec

Queensland Primary Industries and Fisheries, Bundaberg Research Station, 49 Ashfield Road, Bundaberg, Qld 4670, Australia. Email: danielle.lelagadec@dpi.qld.gov.au

Abstract. The incidence of kernel brown centres in macadamia (*Macadamia integrifolia* and *M. tetraphylla* and hybrids) has increased substantially in Australia. Although the defect amounts to only ~1% of all kernels processed in Australia, it costs the macadamia industry over AU$2 million per annum. Little formal research has been conducted, although the defect is mentioned widely in informal grower journals. Possible causal factors are reviewed in this article. Evidence suggests that kernel brown centres may be associated with exposure of enzymes in cell membranes and are also associated with incorrect nut-in-shell drying regimes. There appears to be an interaction among nut-in-shell moisture content, nut drying regime, and the incidence of brown centres. There is some indication that storage of wet nuts in poorly ventilated silos increases the potential for developing kernel brown centres. It is recommended that future research focusses on these issues.

Additional keywords: internal discoloration, kernel quality, kernel browning.

Introduction

Australia produces ~39% of the world's macadamia nuts (*Macadamia integrifolia* and *M. tetraphylla* and hybrids), of which 70% is exported. Australia's investment in the macadamia industry is worth approximately AU$100 million and it is the country's third biggest horticultural export (Goode and Price 2008). Approximately 55% of the 6 million macadamia trees in Australia have yet to reach maturity. It is estimated that production will increase from 40 000 t of nut-in-shell per year to 60 000 t by 2012 (Goode and Price 2008). Countries such as South Africa, Hawaii, Kenya, Brazil, and Costa Rica have invested heavily in this nut. Since many of these countries can produce macadamia nuts more cost-efficiently, it is imperative that the Australian industry retains its competitive advantage by producing superior quality kernels.

The kernel brown centres disorder, also known as internal discoloration, is detectable only after the nuts are dried, and was first documented in Australia by McConachie (1992). The disorder produces a foul odour and taste, rendering the kernel unmarketable. It is not limited to specific growing regions or cultivars, and its occurrence is unpredictable (McConachie 1992).

The recent development and adoption of a farm management recording system called MacMan (Queensland and New South Wales Primary Industries and Fisheries, Australia) has served to accurately report the severity of the brown centres problem. Kernel brown centres cost the industry about AU$2 million in 2007, through lost revenue to growers and diminished productivity of processing factories (Le Lagadec *et al*. 2007). This estimate did not include lost revenue due to dissatisfaction by consumers and lack of repeat purchases. The disorder only accounts for 1% of total kernel production. However, with nut production increasing on average by ~6% every year (Goode and Price 2008), kernel brown centres have the potential to become a serious quality issue. Little research on brown centres exists, apart from early studies conducted mainly in Hawaii (Prichavudhi and Yamamoto 1965); however, the defect is mentioned widely in informal grower journals, such as the Australian Macadamia Society's News Bulletin and proceedings of the Australian Macadamia Society's annual conference. The causal factors of kernel brown centres are undetermined.

Internal kernel disorders in other industries

Kernel browning was first recorded in roasted macadamia in Hawaii in 1965 (Prichavudhi and Yamamoto 1965), and has been found recently in raw Brazilian macadamias (Claudia Werner, pers. comm., June 2008). The low incidence and the difficulty involved in the detection of kernel brown centres may explain the lack of reporting in other countries.

Internal kernel discoloration is common in other nut species and often only manifests during roasting. 'Concealed damage' is a browning of roasted almond kernels (*Prunus amygdalus* var. *dulcus*) that is not visible in raw kernels (King *et al*. 1983). As in macadamias, affected almond kernels have a bitter flavour. Concealed damage is thought to be related to the exposure of almonds to warm, moist environments, and is only detectable in raw kernels by using near-infrared technology (Pearson 1999*a*, 1999*b*). An internal kernel browning called 'opalescence' may affect up to 70% of Australian-grown pecans (*Carya illinoinensis*) (Wakeling *et al*. 2002). Opalescence is believed to result from physical damage to kernels during processing (Wakeling *et al*. 2002).

Kernel colour deterioration during roasting has been studied in hazelnuts (*Corylus avellana*) (Özdemir and Devres 2000), cashew nuts (*Anacardium occidentale*) (Sabarez and Noomhorm 1993), and walnuts (*Juglans nigra*) (Lopez *et al*. 1995). These

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studies focused mainly on biochemical processes involved in discoloration, rather than causality.

Relationship between after-roast darkening and kernel brown centres

Given the erratic, unpredictable, and low incidence of macadamia kernel brown centres, the defect has been poorly researched. A similar kernel disorder, which only manifests after roasting, is 'after-roast darkening' (Albertson *et al*. 2005, 2006; McConchie and Albertson 2006). It is unclear whether after-roast darkening and kernel brown centres are related. Studies into after-roast darkening have focused mainly on the biochemistry of kernel browning and have suggested that the process begins with damage to the cell membrane (Albertson *et al*. 2005, 2006; McConchie and Albertson 2006). Damaged membranes allow substances, including the enzyme invertase, to come into contact with compounds within the cells. Enzymatic and non-enzymatic reactions occur, resulting in the conversion of sucrose into two reducing sugars: glucose and fructose. The reducing sugars together with amino acids are key components of the Maillard reaction, which appears to cause the browning of the kernels (McConchie and Albertson 2006).

Opalescence in pecan nuts is believed to be caused by oils escaping from cells due to membrane damage. Escaped oil browns during roasting, resulting in a discoloured kernel (Wakeling *et al*. 2003). Although the biochemistry of brown centres, after-roast darkening, and opalescence may be quite different, these defects may share a common starting point: damaged cell membranes.

Damaged membranes and exposed enzymes are associated with increased concentrations of reducing sugars in macadamia kernels (Albertson 2005). Roasted macadamia kernels with internal discoloration have higher levels of reducing sugars and lower levels of total sugars than unaffected nuts (Albertson *et al*. 2005). Discoloured roasted kernels had reducing sugar concentrations of 0.24–0.27% while non-discoloured roasted kernels had concentrations of ~0.03% (Wall and Gentry 2007). Prichavudhi and Yamamoto (1965) proposed that internal kernel browning is due to uneven distribution of reducing sugars in the macadamia kernels. Similarly, kernel discoloration in hazelnuts is due to a concentration of reducing sugars in the kernel centre (Özdemir *et al*. 2001). High concentrations of reducing sugars have also been observed in almonds affected by internal kernel discoloration (King *et al*. 1983).

Since the incidence of kernel brown centres is often higher in early-season macadamias, the defect has been associated with kernel immaturity (McConachie 1992). However, this association has not been verified. During kernel development, hexose sugars are converted to fatty acids. Immature kernels have high sugar and low oil content and may be more prone to discoloration (Wall and Gentry 2007). Oil content is inversely proportional to total sugar content in kernels and is a common measure of kernel quality (Ripperton *et al*. 1938; Mason 1983). Although kernels with high sugar concentrations tend to brown when roasted, the roast colour of immature kernels is similar to that of mature kernels (McConchie and Albertson 2006). Therefore, after-roast darkening does not appear to be related directly to kernel oil or sugar content and is probably initiated primarily through damage to the cell membrane (McConchie and Albertson 2006).

Possible causal factors of kernel brown centres

The causal factors of kernel discoloration have received limited attention. Farm management practices, such as tree health and nutrition programs, on-farm nut handling, nut drying regimes, and even microbial activity, have all been suggested as possible factors contributing to kernel brown centres.

Pre-harvest factors

Macadamia nut maturity and kernel oil content may influence the incidence of brown centres (McConachie 1992; Wall and Gentry 2007), and ambient temperature is the single most important environmental factor in determining kernel oil content during late-stage kernel growth (Stephenson and Gallagher 1986). Kernel oil content is thought to be directly linked to kernel quality (Ripperton *et al*. 1938; Mason 1983). Therefore, ambient temperature during nut development may be a factor in determining kernel quality. Not all macadamia nuts set and mature simultaneously on an individual tree. Variations in temperature during kernel development could lead to varying levels of kernel brown centres in a crop. Furthermore, water deficits during nut development can cause premature nut drop, resulting in immature nuts with low oil content and poor quality (Stephenson *et al*. 2003). Excessive rain during nut maturation also adversely affects kernel quality (Stephenson *et al*. 2000; Penter 2008). Thus, water deficit or excess and unfavourable ambient temperatures during nut development may result in poor kernel quality. The effect of this on kernel brown centres is unknown.

The effects of tree nutrition on kernel brown centres have not been investigated, although the relationship between kernel quality and tree nutrition has received some attention. In some macadamia cultivars, boron enhances kernel oil content and thus kernel quality (Stephenson and Gallagher 1987), and high nitrogen applications result in poor kernel quality (Kruger 2000*b*; Stephenson *et al*. 2000). The link between tree nutrition and fruit quality has been well established in many crops (Motosugi *et al*. 1995; Alva *et al*. 2006; Retief *et al*. 2008). However, there is no evidence that tree nutrition affects the incidence of brown centres in macadamia.

The susceptibility of different macadamia cultivars to kernel brown centres has not been studied. In walnuts, kernel darkening during roasting varies greatly across different cultivars (Lopez *et al*. 1995). As kernel brown centres may be most prevalent early in the season, McConachie (1992) suggested that early cultivars are most susceptible. However, there is little evidence to support this hypothesis. Large-scale comparisons of macadamia cultivars currently being conducted throughout Australia could be used to assess the susceptibility of the different cultivars to kernel browning.

Harvest management

Macadamias in Australia are mechanically harvested from the orchard floor following abscission. The time that nuts spend on the ground depends on individual farm management practices and environmental conditions. Delays in harvesting adversely affect nut quality (Cavaletto 1989; Wallace and Walton 2005; Walton and Wallace 2005, 2009; Quinlan *et al*. 2008). The extent of quality decline depends on the environmental conditions while the nuts remain on the ground. Under dry conditions, the nuts can remain on the orchard floor for weeks or even months without adversely affecting some aspects of quality (Mason and Wells 1984). In contrast, quality declines very rapidly under wet conditions (Simpson 2000). Quality problems from delaying harvesting include increased external kernel discoloration, germination, and mould (Cavaletto 1989; Liang *et al*. 1996). The extent of the external kernel discoloration depends on the time spent lying on the soil (Cavaletto 1989; Liang *et al*. 1996). The effect of delayed harvesting on kernel brown centres was not included in these studies.

Liang *et al*. (1996) developed an economic model to determine the cost of multiple harvests *v*. the profit achieved through improved kernel quality. The model takes into account the relationship among soil moisture content, the resulting nut moisture content, and the related kernel quality. Walton and Wallace (2005) found that nuts left on the orchard floor for extended periods had higher levels of after-roast darkening than nuts that had been harvested soon after abscission. Similarly in walnuts, kernel darkening during roasting was correlated with the time the nuts spent on the orchard floor (Lopez *et al*. 1995). The effect of delayed harvesting on kernel brown centres in macadamia is unknown.

Dehusking nuts

Harvested macadamia nuts are dehusked before they are dried. If the nuts are stored in-husk, the wet nuts generate heat through respiration and this can affect the quality of the kernels (Mason *et al*. 1998; O'Hare *et al*. 2000). It is recommended that the nuts are dehusked within 24 h after harvesting (Simpson 2000). Cavaletto (1989) stored nuts-in-husk for up to 3 months without deterioration in kernel quality as long as air flow around the nuts was continuous. This removed the heat generated by the husks and prevented kernel deterioration.

It has been suggested that incorrectly adjusted dehuskers may induce kernel browning through mechanical damage to the nuts (Fullerton 2005). A positive association has been found between the volume of nuts passing through a dehusker per time unit and the incidence of brown centres (Quinlan *et al*. 2008). Cavaletto (1989) noted that rough handling of macadamias causes kernel bruising, which becomes evident after roasting. Since after-roast darkening is thought to be related to damage to the cell membrane, and after-roast darkening and kernel brown centres are thought to be closely related, the role of dehuskers in kernel brown centres warrants further investigation.

Drop height

During handling, the nuts are repeatedly dropped from varying heights. The effects of physical damage on kernel quality have been studied (Cavaletto 1989; Wallace *et al*. 2001; Wallace and Walton 2005; McConchie *et al*. 2008; Walton and Wallace 2008). Severity of damage sustained during handling is dependent on the moisture content of the nut-in-shell. Freshly harvested nuts with a moisture content above 15% tend to bruise if handled roughly, while dry nuts can be reduced to half kernels without further damage (Bungay 2003). Although the damage caused by handling is not immediately apparent in raw kernels, it may become visible when the kernels are stored for a long time or are roasted (Mason and Wells 1984; Cavaletto 1989; Bungay 2003; Walton and Wallace 2008). Any relationship between drop height and brown centres is untested.

Nut-in-shell drying and storage systems

Wet nuts continue to generate heat through respiration. If stored in poorly aerated areas, the heat generated may encourage microbial activity and rancidity (Kowitz and Mason 2001) and possibly kernel brown centres. The higher the moisture content of nuts at the start of drying, or while in storage, the greater the risk of kernel deterioration (Prichavudhi and Yamamoto 1965; Simpson 1990; Kowitz *et al*. 1998*a*; Mason *et al*. 1998; Kaijser *et al*. 2000; Özdemir *et al*. 2001; Bungay 2003). Although the drying of nuts inhibits microbes, reduces respiration, and slows chemical reactions (Kowitz and Mason 2001), incorrect drying can be highly detrimental to nut quality (Bungay 2003; Kowitz and Mason 2003). Nut-in-shell drying is possibly the most crucial stage of macadamia kernel quality preservation. It is recommended that nuts are dried from field moisture to 7.5–10% moisture content on farm and dispatched promptly to processors (Kowitz *et al*. 1998*a*; Kowitz and Mason 2000; Simpson 2000).

There have been numerous studies carried out on macadamia drying systems including various bin designs, aeration systems, drying temperatures, and bed depth (Mason 1983; Liang *et al*. 1989; Simpson 1990; Winks 1998, 1999; Kowitz and Mason 2000, 2001; Kowitz 2001; Burnett 2004). Drying the wet nuts too slowly encourages microbial activity, germination, external discoloration, and rancidity, while drying the nuts too rapidly, especially at high temperatures, results in brittle nuts and possibly kernel brown centres (Prichavudhi and Yamamoto 1965; Kowitz 2001; Bungay 2003; Kowitz and Mason 2003). Under cool, wet conditions there is a risk of rewetting drying nuts while fans are operating (Winks 1998; Wilkie 2001), and it is recommended that entering air is heated (Kowitz *et al*. 1998*b*; Kowitz 2001; Kowitz and Mason 2001; Wilkie 2001). However, overheating the air can reduce kernel quality and possibly lead to brown centres, especially at the bottom of the bins where drying occurs more rapidly (Liang *et al*. 1989; McConachie 1994; Mason 2000; Kowitz 2001; Wilkie 2001; Bungay 2003).

The ideal drying regime is undetermined. Recommendations include never heating air above 38°C (Burton 2000) or above 30°C (Wilkie 2001; Bungay 2003). McConachie (1994) suggested that drying temperatures should not be more than 3–4°C above ambient temperatures. Incremental drying systems have also been recommended (Mason 1983; Wall and Gentry 2007). Finally, it has been suggested that the drying rate of wet nuts should not exceed 2% nut-in-shell moisture loss per day (Bungay 2003).

Optimum drying requires even air flow. Areas of poor air flow within silos can result in quality problems (Simpson 2000; Kowitz and Mason 2001). Moisture loss in a bin is initially uneven, with nuts at the base drying faster than those at the top (Mason 2000; Kowitz and Mason 2001). When crop loads are low, silos containing nuts are often topped up with fresh wet nuts. This accentuates the uneven drying of nuts in the silos. By keeping bed depth between 1 m and 2.5 m, the discrepancy in drying rates between the top and bottom can be minimised and kernel quality maintained (Kowitz and Mason 2001; Bungay 2003; Burnett 2004).

In the early days of the Hawaiian macadamia industry, on-farm drying was achieved largely through thin-layer sun drying (Moltzau and Ripperton 1939). Moltzau and Ripperton (1939) suggested that the sun-dried nuts were 'protected' against kernel browning since they required a 25% longer roasting before they browned. Poor quality kernels discolour faster when roasted and thus require a shorter time to achieve the desired colour (Ripperton *et al*. 1938). Although thin-layer drying may not be practical for commercial enterprises, it has been suggested that nuts be allowed to remain on the orchard floor for 6 days before harvest (Kowitz and Mason 2001). This reduces the nut moisture content and possibly reduces the chance of the nuts browning under high temperatures in silos (Kowitz and Mason 2001). Delayed harvesting may be effective under dry ambient conditions, but under wet conditions can reduce kernel quality (O'Hare *et al*. 2000; Quinlan *et al*. 2008; Walton and Wallace 2009).

Early-season macadamia crops contain a high proportion of immature nuts, which have a lower oil and a higher water content than the later crop (Mason 1983; McConachie 1994; Kruger 2000*a*). This affects the rate at which the nuts can safely be dried (Mason 2000; Kowitz and Mason 2001). Immature nuts dry faster than mature nuts and are more susceptible to quality problems (Kowitz and Mason 2001). Drying immature nuts at 40–55°C resulted in kernel browning, compared with mature kernels, which only brown at ~70°C (Kowitz and Mason 2001). It is therefore important to control temperatures used to dry the early nuts.

Drying wet nuts at high temperatures may cause moisture to be removed from the kernel faster than diffusion can occur through the shell (Kowitz and Mason 2001; Bungay 2003). Rapid drying causes hardening of the kernel, resulting in an impervious layer that prevents the further diffusion of moisture. Moisture becomes trapped in the kernel and because of existing heat, creates ideal conditions for reducing sugars to accumulate and kernel brown centres may then occur (Kowitz and Mason 2001). Rapid drying of wet nuts can result in a moisture content of 1% in the kernel outer layer, while the inner kernel remains at ~5% (Bungay 2003). The resulting nut-in-shell moisture content would be 3%, but the moisture is unevenly distributed.

Palipane and Driscoll (1994) theorised that when kernels are dried at high temperatures, oil in the inner kernel migrates to the outer kernel and becomes an impervious barrier to further moisture loss. Moisture trapped within the kernel can possibly lead to brown centres. The impervious layer theory would explain why rapid drying or drying at too high temperatures results in discoloration. Usually only a small portion of kernels develop brown centres, probably due to uneven drying in the larger commercial silos or silos with deep beds. Larger silos produce notably higher proportions of brown-centred kernels (Quinlan *et al*. 2008).

Declines in quality due to incorrect silo drying or storage are not limited to macadamias. Concealed damage in almonds is believed to be caused by incorrect drying temperatures (Pearson 1999*a*). Brown patches on the kernels of cashews are thought to develop from prolonged storage of wet nuts (Hidellage 1999). Excessive heat generated through metabolic activity in soybean silos not only causes product quality losses, but can also result in spontaneous combustion of the soybeans (Ben-Efraim *et al*. 1985).

Crackers

Removing macadamia kernels from the shells requires tremendous force. The nuts are usually cracked by applying compression forces that can result in damage to the kernels (Liang 1977; Mason and McConachie 1994). It has been suggested that one of the factors causing kernel brown centres may be bruising incurred during nut cracking. The mechanical properties of the nuts in response to pressure have been studied and various alternative methods of cracking developed (Sarig *et al*. 1980; Liang *et al*. 1988; Braga *et al*. 1999). This technology has yet to be adopted. A study into the effects of 4 different nut crackers on kernel quality found that although physical pressure on the nuts affected the percentage whole-kernel recovery, it had no effect on kernel browning (Wallace *et al*. 2001).

Storage of kernel

Raw and roasted macadamia kernels should be stored at a moisture content not exceeding 1.5% (Cavaletto 1981). Low moisture content prevents microbial activity, rancidity, and the loss of kernel quality (Mason *et al*. 2004). Cavaletto *et al*. (1966) tested the stability of raw kernels at various moisture contents, temperatures, and light regimes. They found that the kernel deteriorated with increasing moisture content and storage temperature. At higher moisture content and storage temperatures, total sugars in the kernel decrease and reducing sugars increase (Cavaletto *et al*. 1966). Reducing sugars are the reagents of the Maillard reaction (Albertson 2005; Albertson *et al*. 2005; McConchie and Albertson 2006), which is thought to be involved in kernel browning. Thus, storing kernels at high temperatures and moisture contents could lead to brown centres developing. Cavaletto *et al*. (1968) found that raw kernels with 3.8% moisture content stored for several months developed internal discoloration when roasted, whereas nuts with a moisture content of 1.2% did not.

Microbial activity as a possible cause of kernel brown centres

Microbial activity as a possible factor in kernel brown centres was first suggested by McConachie (1992). Pathogens can affect the kernel colour of peanuts (*Arachis hypogaea*) (Ellis *et al*. 1994), almonds (King *et al*. 1983), walnuts (Lopez *et al*. 1995), and macadamias (Nishijima *et al*. 2007). In a preliminary study, Nishijima *et al*. (2007) reported that internal kernel discoloration in Hawaiian macadamias was caused by the *Enterobacter cloaca* pathogen. The pathogen is most prominent in wet seasons, when nut moisture content is high. During particularly wet seasons, up to 10% of all nuts-in-shell can be affected. Contamination can be passed among stored kernels (Nishijima *et al*. 2007). Preliminary studies in Australia have not identified any pathogens associated with kernel brown centres. However, some have identified aflotoxins and elevated levels of free fatty acids and ergosterol in brown-centred kernels, which are associated with microbial activity (McConachie 1992; Proksch and Wood 2000).

Conclusions

Causal factors of macadamia kernel brown centres have not been established. Brown centres and after-roast darkening may share common biochemistry. If this is so, the causal factors which promote after-roast darkening may also be involved in kernel brown centres. There appears to be an association among nut-in-shell moisture content, nut drying regime, and kernel brown centres. Drying wet nuts too rapidly or at excessive temperatures appears to promote brown centres. If brown centres were simply a function of ineffective silo drying, then it could be expected that a given silo would produce a large amount of poor nuts. Since there is no evidence to support this, the problem is probably more complex. It may be that some macadamia nuts are more susceptible than others and that incorrect drying of wet nuts produces the typical brown centre symptoms in those susceptible nuts. Further study into causal factors and remedial strategies is recommended.

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