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Final Report

Pre-harvest practices that will increase the shelf-life and freshness of vegetables

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Contents

Summary

Consumer satisfaction and value chain development are key priorities for the vegetable industry. Quality, including freshness and shelf-life, the length of time produce remains fresh and saleable, is a critical issue for vegetables, which typically withstand the stresses of the farm to fork supply chain operations. External quality of fresh vegetables relates to the appearance and freshness of the product, firmness, and aroma. These characteristics are inspected readily by the senses and determine the acceptability and purchase willingness of consumers. Internal quality, including flavour, internal appearance, and texture, is critical to the eating satisfaction of consumers and is a key driver to promoting repeat sales and vegetable consumption. In addition to being important sources of vitamins, minerals and fibre, the presence of health-promoting bioactive compounds such as antioxidants and pigments has increased interest in vegetable consumption. As a result, health and well-being have been increasingly recognised as powerful non-sensory drivers for vegetable consumption.

Pre-harvest production practices are critical in developing optimal quality of vegetable crops, which depends on the interaction of genetic, agronomic, and environmental factors. Since quality of vegetables cannot be improved postharvest, identifying the best combinations of these pre-harvest factors is a key strategy to maximise vegetable quality to meet consumer needs. Although there is considerable research over the years, the information is scattered across many documents such as industry reports, scientific journals, and conference proceedings. This comprehensive review aimed to compile current knowledge on the effects of pre-harvest factors on shelf-life and quality of vegetables, and develop an information package to increase grower awareness, foster adoption of practices that can enhance quality across the industry, and potentially add value to Australian vegetables. The scope of this review included the following vegetables: Asian vegetables, broccoli, Brussels sprouts, cabbage, capsicum, carrot, cauliflower, celery, chilli, cucumber, eggplant, green beans, kale, lettuce, parsley, pumpkin, rocket, silverbeet, spinach, spring onion, sweetcorn, sweetpotato, turnip, and zucchini.

The project was collaboration between the NSW Department of Primary Industries and Applied Horticultural Research, which developed factsheets and articles highlighting key information extracted from the review.

Overall, the review highlights that worldwide published research on pre-harvest factors that focus not only on yield, but also on the impact on product shelf-life and quality has been generally limited for most vegetables. In addition, quality and shelf-life was shown to be influenced by a large number of specific agronomic, genetic and environmental factors that seem to interact in a complex way.

Leafy and Brassica vegetables were the groups with most research in the topic of the review. The key findings from these groups show that understanding pre-harvest interactions and developing crop schedules that can match the best combination of cultivar, growing area, plant growth rate, and time of the year, can have major benefits in terms of balancing yield and quality/shelf-life. That can only be achieved by targeted research for each key production area, which has been done in Australia to a degree for lettuce, spinach, and broccoli. However, there are considerable gaps for other vegetables.

Several areas offer R&D opportunities for quality improvement, including extended shelf-life, enhanced produce appearance and composition, and higher resistance to postharvest diseases. Recommended areas include:

- Development of crop planting schedules to match current cultivars with growing regions and times of the year in order to achieve an optimum balance between yield and quality/shelf-life for other key commodities such as Asian vegetables, broccoli, cauliflower, cabbage, kale, capsicum, zucchini, cucumber, green beans, and sweetcorn;
- The use of silicon and other fertiliser salts during production of leafy vegetables, cucumber, zucchini, and capsicum. Research areas could include: the impact on yield, quality/shelf-life, and resistance to postharvest diseases, insect control through the formation of phytoliths, nutrient uptake/utilization, and alleviation of abiotic stress;
- Growing conditions that can increase the content of bioactives (e.g. sulphur and nitrogen nutrition to enhance glucosinolate levels in brassicas);
- Regulation of salinity (EC) during production of hydroponic leafy vegetables to improve quality;
- The use of deficit irrigation to improve quality and shelf-life in broccoli and leafy vegetables;
- The use of LED light systems during production of greenhouse lettuce, spinach, and capsicum.

Keywords

Vegetables; pre-harvest factors; quality; shelf-life; review

Introduction

Consumer satisfaction and value chain development are key priorities for the vegetable industry. The shelf-life and freshness are the top priorities of vegetables consumers, as shown in several HAL-vegetable levy funded R&D projects focused on consumer attitudes such as VG12070, VG12069, VG10094, and VG08000. Shelf-life, the length of time produce remains fresh and saleable, is a critical issue for vegetables, which typically withstand the stresses of the farm to fork supply chain operations, including postharvest handling, storage, transport, distribution and retail.

From a consumer's perspective, external quality attributes of fresh vegetables relate to the appearance and freshness of the product and include properties such as colour, size, shape, the absence of surface defects, external texture including firmness and moistness, and aroma. These attributes determine the degree of acceptability and the purchase willingness of consumers, as these properties may be inspected readily by the eye, touch, or smell (Huyskens-Keil and Schreiner, 2003; Nicolai *et al.*, 2014). Internal quality attributes include the perception of flavour, a combination of taste and aroma (Kader, 2008). However, the internal appearance, texture (e.g. crispness, juiciness), mouth feel sensations, temperature, and past experience also play significant roles in flavour perception, suggesting that multiple distinct sensory inputs are processed to generate the overall sensation (Goff and Klee, 2006). These attributes are critical to the organoleptic satisfaction of consumers and are the key drivers towards stimulating repeat sales and increasing consumption. However, more elusive quality attributes such as nutritional value and health-promoting compounds, food safety, production system and location, convenience, and ethical aspects, also affect the quality perception of consumers on a more abstract level (Nicolai *et al.*, 2014). As such, quality is not a fixed value, but rather a time, product, and consumer-dependent dimension (Huyskens-Keil and Schreiner, 2003).

Although consumers' choices are often driven by produce appearance, the health impacts of food are an increasingly important consideration for the consumer. The coming decades will most likely see a more informed consumer attempting to choose foods which they believe will improve their health. This is likely to promote responses in the agribusiness sector aiming to identify and communicate the health benefits of particular products (Hajkowicz and Eady, 2015). In addition to being important sources of vitamins, minerals, and dietary fibre, there has been increasing interest in vegetable consumption due to the presence of bioactive compounds or phytochemicals such as antioxidants and pigments, which have been associated with potential health benefits beyond basic nutrition (Kushad *et al.*, 2003; Boeing *et al.*, 2012). As a result, health and well-being have been increasingly recognised as powerful non-sensory drivers for vegetables consumption (Schreiner and Huyskens-Keil, 2006). Accordingly, the vegetable industry has identified the potential for growers to leverage increased nutrient and bioactive levels in vegetables to enhance demand in both domestic and export markets. This has been supported by several HAL-vegetable levy funded projects and initiatives, such as VG05072, VG12043, and VG08141.

Pre-harvest production practices are critical in establishing and maintaining optimal yield and quality of vegetable crops grown both under open field and protected conditions. Several reviews have shown that quality of a range of vegetable crops depends on the interaction of agronomic (i.e. growing practices such as nutrient, water, and crop management), environmental (e.g. temperature, light, and humidity), and genetic (e.g. cultivar and grafting) factors (Weston and Barth, 1997; Rosenfeld, 1999; Gruda, 2005; Rouphael *et al.*, 2012). Likewise, a number of reviews highlighted the impact of pre-harvest factors on vegetables composition, including the contents of nutrients (Lee and Kader, 2000; Weerakkody, 2003; Martinez-Ballesta *et al.*, 2010) and bioactives (Schreiner, 2005; Leskovar *et al.*, 2009; Tiwari and Cummins, 2013; Bian *et al.*, 2015). Since quality of vegetables cannot be improved postharvest, identifying the best combinations of those factors is a key strategy to maximise vegetable quality to meet consumer needs. Although considerable research has been developed over the years, the information is scattered across a range of multidisciplinary documents in several fields, including industry reports, scientific journals, and conference proceedings. The opportunity for such data to be reviewed, collated, and organised for each crop, in a format that is easy-to-understand and interpret is significant for the Australian vegetable industry. This information has the potential to increase grower awareness and foster adoption of practices that can enhance quality across the industry, adding value to Australian vegetables, and increasing consumption. It can also allow potential gaps of information to be identified and priority areas for further investment in R&D to be highlighted.

Methodology

A number of sources of information were used to identify, collate, analyse, and review the current state of knowledge on the topic of this project: pre-harvest factors influencing quality and shelf-life of vegetables. These included:

- Information collected from published scientific literature worldwide, including research/review papers and conference proceedings, following standard procedures of searching scientific databases, mainly Discovery, CAB Direct, and Web of Science;
- Industry technical reports from R&D and marketing projects;
- Technical and research bulletins, articles, fact sheets, and books from Australian and international research agencies and universities;
- Industry projects and tracker reports on market and consumer issues (e.g. VG12078 Project Harvest), which provided background information on quality and consumer issues
- Statistical data from the Australian Bureau of Statistics, which provided background information on production and value of vegetable commodities;
- The United States Department of Agriculture (USDA) 'National Nutrient Database for Standard Reference', which provided background information on key nutritional content

The scope of this review included the following levied vegetables, which were grouped into six sections based on common quality and shelf-life issues according to their plant characteristics or their family group:

1. Leafy vegetables: lettuce, spinach, rocket, silverbeet, parsley, spring onion, and Asian vegetables;
2. Brassica vegetables: broccoli, cauliflower, cabbage, kale, Brussels sprouts, turnip, and radish;
3. Cucurbit vegetables: cucumber, zucchini, and pumpkin;
4. Fruiting and legume vegetables: capsicum, chilli, eggplant, and green beans;
5. Ear and stalk vegetables: sweetcorn and celery;
6. Root and tuber vegetables: carrot and sweetpotato.

No relevant publications related to the topic of this review were found for the following vegetables: stem broccoli (i.e. Broccolini®), swede, snow pea, rhubarb, artichoke, and beetroot.

Given the wide range of commodities covered by this review and the diverse quality issues involved, a background section was included in each major vegetable commodity or group summarising the commercial importance, main cultivar types, key compositional and nutritional aspects, as well as the key quality issues of that commodity or group. The pre-harvest factors were separated into two main sections: crop nutrition and crop management (other than nutrition). To organise the studies within these sections and make them easier to read, subheadings were used grouping the studies under similar topics, starting generally with those that were more relevant within each topic. In each of the six sections, sub-sections were also included with the key findings, conclusions, and references related to the section.

A careful examination of the studies was made to select those that were both relevant to the topic and scientifically sound. Only publications with a full report in English were considered, so results shown in the abstract could be verified. Given their relevance to the Australian vegetable industry, particular attention was given to studies and R&D projects conducted in Australia, which were generally shown first in each subheading section whenever present.

Review on pre-harvest factors affecting quality and shelf-life of vegetables

1. Pre-harvest factors affecting quality and shelf-life of leafy vegetables

1.1 Key findings

Lettuce

- Matching growing region with optimum production window appears critical to achieving optimum quality and shelf-life. This can be achieved by developing an effective crop planting schedule that matches the best cultivar, region and growing/harvest time of the year;
- Variation in treatment responses to crop nutrition regarding form, rates, timing, and cultivar is large, suggesting that the management of those factors is complex to optimise the yield-quality balance and the impact on plant diseases/disorders. Targeted crop nutrition research under local conditions and current cultivars seems vital rather than a 'one size fits all' approach;
- Under both field and protected conditions, external quality and shelf-life of lettuce were enhanced by a balanced and judicious application of nutrients, especially nitrogen (N), phosphorus (P) and potassium (K) combined and at the appropriate ratio;
- Very high N rates generally resulted in shorter shelf-life, greener and softer leaves, and higher nitrate content than lower rates, although responses were cultivar-dependent;
- Avoiding excessive N, either as fertiliser or in the nutrient solution, and choosing N forms such as calcium nitrate rather than ammonium nitrate, can potentially increase plant resistance to fungal diseases that affect quality such as downy mildew and anthracnose;
- Growing practices preventing excessive growth rates such as balancing N supply, optimising cultivar-climate interactions, growing at cooler times of the year, and selecting resistant cultivars, can better control tipburn than calcium (Ca) foliar sprays, especially in field conditions.

Leafy vegetables other than lettuce

- Growth rate (days to harvest), growing season, and cultivar appear to strongly affect shelf-life of spinach, highlighting the importance of a crop scheduling model to predict harvest date and identify the adequate 'seasonal window' for optimum shelf-life for each cultivar and location;
- Generally, longer shelf-life was associated with slow-growing cultivars and conditions (i.e. cooler areas and times of the year), smaller leaves, and younger plants;
- Cultivar and growing season also affected composition of spinach, with slow-growing cultivars or cooler growing conditions generally resulting in higher contents of vitamin C, folate, and oxalates, and lower nitrate content; cooler growing conditions were also associated with increased shelf-life in baby leaf rocket;
- Most research on crop nutrition affecting quality focused on leaf composition of spinach: higher N rates, particularly as nitrate, generally increased the content of undesirable compounds such as nitrate and oxalates, whereas applied N had little effect on shelf-life of spinach and rocket;
- Applied silicon (Si) enhanced visual quality and shelf-life, increased leaf Si content (a trace element associated with bone health), and reduced nitrate content of baby leafy vegetables and Iceberg lettuce in a few studies, suggesting it is an area that warrants further investigation.

1.2 Lettuce

Background

Commercial importance and main cultivar types

Lettuce (*Lactuca sativa* L.) is a popular salad vegetable and an important horticultural commodity in Australia, with an annual production of 122,589 tonnes and a gross value of $141.4 M in 2013-14 (Anon., 2015f). A recent report on fresh vegetables places lettuce as the 4th most regularly purchased vegetable by about 80% of consumers in Australia (Witham et al., 2015).

There are four widely recognized morphological forms of lettuce (Welbaum, 2015):

- Crisphead: often referred to as 'Iceberg' or simply head lettuce, with a very dense rosette and crispy texture;
- Butterhead: another heading type with smaller tender leaves and delicate flavour;
- Cos: also known as 'Romaine', with elongated, crispy-textured leaves;
- Loose leaf or bunching: with large variation in leaf size, shape, colour, and texture.

One of the outstanding qualities of Iceberg lettuce is its high density, giving it more robust handling, transport and storage capacity and longer shelf-life than the other types. It is widely used as a key ingredient for tossed salads and on sandwiches by consumers, restaurants, and companies, as pre-washed ready-to-eat items premixed. In contrast, butterhead types are more fragile, easily bruised, and susceptible to leaf breakage and wilting than crisphead ones (Turini *et al.*, 2011).

Lettuce crop maturation is highly dependent on temperature, with non-heading cultivars maturing quicker than crisphead types (Welbaum, 2015). There is little growth at temperatures below 7.2°C , whilst temperatures above 30°C usually stunt growth, resulting in bitterness and poor quality head formation, as well as promoting tipburn, a necrosis of the leaf margins leading to head rot through secondary infections in less resistant cultivars (Turini *et al.*, 2011).

In Australia, Iceberg and Cos lettuces are the most commonly available, with other varieties becoming increasingly popular, such as butter, mignonette, oakleaf (red and green) and radicchio. Individual lettuce heads, either bagged or loose, are purchased by the majority of Australian consumers, but there has been a continued increase in purchase of pre-prepared format such as packaged in sealed bags ready for use, as well as individual lettuce leaves (Anon., 2015d). Some cultivars such as 'Coral green', 'Coral red', and 'Salanova' are sold as baby leaf, a term describing a wide range of leafy vegetables harvested and marketed in an immature stage of development (i.e. only a few weeks old), which also include other commodities such as spinach, rocket, tatsoi, and mizuna, forming the basis for the typical mesclun salad mixes as detailed in section 1.3. The fresh-cut and ready-to-eat salad processing industry is the major vector for salad consumption growth in Australia, and a fast-growing market due to consumer demand for convenient, high quality, fresh, and healthy products (Ragaert *et al.*, 2004).

Key compositional and nutritional aspects

As one of the most popular and regularly purchased vegetables in Australia, lettuce's overall nutritional contribution is significant. Lettuce is a good source of vitamins (mainly A, K, C, and folate, in addition to B_1, B_2, and B_6), minerals (mainly K, Mn, and Fe, in addition to Ca, Mg, and P), and dietary fibre (Anon., 2015a).

Newer cultivars are often more strongly coloured than the traditional Iceberg-type cultivars, and the pigments that confer colour have a range of health-promoting phytochemicals such as carotenoids (e.g. β-carotene, lutein, neoxanthin, and violaxanthin), polyphenols (including flavonols and anthocyanins in red cultivars, caffeic acid derivatives in green cultivars, quercetin, and luteolin), chlorophyll, and lignans (Hedges, 2007; Llorach *et al.*, 2008; Baslam *et al.*, 2013b).

In contrast, lettuce, among other vegetables, is prone to accumulation of nitrate, particularly when nitrate is the predominant N source, in the winter season, and under low light intensity and lower temperature conditions in areas such as Europe (Burns *et al.*, 2011). In Australia, an excessive supply of nitrate is more likely to promote nitrate accumulation (Parks et al., 2008). High nitrate levels in tissues are undesirable because they are associated with decreased concentrations of vitamin C in lettuce (Konstantopoulou *et al.*, 2010). The intake of nitrate has also been associated with potential harmful effects on human health, such as increased risk of gastrointestinal cancer and methemoglobinemia in infants, resulting in maximum allowable nitrate levels in lettuce being imposed by markets such as the European Union (Santamaria, 2006). In a survey of Australian leafy vegetables, some samples of green coral lettuce, red coral lettuce and green oak lettuce exceeded the European Commission production limits, whereas Iceberg lettuce was half those limits (Parks *et al.*, 2008). However, current epidemiological data provide conflicting evidence regarding the potential long-term health risks of nitrate levels in the diet (Hord *et al.*, 2009).

Key quality issues

Recent market surveys showed that purchasing lettuce is triggered by health, complementing other food, and ease of preparation by Australian consumers, whereas not wanting to waste any and a short shelf-life are key barriers to purchase (Anon., 2015d). Once purchased, Australian consumers expect lettuce to stay fresh for just over a week, and these expectations are being met most of the time by 70% of consumers (Anon., 2015d).

Shelf-life is a critical issue in baby leaf vegetables, as it relates directly to freshness, a quality that consumers value highly in their buying decisions (Rogers, 2011). It can be defined as the length of time a product can maintain the appearance, safety and nutritional value that appeals to the consumer. Key attributes of leafy vegetables used as quality indices include moisture loss (leading to weight loss, shrivelling, and quality loss), green colour retention, which is associated with chlorophyll content in green vegetables and has a great impact on consumer selection, and microorganism proliferation (Aguero *et al.*, 2011).

With fresh-cut products, appearance and texture are key factors determining quality and shelf-life (Toivonen and Brummell, 2008). The main symptoms of deterioration are browning, bleaching of the green colour, texture breakdown, off-odour and off-flavour formation mostly due to increased respiration rate, water loss, enzymatic activity, and/or microbiological contamination (Tudela et al., 2013). Baby leaf products are actively growing and so use more energy for processes like cell division and cell expansion, have higher rates of respiration, and thus use up stored carbohydrate faster than mature products of the same species when harvested (Rogers, 2008). Young plants are also more susceptible to bruising and physical damage as the leaves are not fully developed and so are less robust than mature ones.

Postharvest handling can maintain quality, but not improve it, so high quality raw material at harvest is vital to prolong the shelf-life of fresh-cut vegetables, preserve their nutritional value, and assure food safety (Tudela et al., 2013). The latter is an important issue as leafy vegetables are the commodity group identified as the highest priority in terms of fresh produce microbial safety from a global perspective (Gil et al., 2015). To achieve this, it is essential to understand the raw material characteristics and to effectively manage the agronomical factors during cultivation that can influence the quality of vegetables during the supply chain.

Crop nutrition

Nutrition management under field conditions

Lettuce is a heavy feeder plant with a shallow fibrous root system, so precision timing and placement of fertiliser applications is vital to reduce waste. Areas under intensive frequent production may have high levels of nutrients, so new applications should be guided by soil testing (Welbaum, 2015).

A comprehensive 3-year evaluation of Iceberg and Cos lettuce cultivars for the fresh-cuts salad industry, with field trials planted 4-5 times over the growing season across 6 major locations in Australia showed that (Rogers, 2007):

- For optimal yield and quality (determined as visual appearance, crispiness, odour, taste, damage, consistency, and overall freshness) it is essential that nutrients are applied in a balanced way, i.e. at the appropriate ratio with other nutrients rather than independently;
- For a basal NPK fertilisation, application of 75:90:120 kg/ha increased shelf-life of Iceberg lettuce from 9 to 10 days and yield by 43%, compared to 50:60:80 kg/ha;
- N applied alone at 100 or 200 kg/ha reduced shelf-life of Iceberg lettuce from 10 to 7 days.

In a 2-year trial with Cos and Iceberg lettuce grown in California and cold stored at 1°C for 14 days (Hoque et al., 2010):

- A rate of 225 kg/ha N combined with 112 kg/ha P resulted in the highest yield and best postharvest quality (i.e. colour, wilt, turgidity, glossiness, decay, and defects);
- High rates of 337 kg/ha of N plus 225 kg/ha of P reduced quality by increasing decay and defects (key quality issues for Cos and Iceberg lettuce, respectively);
- Applied K fertilizer had little effect on quality;
- Higher postharvest quality index, a combined visual rating of all defects, correlated strongly (i.e. $R^2 = 0.84$) with lower leaf glucose content, which was suggested as a potential shelf-life indicator of cold-stored lettuce.

In two 2-year field studies, increasing levels of N from 50 to 200 kg/ha applied to crisphead lettuce (cvs. 'Marius' and 'Saladin') grown in Denmark and cold-stored at 1°C for 1 or 2 weeks resulted in (Poulsen *et al.*, 1994; Poulsen *et al.*, 1995):

- Lower contents of dry matter, sugars, and vitamin C, and higher content of nitrate;
- Optimum yield of marketable heads at 150 kg/ha;
- Little effect of N on total weight loss during cold-storage;

Applied N as ammonium nitrate at 120 kg/ha to Iceberg lettuce grown in the UK reduced leaf tissue strength and stiffness, which were associated with reduced hydration or more wilting, compared to a lower N rate of 22-33 kg/ha, but that effect was reverted by the addition of Ca at 80 kg/ha (Newman *et al.*, 2005).

Nitrogen form can affect the nitrate content in lettuce. For example, replacing 40% of nitrate N with ammonium N, or reducing nitrate N from 260 to 200 kg/ha of N, reduced nitrate content in butterhead lettuce grown in Denmark without affecting yield (McCall and Willumsen, 1998). Likewise, Ca nitrate increased nitrate content in lettuce ('Amar' cultivar) leaves (especially the outer ones) grown in Jordan by up to 270% compared to ammonium sulphate and urea (Abu-Rayyan et al., 2004).

In a 2-year study in Italy, the application of N as ammonium nitrate at either 50 or 100 kg/ha combined with strobilurin (i.e. Azoxystrobin at 0.42 g/L active ingredient, a broad-spectrum fungicide presumably with non-toxic effects on humans or the environment) to butterhead lettuce cold-stored for 7 or 12 days at 5°C, retarded loss of colour and chlorophyll degradation, reduced browning and nitrate content compared with added N without strobilurin; the rate of 50 kg/ha was recommended for more favourable climatic conditions, whereas 100 kg/ha was required to optimise yield and quality under less favourable growing conditions such as heavy rains and low temperatures (Bonasia et al., 2013).

In contrast, some studies report little effect of N fertilisation on lettuce quality. For example, in a 2-year field study in the UK, ammonium nitrate applied at 120 kg/ha had little effect on discolouration of fresh-cut Iceberg lettuce cv 'Saladin' (Hilton et al., 2009). Similarly, N as urea at 75 or 150 kg/ha applied to fresh-cut butterhead (cv. 'Daguan') and loose leaf lettuce (cv. 'Brisa') in Argentina that was bagged and cold-stored for 7 days at 1°C had no impact on visual quality (Chiesa et al., 2009).

Nutrition management under protected cropping

A study with baby leaf lettuce (cvs 'Red Coral', 'Green Coral', and 'Salanova') grown in pots in a glasshouse in Sydney, NSW and cold-stored in plastic bags at 4°C showed that (Rogers, 2008):

- An increase in N from 50 to 100-150 kg/ha as part of a potting mix (resulting in leaf N content >4% at harvest) reduced shelf-life (>50% of leaves 'failed', i.e. were desiccated, broken-down, or yellow) from 27 to 23 days in the coral cultivars, but not 'Salanova'.
- However, as marketable yield was considerably reduced at 50 kg/ha of N, the study also highlighted the need for a compromise between yield and quality.

In two studies over three seasons with hydroponically-grown Cos lettuce in Greece, compared to lower rates of 20 or 80 mg/L, N as calcium nitrate in the nutrient solution at levels of 140-260 mg/L resulted in (Konstantopoulou *et al.*, 2010; Konstantopoulou *et al.*, 2012):

- Greener plants at harvest or during 10 days storage at 5-10°C;
- Higher nitrate content;
- 200 mg/L recommended for a good balance between yield and acceptable nitrate levels.

A 2-year study in Italy with loose leaf lettuce (cv 'Green Salad Bowl') greenhouse-grown in a floating raft growing system showed that (Fallovo *et al.*, 2009):

- Nutrient solution (NPK, Ca, Mg) at 37 or 44 meq/L (for the spring and summer seasons, respectively) was recommended for optimum yield, colour, and leaf minerals content;
- Higher leaf carbohydrate and lower nitrate contents compared to lower concentrations (i.e. 2 or 18 meq/L);
- Plants grown in the cooler spring had lower yield/growth, but higher leaf quality than those grown in the hotter summer.

In a 3-year study in the USA, application of N at 30-240 mg/L and S at 7.5-120 mg/L to hydroponically-grown lettuce (cv 'Grand Rapids') showed that (Cuppett et al., 1999):

- Nitrogen level had a larger impact on the perception of sensory attributes (i.e. appearance, colour, texture, flavour, bitter flavour, and overall acceptability) than S;
- N at 240 mg/L resulted in greener and softer leaves in spring, but not in winter, than those treated with 30 and 60 mg/L.

Butterhead lettuce grown in Italy under 185 kg/ha of N with 10% shading had greener leaves and higher carotenoids content than those grown at the lower rate of 75 kg/ha (Stagnari et al., 2015).

Some studies report little effect of mineral nutrition on quality of hydroponically-grown lettuce. For example, nutrient solution at 1.4, 1.9., or 2.4 dS/m had little impact in the shelf-life, external appearance, texture, and contents of vitamin C and phenolics of fresh-cut lettuce (two red, 'Lollo Rosso' and 'Red Oak Leaf', and one green, butterhead) grown in Spain (Luna et al., 2013). Likewise, the addition of calcium at 3 or 6 meq/L to the nutrient solution had little impact on shelf-life and visual quality of minimally processed butterhead lettuce stored at 1°C or 8°C for 9 days in Italy (Leon et al., 2009).

Nutrition impact on tipburn

Tipburn is an important physiological disorder of lettuce associated with the lack of Ca mobility in the heads or developing heart tissues, resulting in necrosis of leaf margins on young leaves and head rot through secondary infections (Collier and Huntington, 1983; Welbaum, 2015). Its incidence tends to increase during warm weather and rapid growing conditions, and it can greatly reduce product quality and marketability, especially in less resistant cultivars.

Under field conditions, two studies in Australia suggested that tipburn incidence was primarily associated with high crop growth rates, and thus cultural practices that prevent excessive growth rates (e.g. balancing N supply to the plants, optimising varietal and climactic interactions, or growing at cooler times of the year,) are likely more effective strategies for reducing the incidence of tipburn than Ca foliar sprays. In the first study, foliar sprays of calcium chloride, calcium nitrate, or calcium carbonate did not reduce tipburn severity in Iceberg or Cos lettuce grown at three key production areas in southern Victoria in a 2-year trial, and leaf Ca content was a poor indicator of tipburn risk; also, additional N fertiliser increased the crop growth rate and induced premature tipburn in Cos lettuce (Dimsey and Murdoch, 2002). In the second study, foliar sprays of Ca chloride or chelated Ca were not effective in reducing tipburn severity in Cos lettuce grown at Gatton, Qld (Rogers, 2007). Likewise, in California, Ca fertilisers (i.e. nitrate, thiosulfate, and chloride) applied through drip irrigation during the final weeks of Cos lettuce were also ineffective in increasing leaf Ca concentration or reducing tipburn severity (Hartz et al., 2007). In that work, a survey of 15 commercial orchards showed that tipburn severity was unrelated to either leaf Ca concentration or soil Ca availability, with most severe symptoms observed in fields in which transpiration was reduced by foggy weather during the final 2 weeks of growth.

In contrast, under protected conditions, frequent foliar applications of a Ca chloride solution as low as 90 mg/L to Cos lettuce soil-grown in the greenhouse in Canada decreased the number of leaves and percent leaf area with tipburn, and increased Ca content in young leaves (Corriveau et al., 2012). Likewise, application of a Ca nitrate solution at 15 mM twice a week was effective in controlling tipburn in Cos lettuce hydroponically-grown in Greece (Tzortzakis, 2009). A recent study in Greece showed that the incidence of tipburn was affected by the hydroponic system, and that both Ca and N seemed to be implicated in that, as lettuce grown with a deep flow technique had high incidence of tipburn, lower Ca, and higher N contents compared to lettuce grown on perlite (Assimakopoulou et al., 2013). Tipburn was also affected by cultivar, as well as positively correlated with lettuce shoot growth, tissue water content, K and B concentrations, whereas negatively correlated with Mg.

Nutrition impact on diseases

Leafy vegetables in general and lettuce in particular can be affected by diseases that can greatly diminish quality. Crops affected by diseases can already breakdown at harvest, resulting in poor raw material for the fresh cut industry and, if processed together with healthy products, seriously reduce their shelf-life. Nutrition plays an important role in the development of plant diseases and management towards providing optimum nutrition might assist in disease control. Pathogens can limit plant capacity to take nutrients up and to distribute and utilise them. In general, excess N fertilisation increases the severity of plant fungal diseases, as it increases vegetative growth and promotes a higher proportion of young tissue, which is more susceptible to disease (Veresoglou et al., 2013). High N can also reduce the phenolic and lignin content of plants which in turn reduces their natural defence systems (Dordas, 2008).

The source of N appears also to be more important than the rate regarding plant susceptibility to diseases (Dordas, 2008). In Australia, application of high rates of Ca nitrate to lettuce (cvs 'Iceberg' and 'Cos') seedlings grown in four commercial locations in Victoria, reduced their susceptibility to downy mildew (*Bremia lactucae*; one of the most serious diseases of lettuce in temperate areas) and anthracnose (*Microdochium panattonianum*), whereas the application of ammonium nitrate increased disease susceptibility (Minchinton, 2012). That study also showed a strong varietal response in susceptibility to disease and response to N, highlighting the importance of a balanced nutrient schedule tailored for particular lettuce cultivars.

Likewise, an increase in the number of leaf spot (*Septoria lactucae*) lesions was associated with a higher supply of nitrate and total N concentration of the lettuce shoot grown in Japan (Nao, 2008), whereas high nitrate fertilisation favoured the necrotrophic fungi *Botrytis cinerea* and *Sclerotinia sclerotiorum* in France (Lecompte et al., 2013). Management of nitrate in the nutrient solution for leafy vegetables is limited, since nitrate is the predominant N form in the nutrient solution. However, ensuring that the nutrient solution concentration is not excessive is a beneficial practice.

Salinity conditions in greenhouse soilless systems

In two studies with fresh-cut baby Cos lettuce (cultivar 'Duende') grown in a floating system in Italy, increasing the salinity (i.e. electrical conductivity changed from 2.8 to 3.8 or 4.8 dS/m) of the nutrient solution (N, P, K, Ca, Mg, and S + micronutrients) by adding Na chloride resulted in (Chisari *et al.*, 2010; Scuderi *et al.*, 2011):

- A firmer product, with better colour, less browning and decay caused by bacteria, moulds, and yeasts, higher total phenolic content and antioxidant activity after cutting and during cold-storage at 4°C for 9-10 days due to lower respiration on lower oxidase activity;
- Negligible contamination of raw lettuce, suggesting the system is appropriate for the fresh-cut processed market.

Similarly, in a greenhouse study with bagged baby leaf salad mix, including Cos lettuce and a red loose leaf (cv 'Lollo Rosso'), watering plants from below with 50 mM Na chloride resulted in leaves with (Clarkson *et al.*, 2003):

- Improved visual/sensory quality based on wetness, breakdown, bruising, discolouration, and texture during cold-storage at 4°C for 7 days than control plants watered with tap water;
- Longer shelf-life, with 90% of treated leaves acceptable up to 7 days, whereas control leaves dropped to 65% at 5 days, then to 45% at 7 days;
- Improved processability, i.e. leaves were smaller, thicker, and more malleable, thus able to withstand greater force during processing before being damaged.

Beneficial microorganisms

Symbiosis with beneficial microorganisms such as mycorrhizal fungus or 'effective microorganisms' (i.e. mixed cultures of naturally-occurring photosynthetic bacteria, lactobacilli, and yeast isolated from fertile soils), has been reported to improve the quality and yield of vegetables in several ways, including enhancing growth, photosynthetic efficiency, water uptake, biological N fixation, solubilising soil minerals, and reducing pests, diseases, and weeds (Olle and Williams, 2013).

In lettuce, arbuscular mycorrhizal fungus (as a commercial inoculum mixture) increased carotenoids and anthocyanins content in two greenhouse-grown butterhead red cultivars in Spain, especially in the less favourable seasons (i.e. summer and autumn) for the accumulation of those phytochemicals

(Baslam et al., 2013a). Likewise, it increased total soluble sugars, vitamin C, and phenolics in a butterhead green cultivar (Baslam et al., 2011).

Crop management

Crop scheduling: interactions between location, cultivar, and maturity stage

The study with Iceberg and Cos lettuce described above (Rogers, 2007) showed that it is important to develop effective crop scheduling for each location and cultivar. That will allow growing the crop in the optimal time slot throughout the season aimed to achieve optimum yield and quality/shelf-life, as well as predicting harvest time. For example:

- The optimum harvest period for Iceberg lettuce in Gatton, Qld was July-September; earlier crops aimed for a May-June harvest shortened shelf-life by 25% and reduced yield;
- For Iceberg lettuce grown in Gatton, Qld in 2005, shelf-life of cv 'Cartagenas' had a 1.5- day greater shelf-life early in the season (i.e. harvested in May) than the standard cv 'Raider', while in August, 'Titanic' had a 1.5-day greater shelf-life than 'Patagonia'. Likewise, Cos cv 'Saxon' had in July a 2-day longer shelf-life than 'Cyclone';
- For lettuce grown in East Gippsland, Vic in 2005, Cos cvs 'Cyclone' and the standard 'Verdi' had a 2-day greater shelf-life than 'Shrek' in January, while 'Cyclone' had a 1-day greater shelf-life than 'Verdi' in March. Similarly, Iceberg cv 'Cartagenas' had a 2-day longer shelf-life in January than the standard cultivar 'Silverado';

- Balancing growth rate by optimising varietal and climactic interactions was also important to reduce the incidence of tipburn.

Guidelines for Iceberg and Cos lettuce production developed from that study also highlighted that (Titley et al., 2007):

- Harvesting should aim at an appropriate maturity stage: if too early, less carbohydrate will have been stored; if too late, senescence will have already started in the field and shelf-life will be reduced;
- However, lettuce may be harvested before the optimum head weight has been achieved as a risk management strategy, e.g. during warm dry weather, when there is a greater risk of bolting or tipburn as the crop nears maturity, which can seriously affect quality;
- The crop may also have to be earlier or later if scheduling has failed to provide appropriate processing volumes throughout the season.

A 2-year study with 6 field trials comparing 9-11 baby leaf lettuce cultivars, including the multi-leaf 'Salanova' type ones, both red and green, grown at Stanthorp, Qld and cold-stored, showed a shelf-life variation of up to 7.5 days (i.e. from 8-15.5 days) depending on the trial and year (Rogers, 2008). Cultivars 'Obregon', 'Victorie' and Sartre performed well both in terms of yield and shelf-life.

A 2-year field study in Spain with 6 Iceberg lettuce cultivars processed as fresh-cut, packed into bags, and cold-stored at 4-7°C for 13 days, showed that (Tudela *et al.*, 2013):

- Compared to heads harvested at commercial maturity, those harvested immature developed off-flavours/odours due to fermentation caused by higher respiration rate and the accumulation of ethanol and acetaldehyde;
- Growth under higher field temperatures increased the production of off-odours and respiration rate by more than 100%;
- Cultivar also strongly affected product respiration and off-odours.

Older and larger crisphead lettuce (cvs. 'Marius' and 'Saladin') field-grown in Denmark had lower dry matter and vitamin C contents, and higher nitrate levels at harvest (Sorensen *et al.*, 1994).

Transgenic lettuce with reduced cell membrane permeability increased shelf-life from 9 to 16 days and reduced leaf damage from 70% to 33% 15 days after harvest relative to control plants (Wagstaff *et al.*, 2010). This illustrates the potential for engineering cell wall traits by either genetic modification or by using markers associated with specific genes to guide commercial breeding programmes, thus improving quality and shelf-life of lettuce.

Seasonal effects

In a 3-year study in the USA, hydroponically-grown lettuce (cv 'Grand Rapids') in spring was greener and softer than grown in winter (Cuppett et al., 1999). Similarly, Iceberg lettuce field-grown in Brazil in cooler months (winter) had better visual quality (i.e. greener and with less browning) than those grown in hotter months (summer) after 10 or 20 days after harvest (Resende *et al.*, 2007). Growth of 6 red coloured lettuce cultivars in South Korea at relatively lower day/night temperatures (i.e. 13/10°C) had higher total polyphenol and anthocyanin contents, as well as higher antioxidant activity, than those grown at 25/20°C (Boo et al., 2011).

Method and time of transplant/harvest

In a series of 3 summer field trials at Stanthorpe, Qld, transplanted baby leaf lettuce (cvs Red Coral and Green Coral) had a 2-3 days longer shelf-life depending on the month of planting, and higher yield, compared to direct seeded plant stands (Rogers, 2008). A possible reason for these differences may be the higher density of direct seeded stands, causing plants to grow more rapidly, resulting in thinner, more upright leaves, with weaker structural cell material.

Harvest time had little impact on quality and shelf-life of either Iceberg lettuce (cv 'Patagonia' or 'Titanic') harvested at 56 or 62 days after transplant, or Cos lettuce (cv 'Cyclone'), harvested at 48, 55, 61, or 69 days after transplant (Rogers, 2007). For the latter, the third harvest resulted in the best compromise of yield and quality.

Time of the day at harvest

Field-grown loose head baby leaf lettuce harvested late in the day in the UK had a 3-day or 5-day longer shelf-life when processed, bagged, and cold-stored at 3.5°C or 6°C, respectively, compared to harvesting at the start of the day, which was associated with increased cell elasticity (Clarkson *et al.*, 2005). Similarly, butterhead lettuce grown in the Czech Republic and harvested at 6 pm had better quality during storage than when harvested at 6 am, although that effect was cultivar dependent, suggesting an interaction between genotype and the environment (Moccia *et al.*, 1998).

Hydroponic-grown butterhead lettuce harvested late in the day (after growth in high light) in the USA had higher dry matter and sugar content, lower nitrate content, but smaller yield (Gent, 2012; 2014).

Crop water management

Due to its shallow root system, consistent water supply throughout the season is required to optimise growth of lettuce. As the crop matures, excess water and fertiliser can cause the heads to split or form excessively large heads with low density and reduced shelf-life (Welbaum, 2015).

In a 2-year lettuce trial at Gatton, Qld, growth under trickle irrigation increased shelf-life by 1-2-days (for Iceberg) or by 0-3-days (for Cos, depending on year and month of harvest) compared to overhead irrigation (Rogers, 2007).

A 6-harvest/3-year field study in Spain with Cos lettuce processed as fresh-cut, packed into bags, and cold-stored at 4-7°C for 13 days, showed that (Luna *et al.*, 2013):

- Low deficit irrigation (i.e. 15% below the standard) reduced cut-edge browning and increased phenolic content compared to excessive irrigation (i.e. 35-75% above the standard regime);
- Excessive irrigation (at 75% above the standard) increased microbiological growth compared to standard and deficit irrigation;
- Irrigation regime had little impact on visual quality;
- High excess (+75%) or high deficit (-35%) irrigation reduced yield;

A similar 6-harvest/3-year field study in Spain with Iceberg lettuce processed as fresh-cut, packed into bags, and cold-stored at 4-7°C for 13 days, showed that (Luna et al., 2012):

- Shelf-life due to reduced off-odours and cut-edge browning was extended by about 3 days with an irrigation regime of 0-200 mm compared to 200-400 mm during the growing period;
- Visual quality was reduced at 300-400 mm;
- Phenolic content was reduced at 200-400 mm.

In a 2-year study in Arizona, Iceberg lettuce stored at 2°C for 7-14 days had better visual quality and a lower microbial load when grown in furrow irrigation compared with irrigation using overhead sprinklers; yield was not compromised (Fonseca, 2006).

In a 2-year field study in the UK, irrigation method (either drip or overhead oscillating line) had little effect on discolouration (mostly 'pink' rather than 'brown') of fresh-cut Iceberg lettuce, cv 'Saladin' (Hilton et al., 2009).

Growing system

A study in Spain with 2 red loose leaf (cvs 'Lollo Rosso' and 'Red Oak Leaf') and one green butterhead lettuces processed as fresh-cut, packed into bags, and cold-stored at 4-7°C for 11 days (Selma *et al.*, 2012), showed that, compared to a conventional open field soil system, plants grown in winter under an open field hydroponic system had:

- Better visual quality based on freshness, gloss, and colour, and less cut-edging browning, for the red cultivars, but inverted results in terms of visual quality for butterhead lettuce;
- Higher content of vitamin C and total phenolics for red cultivars;
- Higher sanitary quality, with lower initial microbial load (especially lactic acid bacteria and total coliforms) and slower growth microbial growth during storage for all cultivars;
- Shorter growing period (63 days after transplant, compared to 102 days for soil system) to achieve the same maturity stage in winter;
- No differences in flavour;
- Cultivar and seasonal variations.

Field-grown curly loose-head lettuce plants in Brazil had higher carotenoids contents, including lutein and β-carotene, than hydroponic-grown ones (Kimura and Rodriguez-Amaya, 2003). Similarly, field-grown butterhead lettuce (cv 'Audran') plants in Italy had higher polyphenols contents than greenhouse-grown ones (Romani *et al.*, 2002).

Greenhouse-grown head lettuce in an organic system in Italy had higher lutein, β-carotene and vitamin C contents, but lower quercetin than those grown in the conventional system (Durazzo et al., 2014).

Floating crop covers

In a study with baby-leaf lettuce grown in south Queensland, the use of floating crop covers, also known as row covers, to reduce contamination (Munton, 2013):

- Effectively reduced insect infestation (up to 89%) and insect damage;
- Excluded most wind-borne foreign body contamination, reduced ground moisture loss, provided a level of protection from weather induced damage, and reduced the length of growth cycles during cooler winter and shoulder seasons;
- Had little impact on general quality, strength, and shelf-life compared to standard unprotected growth.

Growing medium

Zeolite, when compared to perlite, led to increased plant growth, and higher N and K contents in crisphead lettuce (Gul et al., 2005). Lettuce plants harvested from perlite culture had a lower chlorophyll a, total chlorophyll and iron (Fe) content and a higher chlorophyll b and manganese (Mn) content than plants harvested from pumice culture (Siomos et al., 2001).

Dry matter content was highest in lettuce grown in tea waste compost and lower in tree bark compost (Mastouri et al., 2005). Compared with lettuce plants harvested from soil culture, those harvested from perlite or pumice culture had lower dry matter, chlorophyll, Mg, Fe and Mn contents and higher titratable acidity, as well as total N, P, and K contents, and more tipburn symptoms (Siomos et al., 2001).

Plant density

Plant density affects availability of water, nutrients and exposure to light, which can affect quality. Higher plant density (by decreasing spacing between rows from 25 to 15) reduced nitrate content in lettuce ('Amar' cultivar) leaves grown in Jordan by up to 78% (Abu-Rayyan et al., 2004). Likewise, an increase from 33 to 50 plants/m^2 reduced leaf nitrate content after harvest by up to 31% in lettuce (cv 'Grand rapids') in Argentina (Tittonell *et al.*, 2001).

Light system

With the development of light-emitting diode (LED) technology, the regulation of light environments has become increasingly feasible for the provision of ideal light quality, intensity and photoperiod, especially in protected facilities, opening exciting new opportunities for increasing phytochemical content in vegetables (Bian et al., 2015).

In a study in Taiwan, hydroponically-grown butterhead lettuce under red, blue, and white LED lights had better growth, development, nutrition, appearance, and edible quality (i.e. sweetness and crispness), as well as lower nitrate contents compared with plants grown red and blue LED and a fluorescent lamp, whereas chlorophyll or carotenoids contents were not affected (Lin *et al.*, 2013). Likewise, pre-harvest exposure of hydroponic lettuce in China to red and blue LED light for 48 hours reduced nitrate content up to 56% and markedly increased soluble sugar content (Zhou et al., 2013).

1.3 Leafy vegetables other than lettuce

Background

Commercial importance and main cultivar types

Leafy vegetables, other than lettuce, also comprise an important horticultural commodity group in Australia, especially spinach, with an annual production of 10,065 tonnes and a gross value of $75.3 M in 2013-14, and Asian vegetables, with an annual production of 26,495 tonnes and a gross value of $77.3 M in 2013-14 (Anon., 2015f). Other leaf vegetables considered in this review include silverbeet, parsley, and spring onion, with gross values of $7.6, 8.5, and 37.1 M, respectively, and annual productions of 4,168, 1,537, and 10,809 tonnes, respectively, in 2013-14, as well as rocket.

Spinach (*Spinacia oleracea* L.) is a popular leafy vegetable with short growing period and rapid growth. Its green leaves can be consumed steamed, boiled, baked, or raw at the early growth stages (i.e. as baby leaf). In Australia, spinach is most common purchased loose or pre-packaged in containers or bags, and generally stir-fried, eaten raw, or boiled (Anon., 2015b).

The baby leaf sector is a significant and rapidly growing part of the leafy vegetable market in Australia, with an annual value estimated in 2011 at around $40 M (Rogers, 2011). It comprises various leafy vegetable crops harvested as young plants and generally used as salad vegetables. Baby leaf spinach, and to a lesser extent baby leaf rocket, are major components of salad leaf mixes, including the popular packaged fresh-cut mixes (Jobling and Rogers, 2012). Other baby leaf vegetables commonly used in salad leaf mixes in Australia other than lettuce, spinach and rocket, are some Asian vegetables such as mizuna and tatsoi.

Rocket is becoming an increasingly popular and widely cultivated vegetable, predominantly eaten raw as a garnish or mixed with other leafy salads, imparting a distinctive nutty flavour. The two most common baby leaf rocket species in Australia are wild rocket (*Diplotaxis tenuifolia*), a species of the mustard family, and cultivated rocket or arugula (*Eruca sativa*), a species of the Brassicaceae family. Rocket has a quick growth cycle, can be successfully cultivated in hydroponics and greenhouses, and can be harvested from regrowth, making it available in the markets most of the year. After harvest, rocket has a relatively long shelf-life under adequate postharvest practices (Cavaiuolo and Ferrante, 2014).

Asian vegetables include a group of leafy crops belonging to the Brassicaceae family. The most common ones in Australia which are considered in this review are: pak choy (*Brassica rapa var. chinensis*; also known by other names such as bok choy, buk choy, or Chinese chard), mizuna (*Brassica rapa var. nipposinica*), mibuna (*Brassica rapa var. japonica*), tatsoi (*Brassica rapa var. rosularis*), Chinese mustard (*Brassica juncea*), and choy sum (*Brassica rapa var. parachinensis*). Other commercially important leafy vegetables belonging to the Brassicaceae family are considered in section 2 of this review ('Brassica vegetables'), including cabbage, kale, Brussels sprouts, and collard greens.

Silverbeet or chard (*Beta vulgaris*) belongs to the Chenopodiaceae family and is closely related to beetroot. Mature silverbeet leaves and stalks are typically cooked or sautéed, whereas fresh young silverbeet can be used raw in salads. Their bitterness fades with cooking, leaving a refined flavour which is more delicate than that of cooked spinach (Welbaum, 2015). In Australia, silverbeet is generally steamed, boiled or cooked in stir fries, whereas most consumers purchase silverbeet in bunches (Anon., 2015c).

Parsley (*Petroselinum crispum*) belongs to the Apieaceae family and it is a popular aromatic herb used fresh or dried in salads, as a garnish, or in cooked dishes. Plain or flat-leaf cultivars (e.g. 'Continental' or 'Italian') are usually used for flavouring, whereas curled ones are more often used as a garnish (Welbaum, 2015).

Spring onion (*Allium fistulosum*), also known as bunching onion, French bunching onion, green onion, or scallion, belong to the Amaryllidaceae family, the same as the common onion, but their hollow green leaves are used as a vegetable and eaten either raw or cooked while they lack a fully developed root bulb (Welbaum, 2015).

Key compositional and nutritional aspects

Spinach contains significant amounts of vitamins (mainly K, A, C, folate, E, B_2, B_6, in addition to B_1, B_3), minerals (mainly Mn, Mg, K, Fe, and Ca, in addition to Cu, P, and Zn), and dietary fibre (Anon., 2015a). Spinach also contains bioactives such as lutein, zeaxanthin, β-carotene, glutathione, and alpha-lipoic (Hedges, 2007)

However, spinach tends to accumulate undesirable compounds such as nitrate (as described for lettuce) and oxalates (Kaminishi and Kita, 2006). Oxalates in plant foods can have a negative impact on human health by acting as antinutrients reducing the bioavailability of minerals such as calcium, magnesium and iron, as well as increasing the risk of stones in kidney and bladder due to higher amounts of oxalic acid excreted (Franceschi and Nakata, 2005).

Rocket contains good amounts of vitamins (especially K, A, C, and folate, in addition to B_2, B_6, and pantothenic acid), minerals (mainly Ca, Mg, Mn, K, and Fe, in addition to P, Cu, and Zn), and dietary fibre (Anon., 2015a). Rocket also contain phytochemicals, especially carotenoids (e.g. lutein, β-carotene), flavonoids, and glucosinolates, an important group of phytochemicals found mainly in Brassica vegetables and detailed in section 1 of the review, and other sulphur compounds (Hedges, 2007). Although rocket is not alone in providing glucosinolates, as is eaten raw, the enzyme that converts glucosinolates into isothiocyanates (a key health-promoting phytochemical) is not destroyed during cooking, ensuring that conversion is optimised (Hedges, 2007). Similar to lettuce and spinach, rocket is also prone to accumulating nitrate (Cavaiuolo and Ferrante, 2014).

Nutritional information of Asian vegetables is limited, except for pak choy, which is a good source of vitamins (mainly A, C, K, folate, and B_6, in addition to B_2), minerals (especially K and Ca, in addition to Mn, Fe, and Mg), and dietary fibre (Anon., 2015a). Bok choi also contains phytochemicals, especially glucosinolates, lutein, zeaxanthin, and β-carotene (Hedges, 2007). A recent consumer study showed that health benefits is a key purchase driver for Asian greens in Australia, in addition to their usage in specific meals, taste/flavour, suitability for specific cuisine taste, and use as a staple vegetable (Adams, 2013).

Silverbeet leaves are a significant source of vitamins (mainly K, A, and C, in addition to E, B_2, and B_6) minerals (especially Mg, Mn, K, Fe, and Cu, in addition to Ca and P), and dietary fibre (Anon., 2015a). Silverbeet is also a source of bioactives, especially phenolics, flavonoids, and proline, but it contains high levels of nitrate and oxalic acid (Sacan and Yanardag, 2010; Miceli and Miceli, 2014).

Parsley leaves are high in vitamins (mainly K, C, A, and folate, in addition to B_1, B_2, B_3, B_6, E, and pantothenic acid), minerals (especially Fe, K, Ca, and Mg, in addition Mn, Zn, Cu, and P), and dietary fibre (Anon., 2015a). Parsley is also a source of bioactives, in particular phenolics, which have shown both antioxidant and antibacterial activities (Wong and Kitts, 2006). Parsley also contain essential oils and several monoterpene hydrocarbons, which give the characteristic aroma of fresh parsley and are shown to be affected by cultivar and processing methods (Petropoulos *et al.*, 2010).

Spring onion are a good source of vitamins (mainly K, C, A, and folate, in addition to B_1, B_2, B_3, B_6, and E), minerals (mainly Fe, K, Ca, and Mn, in addition to Mg, P, Cu, and Zn), and dietary fibre (Anon., 2015a). They also contain several bioactives such as the flavonoids quercetin and kaempferol, fructans, sulphur-containing compounds, including cepaenes and thiosulfinates, saponins, carotenoids, and chlorophyll (Hedges, 2007).

Key quality issues

Most of the quality issues described above for lettuce is also applicable to this group of leafy vegetables. A recent consumer study showed that quality and freshness are the single most important triggers to consumer purchase of green leafy vegetables in Australia (Welsh, 2013). Health, ease of preparation, and taste are the key drivers of purchase for spinach (Anon., 2015b) and silverbeet (Anon., 2015c) in Australia, whereas short shelf-life and desire not to waste any are the key barriers to purchase. Using parsley as an ingredient in dishes, complementing other foods and adding colour to meals are the key drivers of purchase, whilst the key barriers to purchase are not wanting to waste any and growing their own parsley (Anon., 2015c). Using spring onion as an ingredient in dishes, complementing other foods and tasting great are the key drivers of purchase, whereas the key barriers are not wanting to waste any, short shelf-life and already consuming enough to balance their diet (Anon., 2015e). For Asian vegetables, ease of preparation, health, and adding variety to vegetable selection are the main drivers of purchase, whereas short-shelf life and not wanting to waste any are major barriers (Anon., 2015b).

Once purchased, Australian consumers expect spinach and Asian vegetables to stay fresh for about 6 days, whilst parsley for just over a week and spring onion for around 9 days, and these expectations are being met most of the time by 75% (spinach and parsley), 77% (spring onion), and 82% (Asian vegetables) of consumers (Anon., 2015b; c; e).

Crop nutrition

Nutrition management under field conditions

In a field study with 6 baby leaf rocket cultivars grown in south-west Sydney, applied N at 0, 50, 150, and 250 kg N/ha had no effect on shelf-life of either wild or cultivated rocket stored at 0°C (Rogers, 2011).

Applied N as ammonium nitrate at 80 kg/ha to field-grown baby spinach in Italy improved visual quality (i.e. green colour) of cold-stored leaves, reduced weight loss due to respiration, and had a protective effect on membrane integrity during storage than nil applied N (Conversa *et al.*, 2014). The addition of Azoxystrobin at a 417 mg/kg extended shelf-life of cold-stored leaves by 7 days by reducing leaf dehydration, as well as reducing leaf nitrate content.

Applied N as urea at 170 kg/ha to field-grown spinach plants in China, combined with soil water content kept at 16.5%, increased yields and the contents of leaf nitrate and oxalic acid compared to 85 kg/ha, suggesting the importance of a balance between yield and quality (Zhang et al., 2014).

The ammonium N-form can also affect spinach composition. For example, in a 3-year study with spinach grown in a foil tunnel for autumn harvest in Poland, applied ammonium sulphate and calcium nitrate reduced nitrate content in spinach leaves compared to ammonium nitrate. Ammonium sulphate increased vitamin C content, but reduced yield depending on cultivar (Krezel and Kolota, 2014). Likewise, calcium nitrate at 130 kg N/ha or ammonium nitrate at 150 kg N/ha applied to field-grown spinach reduced oxalate and nitrate contents and increased yield compared to urea or ammonium sulphate (Stagnari *et al.*, 2007). In contrast, the N form as either ammonium sulphate or calcium nitrate had little effect on oxalate content of field-grown spinach in 2 locations in Italy, but increasing N level from 125-150 kg/ha to 250-300 kg/ha increased yield and contents of leaf nitrate and oxalates (Elia *et al.*, 1998).

Increasing N as ammonium nitrate application from 100 to 150 and 200 kg/ha to field-grown silverbeet in Italy increased the contents of vitamin C and nitrate and had little effect on leaf colour, sugar content, and weight loss after cold-storage at 4°C for 7 or 14 days of fresh-cut bagged leaves (Miceli and Miceli, 2014). It also increased marketable yield (i.e. fresh leaves), but had little effect on minimal processing yield.

In a 3-year field study in Greece, applied N as ammonium nitrate at 150 mg/kg was considered the optimum level in terms of high yield and low nitrate content, whereas higher rates of 300 or 450 mg/kg increased nitrate content with no further yield gain and a lower rate of 30 mg/kg markedly reduced yield (Petropoulos *et al.*, 2008). Applied nickel at 50 mg/kg to parsley grown in Egypt increased yield and the contents of leaf Ca, Mn, Zn, Cu, and aroma components, whereas reducing the contents of total soluble solids, vitamin C, nitrate, and ammonium (Atta-Aly, 1999).

Increasing S from 2.9 to 5.8 kg/ha applied to 8 spring onion cultivars grown in the UK increased pyruvic acid content (which is associated with flavour) and reduced total soluble solids content, as well as reducing volatiles content in some cultivars as determined by an electronic nose. In contrast, there was little effect on dry matter content (Abbey *et al.*, 2005). The study also showed cultivar and growing condition effects on volatiles content.

Nutrition management under protected cropping

Applied N at 8, 12, or 16 mM/L to fresh-cut baby spinach leaves grown under a hydroponic floating system in Spain had little effect on shelf-life or overall sensory quality (i.e. dehydration, off-odours and off-flavours, colour, and browning) after cold-storage at 5°C for up to 10 days (Rodriguez-Hidalgo et al., 2010).

Increasing N as a nitrate to ammonium ratio of 80:20 to the nutrient solution from 50 to 250 ppm total N in greenhouse-grown spinach in California resulted in leaves that were more fragile and easier to break, suggesting reduced shelf-life (Gutierrez-Rodriguez *et al.*, 2013).

Partially changing the form of N supply from 8 mM/L of nitrate to 4 + 4 mM/L of nitrate and ammonium 6 days before harvest in hydroponically-grown lettuce in China increased levels of several antioxidant compounds, enhanced antioxidant capacity in the edible parts of spinach plants, and reduced oxalate content without affecting yield (Lin *et al.*, 2014).

Added N as nitrate at 120 mg N/kg to greenhouse-grown (in plastic pots with soil) spinach in China increased yield and the contents of vitamin C and nitrate compared to 0, 30, 60, or 240 mg N/kg (Liu *et al.*, 2006). Chlorophyll content determined by a pocket meter 'SPAD-502' correlated well with total N, leaf dry weight, and leaf nitrate content, suggesting potential field application of the device in decision-making and operational nutrient-management programs.

Increasing N in the nutrient solution from 4 to 12 mM increased nitrate and oxalate contents of hydroponically-grown spinach in China, with further increased at 20 mM, whereas oxalate content was reduced by decreasing the ratio of nitrate/ammonium N (Zhang *et al.*, 2005). In contrast, changing the ratio of ammonium sulphate and calcium nitrate of the nutrient solution of hydroponically-grown spinach in Italy, had little effect on leaf oxalate content (Elia *et al.*, 1998)

Reduction of N and Ca 7 days before harvest in hydroponically-grown spinach in China increased vitamin C and reduced both nitrate and oxalate content of leaves, but also reduced yield (Yan *et al.*, 2014).

Greenhouse-grown spinach in China under a mild Fe-deficient nutrient solution (1 µM FeEDTA) had higher marketable yield, higher contents of soluble sugar and vitamin C, and lower nitrate content compared to Fe-omitted (nil Fe) or Fe-sufficient (10 or 50 µM FeEDTA) treatments (Jin *et al.*, 2013).

Increasing N rates from 6, 13, 26, 52, and up to 105 mg/L in the nutrient solution of greenhouse-grown parsley (cv 'Dark Green Italian') in the USA gradually increased plant biomass and the contents of leaf lutein, zeaxanthin, β-carotene, chlorophyll, N, P, K, Ca, Mg, S, B, Cu and Zn, whereas reducing the contents of Fe, Mn, and Mo (Chenard *et al.*, 2005).

The withdrawal (at 3, 5 and 7 days before harvest) of all nutrients or only N in hydroponically-grown mizuna plants in Japan increased total sugar content, reduced nitrate content, and had no effect on leaf colour (Kirimura *et al.*, 2015).

Extract of the brown seaweed Ascophyllum nodosum (at 1.0 g/L) applied to spinach in growth chambers in Canada, improved visual quality (i.e. colour and turgor) and reduced fresh weight loss of fresh-cut bagged leaves during a 35-day cold-storage at 4°C (Fan *et al.*, 2014).

The use of zeolite pre-loaded with ammonium and potassium ('Eco-zeolite') in greenhouse-grown spinach in China, increased yield and oxalate content (Li *et al.*, 2013).

Silicon impact on quality

Silicon (Si) is a non-metallic element that can mitigate the effects of various plant abiotic and biotic stresses by increasing plant resistance to pathogens and insects, as well as against chemical stresses (nutrient imbalance, deficiencies, salt), and physical stresses (freezing, lodging, radiation, high temperature, drought) (Hernandez-Apaolaza, 2014).

Silicon as sodium silicate at the rate of 30 µM added to the nutrient solution of hydroponically-grown baby leaf lamb's lettuce (i.e. corn salad, cvs 'Gala' and 'Eurion') resulted in (Gottardi *et al.*, 2012):

- Prolonged shelf-life from 4.5 to 9 days in cultivar 'Gala' by slowing down chlorophyll degradation and delaying leaf senescence;
- Reduced nitrate uptake and content in edible tissues.

Under field conditions, Si as silicon oxide at the rate of 2 L/ha applied to Iceberg lettuce in Brazil enhanced visual quality (i.e. retained more green and reduced browning) after cold-storage at 5°C for 20 days, but there was little treatment difference after 10 days (Resende et al., 2007).

In contrast, the addition of Si as sodium metasilicate at 30 µM/L to the nutrient solution of hydroponically-grown ready-to-eat corn salad in Italy did not increase shelf-life or improved green colour, although it reduced nitrate content and increased yield by 100% compared to soil-grown and by 63% compared to hydroponically-grown plants without added Si (Manzocco *et al.*, 2011).

The mineral Si is also an essential element for humans and a component of the diet found mainly in plant-based food. There is growing scientific evidence that silicon plays an essential role in bone formation and maintenance, and that higher intake of bioavailable silicon is associated with increased bone mineral density (Price *et al.*, 2013). A recent study showed that the addition of silicon as potassium metasilicate at 50 or 100 mg/L to the nutrient solution of hydroponic-grown (in a floating system) fresh-cut leafy vegetables (including tatsoi, mizuna, basil, chicory, and swiss chard) in Italy, increased both Si content and bioaccessible Si in the leaves, with no impact on yield or leaf colour, which could offer 'added-value' opportunities as a 'biofortified' product (D'Imperio *et al.*, 2016).

Crop management

Crop scheduling: interactions between growth rate, cultivar, and seasonal effects

A comprehensive 2-year evaluation of agronomic factors that affect shelf-life of baby leaf salad spinach (3 commercial cultivars), with field trials planted monthly over a 12 month period in 2 representative temperate locations (a cool vs a warm one) in Australia showed that (Rogers, 2008):

- Days-to-harvest was the strongest factor associated with shelf-life, with spinach needing a 30-32 day minimum growth period to attain maximum quality. This can be achieved by:
    - Selecting slow-growing cultivars during warmer periods, or
    - Growing the crop in a climate cool enough to allow at least 30 days from seeding to harvest;
- Seasonal growing temperature had a strong impact on shelf- life. For example:
    - Shelf-life was highest (i.e. 24-30 days for product cold-stored at 2°C) in the cooler and transitional times during periods of slower plant growth (average minimum temperature of 7-10°C);
    - In contrast, shelf-life was lowest (i.e. 14-22 days), as well as yield, during the summer period (15-18°C) due to the high temperatures, humidity, and rainfall during the production period;
- The interaction between days to harvest and shelf-life was cultivar dependent (e.g. not significant for the slow-growing cultivar 'Crocodile');
- Shelf-life varied up to 4-5 days among cultivars;
- The effects of growing temperature on quality of spinach was confirmed in a controlled growth cabinet study where a 21°C day/12°C night comgination produced 43% longer shelf-life compared to the same heat tolerant cultivar ('Crocodile') grown at 27°C day/18°C night;
- Leaf morphological characteristics such as increased leaf thickness, leaf area, leaf weight and chlorophyll content were positively correlated with increased shelf-life;
- The above results highlighted the importance of a crop scheduling model to predict harvest date and identify the adequate 'seasonal window' for optimum shelf-life of spinach.

A series of 4 field trials on 25 baby leaf spinach cultivars, and 6 baby leaf rocket cultivars, both wild and cultivated species, planted over a 2-year period near Sydney showed that (Rogers, 2011):

For spinach:

- Cultivar, growing season, and growth rate (days to harvest) have a major effect on shelf-life of baby leaf spinach, thus confirming results from the above study;
- Small leaves and younger plants have longer shelf-life than larger leaves and taller, more mature plants;
- After 7 days in cold-storage at 5°C, leaves tend to recover from moderate bruising caused by harvesting, but not from severe bruising, which leads to a loss of shelf-life;
- Most leaf breakdown was due to microbial infection as opposed to loss of chlorophyll or depletion of carbohydrates reserves in the harvested product.

For rocket:

- Summer- grown and winter-grown wild rocket had a longer shelf-life (17 and 16 days, respectively, when cold-stored at 7°C) than spring-grown (12 days). For cultivated rocked, winter grown was the longest (15 days), followed by spring (14 days) and summer (13 days);
- Wild rocket cultivars had longer shelf-life than cultivated ones when stored at the optimum temperature of 0°C.

The contents of total folate and vitamin C in packaged baby spinach and wild rocket leaves marketed in Australia were shown to be affected by both location and season in a recent study, with higher contents in winter crops compared to summer ones (Jobling and Rogers, 2012).

A study with several cultivars grown during fall and winter in the USA showed interactions between cultivar and climate affecting quality of fresh market pre-packaged spinach; for example, grown under normal rainfall conditions, cvs 'Seven R' and 'Grandstand' had the best shelf-life and 'Marathon' the poorest, whereas under high rainfall conditions, 'Gladiator' and 'Melody' had the best shelf-life while 'Seven R', 'Vienna' and 'Chinook II' had the poorest shelf life; also, high rainfall during the growing season reduced postharvest storage potential of spinach by 40%, but temperature had little effect (Johnson *et al.*, 1989).

In contrast, in a study with open field-grown spinach in Italy, different growing periods (i.e. plants sown in October, December and January) had little effect of on overall initial quality of the leaves harvested in the January–March period, in terms of leaf colour and contents of dry matter, vitamin C, chlorophyll, nitrate, and oxalate (Conte *et al.*, 2008). Interestingly in that study, dry matter and vitamin C contents at harvest were positively associated with visual quality and resistance to processing during/after cold-storage at 5°C for 13 days. The association between high dry matter content and vitamin C at harvest with visual quality retention of spinach leaves during cold-storage was also reported in Sweden (Bergquist *et al.*, 2006).

A study in Japan over 4 growing seasons with 182 spinach cultivars showed that growth rate was a major determinant of nitrate and oxalate concentrations, with fast-growing cultivars containing higher nitrate and lower oxalate, whereas slow-growing cultivars containing lower nitrate and higher oxalate; also, nitrate content was lower in winter, as opposed to oxalate content which was higher compared to other seasons (Kaminishi and Kita, 2006).

Spring-harvested wild rocket grown in field conditions in Denmark had higher respiration rates during storage at either 10°C or 20°C (an indication of shorter shelf-life) than harvested in early and late summer (Seefeldt *et al.*, 2012).

Field-grown silverbeet plants harvested in spring in Poland had lower contents of nitrate, vitamin C, Ca, and K, higher contents of Mg and P, lower dry matter, as well as higher yield compared to plants harvested in autumn, presumably due to better solar radiation conditions (Kolota *et al.*, 2010).

Harvesting time (i.e. growth stage)

Two studies in Sweden showed that harvesting baby spinach a few days earlier than the typical commercial stage of harvest (i.e. younger plants) would result in leaves with improved visual quality and higher vitamin C content (Bergquist *et al.*, 2006), or with a higher flavonoid content (Bergquist *et al.*, 2005).

Field-grown silverbeet plants in Spain that were late-harvested (i.e. 19 weeks after sowing) had higher dry matter, sugars, acids, and vitamin C than normal-harvested (i.e. 8 weeks after sowing) plants (Daiss *et al.*, 2008).

The stage of harvest (i.e. 2.5, 4.5 and 6.5 weeks after planting, equating to baby, optimum growth, and overgrown stages, respectively) of pak choy plants grown in high tunnel conditions in the USA affected sensory quality as determined by a panel (i.e. flavour, aroma, and moistness attributes): while the baby plants had more green-unripe, musty/earthy tastes and sweet flavours, the older/overgrown plants had more unpleasant, bitter and sulphur flavours (Talavera-Bianchi *et al.*, 2010a).

In a field study with 6 parsley cultivars grown in Poland, 'Karnaval' produced the highest yield of leaves with high contents of vitamin C and nitrate, especially when harvested in October in poor light conditions, whereas 'Titan' had low nitrate content irrespective of the harvest date (Kolota *et al.*, 2012).

Time of day at harvest

In a glasshouse trial at Sydney, spinach harvested at 6:00 am had a longer shelf-life (of about 2-3 days when bagged and cold-stored at 4°C) and better visual quality than harvested at 9:00 am or at noon, and this effect was associated with the starch content remaining in the leaves: more starch = longer shelf-life (Rogers, 2008).

In a study in the UK, field-grown baby leaf rocket harvested late in the day (i.e. 10 pm) had a 6-day longer shelf-life (when processed, bagged, and cold-stored at 3.5°C) compared to harvesting at the start of the day (i.e. 10 am), which was associated with increased cell elasticity and leaf sucrose content (Clarkson *et al.*, 2005).

Plant density

In a field trial with baby leaf spinach (cv 'Whale - RZ') grown in summer at Stanthorpe, Qld, increasing plant density from 300 to 600 and 900 plants/m^2 reduced shelf-life from 23 to 20 and 16 days, respectively, as well as increasing fresh weight yield and resulting in smaller leaves in correlated trials in other locations (Rogers, 2008). The trial highlighted the required compromise between plant density, yield and shelf-life. In addition, the study also suggested that higher plant densities appear to be correlated with a higher incidence of *Sclerotinia* leaf spot, a damaging disease of baby leaf spinach.

Increasing plant density by reducing within-row spacing from 25 to 15 cm of spinach plants grown in Texas reduced leaf area and leaf dry weight, but had little effect on leaf thickness or leaf number (Leskovar *et al.*, 2000). The potential impact of those leaf changes on shelf-life was not assessed in that study.

Crop water management

Deficit irrigation (i.e. 75% or 50% evapotranspiration rates) applied to spinach plants grown in Texas increased leaf yellowness (especially 50%, but also 75% in less vigorous cultivars), and the extent of that response was dependent on cultivar (Leskovar and Piccinni, 2005).

A field study with spinach grown in China showed that an inadequate supply of water (soil water content of 12.5%) increased both nitrate and oxalic acid contents compared to a soil water content of 16.5% or 20.5% (Zhang et al., 2014).

Deficit irrigation (i.e. topsoil drying) applied to greenhouse-grown Chinese mustard plants in Germany, combined with adequate S fertilisation, increased the content of glucosinolates without affecting yield (Tong *et al.*, 2014).

Growing system

Conventionally-grown pac choy plants in field (but not in high tunnel) conditions in the USA had better sensory quality as determined by a panel (i.e. flavour, pungency, crispness, and moistness attributes) than organically-grown plants (Talavera-Bianchi et al., 2010b).

Corn salad (e.g. lamb's lettuce) plants grown in soil pots in Italy had a 4-day longer shelf-life (based on visual assessment of ready-to-eat bags cold-stored at 4°C) than hydroponically-grown plants in a floating system (Manzocco *et al.*, 2011).

In contrast , red loose leaf lettuce, spinach, cultivated rocket, and mustard greens grown (in high tunnels) either conventionally or organically in the USA showed little difference in overall consumer liking or consumer-perceived sensory quality (e. g. intensity of flavour and bitterness) between the two systems (Zhao *et al.*, 2007).

Light system

The use of either high light (i.e. 800 μM/m^2/s compared to 200) or high CO_2 (i.e. 800 ppm compared to 360) in spinach grown under growth chambers in Italy, increased yield, and vitamin C content, whereas their interactive effect reduced both nitrate and oxalic acid in the leaves (Proietti *et al.*, 2013). Likewise, a three-day exposure of spinach plants grown in the greenhouse in Japan to UV radiation increased the contents of flavonoids in the leaves (Kanazawa *et al.*, 2012).

Spinach grown under shading in Sweden had a lower (by 12-33%) ascorbic acid content depending on planting time, and higher contents of total carotenoids and chlorophylls, whereas there was little effect on postharvest visual quality (Bergquist *et al.*, 2007).

1.4 Conclusions

Health, complementing other food, taste, and ease of preparation are the key drivers of purchase for leafy vegetables by Australian consumers, whereas short shelf-life and not wanting to waste any the main barriers. Once purchased, Australian consumers expect leafy vegetables to stay fresh for about a week, and these expectations are being met most of the time by 70-82% of consumers depending on the commodity.

Lettuce

In terms of crop nutrition, there was considerable variation in treatment responses to different nutrient form, rates and timing, as well as cultivar across the studies worldwide. That suggests that the management of those factors is complex in order to optimise the balance, at times conflicting, between yield and quality/shelf-life, as well as the impact of nutrition on plant diseases and disorders of lettuce. The results also highlight the importance of specific and targeted research under local conditions and current cultivars, rather than a 'one size fits all' approach.

Under both field and protected conditions, quality (especially colour and visual appearance) and shelf-life of lettuce were reported to be enhanced by a balanced and judicious application of nutrients, especially the macronutrients N, P, and K, at the appropriate ratio and in combination rather than independently. Depending on cultivar, higher rates of N generally resulted in reduced shelf-life (especially very high rates), greener and softer leaves at/after harvest, and increased nitrate content than at lower rates.

Optimum nutrition can assist in control of diseases that reduce quality, for example avoiding excessive N fertilisation or ensuring that the nutrient solution concentration is not excessive, as well as choosing N forms that can favour plant resistance to fungal diseases such as downy mildew and anthracnose whenever possible (e.g. calcium nitrate rather than ammonium nitrate).

Under protected conditions, there is some evidence that low salinity conditions could be used to improve visual quality (i.e. colour), texture, and shelf-life of fresh cut or baby leaf lettuce, but further research is required in that area.

In terms of crop management, field studies (especially in Australia) showed that developing an effective crop scheduling (i.e. identifying the best growing/harvest times during the season) for each location and cultivar is important to achieving optimum quality and shelf-life of lettuce. Other factors that impact on quality and shelf-life include harvesting at the appropriate stage of maturity, choosing the appropriate planting method (e.g. transplanted plants rather than direct seeded plant stands), harvesting later in the day rather early in the morning, growing system adopted, and using supplementary light systems (e.g. LED technology). However, the evidence in these areas is generally limited and requires further investigation.

Growing practices that prevent excessive growth rates, such as balancing N supply to the plants, optimising varietal and climactic interactions, or growing at cooler times of the year, together with careful selection of resistant cultivars, appear to be better strategies for preventing or reducing tipburn than Ca foliar sprays, especially under field conditions.

Research on the impact of crop water management on quality and shelf-life of lettuce has been limited, with a few studies suggesting potential benefits on selecting the irrigation method (e.g. trickle rather than overhead irrigation), little benefit in using deficit irrigation, and potential quality reduction with excessive irrigation.

Other leafy vegetables

Most research on crop nutrition of leafy vegetables (other than lettuce) affecting quality has focused on leaf composition (especially spinach), with only a few studies for spinach reporting mixed results on leaf colour with applied N, and little impact on shelf-life of spinach and rocket. Generally, higher levels of applied N (especially as nitrate) increased the contents of both nitrate and oxalates, under field or greenhouse conditions.

There was some evidence that the application of silicon could enhance visual quality and shelf-life, as well as increasing leaf silicon content, a trace element which has been associated with bone health, and reducing nitrate content of leafy vegetables (including lettuce), suggesting it is an area that warrants further investigation.

In terms of crop management, several studies (especially in Australia) showed that growth rate (days to harvest), growing season, and cultivar had a major impact on shelf-life of baby leaf spinach, highlighting the importance of a crop scheduling model to predict harvest date and identify the adequate 'seasonal window' for optimum shelf-life for each cultivar and location. Generally, longer shelf-life is associated with slow-growing cultivars and conditions (i.e. cooler areas and times of the year), smaller leaves, and younger plants. Cultivar and growing season also affected composition of spinach, with slow-growing cultivars or cooler growing conditions generally resulting in higher contents of vitamin C, folate, and oxalates, and lower content of nitrate. Cooler growing conditions were also associated with increased shelf-life in baby leaf rocket.

There was some limited evidence that increasing plant density can change leaf characteristics and reduce shelf-life of spinach, but that warrants confirmation. Likewise, using supplementary light during growth could increase nutritional and phytochemical contents in spinach.

Research on the impact of crop water management on quality and shelf-life of leafy crops other than lettuce has been limited, with a couple of studies suggesting negative effect on using deficit irrigation to spinach quality.

Overall, some areas may offer opportunities for quality improvement of lettuce and other leafy vegetable (especially spinach), such as extended shelf-life, enhanced visual quality, and improved compositional quality (via increasing desirable nutrients such as vitamins and bioactives, and/or reducing undesirable compounds such as nitrate and oxalates). For example, under protected conditions, the use of silicon supplementation to plant nutrition, low salinity, and LED light systems appear promising. However, specific and extended research focused on local conditions and cultivars needs to be conducted to confirm and further understand and explore the potential of those practices.

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2. Pre-harvest factors affecting quality and shelf-life of Brassica vegetables

2.1 Key findings

- The shelf-life, external quality, and composition of broccoli appears to be strongly influenced by an interaction between cultivars and growing conditions, especially field temperatures (e.g. longer shelf-life is generally associated with cooler areas compared to warmer ones);
- Further targeted research is vital to identify the best options in terms of achieving optimum yields of high-quality produce for each key production area and current cultivars; there is also little research on shelf-life and external quality of Brassica vegetables other than Broccoli;
- Determining the optimum maturity stage for harvesting and the impact of plant growth stage during disease management appear to reduce postharvest bruising, blemishes and diseases that affect the quality of cauliflower and broccoli, such as white blister, bracting, and riciness;
- Most research on crop nutrition focused on the association between adequate sulphur (S) fertilisation and its balance with N to achieve higher contents of bioactives in broccoli and kale;
- An optimum N to S ratio between 7-9 to 1 was associated with a higher content of glucosinolates in broccoli and cabbage, suggesting value addition opportunities to enhance their health-promoting compounds.

2.2 Broccoli, cauliflower, cabbage, kale, Brussels sprouts, turnip, and radish

Background

Commercial importance and main cultivar types

The genus Brassica comprises a number of widely cultivated vegetable crops grown for their inflorescences (e.g. broccoli and cauliflower), their leaves (e.g. cabbage, Brussels sprouts, kale, collard greens, tatsoi, mizuna, and pak choi), or their roots (e.g. turnip and swede) (Witzel *et al.*, 2015). Most of these vegetables belong to the taxa *Brassica oleracea,* except for turnip, tatsoi, and mizuna (*Brassica rapa*) and swede (*Brassica napus*). Other commercial crops in the Brassicaceae family include radish (*Raphanus sativus*) and cultivated rocket or arugula (*Eruca sativa*). Except for cabbage, Brussels sprouts, and kale, the other leafy Brassica vegetables described above, together with cultivated rocket, were included in section 2 of this review.

Broccoli, cauliflower, and cabbage are widely consumed and regarded as healthy, tasty vegetables that can add variety to a range of meals. In Australia, broccoli, cauliflower, and cabbage are important horticultural commodities, with gross values of $97 M (in addition to $45 M for broccolini), $55 M, and $57 M, respectively, followed by Brussels sprouts, with $23 M in 2013-14 (Anon., 2015d). Kale is a leafy brassica vegetable that is becoming more popular in Australia due to its high nutritional and phytochemical value. A recent consumer report on fresh vegetables places broccoli and cauliflower as the 5^{th} and 9^{th} most regularly purchased vegetables by about 75% and 62% of consumers in Australia, respectively (Witham et al., 2015). Of six Brassica vegetables, broccoli and cauliflower were reported as the preferred ones by Australian consumers in terms of sensory attributes, with the 'intention to purchase' being higher for broccoli than for any of the other vegetables tested (Cox *et al.*, 2012).

Key compositional and nutritional aspects

Brassica vegetables are a significant source of vitamins (mainly K, C, A, and folate, in addition to E, B_6, B_2, pantothenic acid, and B_1), minerals (majorly Mn, K, and P, in addition to Mg, Ca, Fe, and Zn), and dietary fibre (Anon., 2015a).

In addition to their contribution to the human diet, Brassica vegetables are also known for their abundant supply of a number of phytochemicals, such as glucosinolates, isothiocyanates, and phenolics, which have potential health benefits, including anticancer and antioxidant properties (Delahunty, 2011). Glucosinolates, a group of sulphur-rich plant defence metabolites and their degradation products are found almost exclusively in the Brassicaceae family (Falk *et al.*, 2007). Some of these compounds are responsible for the undesirable bitter taste associated with many Brassica vegetables (Cox *et al.*, 2012).

A frequent dietary intake of the health-promoting compounds found in Brassica vegetables have been shown to reduce the risk of chronic diseases such as atherosclerosis and certain forms of cancer (Herr and Buchler, 2010). These vegetables are potential sources of anticarcinogenic glucosinolates, antioxidant metabolites such as vitamin C, β-carotene, lutein, and zeaxanthin, phenolic acids, flavonols such as quercetin and kaempferol, anthocyanidins, and amino acids (Nilsson *et al.*, 2006; Podsedek, 2007).

The aliphatic glucosinolates have attracted scientific attention, especially the anti-carcinogen isothiocyanate sulforaphane, the major break down product of glucoraphanin in broccoli, an important phytochemical due to its anti-carcinogenic and anti-inflammatory activity (Guerrero-Beltran *et al.*, 2012; Witzel *et al.*, 2015). Because of its relatively well documented health-promoting benefits, broccoli consumption by health conscious consumers has increased, offering a high level of nutrition at a very low caloric cost, making it one of the most nutrient-dense vegetables available. In contrast, some in vitro and experimental animal studies have shown some potential mutagenic activity of broccoli extracts, but the benefits from intake of raw and processed broccoli in modest quantities appear to outweigh the potential risks (Latte *et al.*, 2011).

Kale is a significant source of vitamins (mainly K, A, C, B_6, in addition to folate, B_1, B_2, B_3), minerals (majorly manganese, calcium, potassium, copper, iron, magnesium, in addition to phosphorus and zinc), and dietary fibre (Anon., 2015a). Kale also contains phytochemicals, including high contents of the carotenoids lutein and beta-carotene, as well as polyphenols, and it has high antioxidant activity (Korus, 2011).

Key quality issues

Recent market surveys showed that health and convenience are the main influences on broccoli purchased by Australian consumers, whereas the main barriers to purchase are not being available locally and being too expensive (Anon., 2015c). For cauliflower, taste, ease of preparation, and health are the primary influences on purchase, whereas already consuming enough and not wanting to waste any are the key barriers inhibiting purchase (Anon., 2015b). For kale, the key drivers of purchase are health related due to its specific health and nutritional benefits, whereas wanting to avoid waste is the key barrier to purchase (Anon., 2015c). Once purchased, Australian consumers expect Brassica vegetables to stay fresh for about 7-9 days, and these expectations are being met most of the time by 80-86% of consumers (Anon., 2015b; c).

Appearance is a critical factor affecting selection of specific vegetables at retail. For broccoli, quality is mainly judged by it green colour, which is associated with chlorophyll content. Key quality concerns for Australian consumers include open florets or yellowing, hollow, split or browned stem, excess stem length, , and insect contamination (Hamblin, 2013). Wilting, caused by loss of turgor, is a major problem for broccoli sold at ambient store temperature, but broccoli heads can also suffer from bud yellowing and bud opening, leading to a 'stale looking' product (Wurr *et al.*, 2002). Thus, bud morphology in terms of stem turgor, head colour, compactness and elongation, is a crucial aspect of head quality in broccoli. In Australia, individual broccoli and cauliflower heads are the main format purchased by consumers, with pre-packaged formats in small and large containers, bags and trays making up a small proportion of purchased options; for kale, bunched is the most common format (Anon., 2015c; b).

Regarding internal quality, the bitter and pungent taste of Brassica vegetables is a sensory impediment to consumer acceptance, as most consumers dislike bitter and strong-tasting vegetables and prefer milder and sweeter ones (Doorn *et al.*, 1998; Drewnowski and Gomez-Carneros, 2000). Recent sensory work in Australia showed that the overall taste characteristics largely determined the liking of and intentions to consume Brassica vegetables, and that most of the phytochemicals responsible for the undesirable taste of Brassica vegetables are also major contributors to their health properties (Delahunty, 2011). Likewise, in a 3-year sensory study conducted in Germany, consumer's preferred traits were sweetness, crispness and intensity of flavour for broccoli, and sweetness, juiciness, and flavour for cauliflower, whereas more intense bitter, pungent and green/grassy notes reduced acceptability; also, glucosinolates content affected sweetness, bitterness, and pungency in these vegetables, whilst sugar content was a poor predictor of the sweetness (Bruckner et al., 2005). Similar associations between bitter taste and glucosinolates content have been found in white cabbage (Beck *et al.*, 2014) and Brussels sprouts (Doorn *et al.*, 1998). Thus, striking a balance between flavour and bioactives levels is likely a vital strategy to increase the popularity of Brassica vegetables, in addition to promoting health information (Cox *et al.*, 2012).

Crop nutrition

Nutrition management: S and N

A number of field and greenhouse experiments involving soil, hydroponic, and tissue culture media with several Brassica vegetables have shown that S fertilisation generally results in increased glucosinolate content (from less than 1-fold to more than 50-fold). The results were dependent on the plant species, plant development stage, amount of S applied, type of treatment, soil type, and plant N level (Falk *et al.*, 2007). For instance, in broccoli, applied-S is more effective at the intermediate stages of head development.

In Australia, applying gypsum as anhydrous calcium sulphate at 23 or 92 kg S/ha increased both total S and glucosinolate (i.e. glucoraphanin) content in field-grown broccoli cvs. 'Claudia', 'Marathon' and 'TB-234'in Victoria; 'Claudia' cultivar at 92 kg S/ha resulted in the highest increase of about 190% compared to the control (Rangkadilok *et al.*, 2004). Likewise, applied S as calcium sulphate at 150 kg/ha increased the content of glucosinolates , flavonoids, vitamin C, and hydroxycinnamic acid derivatives in 8 cultivars of field-grown broccoli in Spain (Vallejo *et al.*, 2003a; Vallejo *et al.*, 2003b). In contrast, applied S at 50 or 100 kg/ha had little effect on glucoraphanin and flavonols content in broccoli heads field-grown in Victoria, likely because of the high residual soil S levels in the broccoli field sites used in the study, whereas (Jones *et al.*, 2007). This suggests that the effectiveness of S application in increasing glucosinolates content may depend on S levels in the soil. In that study, the lower N rates (0, 15, and 30 kg/ha) increased the contents of both compounds, but markedly reduced yield.

Keeping an optimum N:S ratio between 7:1 and 9:1 in greenhouse-grown broccoli in Germany resulted in larger heads with a more uniform green colour and higher contents of glucosinolates, compared to a low-S fertilisation regimen having ratios higher than 10:1 (Schonhof *et al.*, 2007a). Likewise, glucosinolate content in broccoli and radish increased with the availability of S (but not in cauliflower) and with reduced supply of N or water, whereas lower water and N availability increased glucosinolates in all three vegetables (Schreiner, 2005). A similar trend of higher N:S ratio associated with lower glucosinolates content has been reported in cabbage (Rosen *et al.*, 2005) and turnip (Kim, 2002). Equal N availability (i.e. split dose) applied to greenhouse-grown cabbage in Denmark increased plant response to S and led to higher glucosinolate content (Groenbaek and Kristensen, 2014). These results suggest that for the production of brassicas, N supply should be balanced with S application, as plants can generally only benefit from having an optimal N supply when sufficient S is available to allow the synthesis of S-containing substances such as glucosinolates.

Nitrogen as ammonium nitrate at 150-600 kg N/ha applied to broccoli plants grown in winter in Turkey increased the contents of K, Ca, Mg, Fe and Zn, as well as yield, and head weight, diameter, and length (Yoldas *et al.*, 2008). In contrast, ammonium nitrate at rates of 125-625 kg/ha applied to broccoli plants grown in the field over three plantings in 2 years in Canada had little impact on weight loss, visual quality, and vitamin C content of heads during a 20-day cold-storage at 1°C (Toivonen *et al.*, 1994).

Several studies suggest that in kale production, N and S fertiliser management and cultivar selection can be used as tools to enhance phytochemicals content and eating quality. For example, higher rates of S, from 4 to 46 mg S/L, in the nutrient solution applied to greenhouse-grown kale plants in the UK increased the leaf content of glucosinolates, reduced Ca and Mg contents, and had no effect on lutein and beta-carotene contents (Kopsell *et al.*, 2003). Likewise, Increasing S application as magnesium sulfate from 4 to 30 kg/ha to field-grown kale plants in Denmark increased the content of glucosinolates, whereas reduced rates of applied N from 230 to 90 kg/ha increased the content of glucosinolates, quercetin, and flavonoids in some cultivars (Groenbaek et al., 2014). Reduced N supply at 185 to 92 kg N/ha to field-grown kale in Denmark improved its flavour, as determined by a sensory panel, by reducing bitterness, astringency and the pungent aroma in the leaves, which was presumably associated with increased aliphatic and total glucosinolates content; also, the total soluble sugars, an important flavour component in kale, increased with plant age, being higher when leaves were 13 or 17 weeks old compared to 8 weeks old (Groenbaek *et al.*, 2015).

Increasing rates of N as urea from 100 to 500 kg/ha to white cabbage grown in winter in Canada increased yield, head size, reduced vitamin C content, and had little effect on head weight loss during cold-storage at 4°C for 24 weeks (Freyman *et al.*, 1991).

Nutrition management: other nutrients

Zinc application at 0.05-25 mg/L to the nutrient solution of hydroponically-grown *Brassica rapa* (type not mentioned) in the USA increased glucosinolates content and their distribution, whereas rates of 50-200 mg/L caused severe Zn toxicity (Coolong *et al.*, 2004). There is limited information on the effects of micronutrients on shelf-life and phytochemicals content in Brassica vegetables.

Crop management

Growing conditions and/or seasonal effects and their interaction with cultivars

The quality and shelf-life of broccoli appears to be strongly influenced by an interaction between growing temperatures and genotype. In a 3-year study with field trials set in Gunalda (Qld), Toowoomba (Qld), and Armidale (NSW), broccoli cultivars grown in cooler locations (i.e. Armidale compared to SE Qld) had 1-2 days longer shelf-life based on head colour and off-smell; the district and the season of production had a bigger impact on the variation in yield between varieties than the selected variety alone, highlighting the importance of growing a crop in the correct seasonal and geographical location for optimum yield and quality (Rogers, 2010).

Similarly, a 3-year study with 4 broccoli cultivars field-grown in the USA, showed that seasonal temperatures (min, max, or both) affected head quality and their shelf-life (i.e. commercial acceptance/rejection based on head shape, colour, density, leafiness, and head size), and that cultivar responses depended on season (Dufault, 1996).

Growth conditions associated with high northern latitudes of low temperature and long photoperiods in Norway, produced larger broccoli floral buds, and florets with sweeter taste, less intense colour, and lower flavonols content than more southern conditions (Molmann *et al.*, 2015).

Broccoli (8 cultivars) grown under field conditions in Spain in spring had generally higher contents of glucosinolates, total phenolics, and vitamin C than plants grown early in winter (Vallejo *et al.*, 2003a; Vallejo *et al.*, 2003b). Similarly, broccoli harvested in spring or autumn in Sweden had higher antioxidant activity than that harvested in winter or summer (Nilsson *et al.*, 2006).

Broccoli plants grown in the greenhouse in Germany at 7–12°C had higher contents of vitamin C (up to 38%), lutein, and glucosinolates than plants grown at 15–20°C (Schonhof *et al.*, 2007b).

Glucosinolates content in cauliflower grown in Sweden varied year-to-year (Nilsson *et al.*, 2006).

Cabbage plants grown in South Korea in spring had higher anthocyanidins contents than those grown in autumn, presumably due to changes in UV exposure between the seasons (Park *et al.*, 2014). Similarly, minimally processed kale plants grown in Brazil in summer had higher carotenoid contents than those grown in winter (Azevedo and Rodriguez-Amaya, 2005).

Cultivar effects

Cultivar evaluations conducted by WA Department of Agriculture and Food during 2006 and 2007, showed considerable variation among varieties in their shelf-life and postharvest quality after storage at 1°C for 14 days (Stirling, 2008). In Victoria, the incidence of white blister in broccoli heads was reduced by 99% when some cultivars (e.g. 'Tyson) were used compared to susceptible cultivar 'Ironman' (Minchinton *et al.*, 2013).

In a 3-year sensory evaluation in Germany, sweetness, bitterness, and consumer acceptability of both broccoli and cauliflower were affected by cultivars, highlighting the importance of careful cultivar choice to avoid loss of product acceptability; also, samples that were less sweet, more bitter, and had low acceptability, were associated with higher glucosinolate content, especially in broccoli (Bruckner et al., 2005).

Method and time of harvest and/or growth stage

A 3-year study over 4 harvests in the Manjimup area of Western Australia showed that harvesting cauliflowers at the optimum maturity stage (i.e. no loose floret development), thus avoiding overmature curds, especially during autumn harvest (April-May), improved postharvest quality (i.e. less severe bruising, discolouration, rots, blemishes, and black spot) after curds were held at 21-25°C for 4-6 days to simulate export market conditions (McVeigh *et al.*, 1999). Careful handling of the curds in the field and packing house was also important to minimise pressure bruising and physical damage, which were associated with curd blackening.

White blister, caused by the fungus *Albugo candida,* is a major disease affecting quality of Brassica crops in Australia, resulting in leaves and heads with white raised lesions (Minchinton et al., 2013). Disease progression data from crop inspections and environmental data from field studies on Chinese cabbage grown in Victoria suggest that (Minchinton, 2012):

- As part of the fungicide spray program, it is important to consider the phenological age (i.e. plant growth stage/cycle as affected by environmental conditions) of the crop for control of white blister on harvested plant parts;
- As the pathogen only infects young tissue, the same would apply to broccoli heads, and thus further studies of broccoli button development would be warranted to determine the phenological time when buttons should be sprayed to provide the most effective protection of heads against white blister infection.

Likewise, a field study in Denmark suggested the use of models (equations including temperature data and functions of developmental stage of the plant) which can potentially predict the proportion of cauliflower plants with bracting or riciness, disorders related to temperature during plant growth that can seriously reduce quality (Grevsen *et al.*, 2003).

The content of vitamin C, flavonoids and phenolic acids in broccoli increased steadily with age, reaching a maximum when the head was at the "over mature" stage. (Vallejo *et al.*, 2003a). In contrast, glucosinolates peaked in the second or third of the five stages, depending on the degree of S fertilisation and cultivar. The stage at which most broccoli is harvested for market was stage 4.

In kale, lutein and β-carotene contents were shown to be higher in fully expanded mature leaves than in younger ones (Walsh *et al.*, 2015).

Time of the day at harvest

Two studies in Argentina showed that broccoli heads harvested at the end of the day compared to early morning, and held at 20°C for 4-5 days, had a 1-day longer shelf-life, were greener and had higher contents of total sugars, antioxidants, and phenolics, presumably because starch accumulated during daylight may delay senescence in broccoli (Hasperue *et al.*, 2011; Hasperué *et al.*, 2013).

Planting density

In the 3-year study with broccoli grown in Qld and NSW mentioned above (Rogers, 2010), increasing plant density from 60,000 to 90,000 plants/ha resulted in smaller heads, thus improving head resistance to damage of mechanically-harvested plants.

Field-grown cabbage (3 cvs) plants in the UK spaced at 60 cm resulted in heads with better flavour as assessed by chemical analysis and confirmed by tasting tests compared with plants spaced at 45 cm or 75 cm (MacLeod and Nussbaum, 1977). Similarly, field-grown Brussels sprouts (6 cvs) in the UK spaced at 45 cm resulted in heads with better flavour compared to plants spaced at 30 cm, in which flavour was too strong presumably due to higher isothiocyanate content, or at 60 cm, in which flavour was too bland (MacLeod and Pikk, 1978).

High levels of supplemental UV-B radiation applied to hydroponically-grown broccoli in Turkey during growth, increased the contents of vitamin C and bioactives (i.e. total phenolic, flavonoid, sinigrin, and glucotropaeolin), but also reduced visual quality and chlorophyll content, as well as resulting in uneven head formation (Topcu *et al.*, 2015).

Water management

Systematic surveys conducted in Australia showed that overhead irrigation early in the morning reduced the incidence of white blister in broccoli (Minchinton, 2012) and in radish plants (Minchinton *et al.*, 2013) grown in Victoria, compared to irrigating in the evening, presumably due to a reduction in the periods of leaf wetness.

In a 2-year greenhouse study in the UK, controlled water stress imposed for 14 days before harvest of broccoli, which were placed into sealed bag and stored at 15°C, increased shelf-life from 3-6 days to 12-13 days based on visual acceptability of key commercially quality parameters: head colour and stem turgor, i.e. heads were greener and more turgid; however, head weight and head diameter was about 30% less than the control heads (Wurr *et al.*, 2002).

Similarly, water soil stress (at 0.4MPa) applied to greenhouse-grown broccoli in Brazil resulted in greener florets held at 23°C for the whole duration of the trial (96 hours), whereas control florets became yellow after 24 hours, presumably due to increases in cytokinin biosynthesis (Zaicovski *et al.*, 2008).

Supplying irrigation to achieve maximum yield (i.e. no deficit irrigation during head development) in greenhouse-grown cabbage in the USA reduced glucosinolates content (typically responsive for the unpleasant pungency in cabbage) and increased sugars content, thus likely increasing the perception of sweetness and improving flavour (Radovich *et al.*, 2005).

Growing system

There were no overall differences in phytochemical content of broccoli grown under either organic or conventional management systems under field conditions in the Netherlands (Renaud *et al.*, 2014). Similarly, Wunderlich *et al.* (2008) found no significant difference in the vitamin C content of organically and conventionally labelled broccoli purchased from supermarkets in the USA, with larger differences in seasonal changes rather than the growing system.

Light condition

Broccoli plants grown in the greenhouse in Germany under higher light intensity, combined with lower temperatures during growth, increased glucosinolates content (Schonhof *et al.*, 2007b). In contrast, supplemental far-red and red LED light applied to broccoli grown in controlled chambers in Norway resulted in elongated plants and reduced content of glucosinolates in the florets, higher quercetin content with red light, whereas vitamin C was not affected by light treatments (Steindal *et al.*, 2015).

Beneficial microorganisms

There is some recent evidence for the potential use of endophytic microorganisms in adding beneficial traits (i.e. pest and disease resistance, which will impact on product quality) to Brassica crops, especially asymptomatic mutualistic plant/microbial associations (Card *et al.*, 2015). For example, bacterial strains have been incorporated into two commercially available biological control products, which are currently being trialled on cabbage grown in New Zealand for protection against Black rot (the most important bacterial disease of cabbage crops worldwide) and reduced seed to seedling transmission of the pathogen (Card *et al.*, 2015). The research aims to produce "smart" vegetable seeds with novel and enhanced attributes, and to develop technologies for reducing product losses (including loss of postharvest quality) from pests and diseases through bio-control rather than chemicals.

Bioregulators

Applied methyl jasmonate (a plant signal transduction compound) as a spray solution at a concentration of 500 µM four days prior to harvest increased glucosinolate content of field-grown cauliflower in Canada (Ku *et al.*, 2013). Likewise, spraying the foliage of greenhouse-grown broccoli plants in Germany with the amino acid methionine increased (by 28%) the content of glucosinolates (Scheuner *et al.*, 2005).

2.3 Conclusions

Health, convenience, and taste were shown to be the main influences on Brassica vegetables purchased by Australian consumers, whereas not being available locally and not wanting to waste any, the main barriers. Once purchased, Australian consumers expect Brassica vegetables to stay fresh for 7-9 days, and these expectations are being met most of the time by about 80-86% of consumers.

Overall, most published research worldwide involving pre-harvest factors affecting quality of Brassica vegetables have focused on impacts on product composition, especially glucosinolates content. There were fewer studies on pre-harvest effects on product shelf-life, external quality, or sensory quality.

In terms of crop nutrition, most research focused on the association between an adequate S fertilisation (and its balance with N) and an increased content of glucosinolates, especially in broccoli and kale. A lower (i.e. <10:1) N:S ratio balance between sulphur and N fertilisation was often associated with higher content of glucosinolates in several crops, including broccoli, cabbage, radish, and turnip, and (in one study) with more uniform green colour in greenhouse-grown Broccoli. These results suggest that there are potential adding-value opportunities to manipulate the glucosinolate concentration of Brassicas to enhance their health-promoting compounds.

In terms of crop management, the quality/shelf-life of broccoli appears to be strongly influenced by an interaction between growing conditions (especially field temperatures) and cultivars (which are shown to impact on shelf-life and quality, including sensory attributes and composition of Brassicas). For example, production of Broccoli in cooler areas in Australia slightly increased shelf-life, but further specific research is important to reliably determine the best options in terms of achieving optimum yields of high-quality produce for each key production area and current cultivars.

Also, determining the optimum maturity stage for harvesting and understanding the impact of plant growth stage during disease management, appear to be important in reducing postharvest bruising, blemishes and diseases that affect the quality (such as white blister, bracting, or riciness) of harvested brassica vegetables (especially cauliflower and broccoli).

Other factors with more limited evidence that would warrant further investigation are:

- Using plant density to alter head size and potentially increase resistance to damage in mechanically-harvested broccoli and flavour of cabbage and Brussels sprouts;
- Control of irrigation timing (i.e. early in the morning rather than in the evening) to reduce the incidence of diseases such as white blister in Broccoli;
- Use of deficit irrigation before harvest to improve shelf-life and head colour of greenhouse broccoli;
- Harvesting late in the day rather than early in the morning to increase shelf-life, enhance colour and composition of Broccoli;
- The use of beneficial plant/microorganisms associations that can increase resistant to pests and diseases and reduce losses through bio-control rather than chemicals.

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3. Pre-harvest factors affecting quality and shelf-life of cucurbit vegetables

3.1 Key findings

- The use of training systems that allow high light penetration and more rapid fruit growth, as well as fruit thinning reducing crop load and increasing leaf to fruit ratio, generally resulted in greener cucumbers at harvest with a longer shelf-life. As most studies were conducted with the same cultivar and location, further research is warranted;
- Applied Si (e.g. silicate salts) in the nutrient solution or as foliar sprays appear to increase resistance of continental cucumber and zucchini plants to fungal diseases that reduce fruit quality such as powdery mildew; other fertiliser salts such as bicarbonates and phosphates can have a similar effect, which warrants further investigation including effects on other cultivars;
- Increasing N levels during greenhouse-grown cucumber generally resulted in greener and softer fruit with more nitrate and less Ca, suggesting the importance of a balanced nutrition;
- The harvesting of pumpkins at proper maturity without delay, together with careful handling and minimum damage to stalks, can increase fruit resistance to rots postharvest.

3.2 Cucumber

Background

Commercial importance and main cultivar types

Cucumber (*Cucumis sativus* L.) is a widely grown vegetable in Australia with an annual production of 14,085 tonnes and a gross value of $29.7 M in 2013-14 (Anon., 2015d). A recent consumer report on fresh vegetables places cucumber as the 6th most regularly purchased vegetable by almost 70% of consumers in Australia (Witham et al., 2015).

The main types commercially grown in Australia are the 'Lebanese' (or 'mini', or 'Beit Alpha'), 'Continental' (or 'European' or 'Telegraph' or 'Long English'), the standard green slicing 'Green' (or 'Aussie' or 'American' slicers), and the 'Cocktail' (or 'Baby') cucumbers, which are all green-skinned cylindrical fruit (Badgery-Parker *et al.*, 2010).

Key compositional and nutritional aspects

Cucumber is usually consumed for its refreshing and crisp sensory characteristics more than for its nutritional quality, as it is not a nutrient-rich vegetable, with about 96% water. It contains relatively small amounts of nutrients, including vitamins (K, C and pantothenic acid), minerals (K, Mn, and Mg), and some dietary fibre (Anon., 2015a). However, cucumber is one of only a few foods to contain Si, a trace element which is important in human health as part of connective tissues in the skin, hair and nails (Hedges, 2007), as well as being recently associated with bone formation, maintenance, and increased bone mineral density (Price *et al.*, 2013).

Compounds responsible for fresh cucumber flavour, especially (E, Z)-2, 6-nonadienal (NDE), are formed within seconds by enzymatic reactions triggered by tissue disruption such as slicing (Palma-Harris *et al.*, 2001). Cucurbitacin-C is the cause of bitterness in cucumber, and has shown chemopreventative activity against prostate cancer in rats with no noticeable toxicity (Gao et al., 2014). The astringency sometimes found in cucumber is reported to be due to formic acid in the skin and vascular bundles (Kaneko and Miyake, 2013).

Key quality issues

Recent market surveys showed that taste and health are the key drivers of purchase for cucumber, whereas not wanting to waste is the major barrier (Anon., 2015b). Once purchased, Australian consumers expect cucumbers to stay fresh for about 8 days, and these expectations are being met most of the time by 74% of consumers (Anon., 2015b).

The main quality attributes of cucumbers include visual appearance, especially colour, as shelf-life is largely limited by fruit skin yellowing due to the loss of chlorophyll, skin turgidity, size, sensory quality, particularly firmness and crispness, defects, and diseases (Schouten *et al.*, 1997).

Although cucumber is a non-climacteric vegetable, it still displays biochemical changes of ripening associated with climacteric fruit at a slower rate, gradually becoming shrivelled, discoloured, and eventually starting to breakdown (Badgery-Parker *et al.*, 2010). As such, it requires postharvest treatments including cooling to 10-13°C and packaging, such as individually shrink-wrapping, to slow down postharvest respiration and reduce moisture loss.

Crop nutrition

Nutrition management

In a study in Canada with continental cucumber (cv 'Mustang') grown in the greenhouse under nutrient concentrations of 50%, 100%, and 150% of the standard nutrient solution based on N, P, K, Ca, Mg, S, and micronutrients (Lin and Ehret, 1991):

- Compared to the standard solution, the high nutrient solution treatment increased shelf-life based on visual colour from 12.7 to 16 days, after cold-storage at 13.5°C for 3 weeks, probably through enhanced fruit colour at harvest; in contrast, the low solution treatment decreased shelf-life by 2 days.
- The number of marketable fruit per plant was reduced by about 10% with high solution, whereas increased by 15% with the low solution;
- Shelf-life was correlated with fruit colour at harvest, i.e. the darker green the fruit, the longer the shelf-life, suggesting colour may be an indicative of potential shelf-life.

Increasing N rates as nitrate from 75 to 375 mg/L in the nutrient solution of cucumber plants (a continental and a Lebanese type) grown in the greenhouse in Florida over 2 seasons resulted in softer and greener fruit at harvest, with intermediate to higher N concentrations resulting in the darkest and most intense colours (Jasso-Chaverria et al., 2005).

Likewise, applied-N (as potassium nitrate, from 2.5-40 g/m) to greenhouse-grown cucumber plants (cv 'Bunex') in Spain, resulted in softer fruit with higher contents of nitrate and lower content of Ca at the rate of 40 g/m, whereas rates of 10-20 g/m resulted in fruit with higher contents of soluble solids and sugars, as well as higher commercial yield (Ruiz and Romero, 1998). Accordingly, Ca concentrations in cucumber fruit sampled from 21 greenhouses in Iran were positively related to fruit firmness, whilst higher fruit K concentration was associated with darker green on the skin (Aghili *et al.*, 2009). Those results suggest that adequate levels of plant nutrients during growth of cucumbers can impact on fruit quality and postharvest shelf-life

Effects of Si and other fertiliser salts on diseases

Powdery mildew caused by the pathogens *Podosphaera fusca* or *Golovinomyces cichoracearum* is the most widespread and serious foliar fungal disease of cucurbits, which causes premature leaf senescence and exposes the fruit to sunscald. Fruit from severely infected plants are typically regarded as low quality products by the market due to poor taste, texture, and small size (Minchinton, 2012).

As seen in section 1.3, Si can increase plant resistance to diseases, and cucumber plants can actively uptake and moderately accumulate Si, which can be supplied as silicate salts in the hydroponic solution or applied as a foliar spray (Faisal et al., 2012). In cucumber leaves, Si deposition can inhibit colony growth of the powdery mildew fungus, presumably by providing a physical barrier to pathogen attack through increasing lignification and thus strength of cell walls (Samuels et al., 1993). Flavonoids associated with defence can also accumulate in Si-treated cucumber plants (Fawe et al., 1998).

Applied Si as silicon dioxide at 0.1 g/L to continental cucumber (cv 'Corona') grown in recirculating nutrient solution in the UK increased resistance to powdery mildew (Adatia and Besford, 1986). Likewise, Si applied as potassium silicate either in the nutrient solution at 1.7 mM or as foliar spray at 8.5 or 17 mM to continental cucumber (cv 'Corona') greenhouse-grown in Canada reduced the incidence of powdery mildew by up to 43-53% compared to control, whereas sprays at 1.7 mM were ineffective and sprays at 34 mM had little further reduction (Menzies et al., 1992). In another study with continental cucumber (cv 'Corona') greenhouse-grown in Canada, the addition of Si as potassium silicate at 100 ppm to hydroponic nutrient media increased resistance to powdery mildew and increased fruit Si content, but also resulted in fruit with a dull skin or 'bloom' appearance (Samuels et al., 1993).

Addition of Si as potassium silicate at 100 or 200 ppm to recirculating nutrient solution reduced root rot caused by the fungus Pythium ultimum in continental cucumber (cvs 'Corona' and 'Marillo') greenhouse-grown in Canada and increased the proportion of high-grade fruit (Cherif and Belanger, 1992).

Apart from Si, other fertiliser salts such as bicarbonates, phosphates, and chlorides, applied as foliar sprays have also been used to reduce incidence of powdery mildew in greenhouse cucumber (cv 'Delilla') in Israel (Reuveni et al., 1996; Reuveni and Agapov, 1997; Reuveni et al., 2000), as well as other fungal diseases such as anthracnose, leaf spot and scab in cucumber plants as reviewed by Deliopoulos et al. (2010). These salts appear to work in several ways, including altering the pH of the leaf surface, dehydrating the fungal spores, and stimulating systemic processes of plant defence (Deliopoulos et al., 2010).

Crop management

Training systems

Training systems, fruit thinning and fruit position on the plant have been reported to influence fruit quality and shelf-life of greenhouse-grown cucumbers.

Thinning of one-third of the fruit from the main stem and laterals in greenhouse-grown continental cucumber (cv 'Mustang') in Canada resulted in (Lin and Ehret, 1991):

- Increased shelf-life based on visual colour from 12.7 to 14.5 days after cold-storage at 13.5°C for 3 weeks, suggesting a higher source: to sink ratio may increase shelf-life through a higher fruit growth rate, as days to harvest was inversely related to the shelf-life;

- Reduced the number of marketable fruit per plant by about 8%;
- Cucumbers harvested from the top of the main stem and second laterals (but not first laterals) had longer shelf-life than those harvested from the bottom of the canopy.

In another greenhouse-grown continental cucumber (cv 'Mustang') study in Canada, training systems permitting high canopy light penetration resulted in 2-3 days longer fruit shelf-life based on colour during cold-storage at 13°C in plastic bags, although the number of fruit per plant was reduced; longer shelf-life correlated to darker green fruit colour at harvest and to rapid fruit growth (Klieber et al., 1993). That study proposed the following techniques for training cucumber plants to produce fruit with longer shelf-life:

- Have the minimum number of stems per plant;
- Orient the stems for maximum light exposure;
- Increase leaf to fruit ratio by allowing more than two leaves per fruit .

Likewise, a series of 6 trials in additional 2 studies with greenhouse-grown continental cucumber (cv 'Mustang') in Canada confirmed that a 2-3 days longer fruit shelf-life during a 4-week storage at 13 °C was generally associated with (Lin and Jolliffe, 1996; Jolliffe and Lin, 1997):

- Greener skin at harvest measured non-destructively by video imaging;
- More intense incident light during cucumber production, which increased chlorophyll content in the fruit skin;
- Faster fruit growth up to marketable length.

Growing conditions

In a study in Gosford, NSW, Lebanese cucumber (cv 'Deena') greenhouse-grown in fully-controlled conditions in terms of temperature and RH had a higher yield and were consistently firmer, less prone to postharvest yellowing, had fewer rots, developed less pitting due to chilling injury, and had higher overall quality after storage at 5°C for 12 days plus 2 days at 20°C compared to those grown in adjacent greenhouses with little environmental control, i.e. cold nights, minimum ventilation, cold/hot days, high RH (Ekman *et al.*, 2010). The study also showed that plant density (at either 2, 3, or 4 plant/m^2) had little effect on postharvest quality.

Cucumber fruit (cv. 'Tropico F1') grown hydroponically in spring in Spain generally had lower quality at harvest (i.e. poorer skin colour, more flesh whitening, and more acid) than fruit grown during winter (Gomez-Lopez et al., 2006). Similarly, greenhouse-grown cucumber plants in Poland in summer had better flesh colour, flavour and aroma, but little differences in texture or juiciness than fruit gown in autumn or spring (Kowalczyk *et al.*, 2010).

Growing medium

Mini cucumber (cv 'Tandora') hydroponically–grown in NSW using various substrates (i.e. coir, sawdust, rockwool, perlite, and 'cucumber mix, a commercial soil conditioner), resulted in little effect on fruit weight loss, skin colour, firmness, crush strength, and yield after storage at 10°C for 2 weeks (James, 2005).

Cucumber fruit grown in mineral wool in the greenhouse in Finland had better flavour early in the harvesting season than plants grown on peat (Luoto, 1984). Likewise, cucumber (cv 'Jinlv No. 3') grown on a mixture of peat to vermiculite 1:1 resulted in higher soluble solids content than cucumber grown on peat alone (Gao *et al.*, 2010). Also, compared to perlite substrate, cucumber fruit (cv. 'Tropico F1') grown hydroponically in a 'Nutrient Film Technique' in Spain over winter and spring had a darker green skin irrespective of the season and were less acid in spring (Gomez-Lopez et al., 2006).

Rootstocks effects

Rootstocks affected the contents of soluble sugars, vitamin C, astringency, and fruit size of several greenhouse-grown cucumber cultivars in China (Gu *et al.*, 2008). Similarly, rootstocks affected fruit acidity, weight, and length, as well as yield of grafted cucumber plants (cv 'Adrian') grown in Croatia (Ban *et al.*, 2014), and flavour, fruit acidity, soluble sugars and vitamin C contents of grafted plants (cv 'Jinchun No 2') in China (Huang *et al.*, 2009; Zhou *et al.*, 2010). Various scion/rootstock combinations also affected flavour and volatiles content of fruit from cucumber plants grown in China (Dong *et al.*, 2013). In contrast, rootstocks had no effect on fruit flavour, size or shape from greenhouse-grown cucumber plants (cv 'Serena') in Spain (Hoyos Echebarría, 2001).

Harvest maturity

Shelf-life at 20°C based on visual quality of greenhouse-grown cucumber (cv 'Deliva') in California was reduced from 22 days when fruit was harvested at commercial maturity (i.e. 11-12 days after flowering) to 13, 11, and 6 days when fruit was harvested respectively at 3, 8, and 13 days after maturity (Kanellis *et al.*, 1986). In that study, both visual colour and chlorophyll content decreased with fruit age at harvest. Similarly, a study with greenhouse-grown continental cucumber (cv 'Mustang') in Canada showed a negative correlation between fruit age and shelf-life confirming that the physiological age of the fruit at harvest influences the shelf-life of cucumber (Lin and Ehret, 1991).

3.3 Zucchini

Background

Commercial importance and main cultivar types

Zucchini (*Cucurbita pepo*), also called summer squash or courgette, is defined as a fruit harvested at an immature stage, usually a few days after anthesis and before the rind becomes hard (Welbaum, 2015). Its great economic value is based mainly on the culinary use of the immature fruit as a vegetable (Martinez-Valdivieso *et al.*, 2015). Zucchini is a significant horticultural commodity in Australia, with an annual production of 25,056 tonnes and a gross value of $72.2 M in 2013-14 (Anon., 2015d). A recent consumer report on fresh vegetables shows that zucchini is regularly purchased by about 50% of Australians (Witham et al., 2015).

Key compositional and nutritional aspects

Zucchinis are made up of 95% water by weight, and can be eaten raw or cooked. They contain reasonable amounts of vitamins A and C, in addition to K, folate, B_6, and B_1, minerals (mainly Mn and K, in addition to Mg, P, and Cu), and dietary fibre (Anon., 2015a). Lutein is the major carotenoid found in zucchini, followed by β-carotene, with higher contents in the skin than the flesh (Martinez-Valdivieso *et al.*, 2015).

Key quality issues

Recent market surveys showed that ease of cooking, to use as an ingredient in dishes, and health are the key influences on purchase of zucchini, whereas the main barriers are that people want to buy a variety of vegetables and do not want to waste any (Anon., 2015b). Once purchased, Australian consumers expect zucchinis to stay fresh for about 8 days, and these expectations are being met most of the time by 82% of consumers (Anon., 2015b).

The consumer preference for zucchini is greatly influenced by its external appearance (Martinez-Valdivieso *et al.*, 2015).

As a non-climacteric fruit harvested at an immature stage, zucchinis are prone to chilling injury (i.e. pits and damaged areas on the skin) if stored below 7-10°C (Carvajal *et al.*, 2015).

Crop nutrition

Nutrition management

Applied N as nitrate, from 2-36 mM/L to zucchini plants grown in sand-filled drainage outdoor lysimeters in Australia resulted in increased fruit dry matter content, with best yield/quality recorded at N levels of 14 mM/L (Huett and Dettmann, 1991).

Silicon applied as potassium silicate either in the nutrient solution at 1.7 mM or as foliar spray at 8.5 or 17 mM to greenhouse-grown zucchini (cv 'Select') in Canada, reduced the incidence of powdery mildew by up to 27-39% compared to control, whereas sprays at 1.7 mM were ineffective and sprays at 34 mM had little further reduction (Menzies *et al.*, 1992). In contrast, 6 foliar sprays of sodium silicate at 5 g/L in mixture with mineral oil at 10 ml/L to field-grown zucchini in Italy had no effect on powdery mildew activity (La Torre *et al.*, 2004).

Beneficial microorganisms

Zucchini grown in Italy in sand culture with nutrient solution and inoculated with arbuscular mycorrhizal fungi had higher crop tolerance to soil acidity and aluminium toxicity, resulting in better fruit quality (i.e. higher dry matter and soluble solids content), as well as higher marketable yield (Rouphael *et al.*, 2015).

Moderate salinity conditions

Zucchini (cv 'Moschata) grown in the greenhouse under moderate salinity conditions (i.e. 0.25-1.0 g/L of sodium chloride compared to water control) in Spain resulted in firmer fruit, with higher total acidity, soluble solids content (at 1.0 g/L), and yield (Villora *et al.*, 1999). Similarly, increasing salinity of the nutrient solution from 2.0 to 4.1 dS/m increased contents of fruit dry matter, soluble sugars, starch, total carbohydrates, and vitamin C, and reduced nitrate content, especially with growth under a sub-irrigation system compared to a drip-irrigation one (Rouphael *et al.*, 2006).

Crop management

Crop scheduling: interactions between cultivar and seasonal effects

Some zucchini varieties grown in Spain showed better genetic adaptation to low-temperature storage, with reduced sensitivity to chilling injury and increased shelf-life (Carvajal *et al.*, 2011).

Zucchini plants grown in closed soilless systems in a polyethylene greenhouse in summer-autumn in Italy, resulted in 10 days earlier production, higher fruit contents of glucose, fructose, sucrose, starch, P, K, and Mg, but higher nitrate content and lower yields than plants grown in spring-summer (Rouphael and Colla, 2005).

Growing system

In a study conducted in Rockhampton, QLD, the use of floating row covers applied before the fruit are infested with silverleaf whitefly (*Bemisia tabaci*), combined with the insect growth regulator pyriproxyfen (i.e. a juvenile hormone analogue causing deformation and death at moulting and pupation) in zucchini, improved fruit quality by reducing skin damage and increased fruit size and marketable yield (Qureshi *et al.*, 2007).

Water management

Zucchini plants hydroponically-grown in spring-summer in Italy under sub-irrigation resulted in dry matter and contents of glucose and fructose, but reduced yield by 18%, than under a drip-irrigation system (Rouphael and Colla, 2005; Rouphael *et al.*, 2006).

3.4 Pumpkin

Background

Commercial importance and main cultivar types

Pumpkin (*Cucurbita* spp.; also called winter squash) is a popular vegetable worldwide, and an important horticultural commodity in Australia, with an annual production of 118,495 tonnes and a gross value of $81.2 M in 2013-14 (Anon., 2015d). A recent consumer report on fresh vegetables places pumpkin as the 7th most regularly purchased vegetable by almost 70% of consumers in Australia (Witham et al., 2015).

Commercial pumpkins in Australia are comprised of two main species (Napier, 2009):

- Cucurbita maxima: includes the grey types (e.g. the popular 'Jarrahdale', 'Sweet grey', 'Early Jarragrey', and 'Sampson') and the Kabocha types (often called Buttercup squash, including 'Delica', and hybrids such as 'Tetsukabuto', also known as 'Late Potkin');
- Cucurbita moschata: includes the butternut types (e.g. 'Butternut large', 'Sunset QHI') and the Japanese types (e.g. 'Jap' or 'Kent', 'Kens', 'OOAK').

Key compositional and nutritional aspects

Pumpkins are an excellent source of vitamin A, in addition to C, E, and B_2, minerals such as K, Cu, Mn, Fe, and P, and some dietary fibre (Anon., 2015a).

In terms of phytochemicals, pumpkins contain large amounts of the carotenoids- α- and β-carotene, as well as lutein, zeaxanthin, and β-cryptoxanthin, a phytochemical mostly found in fruits that may assist in cardiovascular health, and some phenolic compounds, particularly chlorogenic acid (Dragovic-Uzelac *et al.*, 2005; Hedges, 2007). Pumpkin is relatively low in calories, containing fewer calories than other vegetables with similar cooking uses and textures. It is also versatile, being used in both sweet and savoury dishes.

Key quality issues

Recent market surveys showed that taste, ease of preparation, and health are the key drivers of pumpkin purchase, whereas perceptions of consuming enough for needs and not wanting to waste any remain the key barriers (Anon., 2015c). Once purchased, Australian consumers expect pumpkins to stay fresh for over 11 days, and these expectations are being met most of the time by 83% of consumers (Anon., 2015c).

Sensory quality and consumer preference of pumpkins is largely determined by flesh dry matter and the balance of sugars and starch, which is the major component in the flesh and is gradually converted to sugars during shelf-life (Loy, 2004). For example, for buttercup pumpkin, fruit with a dry matter above 28% is unacceptably dry except for processing applications, and fruit with dry matter below 20% is watery and lacking in flavour (Harvey *et al.*, 1997). Sugar content, especially sucrose, is an important predictor of sweetness (Corrigan *et al.*, 2000), but for high-starch cultivars (e.g. buttercup types), textural properties are strongly associated with dry matter content and appear to play a key role in the perception of sweetness and flavour of the cooked product (Cumarasamy *et al.*, 2002).

Pumpkin fruit with high sugar and carotenoid contents are regarded as the better quality products as determined by a sensory testing in Poland (Gajewski *et al.*, 2008). Overall quality in that study was strongly related to several parameters, including sweet taste, soluble solids (i.e. sugar) content, total carotenoid content (β-carotene in particular), and antioxidant activity.

Shelf-life of pumpkin is strongly dependent on its susceptibility to the development of postharvest fungal rots (Hawthorne, 1990).

Crop nutrition

Applied N at 0, 120, or 240 kg/ha had little effect on flesh appearance, texture, flavour, and consumer acceptance of cooked Jarrahdale pumpkin grown in north Qld (Armour, 1996).

Crop management

Method and time of harvest (i.e. fruit age) and/or fruit handling practices

Two 4-year field studies in New Zealand with 5 pumpkin cultivars (3 *C. maxima* and 2 *C. moshata*) showed that fruit susceptibility to rots during/after storage for 22-28 weeks in slatted racks in an unheated barn at mean daily temperatures of 10-16°C was reduced by (Hawthorne, 1989; 1990):

- Shortening the time after maturity that fruit remained attached to the vines before harvesting by 4-5 weeks, presumably due to higher levels of a plant defense mechanism in early-harvested fruit and/or by delaying vine and fruit senescence;
- Not removing the stalks at harvest, although results varied depending on cultivar and year.

Likewise, a 2-year study in New Zealand with buttercup pumpkin (cv 'Delica') suggested that fruit handling practices during and after harvest which minimise wounds and damage to stalks would be beneficial in reducing fungal rots (Hawthorne and Sutherland, 1991). The study showed that the scar tissue produced by the wound repair process particularly in older fruit increased the potential for later invasion by fungal pathogens, since rots occurred much more often at the edges of scar tissue than elsewhere on the fruit surface.

In contrast, the susceptibility to *Phytophthora* fruit rot decreased with fruit age at harvest, together with an increase in soluble solids and firmness, in field-grown processing pumpkin (*C. moschata*, cv 'Dickenson Field') in the USA, but not in the cultivar 'Golden Delicious' (*C. maxima*) (Meyer and Hausbeck, 2013).

Study with buttercup pumpkin (cv 'Delica') grown in New Zealand showed that there are increased risks of quality loss by leaving fruit longer than 40 days after flowering unharvested, with no advantage in fruit sensory quality or consumer acceptance, as there is little additional increase in dry matter and starch after that time (Harvey *et al.*, 1997). That study also suggested that skin firmness of 6.5-7.5 kgf as measured by a penetrometer and heat accumulation levels of 240-300 growing degree days from flowering, at a base temperature of 8°C, were the most effective means of estimating the optimum harvest date. Sucrose levels, Brix, and flesh colour varied too much with site and season to be used to indicate optimum harvest dates. Similarly, a trial conducted in Italy with buttercup and butternut pumpkin suggested they should be harvested 3-4 weeks past anthesis to ensure best quality and longest shelf-life, but responses varied considerably between cultivars. Butternut fruit had longer shelf-life if harvested during maturation at about 6 weeks after anthesis and before reaching mature skin colour, whereas buttercup fruit had the longest shelf-life when harvested earlier, just after growth termination (Nerson, 1995).

Growing system

Pumpkin fruit (cvs 'Amazonka' and 'Kawonita') from field-grown plants in Poland that had been fertilised organically with composted cattle manure at the rate of 40 t/ha had higher dry matter, and higher contents of soluble solids, vitamin C, and carotenoids than those grown using conventional fertiliser, but that response was cultivar-dependant (Biesiada *et al.*, 2009).

Water management

In butternut pumpkins, splitting of pumpkins can be caused by irregular or excess watering during late fruit development, so it has been recommended that watering should be reduced steadily after first pick in the Northern Territory (Walduck, 2004).

In a 4-year field study in New Zealand, one out of 4 pumpkin cultivars from irrigated plots (i.e. sprinklers for 1-2 days before harvest) had more rots after 24 weeks storage at 10-16°C than fruit from non-irrigated plots (Hawthorne, 1989).

3.5 Conclusions

Taste, health, and ease of cooking are the key drivers of purchase for cucurbit vegetables in Australia, whereas not wanting to waste any, perceptions of consuming enough for needs, and short shelf-life (but not for pumpkin) are the major barriers. Once purchased, Australian consumers expect cucumber and zucchini to stay fresh for about 8 days, whilst pumpkin for over 11 days, and these expectations are being met most of the time by 74-83% of consumers.

There is limited published research on pre-harvest factors affecting quality and shelf-life of cucurbit vegetables worldwide. The experimental findings are less conclusive due to a number of production variables including soil and climatic conditions.

In terms of crop nutrition management, in a few studies on cucumber under glasshouse, increasing N levels during growth generally resulted in greener and softer fruit, with higher nitrate content and lower Ca concentrations, suggesting the importance of a balanced nutrition. Several studies showed that Si (e.g. potassium silicate) applied either in the nutrient solution or as foliar sprays increased the resistance of continental cucumber (and to a lesser degree zucchini) plants to fungal diseases that reduce fruit quality such as powdery mildew, although no other cultivars were reported, which warrants further investigation. Other fertiliser salts such as bicarbonates, phosphates, and chlorides applied as foliar sprays had a similar effect.

Regarding crop management, several studies with greenhouse-grown long continental cucumbers showed that the use of training systems that allow high light penetration and more rapid fruit growth, as well as fruit thinning reducing crop load and increasing leaf to fruit ratio, generally resulted in greener fruit at harvest with longer shelf-life. However, most studies were conducted with the same cultivar and at the same location, so further research in this area is warranted. There is also some evidence that rootstocks can impact on flavour of cucumbers.

The harvesting of pumpkins at proper maturity without delay together with careful postharvest handling with minimum damage to stalks appear to reduce fruit susceptibility to rots during and after storage.

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4. Pre-harvest factors affecting quality and shelf-life of fruiting and legume vegetables

4.1 Key findings

- Greater maturity at harvest (e.g. red stage) seems to improve quality of capsicum and chillies (e.g. skin colour, firmness, flavour, aroma, and contents of sugars, vitamin C, and bioactives);
- Full irrigation regimes during flowering and fruit/pod growth stages of capsicum, eggplant, and green beans production appear to increase marketable yield and quality (e.g. better colour and less fibre in green beans, higher dry matter in eggplant, and better capsicum size);
- Applied Ca either as foliar sprays or added to the nutrient solution during capsicum production appears to improve fruit firmness and resistance to decay and sunburn;
- Applied Si and other fertiliser salts such as bicarbonates may enhance plant resistance, increase fruit cuticle thickness, and reduce postharvest decay on capsicum caused by fungal diseases such as anthracnose and powdery mildew, which warrants further investigation;
- Cultivar appears to affect mainly intrinsic attributes such as flavour and bioactives in capsicum and chillies, and to a lesser extent skin colour and firmness, with red fruit generally having higher quality than green or yellow ones.

4.2 Capsicum and chilli

Background

Commercial importance and main cultivar types

The genus Capsicum belongs to the Solanaceae family and includes many species, both sweet (i.e. non-pungent) cultivars typically eaten as vegetables such as capsicum, and 'hot' (i.e. pungent) ones such as chillies, also known as chilli peppers, often used as spice (Silva *et al.*, 2014).

Capsicum (*Capsicum annuum* L.), also called sweet pepper or bell pepper, is the most popular and commercially important non-pungent species worldwide and a significant horticultural commodity in Australia, with an annual production of 51,969 tonnes and a gross value of $143.9 M in 2013-14 (Anon., 2015f). A recent consumer report on fresh vegetables places capsicum as the 8th most regularly purchased vegetable in Australia by about 65% of consumers (Witham et al., 2015). Mature capsicum fruit come in a variety of shapes, sizes, and colours, with red, green, and yellow capsicums being the most important commercially in Australia. They can be used fresh in salads or cooked, stir-fried and added to various dishes for colour, texture, and flavour.

Chillies are generally smaller and elongated, with the red and yellow types being the most common ones. Some of the main species include *Capsicum annuum* (e.g. 'Jalapeno', 'Cayenne', and 'Cherry'), *Capsicum chinense* (e.g. 'Habanero', 'Scotch Bonnet', 'Thai chili'), and *Capsicum frutescens* (e.g. 'Tabasco') (Welbaum, 2015). Australia had in 2013-14 an annual chillies production of 2.6 MT and a gross value of $21.2 M (Anon., 2015f).

Key compositional and nutritional aspects

In addition to its popular flavour and aroma, capsicums are recognized for their nutritional composition and health-promoting compounds. Capsicum has the highest content of vitamin C among all vegetables and is also an excellent source of vitamin A, as well as a significant source of other vitamins such as E, B_6, and folate, in addition to B_1, B_2, B_3, K, and pantothenic acid, minerals such as K, Mn, Fe, Mg, P, and Zn, and dietary fibre (Anon., 2015a). Depending on the colour-type when ripe, capsicums also contain significant levels of phytochemicals, including α-and β-carotene, β-cryptoxanthin, lutein and zeaxanthin, capsanthin, lycopene, phenolic compounds such as quercetin, luteolin, and hydroxycinnamic acid derivatives, and fatty acids (Marin *et al.*, 2004; Hedges, 2007; Silva *et al.*, 2014). The attractive red colour of capsicum fruit is due to the abundant synthesis of various carotenoid pigments during ripening, including capsanthin, capsorubin and crypto-capsin, which are exclusive to this genus and have shown to be effective free radical scavengers (Deepa *et al.*, 2007).

Chillies are also a good source of vitamins C, B_6, A, and K, in additon to B_1, B_2, B_3, and folate, as well as a moderate source of minerals such as potassium, manganese, iron, magnesium, phosphorus, and copper (Anon., 2015a). They also contain various phytochemicals, including β-carotene, phenolic acids, flavonoids, capxanthin, zeaxanthin, and caffeic acid (Howard *et al.*, 2000; Wall *et al.*, 2001).

Generally, the contents of vitamin C, provitamin A, carotenoids, phenolics, and soluble sugars increase in capsicum and chillies fruit as they mature from green to full coloured, whereas lutein and capsaicin contents decrease (Howard *et al.*, 2000; Deepa *et al.*, 2007). The colour change in capsicum with maturity and senescence from dark green to light green to red or yellow is related to a decrease in chlorophyll and an increase in carotenoid synthesis (Hedges, 2007).

The degree of pungency giving the 'heat' sensation in capsicum and chillies is mostly determined by the presence of one or more of the fourteen alkaloid compounds known as capsaicinoids (Zewdie and Bosland, 2000), and in particular capsaicin, a phenolic compound not associated with colour, but sometimes erroneously linked to it (Hedges, 2007).

Key quality issues

Taste, to add colour to a meal, and to use as an ingredient in dishes are the key purchase drivers for capsicums in Australia, whereas not wanting to waste any, already consuming enough vegetables, and short shelf-life the main barriers to purchase (Anon., 2015c). For chillies, the key purchase triggers are their use as an ingredient in dishes, taste, and complementing other food, whereas consuming enough for their needs and not wanting to waste any remain the main barriers (Anon., 2015e). Once purchased, Australian consumers expect capsicums to stay fresh for about 8 days and chillies over 10 days, and these expectations are being met most of the time for both commodities by around 80% of consumers (Anon., 2015c; e).

Major quality attributes for capsicum fruit include colour, shape, size, and absence of defects (Frank *et al.*, 2001; Del Amor, 2007). For chillies, colour and the stronger pungency or heat sensation are major factors determining fruit quality (Zewdie and Bosland, 2000).

Capsicum fruit are generally harvested after reaching their mature size, but before physiological maturity and colour change occur, typically at either the green mature or colouring stage (Welbaum, 2015). Immature fruit tend to be smaller (i.e. reduced yield) and may not develop acceptable colour and flavour upon ripening, leading to loss of consumer confidence, whilst over-mature fruit are less attractive and crisp, becoming slimy in texture within very short time (Rahman *et al.*, 2014). Shelf-life deterioration is often due to moisture loss and desiccation, and more mature fruit tend to better resist shrinkage after harvest than less mature fruit whose cuticle is not fully developed (Welbaum, 2015). Red and yellow capsicum fruit are generally more expensive to produce than green ones, because fruit remain on the plant longer to develop colour, which reduces total yields as mature fruit inhibits the set and growth of new fruit, as well as increasing risks of pests and diseases (Welbaum, 2015).

Capsicum is a non-climacteric fruit during maturation, which does not seem to be regulated by ethylene, and thus generally does not ripen as easily after harvest (Pretel *et al.*, 1995).

Crop nutrition

Nutrition management

Several studies reported on the impact of pre-harvest application of calcium (Ca) and potassium (K) on quality of capsicum fruit. For example:

- In a 2-year study in Canada, 3 pre-harvest foliar sprays of Ca as calcium chloride at 0.4% w/v to capsicum plants (cvs 'Oriole' and 'Bell Boy') grown under plasti-culture and cold-stored at either 4°C for 21 days or at 10°C for 7 days in perforated plastic bags, resulted in firmer fruit, with thicker skin and more pectin compounds, and less decay at the end of storage (Toivonen and Bowen, 1999);
- In a 2-year greenhouse study in the USA, supplemental Ca applied through the drip irrigation system as calcium nitrate at either 34 or 68 kg/ha to capsicum (cvs 'Vidi' and 'Ranger') reduced the proportion of fruit with sunburn and blossom-end-rot, the major defects that limit the quality of capsicum, and increased marketable yield (Alexander and Clough, 1998);
- Similarly, increasing Ca content as calcium chloride at 1.5, 4 and 8 mM/L to the nutrient solution of hydroponically-grown capsicum plants (cv 'Orlando') in Spain increased marketable yield and soluble solids content, as well as improving fruit shape; also, the application of K as potassium sulfate at 12 mM/L reduced marketable yield, increased acidity, and negatively affected fruit shape (Rubio *et al.*, 2010);
- Red and green capsicum fruit (cv 'Somontano') greenhouse-grown under low salinity in Spain with increased concentrations of K at 0.2, 2, 7 and 14 mM/L, as part of a modified Hoagland nutrient solution, had higher contents of dry matter, vitamin C, provitamin A, and phenolics, whereas fruit grown under lower concentrations of Ca at 2, 4, and 8 mM/L, as part of the same nutrient solution, had higher contents of carotenoids and provitamin A (Marin *et al.*, 2009).

Field-grown red capsicum (cvs 'California Wonder' and 'Gangavati Local') plants in India fertilised with 100 % recommended dose of N via organic sources (i.e. a combination of 50% farm yard manure and 50% poultry manure as basal dose) resulted in fruit with more intense colour, higher contents of soluble solids, total sugars, acidity, and vitamin C after 16 days under ambient temperature than fruit from plants fertilised with inorganic sources (Ganiger et al., 2013).

Effects of silicon (Si) and other fertiliser salts on diseases

The application of Si as potassium silicate at 75 mg/L to the nutrient solution of hydroponically-grown capsicum (cv 'Muria FT') in Sri Lanka during the flowering stage reduced fruit anthracnose lesions by 71%, whereas there were little effects on plant growth or on fruit firmness, Brix, or soluble solids content (Jayawardana *et al.*, 2015). The study also showed that the mechanisms underlying Si effects were an increase in the concentrations of cell wall-bound phenolic compounds and cuticle thickness in Si-treated fruit compared to control ones. In a study in Brazil, although fruit quality was not assessed, Si as Ca silicate at 6.8 g Si/kg of substrate reduced the severity of

Phytophthora blight in capsicum plants, a serious fungal disease that causes rots of all parts of the plant, including fruit (French-Monar *et al.*, 2010).

In a 2-year study in Israel, 5 pre-harvest weekly applications of bicarbonate salts solutions at 0.5% w/v reduced postharvest decay development on red capsicum fruit (cv 'Maor') by 45% (sodium bicarbonate) and by 82% (potassium bicarbonate), as well as reducing fruit sunburnt, foliar disease severity and leaf defoliation caused by powdery mildew, a serious disease of capsicum under greenhouse and field conditions worldwide that can significantly reduce fruit quality (Fallik *et al.*, 1997). Similarly, spraying of monopotassium phosphate reduced leaf powdery mildew incidence by 75% in greenhouse-grown capsicum (cv 'Ayalon') in Israel (Reuveni *et al.*, 1998) and in chilli grown in India under field and greenhouse conditions (Sudha and Lakshmanan, 2009).

Beneficial microorganisms

Greenhouse-grown capsicum plants (cv 'Valeria') under a system of fertigation in Mexico inoculated with the arbuscular mycorrhizal fungus *Rhizofagus intraradices* increased the proportion of fruit with export standard size and weight (i.e. grade 1) by increasing fruit size and weight, length, and width (Franco *et al.*, 2013).

Crop management

Fruit maturity stage at harvest

Field-grown capsicum fruit (cv 'Bari Misti Morich-1') harvested at a more advanced maturity stage in Bangladesh and stored in plastic bags at 12°C Rahman et al. (2014):

- Had longer shelf-life: e.g. either 10, 16, or 21 days for fruit harvested at 33, 36, or 45 days after flowering, respectively, as determined by a sensory panel based on general visual appeal, colour, crispiness, flavour, and taste;
- Were firmer and had higher dry matter and soluble solids contents.

Greenhouse-grown red capsicum fruit (cvs 'Mazurca' and 'Evident') harvested at the red stage (i.e. 10 weeks after fruit setting) in the Netherlands had (Luning et al., 1994):

- Better sensory quality (i.e. were sweeter, more sour, with a distinctive red capsicum aroma) than fruit harvested 4 weeks earlier at the green stage, which were more bitter and with grassy flavour and cucumber/green capsicum aromas, as assessed by a tasting panel; (Note: sensory evaluation was conducted after storage at 13°C, but the study does not inform the storage time or the ripening procedure after storage for each maturity stage);
- Higher contents of sugars, citric acid, and to a lesser extent, ascorbic acid;
- Fruit harvested at the 'turning' stage (i.e. 2 weeks before the red stage) had intermediate scores for flavour and aroma.

Greenhouse-grown red and yellow capsicum fruit (cvs 'Bison' and 'Doria', respectively) harvested at the 'ripe' stage (>95% of surface red or yellow) in Canada and stored at 1°C for 1-2 weeks had better external quality (i.e. no chilling injury caused by skin pitting) than fruit harvested at the 'mature green stage' (>95% surface green), but there were no differences when fruit were stored at 13°C (Lin et al., 1993).

A study with several red chilli cultivars in Laos showed that, depending on cultivar, fruit harvested at the more mature 'red' stage generally had better spicy flavour (as determined by tasting panel), better colour development at full ripe, higher decay incidence, and increased soluble solids content compared to fruit harvested at the less mature 'green' stage, whereas there was little difference between the 'red' and the intermediate 'turning' stage (Acedo *et al.*, 2009).

A number of additional studies have shown that maturity stage at harvest affects the composition of capsicum and chilli fruit. For example:

- Greenhouse-grown capsicum fruit (10 cvs) in India harvested at a more advanced maturity stage (from green to intermediate to red/yellow) had higher contents (on a fresh weight basis) of antioxidants (i.e. ascorbic acid, phenolics, and carotenoids) and their activity (Deepa *et al.*, 2007).
- Red capsicum (cv 'Almuden') grown in a plastic greenhouse in Spain and harvested at more mature stages (from immature green to green to red) had increasing contents of vitamin C, phenolics, and carotenoids (Perez-Lopez *et al.*, 2007).
- Red capsicum fruit (cv 'Vergasa') grown in Spain had higher contents of vitamin C, carotenoids, and pro-vitamin A, but lower contents of polyphenols than immature green fruit (Marin *et al.*, 2004).
- Field and greenhouse grown capsicum (5 cvs) and chilli pepper (5 cvs) in the USA generally had higher contents of total carotenoids and provitamin A when harvested at the red stage compared to turning (50% green) and green stages (Russo and Howard, 2002).

In contrast, fruit maturity (from 10% red to full red) at harvest had little impact on soluble solids, acidity, or contents of vitamin C, total carotenoids, and phenolics of greenhouse-grown red capsicum plants (bell pepper, cv 'Robusta') in Florida over two seasons (Fox et al., 2005). That study also showed that the ripening of red capsicum could be accelerated by harvesting fruit at a partially ripened stage and treating them with ethylene at 20°C. Such results differ from an earlier study (Pretel et al., 1995), in which postharvest ripening of a different capsicum cultivar was tested by using propylene (an ethylene analog) rather than ethylene.

Water management

In a 3-year field study in Serbia, capsicum plants (cv 'Elephant Ear') grown under full irrigation resulted in higher marketable yields due to less fruit sunburn, as well as fruit with higher acidity than those grown under deficit irrigation at either 70% or 80% of crop evapotranspiration, especially if combined with the application of a 5% kaolin suspension at 0.08 L/m^2 3-4 times from flowering Cosic *et al.* (2015). The study suggested capsicum is very sensitive to water stress, which should be avoided during flowering and fruit growth stages.

In a field-grown study in Turkey, capsicum plants drip irrigated with a higher plant-pan coefficient of 1.0 (compared to 0.75 or 0.50) and a shorter irrigation interval of 3-6 days (compared to 6-11 or 9-15 days) resulted in higher marketable yields and improved fruit size and shape (Sezen et al., 2006).

In a 2-year study in Canada, reducing the trickle irrigation emitter spacing from 1.62 to 0.45 m reduced the proportion of capsicum fruit (cv 'Lady Bell') with sunburn and blossom-end-rot and increased marketable yield (Madramootoo and Rigby, 1991).

Capsicum fruit (cv 'Somontano') greenhouse-grown in Spain under conditions of low drip fertigation frequency (i.e. 0.5 as opposed to 8 events per day) combined with salinity conditions (i.e. NaCl at 20 mM/L) had higher contents of dry matter, soluble solids, acids, vitamin C, provitamin A, and carotenoids, lower fresh weight, but the impact on yield was not determined (Marin *et al.*, 2009).

In a two-year field study in China, a soil matric potential threshold range of -30 to -40 kPa at 20 cm depth was recommended for irrigation management of chilli pepper (cv 'Meiguohong') under mulched-drip conditions compared to -10, -20, or -50 kPa, resulting in fruit with higher total soluble solids content, as well as increased proportion of marketable fruit (Liu *et al.*, 2012).

Cultivar effects

In a study with 5 red and 3 yellow capsicum cultivars hydroponically-grown in Spain, red fruit were generally firmer and had thicker skin than yellow ones, with little differences in the contents of dry matter, total protein, and phenolics (Del Amor et al., 2013).

The variability in the composition of capsicum fruit (including contents of total soluble solids, vitamin C, β-carotene, and minerals) was shown to be wide and considerably affected by cultivars in two studies in South Africa and India (Geleta and Labuschagne, 2006; Hedau *et al.*, 2013). Similarly, a 2-year study in the USA with 57 chilli pepper cultivars of 6 species showed large cultivar variation in the contents of total carotenoids and β–carotene, with red cultivars generally having higher contents than the yellow and orange cultivars ones (Wall *et al.*, 2001).

A study with 24 capsicum lines and hybrids in The Netherlands showed that some fruit sensory attributes, like sweetness and texture, had high heritability and thus could be more easily manipulated into breeding programs, as opposed to sourness, which has a low heritability and can be masked by other volatile and non-volatile compounds or by texture differences (Eggink *et al.*, 2012).

Field-grown chilli peppers in Laos showed large cultivar variation (among 5 cvs, including 2 commercial ones) in the ripe fruit for spicy flavour as determined by tasting panel, skin colour, weight loss, decay incidence, and soluble solids contents (Acedo *et al.*, 2009). Likewise, study with 9 chilli pepper lines (including 2 commercial cultivars) field-grown in the Netherlands showed large variability in the content of capsaicinoids, as well as some significant genotype-environmental interactions (Zewdie and Bosland, 2000).

Season effects

Capsicum plants (cv 'Robusta') hydroponically-grown in Florida during months of longer day-length, higher ambient temperature, and stronger light intensity (i.e. March and April) had higher contents of soluble solids, vitamin C, carotenoids, phenolics, and antioxidant capacity compared to plants grown in December and January, presumably due to enhanced carbohydrate accumulation (Fox et al., 2005). Similarly, the contents of total carotenoids and β–carotene in chillies fruit from 6 species and many cultivars were affected by season in a 2-year study in the USA (Wall *et al.*, 2001).

Growing system

In 2 studies with capsicum plants grown in a plastic greenhouse in Spain, organically-grown (cv 'Almuden') had more intense red colour, as well as higher contents of vitamin C, phenolics, and carotenoids than conventionally-grown ones (Perez-Lopez *et al.*, 2007); similarly, organically-grown (cv 'Requena') had higher antioxidant activity, but lower contents of chlorophylls and β-carotene compared to conventionally-grown ones, whereas there was little difference between both systems for marketable yield, fruit firmness, pericarp thickness and total soluble solids content (Del Amor, 2007).

In a study with 5 capsicum and 5 chilli pepper cultivars in the USA, greenhouse-grown fruit of both groups harvested at the red stage generally had higher contents of total carotenoids and provitamin A than fruit grown in the field (Russo and Howard, 2002).

Row covers

In a 2-year greenhouse study in Oregon, the use of hooped spun-bonded polypropylene row covers during growth of capsicum (cvs 'Vidi' and 'Ranger') markedly reduced the proportion of fruit with sunburn and blossom-end-rot, particularly during the earlier harvests, thus increasing marketable yield (Alexander and Clough, 1998). Similarly, in a 3-year study in Oklahoma, the use of spun-bonded polypropylene row covers suspended on arches used as plant canopy shade during growth of capsicum reduced the proportion of sunburnt fruit, as well as increasing fruit size and marketable yield compared to bare soil, black plastic, or white plastic in 2 out of 3 years (Roberts and Anderson, 1994).

Netting system

Shading is traditionally used under semi-arid environmental conditions to reduce solar radiation and ensure fruit quality during summer and early fall. A study with red capsicum (cv 'Vergasa') in Israel using netting systems with 35% shading showed that, compared to a standard black netting, fruit from plants grown under a photo-selective 'Pear' netting and harvested fully coloured four times from October to December had reduced water loss, decay incidence and titratable acidity, and increased firmness, elasticity, ascorbic acid content and antioxidant activity after cold-storage at 7°C for 16 days, followed by 20°C for 3 days (Kong *et al.*, 2013). In two similar studies with cvs 'Romans' and 'Vergasa' (in the same location, shading, and storage conditions), fruit from plants grown under 'Pear' and yellow nets had lower decay incidence compared to standard black and red nets, whereas there was little treatment differences for fruit weight loss, firmness, and sugar content (Goren *et al.*, 2011; Alkalia-Tuvia *et al.*, 2014). However, none of the above studies reported the effects on quality and yield compared to production without a netting system.

Light system

Chilli pepper cultivated in growth chambers in South Korea under red plus blue light emitting diodes (LED) resulted in fruit with increased fresh weight, more intense colour, and higher contents of total carbohydrates, reducing sugars, protein, and carotenoids compared with fluorescent light (Gangadhar *et al.*, 2012).

Growing medium

In a greenhouse study in Florida, capsicum plants (cv 'HA3378') grown using perlite as the medium resulted in lower incidence of both fruit cracking and blossom-end-rot compared to using peat mix (more fruit cracking) and pine park (more blossom-end-rot) (Jovicich *et al.*, 2007).

4.3 Eggplant

Background

Commercial importance and main cultivar types

Eggplant (*Solanum melongena*), also known as aubergine or brinjal, belongs to the Solanaceae family. Commercial cultivars varying in fruit size, shape and colour, with the dark purple-coloured ovoid American type cultivars being the most widely cultivated worldwide (Zaro *et al.*, 2014). In Australia, annual production of eggplant fruit in 2013-14 was 8,146 tonnes with a gross value of $16.6 M (Anon., 2015f).

Key compositional and nutritional aspects

Eggplant is a reasonable source of vitamins (mainly folate, in addition to small amounts of C, K, B_1, B_3, B_6, and pantothenic acid) and minerals (mainly Mn and K, in addition to Mg, P, and Cu), as well as being a very good source of dietary fibre (Anon., 2015a).

Eggplant is rich in health-promoting bioactives, particularly the purple-skinned types, which are high in anthocyanins (e.g. nasunin and tulipanin), pigments belonging to phenolic flavonoids, whose isolations from eggplant fruit have shown strong antioxidant activity, ranking eggplant in the top 10 species for superoxide scavenging assay among 120 vegetable species evaluated (Hanson et al., 2006). Other phenolic compounds in eggplant include hydroxycinnamic acids, especially chlorogenic acid (Zaro et al., 2014). In addition to phenolics, eggplant also contain moderate levels of phytosterols (Anon., 2015a). The high fruit phenolics content in eggplant is also responsible for the flesh browning in cut fruit due to rapid oxidation by polyphenol oxidase.

Key quality issues

The key triggers to eggplant purchase are to use as an ingredient in dishes and adding variety to vegetable selection, whereas already consuming enough is the main barrier (Anon., 2015b). Once purchased, Australian consumers expect eggplants to stay fresh for just over a week, and these expectations are being met most of the time by 88% of consumers (Anon., 2015b).

Eggplant fruit is sensitive to postharvest physical injury, and the storage life of eggplant is generally less than 14 days, as visual and sensory qualities tend to deteriorate rapidly. Water loss under high temperature and low humidity is a critical issue, resulting in visible signs of desiccation such as reduced skin sheen, wrinkling, and calyx browning (Welbaum, 2015).

Crop nutrition

In a 3-year study in Italy, various fertilisers (i.e. mineral fertiliser, commercial manure, and 2 experimental organic fertilisers from anaerobic digestate and waste compost) applied to field-grown eggplant (cv. 'Top Bel') had little effect on fruit total solids content and acidity, whereas the experimental ones reduced dry matter content; also, compared to mineral fertiliser, marketable yield was reduced by 12% with manure and by 21-29% with the experimental fertilisers (Leogrande et al., 2014).

In a 2-year study in Poland, K (as potassium chloride at 24 g of K/plant) applied to eggplant (cv 'Epic F1') grown in an unheated plastic tunnel resulted in fruit with higher dry matter content and increased marketable yield compared to lower doses of 16 or 8 g of K/plant, or compared to other potassium forms (i.e. chloride and sulfate) at the same 3 K rates (Michalojc and Buczkowska, 2009). That study also showed that, regardless of the form, higher rates of K generally reduced the contents of total sugars and vitamin C.

A study with eggplant (cv 'Classic') grown in the greenhouse in Israel showed that increasing the average P concentration in the irrigation solution throughout the winter and spring growing seasons from 36 to 54 g/m^3 increased the number of fruit per plant and the number of class A fruit, whereas increasing the total electrical conductivity (EC) of the nutrient solutions by K fertilizers above 3.8 dS/m reduced fruit dry matter and yield (Zipelevish *et al.*, 2000). Those results suggested that high P levels in the irrigation solution may be needed to secure high yields and fruit quality when eggplant is grown at low temperature (i.e. 4-14 °C) and when the EC of the irrigation solution is high due to high total salinity (i.e. >3 dS/m).

Crop management

Fruit maturity stage at harvest

In a greenhouse study in Argentina, eggplant fruit (cvs 'Monarca' and 'Perla Negra') harvested at early maturity (i.e. 12 days after fruit set) had higher contents of chlorogenic acid, carotenoids, ascorbic acid and higher antioxidant capacity than late harvested fruit (i.e. 18-23 days after fruit set), whereas late pickings resulted in higher yields and less dense fruit with lower respiration rates (Zaro et al., 2014). In contrast, in a study in Spain with hydroponically-grown eggplant (cvs 'Semi-round Striped', 'Purple Long' and 'Black Round'), the contents of total sugars, acids, ascorbic acid, and total phenolics increased during fruit development (as determined at 5, 11, 15, 28, 42 and 54 days after fruit set) and peaked at 42 days (Esteban *et al.*, 1992). Also, in a study with 10 eggplant lines in Italy, contents of phenolics reduced whereas glycoalkaloids increased during fruit development, thus suggesting variations in the pattern of accumulation of phytochemicals during eggplant fruit development (Mennella *et al.*, 2012), which seems to be confirmed by the above studies.

Water management

In a 3-year field study in Italy, eggplant (cv 'Top Bel') grown under deficit irrigation (50% of the calculated maximum evapotranspiration compared to control re-establishing 100%) resulted in fruit with increased contents of dry matter and total soluble solids, with no effect on acidity, but marketable yield was reduced by 22% (Leogrande *et al.*, 2014).

Field-grown eggplant (cv 'Pala') in Turkey under deficit irrigation (90-80% replenishment of evaporation at 4-8 days intervals) increased fruit water-soluble dry matter content, but reduced marketable yield by 12-29% compared with well-watered control plants (Kirnak *et al.*, 2002).

Cultivar and grafting effects

Greenhouse-grown eggplant (cvs 'Scorpio', 'Oscar', 'Tango' and 'DRA2086') study in Poland showed strong genotype effects on fruit sensory quality (i.e. odour, colour, texture, flavour and overall traits) as determined by tasting panel after roasting, whereas growing medium (i.e. rockwool, wood fibre, and coconut fibre) had little effect on fruit quality (Gajewski *et al.*, 2009). Likewise, study with 9 eggplant varietal types grown both in the field and in the greenhouse across 4 growing seasons in Spain showed strong genotype effects on a number of fruit composition traits, including moisture, pH, acidity, total carbohydrates, total soluble sugars, starch, fibre, and vitamin C (San Jose *et al.*, 2014).

In a 2-year study in Slovenia, cultivars (i.e. 3 commercial varieties and one landrace as scions grafted on tomato rootstock) affected fruit phenolics content and browning potential of the pulp, but that response was seasonal-dependent (Marsic *et al.*, 2014).

In a study with eggplant (cvs 'Birgah', 'Black Bell', 'Black Moon' and 'Longo') grown in an unheated plastic greenhouse in Italy, fruit from ungrafted plants generally had a lighter and more vivid skin colour, as well as higher total phenolics content, compared to plants grafted onto *Solanum torvum* rootstock, whereas there was little grafting effect on browning of fruit pulp (Moncada et al., 2013). The study also showed that the intensity of the treatment responses was cultivar-dependent.

4.4 Green beans

Background

Commercial importance and main cultivar types

Green beans are the unripe fruit and protective pods of various cultivars of the common bean (*Phaseolus vulgaris*). It belongs to the Fabaceae family, also known as the legume family, which is large and economically important worldwide (Welbaum, 2015). Green beans is a significant horticultural commodity in Australia, with an annual production of 29,543 tonnes and a gross value of $113.6 M in 2013-14 (Anon., 2015f). A recent consumer report on fresh vegetables shows that green beans are regularly purchased by about 50% of Australians (Witham et al., 2015).

Green beans are generally divided into 3 groups based on pod characteristics: (i) green beans, also known as snap beans, or French beans, or Italian green beans, or dwarf beans (due to the plant type) have stringless fleshly edible round or flat pods that are consumed when immature and tender before seeds develop significantly; (ii) string beans, also known as climbing or runner beans (due to the plant type), have a pod with a fibrous string that is typically removed before eating; (iii) haricot filet or vert, which has a stronger bean flavour and very thin, tender and small pods, which can be stringless or not (Welbaum, 2015).

Key compositional and nutritional aspects

Green beans are a good source of vitamins (mainly A, C, K, and folate, in addition to B_1, B_2 and B_3) and dietary fibre, in addition to minerals (Mn, Ca, Fe, Mg, P, K, and Zn); it also contains about 2% of protein (Anon., 2015a). Due to low levels of inhibitory compounds such as oxalates and phytates, green beans have relatively high Ca bioavailability (Quintana *et al.*, 2001).

The health benefits of legume consumption have gained more interest from researchers, and their consumption and production extends worldwide, as the majority of legumes contain bioactive compounds, including enzyme inhibitors, phytohemagglutinins (lectins), phytoestrogens, oligosaccharides, saponins, and phenolics (Bouchenak and Lamri-Senhadji, 2013). Although green beans do not show strong antioxidant activity compared to other vegetables, it contains several phytochemicals, including carotenoids such as β- and ɑ-carotene, lutein and zeaxanthin, as well as phenolics including the flavonoids quercetin and kaempferol (Hedges, 2007; Wen *et al.*, 2010).

Green beans also have special sensory attributes and good nutrient density since their calorie content is not high (Hedges, 2007). Green beans are typically consumed raw in salads or slightly cooked to improve tenderness and palatability, particularly blanching in boiling water. The process of blanching has shown to increase the contents of carotenoids and total phenolics in green beans, as well as antioxidant activity, but to reduce the content of vitamin C (Wen et al., 2010).

Key quality issues

Health attributes and ease of preparation are the primary motivations to purchasing green beans, whereas already consuming enough for their needs and wanting a variety in their diet are the main barriers (Anon., 2015d). Once purchased, Australian consumers expect green beans to stay fresh for just over a week, and these expectations are being met most of the time by 75% of consumers (Anon., 2015d).

Due to the intense metabolic activity of immature seeds inside the pods, green beans have intense respiration and heat emission, which limits shelf-life. During ripening processes, sugars condense to starch, with loss of sweetness, decrease in water content and increase of dietary fibre components, whereas at later stages of ripening (senescence), degradation processes increase, with the hydrolysis of starch and the consumption of soluble sugars on respiration (Sanchez-Mata *et al.*, 2003).

Crop nutrition

In a 2-year study in Italy, foliar Mg application at 56, 112 and 224 g/ha (in either a single application at flowering or split in half dose at 4-leaf stage and half at flowering) to greenhouse-grown green beans (cvs 'Bronco' and 'Cadillac') increased pod contents of sugars, Ca, and Mg, but also increased nitrate content (Stagnari et al., 2009). That study also showed that split applications were more effective, while the addition of Zn to the fertiliser had little effect.

In a 2-year study with 4 commercial green beans cultivars field-grown in the USA, applied Ca at 80 kg/ha as either calcium sulfate at planting or Ca nitrate 4 times weekly had little effect on pod calcium content or yield (Quintana *et al.*, 1999).

Crop management

Water management

In a 2-year field study in Turkey, green beans (cv 'Gina') drip irrigated at higher frequencies (i.e. intervals of 2-4 days, compared to 5-7, 8-10, or 10-12 days) and higher plant-pan coefficient of 1.0, compared to 0.5 or 0.75 of cumulative pan evaporation, generally resulted in higher yield and quality: pods were longer, had brighter colour and higher bean weight (Sezen *et al.*, 2008). That study also showed that there was little effect of irrigation levels and frequencies on pod firmness, and suggested that green beans are most sensitive to moisture stress during flowering and pod sizing, and moisture deficits during this period are likely to reduce both yield and pod quality. These observations confirmed results from a previous 1-year study conducted by the same research group on the same cultivar and under similar treatment conditions, in terms of yield and bean weight, but not so clearly for bean length, whereas pod colour was not determined (Sezen *et al.*, 2005).

Greenhouse-grown green beans in Italy under closed-cycle sub-irrigation system slightly increased pod length, dry matter content and % of 'extra class' number of pods compared to a traditional open-cycle drip, but reduced marketable yield by 33% (Bouchaaba et al., 2015).

In a field study in the USA, green beans plants grown under normal irrigation resulted in increased pod length, % of set pods, and number of seeds per pod, as well as lower fibre content of pods, compared to plants grown under low irrigation conditions (i.e. water stress at -0.06 MPa soil water potential) (Bonanno and Mack, 1983).

Field-grown green beans for processing in the USA that were rill irrigated had more intense colour and less drained weight loss, but lower vitamin C content than sprinkle irrigated ones (Drake and Silbernagel, 1982).

Cultivar effects

Field study with 60 lines in addition to 4 commercial green beans cultivars grown at 2 locations in the USA showed strong cultivar effects on Ca content in the pods, with higher Ca genotypes remaining high regardless of location or pod size; pods of certain genotypes appeared to have the ability to import Ca more efficiently than others regardless of yield (Quintana et al., 1996). Similarly, a 2-year field study with 4 commercial green beans cultivars grown in the USA also showed strong cultivar effects on pod Ca content, with results remaining consistent, even when significant year effects were found for both yield and Ca content (Quintana et al., 1999).

4.5 Conclusions

Taste, health, and to use as an ingredient in dishes are some of the key purchase drivers for fruit and legume vegetables in Australia, whereas not wanting to waste any, already consuming enough vegetables, and short shelf-life the main barriers. Once purchased, Australian consumers expect these group of vegetables to stay fresh for about a week (over 10 days for chillies), and these expectations are being met most of the time for both commodities by around 75-88% of consumers.

There has been little published research on pre-harvest factors affecting quality and shelf-life of fruiting and legume vegetables worldwide, especially on shelf-life, external, or sensory quality.

In terms of crop nutrition, there are a few studies showing that applied Ca (either as foliar sprays or added to the nutrient solution) during capsicum production may improve fruit firmness and resistance to decay. Also, the balance between Ca and K may improve fruit composition, but that warrants further investigation. Several studies suggest that the use of Si (e.g. potassium silicate) and other fertiliser salts such as bicarbonates may enhance plant resistance, increase cuticle thickness, and reduce postharvest decay on capsicum caused by fungal diseases such as anthracnose and powdery mildew (as seen with cucumber), which warrants further investigation.

With eggplant and green beans production, the information on crop nutrition is scant and inconclusive.

Regarding crop management, there was reasonable evidence that fruit maturity at harvest is important in postharvest quality of capsicum and chillies: later maturity (e.g. red stage) generally resulted in improved external quality (i.e. skin colour, firmness), sensory quality (i.e. flavour and aroma), and higher contents of sugars, vitamin C and bioactives. Similarly, a few studies suggested that fruit maturity can affect the phytochemicals levels in eggplant, but patterns of accumulation over time were variable.

A number of studies on crop water management showed that full irrigation regimes during flowering and fruit/pod growth stages is generally beneficial to capsicum, eggplant, and green beans production in terms of marketable yield and quality (e.g. better colour and less fibre in green beans, higher dry matter in eggplant, and better capsicum size).

Several studies have shown that cultivar mainly affects intrinsic attributes such as flavour and phytochemicals of capsicum and chillies, and to a lesser extent the external attributes such as skin colour and firmness, with red fruit generally having higher quality than green or yellow ones. A few studies also showed cultivar effects on postharvest quality of eggplant, both external and internal, and on Ca content of green beans.

The use of row covers was shown to reduce capsicum fruit sunburn and blossom-end-rot in a couple of studies, which warrants further investigation.

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5. Pre-harvest factors affecting quality and shelf-life of ear and stalk vegetables

5.1 Key findings

- Harvesting sweetcorn at the optimum maturity stage is important, as kernel quality reduces a maturity progresses due to lower moisture and sugars contents, and increased toughness;
- Cultivar is shown to have a strong impact on sweetcorn kernel quality, with supersweet types generally having a longer shelf-life and preferred eating quality than sweet types;
- Adequate N and P during plant growth appears to improve sweetcorn composition (e.g. protein, minerals, moisture, and fresh weight), especially if P soil availability is not too high;
- There appears to be little benefit in using deficit irrigation in terms of sweetcorn quality, and risk of yield reduction;
- A balanced N regime appears important to allow a good yield-quality balance in celery.

5.2 Sweetcorn

Background

Commercial importance and main cultivar types

Sweetcorn (*Zea mays* var. *saccharata*), also known as sweet maize or green maize, is a vegetable in which the kernels have high content of sugars and are eaten when immature while either on the cob or detached (Welbaum, 2015). Sweetcorn is a significant horticultural commodity in Australia, with an annual production of 74,483 tonnes and a gross value of $83.5 M in 2013-14 (Anon., 2015d). A recent consumer report on fresh vegetables shows that sweetcorn is regularly purchased by about 48% of Australians (Witham et al., 2015).

The main cultivar types of sweetcorn are the normal (or standard) and the supersweet, the latter being the favourite for the fresh market as it contains higher sugars content, in addition to having a reduced rate of conversion of sugar to starch (Wright *et al.*, 2005).

Key compositional and nutritional aspects

Sweetcorn is a good source of vitamins (mainly B_1, folate, B_3, C and pantothenic acid, in addition to B_6, A, and E), minerals (mainly K, Mg, P, and Mn, in addition to Fe, Zn, Cu, and Se), and dietary fibre, as well as containing more protein than most vegetables, i.e. about 3.3% (Anon., 2015a).

Sweetcorn contains significant levels of phytochemicals such as xanthophylls, lutein, zeaxanthin and cryptoxanthin, α- and β-carotene, and phenolic compounds, primarily ferulic acid, which in sweetcorn has shown to have strong antioxidant activity (Hedges, 2007). Zeaxanthin and lutein are the major carotenoids contributing to the characteristic colour of yellow sweet-corn, which is a particularly good source of those bioactives. From a health perspective, they are actively absorbed and accumulated in the human macula where they are thought to protect the photoreceptor cells of the eye from blue light oxidative damage, thus preventing macular degeneration, the leading cause of blindness in developed countries, as well as improving visual acuity (O'Hare et al., 2015). As humans cannot synthesise these compounds, they must be obtained from dietary components. Carotenoids content in sweetcorn generally increases with kernel maturity, mainly due to increased synthesis, but also due to a decline in moisture content of the kernels.

Key quality issues

Recent market surveys showed that the key drivers of purchase for sweetcorn are taste and ease of preparation, whereas key barriers for consumers include already consuming enough and wanting a variety of vegetables in their diet (Anon., 2015c). Once purchased, Australian consumers expect sweetcorn to stay fresh for about 8 days, and these expectations are being met most of the time by 81% of consumers (Anon., 2015c).

Quality of sweetcorn is determined by five factors: colour, size, cleanliness/appearance, eating quality/soundness, and shelf-life (Wright et al., 2005). Tenderness (i.e. toughness of kernels) and sweetness (i.e. flavour) are the key sensory attributes that determine overall acceptability of fresh and processed sweetcorn (Azanza and Klein, 1996). In a sensory evaluation study with sweetcorn in the USA, overall liking/acceptability was positively correlated with sweetness, aroma and texture, and negatively correlated with grassiness and starchiness in the kernels (Wong et al., 1995b). While sweetness and taste are closely related to kernel sucrose content and total sugars (Hale et al., 2005), texture depends on several factors including pericarp tenderness, moisture content, and the levels of water soluble polysaccharides, whereas the characteristic aroma of cooked sweetcorn has been associated with the content of dimethyl sulfide (Wong et al., 1995a).

Sweetcorn production typically targets three distinct markets: fresh, canning, and freezing. Fresh cobs (usually 3-4) are often marketed in pre-packed polystyrene trays covered with transparent plastic wrap, with large part of the husk covering removed to show the kernels (Wright et al., 2005). In Australia, individual fresh cobs and small trays of corn are the most common formats purchased, followed by pre-packaged large trays (Anon., 2015c). Sweetcorn for processing is picked at different stages of maturity depending on the way it is to be processed, e.g. sweetcorn for freezing is harvested at about the same stage as that for fresh market, while the corn for whole kernel pack and cream-style canning is harvested at a slightly later stage of maturity (Azanza and Klein, 1996).

Sweetcorn has a very short period of optimum harvest maturity, and its quality changes rapidly close to and following the peak. Ears harvested immature will have small diameter, poor cob fill, and watery kernels lacking sweetness. At optimum harvest maturity, the kernels are plump, sweet, milky, tender, and nearly of maximum size; after that, eating quality decreases rapidly, and over-mature corn is rather starchy than sweet, tough, with kernels often dented (Azanza and Klein, 1996).

Sweetcorn has a very high respiration rate and its high sugar content can rapidly reduce after harvest, especially under high temperature conditions, with the supersweet varieties generally having longer shelf-life than the standard ones (Wright *et al.*, 2005).

Crop nutrition

Higher rates of N as urea and P as DAP (i.e. 90+40 kg/ha compared to 70+30, respectively) applied to 4 sweetcorn cultivars grown in India resulted in cobs with higher contents of protein and moisture, with little benefit when rates were further increased to 110+50 or 130+60 kg/ha (Kumawat *et al.*, 2014).

In a 2-year study with sweetcorn (cv 'Vega') grown in Turkey, increasing N (as urea) rates from 120 to 360 kg/ha resulted in higher contents of protein, iron, zinc and copper in the kernels, as well as increased ear length, diameter, weight, and fresh ear yield (Oktem *et al.*, 2010).

Higher rates (i.e. 310 compared to 168 kg/ha) of N as ammonium nitrate applied to sweetcorn grown in the USA resulted in kernels with an increased content of dimethyl sulfide, although the response was cultivar-dependent, whereas applied S as calcium sulfate had little effect (Wong *et al.*, 1995a).

A higher rate of 80 kg/ha of P fertilisation as triple calcium superphosphate, combined with 100 kg/ha of N as urea and K as potassium chloride, applied to sweetcorn grown in Mexico resulted in ears with higher fresh weight, dry weight, number of kernels per ear, and yield compared to a rate of 60 kg/ha, particularly at a soil moisture tension of -30 kPa, compared to -55 or - 80 (Rivera-Hernandez et al., 2010). In contrast, in a study with sweetcorn grown in Florida, increasing P from 1.7 to 44 or 80 kg/ha via foliar applications had little impact on ear visual appearance, length, diameter, tip fill, and flag chlorophyll content (Olczyk et al., 2003). Similarly, a 3-year study in the USA showed small inconsistent increases in sugar content and ear weight in response to P fertilization combined or not with a preceding rye cover crop, without affecting yield, which would be of little significance to farmers (Geleta et al., 2004). That was confirmed by a study compiling research on fertilisation of sweetcorn conducted in Florida over a number of trials and seasons, which showed little effect of increasing P applications on ear quality or yield, presumably because most soils used for sweetcorn production in that state are rich in P, suggesting that crop response to applied P depends on P soil content (Hochmuth and Hanlon, 2008).

In a 2-year study in Spain, there was little difference in sweetcorn appearance, length and diameter of marketable ear between plants grown under a conventional fertilisation regime (i.e. inorganic fertilisers) and an integrated one in which 25% of the nutrients were supplied by vermicompost, whereas an integrated one with 25% rabbit manure negatively impacted on appearance (Lazcano *et al.*, 2011).

In a 2-year study with sweetcorn grown in Serbia, increasing rates of biofertilisers, i.e. either soil applications of *Azotobacter chroococcum* or foliar applications of an organic fertiliser ('Guana'), resulted in kernels with higher sugar content, with little effect on yield or moisture content (Dragana *et al.*, 2013).

Crop management

Maturity stage at harvest

In a 2-year study with 31 sweetcorn hybrids (both sweet and supersweet types) grown in the USA, delaying harvest dates from 20 to 23 or 26 days after planting generally reduced kernel quality, i.e. lower moisture, total sugars, and dimethyl sulfide contents (Wong *et al.*, 1994). That study also showed strong genotype effects on kernel quality. Similarly, increasing harvest dates from day 1, then 3, 5 and 7 in sweetcorn (cv 'Boston') grown in Poland reduced kernel quality, i.e. lower moisture and sugar contents, higher starch content, as well as increased toughness as determined by higher force in compression, shear and puncture tests (Szymanek, 2009).

Sensory evaluation of sweetcorn grown in the USA showed that supersweet cultivars did not lose sucrose and total sugars with maturity and were considered sweet and acceptable regardless of the maturity stage. In contrast, standard cultivars were only acceptable at early maturity, but not at the mature and late maturity stages, suggesting that supersweet cultivars would provide growers with a longer harvest window than standard types (Hale *et al.*, 2005).

Less mature sweetcorn (cvs 'Xtra Sweet 77', a supersweet type, and 'Jubilee', a sweet type) grown in Brazil and processed into frozen product had higher contents of sucrose and total sugars than samples harvested at a more mature stage, although there were little differences in sweetness or overall sensory preference as determined by taste panel between maturity stages within each cultivar (Reyes *et al.*, 1982).

A study with 44 sweetcorn lines in the USA showed that β-cryptoxanthin contents tended to increase as kernels matured, but that there was no consistent change in the contents of zeaxanthin, α-carotene, or β-carotene (Kurilich and Juvik, 1999). That study also showed strong genotype effect on the contents of lutein and vitamin E.

Cultivar effects

In a study with sweetcorn grown in Bundaberg, Qld, the supersweet cv 'Sucro' showed (Olsen *et al.*, 1990):

- Longer shelf-life (i.e. >10 days of acceptable quality at 1°C), compared to 8 and 4 days for sweet cvs 'Aussie Gold 12' and 'Rosella 425', respectively;
- Higher scores for sweetness, flavour and general eating quality than the other 2 cvs;
- 3-fold higher total sugars (mainly sucrose) contents before storage, and higher sugars retention after cold-storage at either 1, 4, 7, or 18°C compared to the other 2 cvs.

A 2-year study in the USA with 10 white sweetcorn cultivars (both standard and supersweet types) showed strong genotypic effects on sensory attributes such as appearance, sweetness, flavour and overall preference (Simonne *et al.*, 1999). Similarly, sweetcorn hybrids grown in the USA significantly affected the primary components of eating quality, i.e. sweetness, sweetcorn aroma, crisp pericarp and tender endosperm, as well as the content of dimethyl sulphide (Wong *et al.*, 1995a; Wong *et al.*, 1995b).

Water management

A 2-year study in Turkey showed that sweetcorn (hybrid 'Lumina F1') grown under deficit irrigation at 70% water replacement had higher sugar (+10%) and protein (+6%) contents than 100% and 85%, but also lower ear length, diameter, and weight, with a reduction of 4% in ear yield (Ertek and Kara, 2013). In another 2-year study in Turkey, sweetcorn (cv 'Reward') grown under mild deficit irrigation (i.e. 10% deficiency of class A pan evaporation) had little impact on kernel contents of protein, zinc and copper, reduced iron content, and had little effect on marketable yield, whereas further deficit of 20% or 30% increased protein and reduced minerals content, but also reduced marketable yield by 8% or 38%, respectively (Oktem, 2008).

Potential management of spatial variation and yield

A study on sweetcorn production across 5 field sites at Bathurst, NSW showed large variation in cob quality as determined by cob length, diameter and moisture content at harvest, which would likely impact on the marketability of production in the fresh market (Taylor *et al.*, 2008). The study suggested that it should be possible to optimise quality at each site in the production system by manipulating yield, and that could be done by varying management spatially in the fields. Researchers in that study also suggested that spatial crop modelling could be a potentially useful tool for site-specific management, if existing models can be successfully adapted and the correct input information, particularly information on plant density, can be cheaply and easily collected.

Soil cover (plastic mulch)

A 2-year study with 4 commercial cultivars grown in Canada showed that the use of plastic mulch resulted in cobs with better appearance, higher weight, length and ear fill rating, but little overall impact on marketable yield (Kwabiah, 2004). That study also showed that appearance responses depended on planting date (i.e. were significant when planted on May 1st and 15th, but not 29th).

5.3 Celery

Background

Commercial importance and main cultivar types

Celery (*Apium graveolens* L.) belongs to the Apiaceae family and its stalks are comprised of several enlarged, long, thick, fleshly and solid edible petioles. Generally, the petiole is the most important edible portion as celery leaves are not consumed because of their strong flavour, although they are sometimes cooked or used as garnish (Welbaum, 2015). Chopped into small sticks, the stalks are a popular ingredient in salads and a range of cooked dishes due to its crunchy texture and distinctive flavour. Celery stalks are generally marketed in bulk or in plastic bags, but they are also available in markets as ready-to-eat convenience-packaged products such as celery sticks and sliced celery.

Celery had in Australia an annual production in 2013-14 of 53,261 tonnes and a gross value of $47.2 M (Anon., 2015d). A recent consumer report on fresh vegetables shows that celery is regularly purchased by about 50% of Australians (Witham et al., 2015).

Celery cultivars are usually grouped into two classes, the yellow or 'self blanching" and the green cultivars. The yellow cultivars, characterised by golden foliage, earlier, less vigorous, thinner petioles, more sharply ribbed and stringy, are considered inferior to green cultivars in eating and shelf-life, and are primarily used for specialty markets (Raffo *et al.*, 2006).

Key compositional and nutritional aspects

Celery is very low in calories with a high water content of 90-96%. It is a good source of vitamins (mainly K, A, and folate, in addition to C, B_6, B_2, B_3, and pantothenic acid), minerals (mainly K and Mn, in addition to Ca, Mg, P, and Cu), and dietary fibre (Anon., 2015a).

In terms of bioactives, celery is shown to contain variable amounts of β-carotene, lutein/zeaxanthin and the flavones, apigenin and luteolin, which has been shown various potential beneficial health effects, such as antioxidant and anti-inflammatory activity, and is thought to contribute towards reducing the process of atherosclerosis (Raffo *et al.*, 2006; Hedges, 2007). Celery is a very aromatic plant with a characteristic smell due to the presence of 3-butylphthalid (Welbaum, 2015).

Key quality issues

Recent market surveys showed that the key drivers of purchase for celery are use as an ingredient in dishes and health, whereas key barriers for consumers include people not wanting to waste any and wanting a variety of vegetables in their diet (Anon., 2015b). Once purchased, Australian consumers expect celery to stay fresh for about 10 days, and these expectations are being met most of the time by 81% of consumers (Anon., 2015b).

Quality standards for celery are generally based on external criteria and refer to the shape of stalks and petioles, external appearance, freedom from defects and traces of disease. Stalks with good tight formation, minimally twisted petioles, and light green and fresh appearance are considered of high quality. On the other hand, flavour and texture also contribute to the perception of eating quality and play a key role in determining consumer acceptability (Raffo *et al.*, 2006).

Crop nutrition

In a study with field-grown celery (cv 'D'Elne') in Italy, N applied as either ammonium sulfate or organic N as water soluble peptides at either 80 or 120 kg/ha, followed by packaging in plastic film and cold-storage at 4°C, resulted in 10-17 days longer shelf-life as determined by softening rate compared to no added N, as well as higher contents of protein and total phenols (Rizzo *et al.*, 2011):

In a 2-year study in Finland, celery (cvs 'Deacon' and 'Tall Utah Triumph') grown in the greenhouse under reduced N rates (i.e. ammonium nitrate at 30 and 60 kg/ha compared to 90 kg/ha) combined with irrigation had higher contents of dry matter, vitamin C, and dietary fiber, with little effect on total sugar and β-carotene contents, but yields were markedly reduced (Evers *et al.*, 1997).

In a greenhouse study in Israel, managing the N concentration in the nutrient solution with a low fertilisation of 50 ppm during the first 80 days from planting, followed by irrigation with a high rate of 200 ppm N until harvest, resulted in celery heads of high quality, i.e. with nil incidence of petiole pithiness, a quality disorder involving the breakdown of parenchyma tissue in marketable petioles, compared to 16.5% incidence of pithy heads when the fertilisation was 200 ppm throughout the plant growth period (Aloni *et al.*, 1983).

Crop management

Fruit maturity stage at harvest

In a greenhouse study in Argentina, celery (cv 'Golden Boy') harvested at 108 days after transplant (DAT) resulted in juicier and less flexible stalks as determined by sensory evaluation than harvested than 80 DAT, whereas there was little differences between harvesting dates (from 80-129 DAT) for other sensory traits (i.e. flavour, hardness, crunchiness, and fibrousness), or for colour, texture (i.e. cutting force), soluble solids content, and acidity (Yommi *et al.*, 2013). In another greenhouse study with celery (cv 'Golden Clause') in Argentina, a harvest delay from 93 to 124 days after transplant resulted in higher contents of soluble solids and total polyphenols (i.e. quinones), but also petioles with higher cutting force, more fibrous and with higher incidence of pithiness, whereas there was little differences in colour, acidity, and contents of water or vitamin C (Guerra *et al.*, 2010).

Water management

A 3-year study across 9 commercial celery fields in California showed that improving drip irrigation management by more frequent irrigation, lower volume per irrigation, and more closely matching irrigation volume to evapo-transpiration and crop growth stage, reduced the incidence of petiole pithiness (Breschini and Hartz, 2002).

5.4 Conclusions

Sweetcorn

Taste, ease of preparation, and health are the key drivers of purchase for sweetcorn and celery, whereas key barriers for consumers include already consuming enough and wanting a variety of vegetables in their diet. Once purchased, Australian consumers expect sweetcorn to stay fresh for about 8 days and celery for 10 days, and these expectations are being met most of the time by 81% of consumers.

There has been little published research on pre-harvest factors affecting quality and shelf-life of sweetcorn worldwide, especially on shelf-life and external quality.

In terms of crop nutrition, adequate N and P during plant growth appears to improve the composition of sweetcorn (i.e. protein, minerals, moisture, or fresh weight), while P could also improve kernel quality if soil availability is not high.

Regarding crop management, harvesting sweetcorn at the optimum maturity stage was shown to be important, as kernel quality is generally reduced due to lower moisture and sugars contents, and increased toughness as the maturity progresses. Cultivar is shown to have a strong impact on kernel quality, with supersweet types generally having a longer shelf-life and preferred eating quality than sweet types. There appears to be little benefit in using deficit irrigation in terms of quality, and potential reduction in yield.

Celery

Worldwide published information on pre-harvest factors affecting quality and shelf-life of celery has been very limited.

Regarding crop nutrition, a few studies suggest that a balanced N regime may be important to allow a good balance between quality/shelf-life and yield. Harvest date could have some impact on celery quality, but the evidence is inconsistent.

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6. Pre-harvest factors affecting quality and shelf-life of root and tuber vegetables

6.1 Key findings

- Genetic factors were shown the highest impact on carrot sensory quality (i.e. flavour, aroma, and texture), as well as the contents of sugars, nutrients, and bioactives;
- Growing location and season effects due to environmental and soil type differences have also shown to affect carrot shelf-life during cold-storage, sensory quality and composition;
- An adequate but not excessive N fertilisation may assist with a good balance between carrot quality and yield, including composition, flavour, and texture, although responses were varied;
- Pre-harvest canopy removal (i.e. defoliation) or pruning was shown to reduce sweetpotato root skinning damage, rots, and weight loss;
- Delaying harvest date can increase sweetpotato yield and quality, particularly compositional attributes such as the contents of dry matter, sugars, and carotenes;
- The effects of K and N fertilisation on quality suggest some potential impact on root size or composition, but the evidence is too scarce.

6.2 Carrot

Background

Commercial importance and main cultivar types

Carrot (*Daucus carota* L.) belongs to the family Apiaceae and is one of the most widely grown and consumed vegetables due to its characteristic flavour and health benefits (Welbaum, 2015). It is a significant horticultural commodity in Australia with an annual production of 242,664 tonnes and a gross value of $131.5 M in 2013-14 (Anon., 2015d). A recent report on fresh vegetables shows that carrot is the most regularly purchased vegetable by 88% of consumers in Australia (Witham et al., 2015).

A range of cultivars and colours are now available, including the most common orange, but also yellow, red, purple, and white (Kreutzmann *et al.*, 2008). Various cultivars are grown in Australia, including Nantes, Dutch carrots, Imperator, and Kuroda. The orange-coloured types are more popular, with Nantes being the most important cultivar due to its sweet carrot flavour. Australian grown carrots are mostly marketed fresh in small or large plastic bags, followed by individual and bunched carrots, and baby/miniature carrots. Processed products are mainly frozen and juice (Anon., 2015c). 'Baby cut' carrots are a value-added, washed, and peeled convenience product, whereas shredded carrots are used in pre-made salad mixes (Welbaum, 2015).

Key compositional and nutritional aspects

Carrot is an excellent source of vitamin A, in addition to being a good source of other vitamins (mainly K and C, in addition to B_6, folate, B_1, B_3, and E), minerals (mainly K and Mn, in addition to P, Ca, and Mg), and dietary fibre (Anon., 2015a).

Previously known for its provitamin A carotenoids, carrot is gaining recognition for a number of other phytochemicals such as polyacetylenes, phenolics, and α-tocopherol (Metzger and Barnes, 2009). β-carotene and α-carotene are the main carotenoids, which give carrots their characteristic orange colour, in addition to potential health-promoting benefits. Lutein, another carotenoid, is present in carrots and is associated with eye health, as mentioned in section 5.2 of this review. Coloured carrots also contain various amounts of polyacetylenes, especially falcarinol and falcarindiol, which have shown anti-inflammatory and anti-cancerous activities (Hedges, 2007; Metzger and Barnes, 2009). Other phytochemicals present in carrots in varying amounts include anthocyanins, phenolic acids, and terpenes. The contents of nutrients and phytochemicals in carrots are shown to depend on type and variety/cultivar, growing location and climatic conditions (Hedges, 2007; Metzger and Barnes, 2009). The phytochemicals in carrots affect sensory quality, together with volatile compounds, now-volatile bitter taste compounds, and sugars, which are also shown to be highly affected by genotype (Simon *et al.*, 1982). For example, orange genotypes were shown to be characterised by higher intensities in carrot flavour and aroma than yellow types, whereas purple genotypes have a sweeter and nuttier flavour than other types (Kreutzmann et al., 2008). Likewise, purple carrots were shown to have higher contents of polyacetylenes, anthocyanins and α- and β-carotenes than orange carrots, whereas white carrots had the highest content of volatiles, followed by orange, purple, and yellow (Alasalvar et al., 2001).

Key quality issues

Health, taste and ease of preparation are the main drivers of carrot by Australian consumers, whereas already consuming enough and not wanting to waste any are the main barriers (Anon., 2015c). Once purchased, Australian consumers expect carrots to stay fresh for about 12 days, and these expectations are being met most of the time by 89% of consumers (Anon., 2015c).

Carrot quality deteriorates during storage due to moisture loss in unrefrigerated and/or low RH conditions, as well as loss of sugars due to respiration (Welbaum, 2015). Carrot shelf-life has been defined as the number of days carrots remain at specified storage conditions before losing 8% moisture (Shibairo *et al.*, 1997). Freshness is a critical variable affecting its quality and consumers' selection of carrots; it has been defined as having no film and no bruises on it, with a shiny and not shrivelled surface without dried ends, firm texture and not gummy, moist area when cut without any sour, fermentation or strong sweet odours, and crisp, juicy and not fibrous texture in the mouth (Peneau *et al.*, 2007).

Crop nutrition

Nutrition management

In a 2-year study in Norway across 3 carrot field trials (cvs 'Fontana', 'Natalja', 'Nelson' and 'Newburg'), applied N as calcium nitrate at 0, 80 and 160 kg/ha and K as potassium sulfate at 0, 120 and 240 kg/ha resulted in (Seljasen *et al.*, 2012):

- Markedly larger number of grade 1 roots and higher nitrate content with higher rates of N;
- Interactions between N fertilisation, soil type (i.e loam, peat or sand) and cultivar, highlighting that cultivar and climate had a higher impact on quality characteristics than N fertilisation or soil type;
- Little impact of either N or K on dry matter and soluble solids contents or on sensory attributes, including taste, sweetness, bitterness, firmness, crispness, and juiciness;
- The study did not determine the impact of those two key nutrients applied in combination, which would have better reflected commercial reality and provided interesting comparisons.

In a field study in Norway, reduced N rates of 40-80 kg/ha improved carrot flavour intensity, increased contents of total sugars, protein, and carotenoids, and reduced crispness and pH compared to higher rates of 100-190 kg/ha (Hogstad *et al.*, 1997). Similarly, in a 2-year study in Denmark, farming systems with low N input resulted in increased bitter and 'green' flavour compared to conventional and organic systems with higher levels of N (Paoletti *et al.*, 2012). Conversely, carrots (cv 'Nanthya') grown in pots in a greenhouse trial in Germany under lower rates of N as ammonium nitrate at 0.3, 0.6, 0.9, 1.2, and 2.4 g/pot had increased contents of sucrose and essential oils, whereas lower contents of glucose, fructose and nitrate (Schaller and Schnitzler, 2000).

In a hydroponically-grown carrot (cv 'Paramount') study in Canada, increasing K concentrations in the nutrient medium from 0 or 0.1 to 1 mM reduced postharvest moisture loss, a measure of shelf-life, whereas further increase of 10 or 15 mM had little impact (Shibairo *et al.*, 1998b). In contrast, in a field study in Florida, applied K as potassium nitrate at 19 kg/ha had little impact on the contents of soluble sugars or carotenoids, or on the number of grade 1 carrots or marketable yield (Hochmuth *et al.*, 2006).

Crop management

Cultivar effects

In a recent comprehensive review on pre- and postharvest factors that affect the quality of carrots, genetic factors were shown to have the highest impact on quality variables, especially sensory quality and nutritional value, highlighting that the choice of cultivar is a very important grower-controllable factor (Seljasen *et al.*, 2013). That review also highlighted that a large number of quality characteristics in carrots, including nutrients, sugars, aroma components such as terpenes, and possible health-related compounds such as carotenes and falcarinol, seem to be genetically determined. For example, in a study with 11 genotypes grown across field sites in Denmark, Holland, and Norway, sensory scores among cultivars as determined by tasting panels differed by 209% for sweet taste and 119% for bitter taste (Kreutzmann et al., 2008). Likewise, in another 2-year study over 3 field trials in Norway, carrot cultivars ('Fontana' and 'Natalja') affected most of the sensory attributes studied as determined by tasting panel, including taste intensity, sweetness, bitterness, firmness, crispness, juiciness, and toughness, as well as the contents of dry matter, soluble solids and nitrate, and the number of grade 1 roots (Seljasen *et al.*, 2012).

An earlier 2-year study with 8 carrot cultivars grown in Canada showed that shelf-life based on moisture loss differed by up to 4-6 days among cultivars during storage at 13° and low RH (35%), particularly for fruit harvested late in the season, i.e. 120 days after harvest compared to 87 (Shibairo *et al.*, 1997).

Growing location and seasonal effects

A study with several cultivars of carrots grown in environmentally controlled rooms to simulate the natural climate of 3 growing locations in the USA in an average year showed that climate affected sensory quality, including sweetness, harsh flavour, and overall preference, as well as the contents of carotenoids, total sugars, terpinolene, and total terpenoids (Simon *et al.*, 1982).

A 2-year field study with carrot (cv 'Bolero') grown in Denmark showed differences between years in the contents of sugars, β-carotene, citric and fumaric acids, and acidity (Paoletti *et al.*, 2012).

In a 2-year study over 3 field trials in Norway, carrot (cvs 'Fontana' and 'Natalja') grown in peat soil were sweeter, and had lower scores for the negative sensory attributes bitterness, earthy and terpene flavours, and firmness compared to those grown in sandy soil, presumably due to the lower soil temperatures in peat soil, whereas carrot grown in sandy soil had lower incidence of split and forked roots, higher dry matter and soluble solids contents, and markedly reduced nitrate content (Seljasen *et al.*, 2012).

Toxic compounds such as mercury, cadmium, and other heavy metals and radioactive compounds (i.e. radionuclides) released from soil particles can accumulate in crops such as carrot, thus affecting its safety for consumption (Seljasen *et al.*, 2013). For example, a 4-fold variation in cadmium content was found in carrots grown in different locations in Sweden (Jansson and Oeborn, 2000).

Growing system

In 2 field studies with carrots (cv 'Bolero') grown in Denmark either conventionally or organically, there was little difference in the contents of α-carotene, β-carotene, and lutein (Soltoft *et al.*, 2011), polyacetylenes, including facarinol and facarindiol (Soltoft *et al.*, 2010a), and phenolic acids (Soltoft *et al.*, 2010b) between the two systems.

In a 2-year field study across 6 locations in Sweden, carrot (several cvs) grown conventionally had more intense carrot flavour, were sweeter, less bitter, and had a less pronounced after taste than those grown organically (Haglund et al., 1998).

A study with 10 carrot cultivars hydroponically-grown in the USA with either nutrient film technique or a microporous tube membrane system showed an interaction between cultivar and growing system for sensory quality (i.e. colour, crunchiness, sweetness, fibrousness, blandness, and overall preference) as determined by consumer testing (Gichuhi *et al.*, 2009).

Water management

In a greenhouse study in Canada, carrot (cvs 'Eagle' and 'Paramount') grown under increasing water stress conditions for 4.5 weeks (at 100%, 75%, 50%, and 25% field capacity, after 5.5 months of being watered to field capacity) had increased moisture loss (a measure of shelf-life) during storage at 13°C and 32% RH for 3 weeks, reduced root diameter and weight, as well as higher surface and relative solute leakage (Shibairo *et al.*, 1998a). The study suggested that pre-harvest water stress lowered membrane integrity of carrot roots, which might enhance moisture loss during storage.

Carrot (cv 'Orlando Gold') greenhouse-grown in the USA under water stress (i.e. conditions simulating drought or waterlogging) had lower concentrations of polyacetylenes than those grown in pots under normal water conditions (Lund and White, 1990).

Plant density

In a 2-year field study in Finland, carrot (cv 'Fontana BZ') grown under the lower plant density of 4,000 plants/had had higher carotenoids content than at 7,000 plants/ha in one of the years in which climatic condition were more unfavourable (Evers et al., 1997).

6.3 Sweetpotato

Background

Commercial importance and main cultivar types

Sweetpotato or kumara (*Ipomoea batatas* L.) has large, starchy, sweet-tasting, tuberous roots and belongs to the family Convolvulaceae (Welbaum, 2015). It is a significant horticultural commodity in Australia with an annual production of 75,287 tonnes and a gross value of $80.5 M in 2013-14 (Anon., 2015d). A recent report on fresh vegetables shows that sweetpotato is the 11th most regularly purchased vegetable by 60% of consumers in Australia (Witham et al., 2015). The main variety grown in Australia with over 90% of production is 'Beauregard', an orange-fleshed or 'Gold' type with a pale pink skin. There are also smaller volumes of white-fleshed staple types such as 'Northern Star' (a red/purple skinned cv) and 'Kestle' (a pale cream skin cv), whereas markets are emerging for purple-fleshed types (Wolfenden, 2014).

Key compositional and nutritional aspects

Sweetpotato is a good source of vitamins (K, A, and folate, in addition to C, B_6, B_2, B_3, and pantothenic acid), minerals (K and Mn, in addition to Ca, Mg, P, and Cu), and dietary fibre (Anon., 2015a).

In terms of bioactives, sweetpotato has one of the highest contents of β-carotene content among vegetables, particularly the orange-fleshed types, as well as phenolic acids and anthocyanins, mainly in cultivars with red or purple skin or flesh (Bovell-Benjamin, 2007; Hedges, 2007). In addition to these antioxidative qualities, an acidic glycoprotein was identified in sweetpotato as the compound responsible for an observed improvement in insulin sensitivity in diabetic patients (Hedges, 2007).

Key quality issues

Taste, ease of preparation and health are the key drivers for sweetpotato purchases, whereas already consuming enough and wanting a variety of vegetables are the key barriers (Anon., 2015b). Once purchased, Australian consumers expect sweetpotatoes to stay fresh for nearly 2 weeks, and these expectations are being met most of the time by 92% of consumers (Anon., 2015b).

Recent study showed that Australian consumers prefer a smaller torpedo shaped sweetpotato; a high quality sweetpotato was identified as having a deep orange/red colour, smooth skin, and very dense and hard texture, whereas an inferior one was wrinkly, spongy, pitted and damaged (Henderson et al., 2012).

Crop nutrition

In a 3-year sweetpotato (cv 'Beauregard') study in the USA, application of N as ammonium nitrate at either 28 kg/ha (under normal rainfall conditions) or 56 kg/ha (under wet conditions) resulted in optimum marketable yield (i.e. higher percentage of first grade roots based on preferred diameter and shape) compared to a higher dose of 84 kg/ha, although protein content of the roots was increased with higher N rates (Phillips *et al.*, 2005). The study also showed that delaying N application until 2-3 weeks after transplant further increased marketable root yield compared with applying N before transplant or 4-5 weeks after transplant.

Application of potassium sulphate at the rate of 300 kg/ha to sweetpotato (several genotypes) grown in China resulted in higher root yield, root dry weight and carotenoid content than rates of 0, 150, 450, and 600 kg/ha, whereas there was little treatment effect on brix, and the contents of protein and anthocyanin; the responses were generally dependent on genotype (George *et al.*, 2002).

Enhancing K fertilisation from a 1:1 N:K ratio to 1:2.5 and 1:5 in sweetpotato (cvs 'Bat1' and 'Boniato') grown in Croatia increased flavonoids content by 300% on both cultivars, whereas phenolic acids contents increased by 20% in one of the cultivar at the higher K rate (Redovnikovic *et al.*, 2012).

Crop management

Harvesting date and cultivar effects

Two sweetpotato studies in India, one with 15 orange-fleshed sweetpotato cultivars grown over 2 seasons (Mitra *et al.*, 2010) and the other with 10 cultivars of white or light yellow/cream flesh grown in one season (Chattopadhyay *et al.*, 2006) showed similar results: increasing harvesting date from 90 to 105 and 120 days after planting generally resulted in a linear increase in yield, dry matter, starch, and total sugar contents, as well as higher content of β-carotene (up to 105 days), whereas vitamin C content was reduced; both studies also showed that cultivar affected sensory quality as determined by tasting panel based on overall acceptability, flavour, taste, texture, and appearance, as well as the contents of β-carotene (and its retention in cooked tubers), total sugars, vitamin C, and starch.

Pre-harvest canopy removal or pruning

In a 3-year sweetpotato (cv 'Beauregard') study in the USA, the application of ethephon to defoliate plants at 3 and 7 days before harvest increased skin resistance and thus reduced root skinning damage (i.e. surface abrasion, which can cause loss of marketable produce in storage due to rots, loss of moisture, and reduced visual appeal) in 2 of 3 years compared with application at 1 day before harvest or defoliation with no ethephon using a flail mower (Xiang et al., 2013). Likewise, the removal of sweetpotato (cvs 'Beauregard' and 'Jewel') canopy at ground level at 8-10 days before harvest using a flail mower in the USA reduced overall skinning root damage by 53-62% (La Bonte and Wright, 1993).

The use of pre-harvest curing by pruning the sweetpotato plant canopy 14 d before harvest reduced root skinning injury during harvesting and post-harvest handling in sacks, thus increasing shelf-life as determined by weight loss during storage under tropical conditions in Tanzania (Tomlins et al., 2002). Skinning injury was also associated with the increased occurrence of rots.

Water management

In a sweetpotato study (cvs 'Centennial' and 'Jewel') in the USA, the highest sensory ratings for appearance, flavour, texture, overall preference, and objective colour of cooked flesh, together with maximum marketable yields and minimum weight loss and root decay during curing and storage, were obtained when sprinkler irrigation amounts reached a total water application of 76% of pan evaporation compared with lower (52-63%) or higher (89-147%) amounts, whereas there was little treatment effects on total sugars (Thompson et al., 1992).

6.4 Conclusions

Carrot

Health, taste and ease of preparation are the main drivers of carrot and sweetpotato by Australian consumers, whereas already consuming enough and not wanting to waste any are the main barriers. Once purchased, Australian consumers expect carrots and sweetpotato to stay fresh for 12-13 days, and these expectations are being met most of the time by about 90% of consumers.

Like other vegetables, published research on pre-harvest factors affecting quality and shelf-life of carrots is limited. Genetic factors have shown the highest impact on quality parameters, particularly sensory attributes such as flavour, aroma, and texture, as well as the contents of sugars, nutrients, and bioactives, highlighting that the choice of cultivar is a key factor under grower's control for carrots. Growing location and seasonal effects due to differences in environmental conditions and soil types have also shown to affect sensory quality and composition of carrots, as well as shelf-life during cold-storage .

In terms of crop nutrition, several studies suggest that an adequate but not excessive N fertilisation may assist in providing a good balance between yield and quality, including composition and sensory traits such as flavour and texture, although responses were varied. It does not appear that higher doses of potassium can significantly benefit carrot quality.

Regarding crop water management, besides cultivars and growing location effects, limited evidence suggests that water stress conditions may potentially increase carrot moisture loss and reduce shelf-life during storage, as well as lower bioactives content.

Sweetpotato

Studies on pre-harvest factors affecting quality and shelf-life of sweetpotato have been very limited. Few studies on the effects of crop nutrition (K and N fertilisation) on quality were found, with some potential impact on root size or composition, but the evidence is too scarce. Regarding crop management, a couple of studies suggest that delaying harvest date can benefit both yield and quality, particularly compositional attributes such as higher contents of dry matter, sugars, and carotenes. Likewise, pre-harvest canopy removal (i.e. defoliation) or pruning was shown to reduce root skinning damage, rots, and weight loss in a few studies.

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Outputs (other than the review)

In addition to the above review, this project provided additional extension resources highlighting key information extracted from the review. These resources were developed by Applied Horticultural Research, and included:

- Three fact sheets, which were submitted together with this final report:
  - Pre-harvest effects on lettuce quality
  - Pre-harvest effects on the quality of babyleaf spinach
  - How to maximise the health benefits of Brassica vegetables
- Three articles to be submitted to 'Vegetables Australia' magazine, which are included in the appendices section of this final report:
  - Benefits of silicon in vegetables crops (Appendix 1)
  - Effects of growing environment on greenhouse cucumber quality (Appendix 2)
  - Health benefits of eating vegetables (Appendix 3)

This final report also provides information outlining areas of research or knowledge gaps for potential further investment by the vegetable industry, as detailed in the 'Evaluation and Discussion' section of this final report.

Outcomes

As this project was mostly a review of current information, with no experimental work being conducted, its outcomes will be indirect. The effectiveness of the outcome will likely depend on various factors, especially industry response to the research areas recommended by the project (as listed in the 'Recommendations' section of this report), which were based on key areas of research gaps identified by the review (as shown in section 'Evaluation and Discussion'). It is also expected that the information contained in the fact sheets and articles provided by this project, together with the review, will assist growers to increase awareness, foster adoption of practices that can enhance quality, and potentially improve product quality that better meet consumers' expectations.

A basic Benefit Cost Analysis (BCA) was developed and included in this final report (Appendix 4) as a case study to exemplify the potential of using a pre-harvest practice (i.e. applying silicon during plant growth) to improve quality and/or yield of a vegetable crop (i.e. cucumber). The analysis considered the extra costs and extra benefits of applying silicon over a 5-year period under a number of assumptions. As no experimental work was done to underpin the BCA or to validate results reported by other studies, such exercise was purely hypothetical. Before any conclusions or recommendations can be drawn from this BCA, proper experimental work is required to test and confirm the applicability of this practice under local and current conditions, as well as accounting for variations in treatment responses.

Evaluation and Discussion

The review highlights that worldwide published research on pre-harvest practices that can affect product shelf-life and general quality, in addition to yield, has been generally limited for most vegetables. In addition, quality and shelf-life was shown to be influenced by a large number of specific agronomic, genetic and environmental factors that appear to interact in a complex way.

Leafy and Brassica vegetables were the groups with most research in the topic of the review. The key findings from these groups show that understanding pre-harvest interactions and developing crop schedules that can match the best combination of cultivar, growing area, plant growth rate, and time of the year, can have major benefits in terms of balancing yield and quality/shelf-life. That can only be achieved by targeted research for each key production area, which has been done in Australia to a degree for lettuce, spinach, and broccoli. However, there are considerable gaps for other vegetables, in addition to the need of updated research to address industry changes such as the introduction of new cultivars and novel agricultural supplies.

The area of supplying silicon to vegetable crops has attracted considerable research interest, and silicon is now commercially available in Australia in liquid and granular form. This review shows that, based on overseas studies, silicon has potential to increase product resistance to pre- and postharvest diseases and enhance quality and shelf-life in commodities such as leafy vegetables, cucumber, zucchini, and capsicum. However, there is little information on its effects under Australian conditions and current commercial cultivars.

Consumer information from the review suggests that some groups of vegetables such as roots/tubers, ear/stalk and Brassica have a high proportion (>80%) of consumers mostly satisfied with the expected freshness/shelf-life of those vegetables after purchase. However, in other groups such as leafy, cucurbits and fruiting/legume vegetables, the expected shelf-life may not be met by up to 25-30% of consumers, and short shelf-life is generally listed as one of the key purchase barriers. Thus, in order to increase vegetable consumption, it is vital that future R&D work is consumer-focused and reflects current supply chain conditions, including assessments on external, internal and sensory quality, freshness, and shelf-life.

Recommendations

As seen above, several research gap areas offer R&D opportunities for future quality improvement, including extended shelf-life, enhanced produce appearance and composition, and higher resistance to postharvest diseases. Recommended areas include:

1. Systematic evaluation of the impact of growing region x time of year on the yield and quality of selected vegetable crops. This work could follow on from the effects found in previous projects, particularly in lettuce (VG03092) and babyleaf vegetables (VG05068, VG08166).
    a. The project could aim to develop and evaluate crop planting schedules in order to match current cultivars/cultivar types with growing regions, and times of the year to achieve an optimum balance between yield and quality/shelf-life (similar to the ones developed in Australia for lettuce, spinach, and broccoli) for other key commodities such as Asian vegetables, broccoli, cauliflower, cabbage, kale, capsicum, zucchini, cucumber, green beans, and sweetcorn;
    b. The research should be consumer-focused and thus include assessments on quality (both external and internal, including sensory evaluation), freshness, and shelf-life aimed to simulate supply chain conditions.
2. The use of silicon (e.g. potassium silicate) and other fertiliser salts (e.g. phosphates and bicarbonates) during production of leafy vegetables, cucumber, zucchini, and capsicum. Areas of investigation could include:
    a. Impacts on yield and quality, including resistance to postharvest diseases and shelf-life of leafy vegetables (e.g. lettuce, babyleaf crops, etc.), capsicum, cucumber, and zucchini;
    b. Disease reaction and activation of systematic acquired resistance (SAR);
    c. Insect control through the formation of phytoliths;
    d. Effects on nutrient uptake/utilization;
    e. Alleviation of abiotic stress, i.e. yield and quality under high stress conditions. This could also be an adaptation to climate change.
3. Investigation and ground truthing of growing conditions that results in increased expression of bioactives and antioxidants in vegetable crops. A good example would be the enhancement of glucosinolate levels in brassicas through managing sulphur and nitrogen nutrition.
4. Investigation into the regulation of salinity (EC) during production of hydroponic lettuce and other leafy vegetables to improve quality.
5. The use of short periods of deficit irrigation to improve shelf-life and quality in broccoli and leafy vegetables.
6. The use of LED light systems during production of greenhouse lettuce, spinach, and capsicum.

Scientific Refereed Publications

None to report.

Intellectual Property/Commercialisation

No commercial IP generated.

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Appendix 1: Article “Benefits of silicon in vegetables crops”

By Gordon Rogers (Applied Horticultural Research) and Roberto Marques (NSW Department of Primary Industries).

Silicon is gaining attention for helping vegetable crops to fight disease, while improving yield and quality.

Plant available silicon can increase the plant’s resistance to pathogens and insects by activating systemic acquired resistance (SAR) and promoting the formation of phytoliths which damage the mouthparts of insect pests.

Silicon can also help the plant fight so-called abiotic stress, e.g. chemical stresses such as nutrient toxicity or deficiency and salinity. It can also help the plant deal with water stress (too much or too little), sunburn and frost damage.

There is growing scientific evidence that silicon plays an essential role in bone formation and maintenance, and that higher intake of bioavailable silicon is associated with increased bone mineral density.

A recent review of the impacts of plant available silicon on vegetable crops highlighted some of the benefits in leafy vegetables, cucurbits and capsicums.

Beneficial effects on leafy vegetables

Some of the reported effects of silicon in relation to leafy vegetable crops include:

- Prolonged shelf-life and increased yield in corn salad
- Reduced nitrate uptake and nitrate content in leafy vegetables

Mache (lambs tongue, corn salad)

Silicon added to the nutrient solution of hydroponically grown baby leaf mache resulted in

- Prolonged shelf-life from 4.5 to 9 days in cultivar Gala by slowing down chlorophyll degradation and delaying leaf senescence
- Reduced nitrate uptake and content in edible tissues

Lettuce

Under field conditions, silicon applied at 2 L/ha in a formulation SiO_{2bio-} applied to Iceberg lettuce in Brazil enhanced visual quality (i.e. retained more green and reduced browning) in Iceberg lettuce in long-term storage (20 days at 5°C), but there was little treatment difference after storage for 10 days.

A recent study showed that the addition of silicon (at 50 or 100 mg/L, as potassium metasilicate) to the nutrient solution of hydroponically grown fresh-cut leafy vegetables (tatsoi, mizuna, basil, chicory, and swiss chard) in Italy, increased both silicon content and bioaccessible silicon in the leaves, with no impact on yield or leaf colour, which could offer added value marketing opportunities as a biofortified product.

Effects of silicon and other fertiliser salts on capsicum disease

The application of silicon as potassium silicate at 75 mg/L to the nutrient solution of hydroponically grown capsicum in Sri Lanka during the flowering stage reduced the fruit disease anthracnose by 70%, with no effect on growth or on fruit firmness, Brix, or soluble solids content.

In a study in Brazil, although fruit quality was not assessed, silicon as Ca silicate at 6.8 g silicon/kg of substrate reduced the severity of *Phytophthora* blight in capsicum plants, a serious fungal disease that causes rots of all parts of the plant, including fruit.

In a two-year study in Israel, five preharvest weekly applications of bicarbonate salts solutions at 0.5% w/v reduced postharvest decay development on red capsicum fruit by 45% (sodium bicarbonate) and by 82% (potassium bicarbonate), as well as reducing fruit sunburnt, foliar disease severity and leaf defoliation caused by powdery mildew, a serious disease of capsicum under greenhouse and field conditions worldwide that can significantly reduce fruit quality.

Similarly, spraying of monopotassium phosphate reduced leaf powdery mildew incidence by 75% in greenhouse-grown capsicum in Israel and in chilli grown in India under field and greenhouse conditions.

Effects of silicon and fertiliser salts on disease in cucurbits

Powdery mildew caused by the pathogens *Podosphaera fusca* or *Golovinomyces cichoracearum* is the most widespread and serious foliar fungal disease of cucurbits, which causes premature leaf senescence and exposes the fruit to sunscald. Fruit from severely infected plants are typically regarded as low quality products by the market due to poor taste, texture, and small size.

Silicon can increase plant resistance to diseases, and cucumber plants can actively uptake and moderately accumulate silicon, which can be supplied as silicate salts in the hydroponic solution or applied as a foliar spray.

In cucumber leaves, silicon deposition can inhibit colony growth of the powdery mildew fungus, presumably by providing a physical barrier to pathogen attack through increasing lignification and thus strength of cell walls. Flavonoids associated with defence can also accumulate in silicon-treated cucumber plants.

Applied silicon as silicon dioxide at 0.1 g/L to continental cucumber grown in recirculating nutrient solution in the UK increased resistance to powdery mildew. Silicon applied as potassium silicate either in the nutrient solution at 0.1 g/L or as foliar spray at 0.5 or 1.0 g/L to continental cucumber greenhouse-grown in Canada reduced the incidence of powdery mildew by up to 43–53% compared to control.

In another study with continental cucumber, greenhouse-grown in Canada, the addition of silicon as potassium silicate at 100 ppm to hydroponic nutrient media increased resistance to powdery mildew and increased fruit silicon content, but also resulted in fruit with a dull skin or bloom appearance.

Addition of silicon as potassium silicate at 100 or 200 mg/L to recirculating nutrient solution reduced root rot caused by the fungus *Pythium ultimum* in continental cucumber (cultivars Corona and Marillo) greenhouse-grown in Canada and increased the proportion of high-grade fruit.

Silicon applied as potassium silicate either in the nutrient solution at 0.26 g/L or as foliar spray at 1.31 or 2.62 g/L, respectively to greenhouse-grown zucchini in Canada, reduced the incidence of powdery mildew by up to 27–39% compared to control, whereas sprays at 0.3 g/L were ineffective and sprays at 5.19 g/L had little further reduction.

Apart from silicon, other fertiliser salts such as bicarbonates, phosphates, and chlorides, applied as foliar sprays have also been used to reduce incidence of powdery mildew, anthracnose, leaf spot and scab in greenhouse cucumber.

These salts appear to work in several ways, including altering the pH of the leaf surface, dehydrating the fungal spores, and stimulating systemic processes of plant defence.

For more information contact Dr Gordon Rogers (gordon@ahr.com.au) or Dr Roberto Marques (roberto.marques@dpi.nsw.gov.au)

Appendix 2: Article "Effects of growing environment on greenhouse cucumber quality"

By Gordon Rogers (Applied Horticultural Research) and Roberto Marques (NSW Department of Primary Industries).

Cucumber is a widely grown vegetable in Australia, with each year growers producing 14.1 million tonnes, valued at $30 million.

Some 70% of consumers buy cucumbers regularly and cucumbers are the sixth-most frequently bought vegetable in Australia.

The main commercial types are the Lebanese, continental (wrapped in plastic) the standard green slicing, and more recently, the cocktail or baby cucumbers.

What are the main quality issues?

The main quality attributes are the green skin colour, texture (firmness and crispness), flavour, size, maturity, defects and diseases. In the absence of defects, colour is one of the few practical criteria for assessing cucumber quality.

Although the cucumber is a non-climacteric vegetable (meaning its ripening is not triggered by ethylene), it will still show, albeit at a slower rate, most of the biochemical changes of ripening associated with climacteric fruit.

The fruit gradually becomes shrivelled and discoloured, and will eventually start to break down. The fruit requires careful postharvest treatments to maintain quality after harvest, i.e. cooling to 10–13°C to slow down postharvest respiration.

Interestingly, the fruit is very sensitive to chilling injury. At temperatures below 10°C, the fruit quality degrades quickly, leads to sunken areas on the skin and susceptibility to postharvest rots.

Nutrition and quality

Higher concentrations of the nutrient solution resulted in greener continental cucumber fruit with a longer shelf-life in Canada. Research also suggests that dark green skin colour is associated with longer shelf-life.

In a Florida study, nitrate was applied to continental and Lebanese cucumbers between 75 to 375 mg/L. An intermediate rate of 200 mg nitrate/L resulted in the darkest green but softer fruit at harvest.

In a Spanish study, potassium nitrate applied at rates from 5 to 40 g/m2, 10 or 20 g/m resulted in fruit with higher contents of soluble solids and sugars, and the best commercial yield. Other research indicates that fruit firmness is associated with higher levels of calcium in the fruit.

Those results suggest that adequate levels of plant nutrients during growth of cucumbers can impact on fruit quality after harvest.

Nutrition and disease

Powdery mildew on cucumber is caused by the pathogens *Podosphaera fusca* or *Golovinomyces cichoracearum* and is the most widespread and most serious foliar fungal disease of cucumbers.

A number of fertiliser salts (bicarbonates, phosphates, phosphites, chlorides, and silicates) applied as foliar sprays have been used to manage powdery mildew in cucurbits, especially cucumber. The salts appear to work in several ways, including altering the pH of the leaf surface, dehydrating the fungal spores, and stimulating processes of plant defence. For more information on this, refer to this article by Deliopoulos[1].

Silicon (plant-available silica) can increase cucumber resistance to diseases. Silicon can be supplied in the hydroponic solution or applied as a foliar spray. In cucumber leaves, silicon can inhibit colony growth of the powdery mildew fungus, presumably by providing a physical barrier to pathogen attack through increasing the strength of cell walls. This can result in slightly dull skin appearance on the fruit.

Crop management and quality

Fruit thinning and vine training can affect the quality of cucumbers.

Thinning of one-third of the fruit from the main stem and laterals in greenhouse-grown cucumbers can increase shelf-life from but reduce marketable yield by 8-10%.

Greenhouse-grown cucumbers training systems, with upper reaches' light penetration into the canopy, also results in 2–3 days' longer fruit shelf-life at 13°C, darker green fruit colour at harvest, faster fruit growth and fewer fruit per plant.

The three principles then, for growing cucumbers which can maximise yield, quality and shelf life are:

1. Use the minimum number of stems per plant
2. Orient the stems for maximum light exposure
3. Allow more than two leaves per fruit to remain in the vine (i.e. increased leaf:fruit ratio)

[1] Deliopoulos, T., Kettlewell, P. S. and Hare, M. C. 2010. Fungal disease suppression by inorganic salts: A review. *Crop Protection*, **29**, 1059-1075.

A series of eight trials with continental greenhouse-grown cucumbers in Canada confirmed that a 2–3 days longer fruit shelf-life at 13°C was associated with:

- Greener skin at harvest
- More intense incident light during cucumber production, which increased chlorophyll content in the fruit skin
- Faster fruit growth up to marketable length

Maturity stage at harvest

There is a negative correlation between fruit age at harvest and shelf-life. In other words, the older the fruit is at harvest, the shorter will be the shelf-life after harvest.

For example, if harvesting is delayed by three days beyond normal maturity, the shelf-life of that fruit will be reduced by about seven days at 13°C. These findings have been confirmed by two large studies in California and Canada.

Season effects and growing temperature

Cucumber fruit grown hydroponically in spring in Spain had lower quality at harvest than fruit grown during winter – poorer skin colour, more flesh whitening and more acid.

In an Australian experiment comparing environmental control in a greenhouse in relation to fruit quality clearly showed that the better the control, the better the quality, shelf-life and yield of a Lebanese cucumber crop[2].

The following greenhouses were compared:

1. Full control – heating when required, fan-ventilated or evaporatively cooled during the day, misting at low RH, 60–80% relative humidity (RH)
2. Moderate control – heating when required, passive ventilation during the day, ambient RH
3. Minimum control – cold nights, passive ventilation during the day, ambient RH
4. No environmental control – cold nights, minimal ventilation, cold/hot days, high RH

Although the cucumbers from the four houses looked similar at harvest, significant differences developed during storage. Cucumbers from house 4 (no environmental control) were consistently of a worse quality after storage than those from house 1 (maximum control); the other houses generally yielding intermediate results. After 12 days at 5°C + two days at 20°C, cucumbers from house 4 had more flesh rots, developed more pitting due to chilling injury, yellowed faster and were softer than those from house 1 (Table 1).

[2] Ekman, J. H., Pristijono, P., Parks, S. and Jarvis, J. 2010. Growing conditions affect postharvest quality of greenhouse cucumbers. *Acta Horticulturae*, **877**, 181-186.

Table 1. Quality attributes of cucumbers grown in four different greenhouses following storage at 5°C for 12 days + 2 days at 20°C. Mean values from four harvest dates.

Greenhouse	**Flesh rot (0-3)**	**Chilling injury (0-3)**	**Colour (H°)**	**Firmness (N)**	**Overall quality (1-5)**
1	0.5	1.0	118	60	1.8
2	0.7	1.3	118	55	1.1
3	0.9	1.3	119	55	1.0
4	0.9	1.5	115	50	0.8

* *Grades for flesh rot and chilling injury: 0 (none) – 3 (severe); H°: high number = greenest, N: high number = firmest; quality: high number = best*

Controlling the temperature and humidity inside the greenhouse had significant benefits in terms of increased storage life and reduced chilling injury. The fruit grown in the fully controlled house maintained colour and firmness following storage and were the least likely to develop rots.

For more information contact Dr Gordon Rogers (gordon@ahr.com.au) or Dr Roberto Marques (roberto.marques@dpi.nsw.gov.au)

Appendix 3: Article "Health benefits of eating vegetables"

By Gordon Rogers (Applied Horticultural Research) and Roberto Marques (NSW Department of Primary Industries).

The Australian vegetable industry faces two major challenges: a saturated domestic market and rising input costs.

At the same time, Australians are not eating enough vegetables. The National Health and Medical Research Council recommends that adults eat at least two serves of fruit and five serves of vegetables a day to ensure good nutrition and health. However, the 2011–12 Australian Health Survey found that while 48.3% of Australians ate the recommended number of serves of fruit only 8.3% met the guidelines for vegetable consumption (Figure 1).

There is no doubt that diets rich in vegetables contribute greatly to improved human health. Increased consumption of vegetables, in particular, has been associated with reduced rates of cardiovascular disease, cancer, diabetes, obesity, stroke and other diseases and disorders.[3] Despite this, over half the population does not even consume three servings of vegetables a day.

Increasing consumption of vegetables to five serves per day would double the size of the domestic market for vegetables, something sorely needed by Australian vegetable growers. It would reduce the financial pressure on vegetable growers, and greatly improve the health of the population.

Figure 1. Vegetable consumption by adult Australians; results from the 2011-2012 Australian health survey.

The Australian vegetable industry does not have a marketing levy, but that does not mean there isn't anything that the industry can do about better marketing of Australian vegetables. At least one strategy that could be funded more broadly on the basis of reducing public health spending would be the promotion of the health aspects of vegetables, justified in a similar way to anti- smoking health warnings and promotion of the health benefits of quitting smoking and its corollary: the dangers of not doing so. Instead of government spending increasingly vast amounts of money on continually

[3] Causes of Death, Australia, 2011 (ABS).

enlarging the medical infrastructure to treat preventable diseases, it could spend some of those huge outlays on disease prevention, through promotion of healthy eating.

There is an exciting opportunity for the Australian vegetable industry to leverage public health funds earmarked for promoting healthy lifestyles into promoting vegetable consumption, especially if the Australian industry can show they can deliver the health benefits of vegetables to Australian consumers.

Healthy eating needs promotion, and the health benefits need to be linked to convenience, taste and innovation[4]. Promotion based on health alone has been trialled in the "Go for 2&5" campaign (http://www.gofor2and5.com.au/) and Vital Vegetables® which focused on glucosinolate-enhanced broccoli and high-carotenoid capsicums. These initiatives need strong marketing supported by good science and Australian vegetable growers knowing how to produce healthy Australian vegetables.

Bioactives in vegetables

In addition to being important sources of vitamins, minerals and fibre, the presence of health-promoting bioactive compounds such as antioxidants and pigments has increased interest in vegetable consumption. As a result, health and well-being have been increasingly recognised as powerful non-sensory drivers for vegetable consumption. This has been confirmed by recent surveys showing that health attributes are one of the key drivers of purchase by Australian consumers for most vegetables.

Polyphenols are an important part of the diet and are believed to have many health benefits, due to their antioxidant and anti-inflammatory properties. They include anthocyanins, flavonoids, flavanols and catechins (found in tea)[5]. Evidence has accumulated on the role of polyphenols in reducing the risk of cardiovascular diseases, certain cancers, inflammatory states (e.g. rheumatoid arthritis), cataracts, Parkinson's disease, Alzheimer's and other disorders associated with ageing[6]. The ideal daily intake of polyphenols is 1–2 g per day, and typical polyphenol content in vegetables is shown in Figure 2.

Glucosinolates are a group of sulphur-rich plant defence metabolites found almost exclusively in Brassica vegetables which have shown anti-carcinogenic and anti-inflamatory activity. The frequent dietary intake of brassicas have been associated with reduced risks of some forms of cancer[7].

Carotenoids are responsible for the colour of vegetables such as capsicums, sweet corn, carrots and sweet potato. Some leafy vegetables, such as spinach, are also high in carotenoids6 (Figure 3). All carotenoid compounds are potent antioxidants and have been associated with a wide range of health benefits.

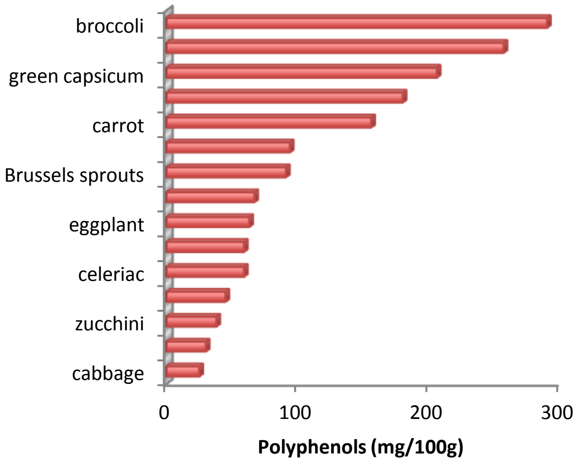
[4] Tony Worsley. 2014. Sustaining Lives: Plants for health. IHC2014 Brisbane.

[5] Scalbert, A., Williamson, G. 2000. Dietary intake and bioavailability of polyphenols. *Journal of Nutrition*, **130**, 20735-20855.

[6] Cieslik, E., Greda, A., Adamus, W. 2006. Contents of polyphenols in fruit and vegetables. *Food Chemistry,* **94**, 135-142.

[7] Herr, I. and Buchler, M. W. 2010. Dietary constituents of broccoli and other cruciferous vegetables: Implications for prevention and therapy of cancer. *Cancer Treatment Reviews*, **36**, 377-383.

β-carotene is an important antioxidant and is the precursor to vitamin A. The carotenoid zeaxanthin, primarily found in sweet corn[8], and lutein, common in green vegetables, have been shown to reduce the risk of macular degeneration and cataracts[9]. Anthocyanins are the red and purple pigments found in purple carrots, purple cabbage, eggplant skin and Jacaranda cauliflower. Studies have suggested that anthocyanins may be useful in obesity control, diabetes control, cardiovascular disease prevention and improvement in eye and brain functions.



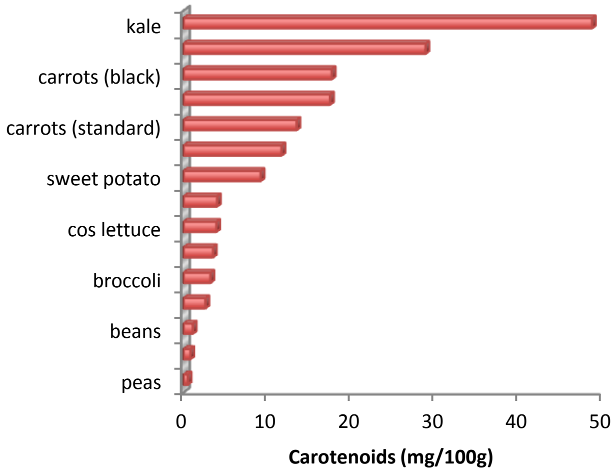


Figure 2. Average total polyphenols in vegetables

Figure 3. Average total carotenoids in

There has been a large research focus internationally on bioactives in vegetables. There is an ISHS commission dedicated to this area which includes an active group of researchers who coordinate international conferences each year, and publish widely.

How to maximise bioactives in vegetable crops

In principle, bioactives protect plants from various types of oxidative stress. Generally, when a plant is stressed by irrigation deficiency, low nutrient availability (especially nitrogen), or other stresses, the plant responds by producing antioxidants to protect itself. There are excellent reviews of this for all the vegetable crops covered by this project[10]. In broad terms, applying a mild stress to vegetable crops increases the amount of antioxidant they produce. There are also some new ways of

[8] Fanning, K.J., Martin, I., Wong, L., Keating, V., Pun, S., O'Hare, T. 2009. Screening sweetcorn for enhanced zeaxanthin concentration. *Journal of the Science of Food and Agriculture*, **90**, 91-96.

[9] Moeller, S.M., Jacques, P.F., Blumberg, J.B. 2000. The potential role of dietary xanthophylls in cataract and age-related macular degeneration. *Journal of the American College of Nutrition*, **19**, 522s-527s.

[10] Schreiner, M. 2005. Vegetable crop management strategies to increase the quantity of phytochemicals. *European Journal of Nutrition* **44**, 85-92.

increasing bioactives in vegetables such as exposing plants to a particular wavelength of light using low cost LEDs[11].

Regulation of health claims in Australia and internationally

Food Standards Australia New Zealand (FSANZ) regulates health claims and food labelling in Australia and New Zealand. They allow *source* and *good source* claims for specific substances. A *source* claim can be made when one serve of the product contains more than 10% of the recommended daily intakes (RDI) set by FSANZ for that nutrient. A *good source* claim can be made if one serve contains more that 25% of the RDI. FSANZ also allows some specific health claims, but a direct link between the food and the health response in humans must be demonstrated. Other countries have a range of regulatory requirements in relation to food labelling and health claims.

The bottom line

Anything that can be done to encourage consumers to eat more vegetables will increase the size of the market for Australian vegetable growers, and at the same time improve the health of Australians.

It's a classic win–win situation.

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[11] Bian, Z. H., Yang, Q. C. and Liu, W. K. 2015. Effects of light quality on the accumulation of phytochemicals in vegetables produced in controlled environments: A review. *Journal of the Science of Food and Agriculture*, **95**, 869-877.

Appendix 4: Benefit cost analysis - Applied silicon in cucumber (A case study)

As this project was basically a review of the literature, no experimental work was conducted to provide any substantial data to underpin a benefit cost analysis (BCA) or to validate results reported by other researchers. Because of that, the BCA presented in this appendix is a purely hypothetical exercise aimed to illustrate the potential of using a pre-harvest practice to improve quality and/or yield of a vegetable crop. The application of silicon to greenhouse-grown cucumber was chosen as a case study, given its potential to increase the proportion of marketable (i.e. first grade) yield shown in the review (section 3.1). However, no conclusions or recommendations can be drawn from this BCA without proper experimental work to test and confirm the applicability of this practice under local and current conditions, as well as accounting for typical variations in treatment responses.

Production costs and marketable weights of greenhouse-grown Lebanese cucumber were based on HAL's project VG07096 'Improving greenhouse systems and production practices (greenhouse technology systems component)', led by NSW DPI (Dr Sophie Parks) and completed in 2011.

The following assumptions were made in the analysis:

- The analysis considered the extra costs and extra benefits of applying silicon over a 5-year period;
- Costs from that project were based on 2010 values and were adjusted by a cumulative price index of 12% (i.e. annual inflation rates from 2010-2016);
- Production system was assumed on greenhouse system with moderate control and three crops per year. Cost and yield values were expressed in $\$/m^2$ based on a plant density of 2.5 plants/ m^2. Each crop was assumed to be harvested 2 or 3 times per week over an eight week period;
- Extra costs were determined by estimating the costs of applying silicon as potassium silicate supplied by Nutri-Tech Solutions, Yandina, Qld. Costs were based on current quotes (i.e. $217 for a 20 L package of a liquid source of potassium silicate with 17.3% silicon, as in June 2016) to be applied as a foliar spray at the rate of 0.3 L/100 L (up to 2L/ha equivalent) solution every two weeks (except during flowering) as recommended. Costs of humic acid, used to buffer alkalinity of the potassium silicate, and labour costs associated with extra applications were also included;
- Extra benefits were estimated by assuming that the application of potassium silicate would increase marketable yield (i.e. first grade fruit) by 5%. Data from the literature with greenhouse-grown continental cucumber shows large variation in plant responses to applied silicon, with increases in marketable yields ranging from nil to up to 37%, depending on a number of variables such as cultivar, location, season, and crop production method;
- A discount rate of 3% was used to calculate net present value (NPV) and benefit cost ratio (BCR).

Under those assumptions, the BCA would result in a positive BCR (Table 1). In this scenario, the present worth of the net benefits from applying silicon would exceed the present worth of not applying it. The results suggest that for every dollar invested in applying silicon, $1.50 per square metre would be returned. And that is considering a conservative increase of 5% in marketable yield. An increase of 10% in marketable yield would double the investment for every dollar, whereas a minimum increase of 3.5% would be required to level the investment over a 5-year period.

Table 1 – Benefit cost analysis – Silicon application to greenhouse-grown cucumber

Year	**Extra benefits**	**Extra costs**	**Net benefit flow**	**Discounted benefits**	**Discounted costs**	**Discounted net benefits**
	($/m^2)					
1	4.2	2.8	1.4	4.1	2.7	1.4
2	4.2	2.8	1.4	4.0	2.7	1.3
3	4.2	2.8	1.4	3.9	2.6	1.3
4	4.2	2.8	1.4	3.7	2.5	1.2
5	4.2	2.8	1.4	3.6	2.4	1.2
Present value benefits ($/m^2)				19.3		
Present value costs ($/m^2)					12.9	
Net Present Value (NPV) - ($/m^2)						**6.4**
Benefit Cost Ratio (BCR)						**1.50**

Appendix 5: List of symbols and abbreviations

B	boron
°C	degree Celsius
Ca	calcium
cm	centimetre
CO_2	carbon dioxide
Cu	copper
cv	cultivar
cvs	cultivars
dS	deciSiemens
Fe	iron
g	gram
ha	hectare
K	potassium
kg	kilogram
L	litre
m	metre
m^2	square metre
M	million
meq	milliequivalent
mg	milligram
Mg	magnesium
mM	millimole
Mn	manganese
Mo	molybdenum
N	nitrogen
Na	sodium
NaCl	sodium chloride
P	phosphorus
ppm	parts per million
RH	relative humidity
s	second
S	sulphur
Se	selenium
UK	United Kingdom
μM	micromole
USA	United States of America
Si	silicon
Zn	zinc