

Review

Quality of fresh-cut fruits and vegetables as affected by exposure to abiotic stress

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Abstract

Abiotic stress potential has a significant impact on quality and nutritional status of fresh cut fruits and vegetables. However, very little work has been directed to defining and documenting the abiotic stresses that occur during fresh cut processing, packaging and storage. Many indicators can be used to infer impact of abiotic stress such as discolouration (e.g. browning of fresh-cut surfaces), increased respiration and ethylene evolution, loss of flavour and texture, weight loss, decline in levels of ascorbate, development of off-odours, membrane breakdown, and tissue softening. Using these indicators, a case is made from existing literature for the importance of abiotic stress in determining quality of fresh cut products. Impact of preharvest stress, genetic variation and stress response, injuries incurred after harvest, and storage regimes will be discussed in detail. From this literature review, it becomes clear that current understanding of abiotic stress levels and mechanisms is relatively sparse. Further research is required to better document this issue as well as to develop effective strategies to modulate stress responses such that quality and nutritive value of fresh cut fruits and vegetables can be improved.

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1. Introduction

A large proportion of published plant research is related to effects of abiotic stress on physiological, biochemical, and/or gene expression aspects of growing plants. An appreciable amount of scientific literature has also appeared regarding impact of production, processing, and postharvest stresses on quality attributes of intact fruits and vegetables. However, relatively little has been published on the effects of abiotic stresses arising from preharvest production, processing techniques, storage environments, and/or packaging protocols on the consequent quality of fresh-cut fruits and vegetables. The shelf-life of uncut or fresh-cut produce is almost invariably dependent upon the stress tolerance and stress-induced senescence dynamics of the raw commodity in question since the process of natural senescence is an uncommon phenomenon in fresh-cut products (Lester, 2003).

The documentation of fresh-cut abiotic stress has mainly focused on observations of symptoms as opposed to discussion of mechanisms of stress-induced change; hence most of this review will reference the reports of symptoms. These symptoms of fresh-cut product abiotic stress effects include discolouration, especially browning of fresh-cut surfaces due to tissue disruption and subsequent oxidative processes (Bhagwat et al., 2004), increased respiration and ethylene evolution (Aguayo et al., 2004a), loss of flavour and texture (Lamikanra and Richard, 2002), weight loss/dehydration (Piagentini et al., 2002), decline in levels of nutrients such as ascorbate (Gil et al., 2006), development of off-odours (Beaulieu, 2006a), membrane breakdown (Hodges et al., 2000), and tissue softening (Aguayo et al., 2004a). These symptoms can be modulated by many factors which will be discussed below.

As stress is generally defined as any environmental factor potentially unfavourable to living organisms (Levitt, 1972), with the exception of decay (i.e. a biotic factor), quality losses in actual fresh-cut produce can be directly or indirectly attributable to a combination of abiotic stress and stress-induced senescence (Lester, 2003). Fresh-cut fruits and vegetables demonstrate increased respiration rates and wound-induced

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ethylene production, and increase the surface area per unit volume, thus exacerbating water loss (Toivonen and DeEll, 2002). Temperature-induced injury during low-temperature storage, physical abrasions resulting from processing, and packaging options which induce abusive atmospheres or desiccation, are all examples of abiotic stresses which affect physiological and metabolic properties of fresh-cut fruits and vegetables, resulting in undesirable changes in product flavour, texture, and nutritional quality (Toivonen, 2003a).

Fresh-cut quality can be affected by both internal and external factors, where internal factors represent metabolic characterizations which affect fresh-cut processing and storage, and external factors represent environmental situations which inhibit or exacerbate the manifestation of the internal factors. Examples of internal factors include morphological, physiological, and biochemical defense mechanisms, genotype, stress-induced senescence programs, and processing maturity, whereas examples of external factors include storage temperature, humidity, cutting-knife sharpness, and chemical treatments.

The primary sources of abiotic stress, how fresh-cut produce responds to stresses, and how stress translates to quality decline of fresh-cut fruits and vegetables will be addressed in this review.

2. Preharvest stress effects and genetic factors

The postharvest quality of fruits and vegetables can be influenced by a large variety of preharvest and genetic factors, but it is generally accepted that produce which is stressed in the preharvest stage will invariably have reduced postharvest quality (Weston and Barth, 1997; Galvis-Sánchez et al., 2004; Calderon-Lopez et al., 2005). A good example of how preharvest factors can influence fresh-cut quality is reported by Hong et al. (2000). They found that slices made from tomatoes (*Lycopersicon esculentum* Mill.) that were harvested from plants grown using hairy vetch mulch were firmer, had less water-soaked areas (indicative of chilling-related injury), and exhibited less increases in electrical conductivity (indicator of stress-induced membrane damage) than slices from plants grown using black polyethylene mulch. While this is the only one of a few examples of how preharvest factors affect fresh-cut quality, there are numerous examples in whole fruit and vegetable handling that provide a basis to extrapolate practices to improve fresh-cut quality through preharvest crop management. Controlled drought during production (regulated deficit irrigation) has been shown to increase soluble solids content and coloration in peaches (*Prunus persica* L.; Gelly et al., 2003). In another study, low light intensity resulted in shortened shelf-life of greenhouse grown long English cucumbers (*Cucumis sativus* L.) primary due to the fact that low light led to reduction in total chlorophyll content of the cucumber skin (Lin and Jolliffe, 1996). A study on fruit quality of 'Kensington Pride' mangos (*Mangifera indica* L.) produced on adjacent sites with and without gravel showed differences in quality parameters such as percent lenticel spotting and body rots during 4 weeks of storage (Hofman et al., 1997). However, comparison of soil composition between the two sites was not reported. A final example of how preharvest production management can affect postharvest quality is the spraying of plum (*Prunus domestica* L.) fruit

trees with titanium in combinations with magnesium and calcium (Alcaraz-Lopez et al., 2003). Titanium-treated fruit were larger, firmer, and experienced less weight loss during storage than water-sprayed controls.

Cultivar/genetic effects on the sensory and nutritional quality of fresh-cut fruits and vegetables have received considerable attention. It has been well documented that different cultivars can vary widely in response to biotic and/or abiotic stresses and in bioactive components (e.g. Hodges et al., 1995, 1996, 1997; Hodges and Lester, 2006; Weston and Barth, 1997; Lee and Kader, 2000). Differences in fresh-cut product quality between species is almost entirely dependent upon abiotic or biotic stress tolerance involving aspects of species-specific morphology, physiology, genetics, and/or biochemistry. Stress tolerance can also affect stress-induced senescence dynamics, and natural senescence may also play a role in certain cases. As an example, slices of overripe peach have a shelf-life of 2 days or less compared to slices of overripe nectarine (*P. persica* var. nectarina) which had a shelf-life of 3–6 days (Gorny et al., 1998). In subsequent work, fresh slices made from 13 cultivars of nectarines and 8 cultivars of peach demonstrated wide differences in shelf-life potential, ranging from 1 to 12 days (Gorny et al., 1999).

Different cultivars within a species can also vary in fresh-cut quality. Although no specific published research has associated shelf-life potential of a fresh-cut product with the stress tolerance of its un-cut postharvest or preharvest form, it can be assumed that a fresh-cut product's sensory and nutritional quality is highly dependent upon its ability to respond to stress, and that its stress response potential should be related to that of its un-cut form. Examples of shelf-life quality comparisons between cultivars of fresh-cut fruits and vegetables include firmness work with fruit slices from five MCP-treated apple (*Malus × domestica* Borkh) cultivars (Calderon-Lopez et al., 2005), sensory acceptability (overall eating quality) in slices from two apple cultivars (Bhagwat et al., 2004), browning in five cultivars of potatoes (*Solanum tuberosum* L.; Cantos et al., 2002), volatile and quality attributes in six cantaloupe (*Cucumis melo* L.) cultivars (Beaulieu, 2005), and a range of quality attributes for mango cubes (Rattanapanone et al., 2001; Poubol and Izumi, 2005a,b) and carrots (*Daucus carota* L.; Ahvenainen and Hurme, 1994). Within each of the above examples, the cultivars were treated the same, and each of these cultivar comparisons indicated differences in the cultivars' stress response to particular fresh-cut processing and/or storage protocols.

Maturity of the harvested product can also influence its response to fresh-cut stress, thus emphasizing the fact that stress tolerance changes with maturity. The fresh-cut industry often prefers to process firmer and less mature fruit to improve shelf-life duration. For example, Gorny et al. (1998) found that although overripe peach and nectarine slices had a higher organoleptic sensory rating than mature green fruit, slices from the overripe fruit demonstrated significantly shorter shelf-life compared to less mature fruit based on visual quality. In addition, slices of slightly under ripe Conference pears (*Pyrus communis* L.) exhibited less browning and softening than those from more ripe fruit (Soliva-Fortuny et al., 2004). Similarly, mature green apple slices maintained their initial firmness and colour

better than partially ripe and ripe slices (Soliva-Fortuny et al., 2002). Generally, flavours in fresh-cut products decline more rapidly than does appearance, as physical cutting stress during fresh-cut processing causes mixing of enzymes and substrates, contributing to flavour changes due to two processes: (1) principal flavour-related volatile losses, and (2) synthesis of stress related off-flavour volatiles. More often than not, processing maturity can influence flavour volatile levels/profiles during storage (Beaulieu et al., 2004). Beaulieu (2006b) showed that more mature cantaloupe fruit contained greater quantities of flavour-related compounds, and concentrations of these decreased after 7 days of storage at 4 °C. Other attributes can also be affected by processing maturity. For example, Lana and Tijssens (2006) reported that the hydrophilic and lipophilic antioxidant levels (measured as the capacity to scavenge the ABTS^{•+} radical) were higher in slices of more mature tomato. Reyes et al. (2007) suggests that the increase in antioxidant capacity following wounding of fresh produce is dependent upon the fruit or vegetable selected.

3. Postharvest physical damage

Wounding is one of the primary stresses experienced by fresh-cut produce, which by its very definition undergoes some form of processing (e.g. slicing, dicing, chopping, trimming, peeling, coring, and/or shredding). Internal and external factors that can affect the wound response include species, cultivar, maturity, storage/processing temperature, cutting protocols, CO₂ and O₂ levels, and water vapour pressure (Brecht, 1995; Cantwell and Suslow, 2002). Cutting shape has also been identified as having an effect on quality of fresh-cut commodities, often in association with precut product turgidity. Cut cylinders of melon stored for up to 10 days were firmer than slices or trapezoidal sections, but exhibited a higher degree of translucency than the other two cuts; trapezoidal cutting was determined to be the optimal protocol (Aguayo et al., 2004a). Similarly, shelf-life quality of papaya (*Carica papaya* L.) slices stored at 5 and 10 °C was 2 and 1 days, respectively, longer than that of cubes (Rivera-López et al., 2005). The sharpness of the cutting blade may also affect quality attributes of fresh-cut products. Portela and Cantwell (2001) demonstrated that melon cylinders cut with a blunt blade exhibited increased ethanol concentrations, off-odour scores, electrolyte leakage, and higher potential for ethylene production than in comparison to pieces processed with a sharp blade. Similarly, use of sharp cutting implements will also reduce the wound response, lignin accumulation, white blush, softening and microbial growth in fresh-cut carrots (Bolin and Huxsoll, 1991; Tatsumi et al., 1991; Barry-Ryan and O'Beirne, 1998). This work collectively suggests that cutting-induced injury affects immediate visual quality of the products and also has longer-term effects on metabolism with consequent quality changes that are detected at a later time.

The actual cutting process results in major tissue disruption as previously sequestered enzymes and substrates mix, hydrolytic enzymes are released and signaling-induced wounding responses may be initiated, as shown by Myung et al. (2006) for strawberries (*Fragaria ananassa* L.). Wound-induced sig-

naling is initiated at the site of injury, and then migrates into adjacent, non-wounded, tissue where it can affect such metabolic activities as phenolic production in fresh-cut lettuce (*Lactuca sativa* L.; Choi et al., 2005). In wounded lettuce leaf, the signal arises within 30 min of damage, and moves into unwounded tissue at 0.5 cm h⁻¹ (Ke and Saltveit, 1989). A number of volatile compounds may be released upon wounding, including phenylpropanoids, lipoxygenase derived compounds, and terpenoids as demonstrated in strawberries (Myung et al., 2006). Jasmonic acid, auxin and abscisic acid, as well as active oxygen species (AOS), have all been associated with wounding of tissues of numerous plant species (Swamy and Smith, 1999; Hodges et al., 2004; Mur et al., 2006; Takabatake et al., 2006). Salicylic acid, which can act synergistically or antagonistically with jasmonic acid (Lee et al., 2004), may also have a role in the wound response (Saltveit et al., 2005). The jasmonic acid mediated wound signal transduction pathway requires the activation of a wound-induced protein kinase (WIPK), a defence related mitogen-activated protein kinase (MAPK) (Seo et al., 1999). Another MAPK, the salicylic acid-induced protein kinase (SIPK), is activated in response to a number of abiotic and biotic stresses (Zhang and Klessig, 1997). SIPK has been reported to function upstream of WIPK in an AOS-based signal transduction pathway (Samuel and Ellis, 2002). Enzymatic activation of both WIPK and SIPK are induced by wounding or pathogen infection (Takabatake et al., 2006).

One of the most common responses to wounding in plant tissue is an increase in both respiration rate and ethylene production (Saltveit, 1997; Escalona et al., 2003; Saltveit et al., 2005). Wound-induced respiration has been associated with enhanced synthesis of enzymes involved in the respiratory pathway and to a transitory increase in aerobic respiration in fresh-cut carrots (Surjadinata and Cisneros-Zevallos, 2003). In addition, phenolic levels are also increased through wound-induction of phenylalanine ammonium lyase (PAL; EC 4.3.1.5), the committed enzyme in phenolic biosynthesis; these phenolics can be oxidized by polyphenol oxidase (PPO; EC 1.10.3.1) and peroxidase (POD; EC 1.11.1.7) to quinones, which ultimately polymerize to produce the browning appearance common to wounded lettuce (Degl'Innocenti et al., 2005). 2-Aminoindane-2-phosphonic acid (AIP), an inhibitor of PAL and glyphosphate, an inhibitor of 5-enol-pyruvylshikimate-3-phosphate synthase of the shikimate pathway, showed significant inhibition of the browning reaction of cut lettuce (Peiser et al., 1998; Hisaminato et al., 2001). Recent work by Saltveit et al. (2005) has implicated the phospholipid signaling pathway in wound signaling associated with phenolic metabolism in wounded lettuce leaf tissue. A common result of the fresh-cutting process is that overall activities of PAL and often POD and/or PPO increase in response to cutting. This response has been reported in fresh-cut potato strips (Cantos et al., 2002), broccoli florets (*Brassica oleracea* var. *italica*; Gong and Mattheis, 2003), jicama (*Pachyrhizus erosus* L.) cylinders (Aquino-Bolaños et al., 2000), carrots (Goldberg et al., 1985), and lettuce leaf segments (Hisaminato et al., 2001; Murata et al., 2004). Campos-Vargas et al. (2005) noted that wounding lettuce leaves increased PAL activity by approximately eightfold, and that maximum accumulation of both PAL

mRNA and enzymatic activity occurred 24 h following wounding.

Sulphites have traditionally been used as a method to prevent browning of fresh-cut produce, but their use in processed fruits and vegetables was banned in 1986 by the U.S. Food and Drug Administration (FDA, 1986). Hot-water dips have been proposed as a treatment to reduce browning development in fresh-cut tissues because of their demonstrated effect on delaying the wound-induced production of PAL (Saltveit, 2000). Evidence from studies with fresh-cut lettuce suggests that the heat treatments, while not affecting the increase in PAL mRNA, inhibit the accumulation of PAL protein either by down-regulating the translation process or by accelerating the turnover of PAL protein in Romaine lettuce (Campos-Vargas et al., 2005). Other treatments to inhibit enzymatic browning of fresh-cut apples, Chinese cabbage (*Brassica campestris* var. Pekinensis), endive (*Cichorium endivia* L.), lettuce, melons and pears include low-oxygen atmospheres and dips containing such compounds as ascorbate, 4-hexylresorcinol, erythorbic acid, citric acid, and/or calcium (Castañer et al., 1997; Kim and Klieber, 1997; Gil et al., 1998; Luna-Guzmán et al., 1999; Dong et al., 2000; Soliva-Fortuny et al., 2005). It is well known that ascorbic acid reduces browning incidence by reducing *o*-quinones back to phenolic compounds prior to polymerization and subsequent formation of coloured pigments (Gil et al., 1998). Most of the other anti-browning compounds listed above have modes of action ranging from direct enzyme inhibition of PPO to pH-induced inactivation of enzymes (Garcia and Barrett, 2002).

Fresh-cut processing can also affect other aspects of product metabolism. For example, activities of both carboxyl esterases (Lamikanra and Watson, 2003) and lipases (Lamikanra and Watson, 2004) of fresh-cut cantaloupe melons are influenced by cutting. In comparing fresh-cut with whole pineapple (*Ananas comosus* (L.) Merr.), mango, cantaloupe, watermelon (*Citrullus lanatus* var. *lanatus*) strawberry and kiwi fruit (*Actinidia deliciosa*), Gil et al. (2006) showed species-specific cutting-induced losses during storage in the antioxidant carotenoids (0–25%) and ascorbate (≤ 5 to 25%), but found that fruit visual quality was appreciably reduced prior to significant nutrient loss. A decline in ascorbate levels during storage is a common response in postharvest fruits and vegetables (Hodges et al., 2001; Hodges and Forney, 2003), though often ascorbate levels can be maintained or even increase in fresh-cut potatoes (Tudela et al., 2003). Different results may well be dependent upon processing and storage protocols used in the different studies. Cutting of fruits and vegetables can enhance their total antioxidant capacity, though this is primarily through increases in wound-induced phenolic levels as opposed to increases in antioxidants such as ascorbate (Reyes et al., 2007). Another concern is that biases in these total antioxidant capacity assays towards ascorbate and carotenoids (Hodges and Lester, 2006) may also confound results.

4. Storage conditions

The two storage parameters that will primarily be considered in this section are storage temperatures and atmospheric compo-

sitions; given the amount of recent work pertaining to chemical and alternative preservation techniques of fresh-cut commodities, these topics warrant a review of their own. It is not always easy to separate interactions between chilling stress and physical damage or other storage protocol during fresh-cut storage, and characterizing the individual effects of less-than-optimum cold temperatures and storage atmospheres on un-cut commodities can often assist in elucidation of how each of these storage conditions may impact quality of resultant fresh-cut products.

Exposure to cold temperatures following harvest in order to minimize and/or inhibit the effects of wounding stress is recognized as one of the principal factors controlling quality of fresh-cut leafy vegetables (Artés and Allende, 2005). As with un-cut products, often a temperature just above that which would induce chilling injury provides optimal quality benefits. Although 0 °C is usually the desirable temperature for most fresh-cut products, in actuality many of them are shipped and marketed at temperatures ranging from 5 to 10 °C (Aguayo et al., 2004b). A good example of the importance of cold temperatures for shipping and handling of fresh-cut fruits and vegetables pertains to celery (*Apium graveolens* var. *dulce*). Internal tissue disorganization (pithiness) in fresh-cut celery occurs along with yellowing, enzymatic browning and whitening of cut surfaces, and off-odours in product that is stored for up to 27 days at 10 °C which is in stark contrast to the highly acceptable quality of fresh-cut celery when it stored for the same period of time at 0 °C (Viña and Chaves, 2003). Duration of cold storage also has an impact on final product quality. For example, overall quality declined, microbial load increased, and sensorial quality declined for fresh-cut tomato stored at 0 °C over 14 days but these changes occurred less rapidly than in product that was held at 5 °C (Aguayo et al., 2004b).

Chilling injury of fresh-cut products can manifest diverse symptoms, although the majority of the published work on chilling injury of fresh-cut products is on tomato slices or wedges (Hong and Gross, 2001; Aguayo et al., 2004b; Jeong et al., 2004) where mealiness, due to altered cell wall pectin solubilization, and water-soaked areas are common responses to chilling injury in tomato slices (Hong and Gross, 2000). Fresh-cut pieces of jicama root exhibited surface browning due to increased phenolic levels and activities of PPO and PAL when stored at 5 or 10 °C; storage at 0 °C led to little change in visual quality over 10 days (Aquino-Bolaños et al., 2000). It is possible to extrapolate the symptoms of chilling injury occurring in un-cut fruits and vegetables to their fresh-cut products. Such injury symptoms to un-cut commodities include reduction in firmness, increased rates of electrolyte leakage, changes in texture, increases in soluble solids content, internal browning, failure to ripen, surface lesions, skin/peel darkening, decreases in colour, water soaking, bleaching, increases in ethylene and CO₂ production (e.g. Flores et al., 2004; Concellón et al., 2005; Salvador et al., 2005; Ratule et al., 2006). Much of the chilling injury symptoms observed in fresh-cut and un-cut postharvest products are due to lipid membrane phase separations, weakened hydrophobic bonding affecting protein-protein and protein-lipid interactions, and effects on cell signaling processes (Hodges, 2001). In particular, physical transition of the membrane from the liquid-

crystalline to a solid-gel phase during chilling, a process highly dependent upon degree of saturation of the membrane lipids, effectuates many chilling injury related symptoms. Membranes, which depend on fluidity, begin to solidify at chilling temperatures, leading to issues with membrane integrity/leakiness, solute diffusion, tissue water loss, and membrane-bound proteins. Sub-optimal chilling temperatures may also accelerate oxidatively induced senescence due to disruptions in electron transport chain-associated membranes and can lead to accumulation of AOS as well as reduce scavenging efficacy through such factors as temperature related inactivation of antioxidants and/or impeded antioxidant turn-over (Hodges et al., 2004). These AOS are associated with superficial scald, lipid peroxidation, core browning, pigment bleaching, protein inactivation, lesions, and mutations of nucleic acids (for reviews on oxidative stress and postharvest quality, see Hodges, 2003 and Hodges et al., 2004).

A larger percentage of fresh-cut products are stored and marketed in modified atmosphere packaging (MAP) in conjunction with chilled storage and other preservation protocols. MAP essentially maintains the quality of fresh-cut products by matching the oxygen transmission rate (OTR) of the packaging film to the respiration rate of the packaged product; O₂ and CO₂ levels within the package can also change as a function of area of the film as well as ambient temperature (Jacxsens et al., 2000; Al-Ati and Hotchkiss, 2003). Immediately after processing and packing, packages are often flushed with N₂ to a desired level of O₂ in order to control browning. When MAP able to generate optimal gas conditions (moderate to low O₂ and high CO₂ levels) is applied, substantial reductions in respiration rates, oxidative stress, tissue senescence, ethylene sensitivity, low-temperature injury, and microbial/insect damage to un-cut horticultural products have been documented (Hodges et al., 2004; Artés and Allende, 2005). Advantages of MAP applications using un-cut horticultural commodities often translate into similar quality benefits with their fresh-cut derivatives. As examples, MAP treatments of tomato slices led to better appearance and overall quality than ambient air-packaged controls (Aguayo et al., 2004b). Naturally attained MAP as well as initially flushed-gas MAP led to lower microbial infection, less translucency and better colour retention in fresh-cut cantaloupe cubes (Bai et al., 2001). Moreover, MAP-treated fresh-cut kohlrabi (*B. oleracea* var. *gongylodes*) had reduced microbial population growth and better colour retention than air-stored material (Escalona et al., 2003). However, using MAP protocols for fresh-cut fruits and vegetables has often led to the generation of anaerobic conditions and/or high CO₂ levels which ultimately have a detrimental effect on product quality through production of ethanol, acetaldehyde, off-flavours and odours (e.g. Beaulieu, 2006b; Saltveit, 2003). This can occur due to improper film selection or flushing protocols, variation in respiration rates from different cultivars or varieties, seasonal variation, and storage duration of the product prior to fresh-cut processing (Kim et al., 2005a,b). Storage of fresh-cut carrots for 7 days in 0.5 and 2.0% O₂ atmospheres caused increases in ethanol and acetaldehyde levels and in activities of alcohol dehydrogenase and pyruvate decarboxylase in comparison with air stored material; no associated sensory studies were per-

formed (Kato-Noguchi and Watada, 1997). Fresh-cut cilantro (*Coriandrum sativum* L.) leaves placed in film with an OTR of 1700 mL day⁻¹ m⁻² exhibited a rapid decrease in O₂ and increase in CO₂ accompanied by an increase in electrolyte leakage, off-odour development, and a decrease in visual quality; leaves placed in films with 3500 or 6200 mL day⁻¹ m⁻² better maintained quality (Luo et al., 2004). Protocols involving delayed MAP in order to avoid the spike in respiration associated with processing (Kim et al., 2005a), the use of argon instead of nitrogen as it reduces microbial growth and better maintain product quality, and super-atmospheric oxygen MAP (higher than 70 kPa O₂) to inhibit decay have been investigated in efforts to improve the MAP process (Artés and Allende, 2005).

5. Conclusions

Fresh-cut processing and packaging protocols result in stress for fruit and vegetable tissues and much of this has been described as a shorter shelf-life for fresh-cut versus intact fruits and vegetables (Gil et al., 2006). The key to developing improved shelf-life, quality and nutritional status in fresh-cut products is to first accept that any process being applied results in a stress-induced change in the tissue physiology and metabolism. Once the mechanism of the stress-induced change is understood, then approaches to ameliorate the stress can be developed in a reliable manner. Many of the approaches to resolving quality loss are in fact approaches which modulate stress-induced changes (Toivonen, 2003b). With this perspective, researchers may find better answers to managing stress of their product and consequently improve quality retention and shelf-life of fresh-cut fruit and vegetable products.

Two excellent examples of how modulation of abiotic stress responses can be successfully used to improve quality retention pertain to the resolution of the “white blush” problem in fresh-cut carrots and the cut-edge browning problem in lettuce. In both cases wounding induces ethylene production and increases PAL activity and lignification (Ke and Saltveit, 1989). Also, in both cases, the greater the severity of tissue injury, the more intense the “white blush” or browning (Ke and Saltveit, 1989). In fresh-cut carrots, the post-processing accumulation of lignified material on cells adjacent to the cut surface results in the formation of a secondary, whitened cell wall (Bolin and Huxsoll, 1991; Bolin, 1992; Howard and Griffin, 1993; Howard et al., 1994; Cisneros-Zevallos et al., 1995). In the case of lettuce, oxidation of the accumulated polyphenols by PPO results in the formation of brown pigments (Ke and Saltveit, 1989). Even though ethylene production increases in response to wounding in both cases, ethylene does not appear to be a part of the mechanism for resultant wound-induced changes (Ke and Saltveit, 1989; Howard and Griffin, 1993), therefore the removal of ethylene accumulation is not a solution to the problem (Howard and Griffin, 1993). A mild heat treatment has been developed as a common solution to both problems. Lignification involves a series of many enzyme conversions beginning with PAL, which is the initial enzyme that provides substrate for the remainder in the phenylpropanoid pathway (Hennion et al., 1992), and ending with syringaldazine oxidase, which converts syringaldazine to lignin (Goldberg et

al., 1985). Heat treatments have been shown to inhibit activities of PAL in both carrots and lettuce (Howard et al., 1994; Loaiza-Velarde et al., 1997), syringaldazine oxidase (a peroxidase) in carrots (Howard et al., 1994) and a phenol peroxidase in lettuce (Loaiza-Velarde et al., 1997). In so doing, phenolic accumulation in response to wounding is dramatically reduced and consequent “white blush” formation in carrots and cut-edge browning in lettuce are prevented. “White blush” can also be controlled with treatments that lower cut surface pH and thus inhibit enzyme activity (Bolin and Huxsoll, 1991; Bolin, 1992). Browning in lettuce can also be inhibited using specific inhibitors of PAL (Tomás-Barberán et al., 1997; Peiser et al., 1998). The understanding that “white blush” and cut-edge browning are mediated by a wound response which includes up-regulation of activities of enzymes involved in the phenylpropanoid synthesis pathway and lignification process has resulted in the development of strategies that modulate this up-regulation, resulting in significant reduction in these two wound-induced defects. These two examples demonstrate that basic understanding of abiotic stress-induced changes in metabolism are key to developing effective strategies to modulate the negative quality effects produced by these stresses in the fresh-cut fruit or vegetable product.

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