Flavour loss during postharvest handling and marketing of fresh-cut produce

Charles F Forney
Agriculture and Agri-Food Canada, Atlantic Food and Horticulture Research Centre, Main Street, Kentville, Nova Scotia, Canada

Abstract
Purpose of review: Loss of flavour of fresh-cut fruits and vegetables following postharvest handling, storage and marketing results in consumer dissatisfaction and often precedes the loss of visual quality. In order to maximise product flavour, causes of its loss must be identified and prevented. Therefore, this review assesses mechanisms and factors that affect flavour loss in fresh-cut produce.
Findings: Flavour loss of fresh-cut fruits and vegetables can be attributed to metabolic changes of flavour compounds and diffusional loss of volatile compounds. The contribution of each of these mechanisms has not been clearly defined in any fresh-cut commodity. Fresh-cut processing stimulates flavour loss by removing natural diffusion barriers and altering normal metabolism. Packaging can alter metabolism of flavour compounds by altering atmosphere composition, which can inhibit flavour compound synthesis or induce the production of off-flavours. Polymer films used in packaging or edible coatings can also inhibit diffusional loss of volatile flavour compounds by serving as a barrier to prevent or stimulate loss by scalping compounds from the package atmosphere. Various postharvest chemical and physical treatments used to prevent browning, reduce microbial growth and maintain product quality may affect product flavour.
Directions for future research: The contribution of metabolic and diffusional processes in determining flavour change of fresh-cut fruits and vegetables during postharvest handling and marketing needs to be determined for fresh products. Determination of the significance of these processes and how packaging and postharvest treatments can affect them could lead to new technologies to preserve flavour quality in fresh-cut produce.

Keywords: fresh-cut; flavour; modified atmosphere packaging; diffusion; scalping; volatiles

Abbreviations
1-MCP 1-Methylcyclopropene
LDPE Low-Density Polyethylene
MAP Modified Atmosphere Packaging
OPP Oriented Polypropylene
UV Ultraviolet

Introduction
The flavour of fresh-cut fruits and vegetables is determined by human perception of a complex combination of volatile, non-volatile and structural components that determine appearance, aroma, taste and texture [1]. Volatile compounds are responsible for aroma and contribute to the unique flavour characteristics that distinguish different fruits and vegetables. Non-volatile compounds contribute to the taste and texture of the product and can influence the perception of volatile compounds [2, 3⁎]. However, to fully understand changes in flavour during postharvest processing and handling of fresh fruits and vegetables, compositional changes in the product must be linked with sensory properties [4⁎].

Many factors determine the flavour of fresh-cut fruits and vegetables that reaches the consumer, starting with the flavour of the product at the time of cutting. The initial flavour is dependent on a variety of factors including genetics, pre-
harvest environment and harvest maturity. The genetic make up of the crop determines its potential flavour as well as how it responds to the environment, which was demonstrated with sliced apples (Malus sylvestris (L.) var. domestica (Borkh.) Mansf.) [5]. Many preharvest factors such as water availability [4], fertilisation [6] and chemical applications [7] can also affect produce flavour development. Harvest maturity of fruits and vegetables has a large effect on postharvest flavour, with fruit harvested under-ripe having limited flavour potential. Maturity of melons (Cucumis melo L.) at harvest affect the flavour of fresh-cut melon cubes with riper fruit having a more sweet aromatic taste than under-ripe fruit [8*].

Even when produce flavour is optimum at the time of cutting and packaging, it may not be maintained by the time it reaches the consumer. Fresh-cut melon flavour decreased [9*, 10*, 11] or developed mustiness [8*] during storage for up to 12 days. In addition, flavour loss during storage has been reported in fresh-cut oranges (Citrus sinensis L.) [12], tomatoes (Lycopersicon esculentum, Mill) [13**], kohlrabi (Brassica oleracea L., Gongylodes group) [14] and carrots (Daucus carota L.) [15*]. Loss of flavour following postharvest handling, storage and marketing of fresh-cut fruits and vegetables often precedes loss of visual quality [16]. Ensuring good flavour is critical for consumer satisfaction. Therefore, the purpose of this review is to assess mechanisms and factors that affect flavour loss in fresh-cut produce.

Mechanisms of flavour loss
Following processing of fresh-cut produce, the two primary mechanisms of flavour loss are metabolic and diffusional [17**]. Metabolic changes in flavour are the result of the synthesis or catabolism of either flavour compounds or compounds responsible for off-flavours. These metabolic processes are dependent on product physiology, which is influenced by maturity and a variety of environmental factors. Diffusional changes in product flavour are a result of diffusion and mass transfer of volatile compounds out of the commodity. In addition, diffusion of compounds (taints) into the product can cause off-flavours, but will not be addressed in this review. Diffusion is dependent on the chemical and physical properties of each flavour compound, the product matrix and the packaging. The role of each of these mechanisms in determining product flavour is dependent on the product physiology and the environment in which it is held.

Metabolism
Metabolic processes that affect postharvest flavour change vary among commodities due to the diversity of product physiology and flavour chemistry among different fruits and vegetables. In a single commodity, many metabolic pathways are involved in producing the complex mixture of both volatile and non-volatile compounds responsible for its flavour. Postharvest synthesis of flavour compounds varies among fruits, where climacteric fruits may actively synthesise flavour compounds following harvest, while nonclimacteric fruits often have more limited postharvest flavour development. Climacteric fruits initiate flavour volatile synthesis in association with a burst of respiration and ethylene synthesis, which can occur pre- or postharvest [18]. When harvested under-ripe, these fruit can be stimulated to ripen and develop flavour by exposing the fruits to the ripening hormone ethylene. However, most under-ripe fruit are not able to obtain full flavour through postharvest ripening as seen in whole tomato [19] and apple [20, 21] fruit. In fresh-cut cantaloupe, total esters increased in cut fruit from maturity stages ¼ to full slip during the first 7 days of storage with total esters in full slip fruit increasing about 45% compared with 150% for ¼ slip melons [22**]. The ratio of acetate to non-acetate esters changed 30-fold after 5 days suggesting the occurrence of metabolic changes in flavour chemistry that could impact fruit flavour. On the other hand, many nonclimacteric fruits have minimal postharvest flavour development as seen in oranges [23].

Metabolic processes that affect postharvest flavour in fresh-cut produce are influenced by processing, the postharvest environment and the duration of storage/marketing. Cutting carrot slices with a dull blade enhanced fresh carrot aroma loss, which was associated with increased metabolic activity during the first 5 days of storage at 8°C in oriented polypropylene (OPP) bags when compared with razor blade cut slices [15*]. Voon et al., [24*] suggest that the rapid loss of esters in minimally processed durian (Durio zibethinus L.) fruit pulp are a result of esters being hydrolysed to alcohols and acids during storage. Cutting can also induce the production of secondary flavour compounds, which is seen in fresh onions (Allium cepa L.) [25*]. Temperature affects the metabolic activity of the product, which can impact changes in flavour compound synthesis and catabolism. Fresh-cut tomato maintained better aroma and flavour after 7 or 14 days of storage at 0°C than at 5°C [26*]. Postharvest environmental stresses, including postharvest treatments and modified atmosphere packaging (MAP) may alter flavour metabolism. Atmosphere modification in packaged fresh products can have significant effects on altering flavour metabolism and may induce fermentation, which leads to off-flavour production. This has been reported to occur in many fresh-cut products such as lettuce (Lactuca sativa L.) [27], carrots [28] and salad savoy (Brassica oleracea L., Capitata group) [29*].

Diffusion
Diffusional loss of flavour volatiles is determined by the volatility of the compound, its partitioning coefficient in the product matrix, diffusional barriers within and surrounding the product, and the concentration gradient of the volatile between the product and the atmosphere, which is determined by packaging and storage conditions [17**]. While many of these processes have been well documented in processed food products and model food systems [30, 31*, 32*, 33], little work has been conducted on fresh fruits and vegetables. Since fresh produce is living and responding to its environment, permeation rates and volatile concentrations may change during storage due to metabolic and physiological
processes, making it difficult to determine whether flavour changes are a result of diffusion or metabolism. Whole fruits and vegetables are surrounded by a cuticle that is composed of cutin and can act as a significant barrier to diffusion [34]. The removal of this barrier during fresh-cut processing further facilitates diffusional loss of volatile compounds in fresh-cut products.

The contribution of diffusional losses of flavour volatiles to flavour loss in fresh-cut fruits and vegetables varies depending on the commodity, nature of cutting, surface area/volume ratios and the storage environment. The significance of this flavour loss mechanism is poorly understood, and is difficult to separate from catabolic-driven changes. In several studies where fruit tissues were thinly sliced creating a very high surface to volume ratio, which would enhance diffusional loss, loss of volatile esters from the fruit tissues was about 80% and 50% in cantaloupe [35**, 36*, 37] and pineapple (Ananas comosus (L.) Merr.) [38], respectively, after 24 h of storage at 4°C. In one of the few studies that considered diffusion as a mechanism of flavour loss, rapid loss of low molecular weight esters (< C8) from thin sliced cantaloupe held in open or closed Petri dishes was attributed to off gassing due to the high vapour pressures and low boiling points of the esters [35**]. There was no evidence for catabolic loss through esterase driven ester loss since there was a loss of esterase activity and no increase of products of esterase-mediated ester metabolism. The role of diffusional loss of volatile flavour compounds in fresh-cut produce needs to be assessed and should be considered when designing packaging.

Factors affecting flavour loss

Cutting

The processing of whole fresh produce into fresh-cut can cause both metabolic and diffusional flavour changes. Secondary aroma volatiles are formed in a number of fruits and vegetables as a result of cellular disruption. For example, thiopropanal S-oxide, prop(en)ylthiol, aldehydes and a variety of sulphides, are formed when fresh onions are cut as a result of the reaction of s-alk(en)yl cysteine sulphoxides with alliinase [25*]. Fresh onion aroma is maximised after about 30 min, but continues to change due to further chemical reactions of the volatiles in the headspace. New aroma volatiles are also formed as a result of lipid oxidation when tomatoes are cut, with increases of many compounds including cis-3-hexenal, hexanal and 1-penten-3-one [39*].

In addition to the postharvest formation of flavour compounds following cutting, flavour loss has been associated with fresh-cut processing. In carrots, the loss of aroma was greater when cut with a dull blade than in those cut with a sharp blade [15*]. Carrots cut with the dull blade also developed off-odours more rapidly, which may have been a result of injurious levels of CO2 that developed more rapidly in packages of dull-blade cut carrots. Cantaloupe cut with a dull cork bore also developed more off-odours and had a slightly higher level of ethanol than fruit cut with a sharp cork bore, although both had a similar loss of aroma [40*]. Lamikanra and Richard [36*] suggested that the rapid loss of esters in cut melon tissue is a result of “stress induced enzymatic hydrolysis of esters”. However, activity of esterase, an enzyme that breaks down esters, decreased 24 h after cutting [41*] and no relationship was observed between ester loss and synthesis of fatty acids, aldehydes or alcohols, which are esterase products [36*]. Subjective aroma ratings of honeydew and cantaloupe pieces were found to decline after 6 days when the cut fruits were held at 5°C in permeable cloth-covered jars [11, 40*]. Sensory tests also determined that fresh-cut orange slices stored at 4°C in a closed plastic box that maintained ambient atmospheres lost flavour during 5 days of storage, which was associated with a loss of flavour components in the fruit [12]. While flavour loss is commonly associated with cutting, no definitive studies have been reported that determine the underlying mechanisms responsible.

Packaging

Packaging is an integral part of fresh-cut products. Often MAP is used to take advantage of atmospheres that aid in maintaining product quality. MAP for fresh-cut products has been primarily focused on reducing browning of cut surfaces, minimising dehydration, reducing decay and preventing contamination of the product [42*, 43*]. Many different types of polymer films with a wide range of CO2 and O2 permeabilities have been developed for MAP [44**]. Models have also been developed to optimise package atmospheres by matching gas permeation properties of polymer films with product respiration rates [45, 46]. The objectives of these models are to maintain a beneficial atmosphere composition within the package, while avoiding injurious ones. However, little attention has been paid to the effects of packaging on product flavour.

Low concentrations of O2 have been shown to reduce the production of volatile compounds that contribute to the flavour of whole fruit, such as apples [47*], pears (Pyrus communis L.) [48] and kiwifruit (Actinidia delicosa [A. Chev.]) C.F. Liang et A.R. Ferguson var delicosa) [49]. This decrease in volatile production during and following low O2 storage is enhanced by storage duration and reduced O2 concentration [48, 50, 51*]. Similarly, elevated concentrations of CO2 also can reduce fruit volatile production [51*]. However, the reduction of volatile esters associated with low O2 storage may not affect sensory flavour ratings [52]. While low O2 or high CO2 storage may reduce the initial flavour of fruit used for fresh-cut products, its effects on flavour change during the relatively short storage of packaged fresh-cut fruits and vegetables has been variable. It is often not clear if flavour changes during MAP storage are the direct result of atmosphere modification or other factors such as senescence, microbial activity or package interactions.

In numerous reports, MAP conditions that maintained product quality also maintained concentrations of flavour com-
pounds and no loss of flavour was observed. Sugar and acid content, as well as sensory characteristics, of fresh-cut mango (Mangifera indica L.) were maintained for 15 days at 10°C in MAP that developed atmospheres of 5–15 kPa O₂ and 4–10 kPa CO₂ [53*]. Pineapple chunks that were held in MAP of 1.5 kPa O₂ and 11 kPa CO₂ for 14 days at 0°C also maintained good appearance and developed no off-flavours [54*]. Aroma and taste of fresh-cut tomato slices stored in modified atmospheres at temperatures of 0–5°C for up to 10 days were better than that of air-stored slices [13**, 55*]. Snow peas (Pisum sativum L. var. saccharatum) held in MAP with a steady-state atmosphere of about 5 kPa O₂ and 5 kPa CO₂ at 5°C maintained quality and developed no off-flavours after 28 days, unlike peas held in ambient atmospheres that became unmarketable [56*]. Carrot discs stored in bags that developed atmospheres of 5–7 kPa O₂ and 12–15 kPa CO₂ also maintained good aroma and flavour [57*]. MAP with 0.2 kPa O₂ and 7.5 kPa CO₂ reduced the loss of soluble solids and thiols responsible for pungency of trimmed green onions after 14 days of storage at 5°C [58]. Broccoli (Brassica oleracea L., I. Italic group), stored in a low-density polyethylene (LDPE) film producing an atmosphere of 5 kPa O₂ and 7 kPa CO₂ and containing an ethylene scrubber had appearance and flavour after cooking closest to fresh broccoli when broccoli was treated with ethylene scavengers in OPP, polyvinylchloride or air having atmospheres of 13 kPa O₂/11 kPa CO₂, 17 kPa O₂/4 kPa CO₂ and 21 kPa O₂/0 kPa CO₂, respectively [59].

In some cases, significant changes in flavour compounds occur, but surprisingly these do not affect sensory flavour scores. Minimally-processed durian fruit pulp over-wrapped with a LDPE cling film and held at 4°C lost 53% of total volatiles, including 77% of esters, after 7 days of storage [24*]. However, a significant decrease in fruity, sulphury, or nutty aromas was not detected by sensory evaluation until day 28, at which time only 1% of the volatile esters remained. When 'Gala' apple slices were stored in perforated polyethylene bags at 5.5°C for 7 days, ethyl ester concentration increased 11-fold, while acetate ester concentration declined about 50%, but no significant changes in apple-like flavour were associated with these changes in ester composition [60**]. Similarly, non-acetate esters increased 87% while acetate esters decrease 66% in fresh-cut cantaloupe cubes during 14 days of storage at 4°C, but sensory analysis showed minimal changes in flavour with the exception of mustiness, which increased after 12 days [8*]. However, in fresh-cut mangoes, volatile terpene concentration, which decreased about 80% during 11 days in MAP, was related to a loss of product aroma, rendering the fruit unmarketable [61**].

Rapid establishment of MAP can be achieved by flushing with a desirable gas mixture, such as optimum concentrations of O₂ and CO₂, elevated concentrations of O₂, or N₂ prior to sealing. Flushing packages containing melon cubes with 4 kPa O₂ and 10 kPa CO₂ maintained a mild melon aroma after 12 days at 5°C, compared with fruit held in perforated packages or unflushed packages that developed an off-odour associated with fungal growth [62*]. Similarly, fresh-cut pineapple flushed with 4 kPa O₂ and 10 kPa CO₂ maintained sensory quality for 5–7 days at 4°C versus only 3–5 days for pineapple held in passive MAP [63]. Flushing packages of fresh-cut ‘Conference’ pears with N₂ reduced microbial growth and did not induce any off-odours during 3 weeks of storage at 4°C, whereas packages flushed with 7 kPa CO₂ developed undesirable odours [64]. Flushing packages of grated celeriac (Apium graveolens L., Rapaceum group) or sliced mushrooms (Agaricus bisporus (Lge.) Sing.) with 95 kPa O₂ maintained fresh taste and smell after 7 days at 7°C, when compared with product held in passive MAP containing 3 kPa O₂ and 5 kPa CO₂ [65*].

When concentrations of O₂ or CO₂ in MAP exceed the tolerance limit of the product, off-flavours may develop. The primary response of fresh fruits and vegetables is the induction of fermentation, which produces elevated concentrations of ethanol and acetaldehyde. The accumulation of ethanol associated with anaerobic atmospheres does not always render products unmarketable. In a survey of fresh-cut mixed salads in MAP, most packages contained < 0.5 kPa O₂ and > 2 Pa ethanol, an atmosphere that prevents browning but causes a slight fermented odour [66**]. However, the odour was not objectionable and the salads remained marketable. The aroma of fresh-cut mango fruit held in MAP was not affected by anaerobic atmospheres that increased production of ethanol, ethyl acetate and ethyl butanoate, and overall sensory ratings were similar to fruit held in aerobic packaging [61**]. ‘Gala’ apple slices stored for 14 days in barrier bags maintained acceptable flavour and developed no off-flavours or fermented flavours as judged by a sensory panel, although there were significant changes in esters [67**]. Pineapple chunks that were held in MAP for 14 days at 5°C developed atmospheres of <1 kPa O₂ and 15 kPa CO₂, but developed no off-flavours and maintained good appearance [54*]. However, a slight off-odour, associated with the anaerobic atmosphere, was detected when packages were first opened, which quickly dissipated.

While many fresh-cut products show high tolerance to atmosphere modification, anaerobic metabolism in many products can result in objectionable odours and flavours that can render the product unmarketable. Strong sulphur-based odours can be produced by some Brassica vegetables when subjected to anaerobic atmospheres. Broccoli produces significant quantities of methanethiol, hydrogen sulphide, dimethyl disulphide and dimethyl trisulphide, resulting in severe off-odours and flavours [68, 69]. However, when 12 different fresh-cut Brassica vegetables were subjected to anaerobic atmospheres by N₂ flushing, some, including cauliflower (Brassica oleracea L., Botrytis group), Chinese cabbage (Brassica rapa L., Pekinensis group) and kohlrabi, produced low levels of these compounds making them a low risk to develop off-flavours under anaerobic atmospheres that may
develop in MAP [70*]. Carrots packaged in perforated LDPE bags that developed an atmosphere of 7 kPa O₂ and 7 kPa CO₂ produced elevated concentrations of ethanol and had increased sensory scores for ethanolic and sickening sweet flavours [28]. Fresh-cut carrot slices sealed in OPP bags lost fresh carrot aroma during the first 5 days of storage at 8°C, which was followed by the development of off-odours associated with atmospheres of 1–2 kPa O₂ and 30 kPa CO₂, and tissue decay [15*]. Anaerobic atmospheres also induced off-flavour formation in fresh-cut salad savoy (Brassica oleracea L., Capitata group) [29*] and snow peas [56*], rendering them inedible.

**Interactions with packaging materials**

The package can also act as a barrier to diffusion and reduce loss of volatile flavour compounds. By reducing the concentration gradients of flavour volatiles between the product and its surrounding atmosphere, packaging can minimise volatile loss from the product. If the volatile concentration in the package atmosphere is in equilibrium with the product there will be no net diffusional loss from the product. No studies have been conducted to determine the magnitude of diffusional losses from fresh-cut produce. However, rapid loss of volatile esters from cantaloupe tissue have been observed under conditions conducive to diffusional loss [35**], whereas total esters increased when melon cubes were sealed in polyethylene terephthalate bowls [22**]. These results suggest that the sealed package was effective in minimising diffusional volatile loss.

The concentration of flavour volatiles in the package atmosphere is also influenced by the interaction of the packaging material with the specific volatiles released by the product. Mass transfer of volatile flavour compounds into and through polymer films is a three step process that is dependent on the chemistry of both the volatile and the film [71**]. Volatiles first interact by sorption into the film, then diffuse through the film driven by chemical potential differences, and finally are desorbed from the film and released into the atmosphere. As a result of this process, volatile compounds are removed from the package headspace through sorption (scalping) and permeation, which can enhance diffusional loss from the product [72, 73*]. Sorption and permeation are dependent on the solubility (partitioning) of the compound in the packaging material. Polypropylene and polyethylene, which are widely used in the packaging of fresh-cut fruits and vegetables, have a high affinity for volatile compounds due to their nonpolar properties, whereas polyesters, including the bio-based polymer poly(lactic acid) are more polar and have a weaker affinity for flavour volatiles [74**]. Scalping of flavour compounds from processed food by polyethylene and polypropylene has been observed [75]. In studies conducted on the scaling of d-limonene from orange juice, strips of LDPE reduced d-limonene concentrations by 40–60% in 6 h [76]. DeLassus et al. [77**] estimated the permeability of the flavour volatile trans-2-hexenal to be about 10,000-fold greater for LDPE than ethylene vinyl acetate or vinylidene chloride copoly-

mers. The affinity of volatile compounds to LDPE is dependent on polarity and is greatest with hydrocarbons followed by ketones, esters, aldehydes and alcohols [78*]. Sorption also increases with molecular size (carbon chain length) and branching [79, 80]. Therefore, the differential effects of sorption could alter volatile profiles and thus affect flavour. Environmental factors also affect the interaction of flavour volatiles with packaging materials. Low temperature and high humidity environments, which are typical of fresh-cut MAP, may enhance flavour scalping and permeation [71**, 78*, 81]. Understanding the properties of packaging materials in relation to flavour volatiles could identify additional methods for preserving product flavour and aroma.

An additional factor that contributes to the loss of volatiles from the package atmosphere is the presence of perforations. Perforations are commonly used to provide adequate gas exchange to avoid anaerobic conditions. Diffusion of O₂ and CO₂ through perforations has been modelled and follows a modified Fick’s equation [82*]. The loss of ethanol through three 100-µm pores increased the rate of ethanol permeation through a 60-µm thick polypropylene film 186-fold [83**]. The loss of other flavour volatiles through perforations would be expected to be similar and could lead to organoleptic deterioration of foods. Similarly, small leaks in package seals or micro pores present in some materials can greatly enhance volatile loss [71**].

**Edible coatings**

Edible coatings also can act as a barrier to gas and flavour volatile transmission in fresh-cut produce. Similar to MAP, edible coatings can modify the internal atmosphere of the product and thus affect ripening and maintain product quality [84*]. If coatings prevent adequate respiratory gas exchange, anaerobic conditions can develop resulting in the formation of off-flavours [23, 85]. In addition coatings can prevent volatile off-gassing and thus maintain flavour. The application of coatings to fresh-cut fruit has had a variety of effects on fruit flavour. Mango pieces coated with carboxy methylcellulose or maltodextrin had better volatile retention than uncoated fruit [86*]. However, coatings of chitosan, starch, whey protein or soybean oil emulsion resulted in poor flavour. Apple slices coated with soybean oil emulsion or carboxy methylcellulose lost important aroma volatiles when compared with uncoated slices [87]. The flavour of mini-peeled carrots, stored in 1.5 mil polyethylene sealed bags at 2°C, was preserved by an edible coating of Nature Seal 1000, a cellulose-based polymer [88**]. Sensory ratings for fresh carrot aroma and flavour were higher for coated carrots than uncoated carrots after storage for 7–35 days, and it was suggested that the coating may have retarded loss of flavour volatiles from the abraded surface.

**Postharvest treatments**

After harvest, many fruits and vegetables are subjected to various treatments prior to or following cutting to delay ripening, control decay or maintain product quality. Many of
these treatments can affect product flavour although reports on flavour effects are limited. Treatments that have been applied to fresh-cut fruits and vegetables include the application of a variety of solutions through dips and sprays, fumigation with compounds to inhibit ripening or decay, and the use of physical treatments such as heat or irradiation.

Routinely, fresh-cut fruits and vegetables are treated following processing with solutions containing a variety of compounds including antioxidants, antimicrobials and salts. Most of these treatments have no effect on product flavour [89, 90, 91]. However, when fresh-cut cantaloupe was dipped in 1% or 2.5% CaCl₂, bitterness developed in the melon [92]. Potato (Solanum tuberosum L.) strips developed an off-odour when treated with sodium sulphite and held in passive MAP for 14 days at 4°C [93]. An off-flavour of ‘Bartlett’ and ‘Anjou’ pear slices also developed one day after treatment with 0.01% 4-hexylresorcinol [94].

Treatment of many fruit with 1-methylcyclopropene (1-MCP), an ethylene-action inhibitor, maintains fruit firmness by inhibiting ripening, but also inhibits the formation of flavour volatiles, particularly esters, which are responsible for much of the fruity flavour [95]. When ‘Gala’ apples were pretreated with 1-MCP prior to being cut into slices and stored 7 days in perforated polyethylene bags at 5.5°C, apple slice flavour and volatiles in 1-MCP treated fruit were similar to that of control fruit [60]. In the same study, when apples were treated with ethanol vapours prior to cutting, apple slices had lower apple-like flavour, acidity and firmness, and an increase in off-flavour caused by an accumulation of ethanol and some ethyl esters. When ‘Jonagold’ and ‘Golden Delicious’ apple slices were treated with hexanal vapours, decay was retarded and aroma was temporarily enhanced [96]. Hexanal vapours were metabolised by the fruit tissue to form hexanol, hexyl acetate and lesser amounts of butyl hexanoate and hexyl hexanoate.

Heat treatments, used to control decay, reduce microbial contamination, or slow physiological changes, can alter product flavour [97]. Heat treatments can reduce fruit acidity and alter volatile production and texture. In ‘Gala’ apples pretreated with heat prior to being cut into slices and stored for 7 days in perforated polyethylene bags at 5.5°C, heat-treated apples had lower sensory ratings for apple-like flavour and acidity [60]. Heat treatments caused a reduction in the content of acids and volatile compounds. Fresh-cut cantaloupe melon dipped in 50°C water for 60 min had more fruity/melon aroma and taste than control fruit after 1 day of storage at 10°C in sealed plastic bowls and these differences were maintained during 8 days of storage [98]. Unheated fruit were judged to be more bitter after 1 day and more musty, chemical, bitter, sour and fermented after 5 days. Carrot sticks treated with a radio-frequency thermal treatment of 60°C for 1–3 min maintained a higher sensory odour and taste rating than untreated controls following 14 days of storage at 6°C in a vacuum package [99]. This treatment was believed to inactivate some enzymes, but microbial counts of treated carrots became unacceptably high.

Irradiation with ultraviolet (UV) and ionising radiation has been used in attempts to reduce microbial load and in some cases induce decay resistance. Exposure of thin slices of apple to UV light caused a 2-fold increase of the sesquiterpenes copaene and ocimene, which have antimicrobial activity [38]. UV treatments also increased the production of the terpenoids ß-ionone, ß-ionone epoxide, and dihydroactinidiolide in fresh-cut cantaloupe and it was suggested that these terpenoids could be detrimental to fresh melon flavour [35]. Lamikanra et al. [100] reported that fresh-cut cantaloupe treated with UV light (1.180 mW/cm² for 4 min) smelled less rancid and more fruity after 6 days of storage than control fruit. The reduction in rancid smell was associated with a reduction in lipase activity in the treated fruit. Ionising radiation treatments have not been shown to have significant effects on fresh-cut product flavour. Romaine lettuce sealed in laminated polyethylene bags and irradiated with 0.15 or 0.35 kGy of gamma radiation developed off-odours after 11 days of storage at 4°C, but the irradiation treatment had no effect on off-odour induction [56].

**Microbial effects**

Fresh-cut processing of fruits and vegetables often enables microbial growth, which can be detrimental to product aroma and flavour. Off-odours associated with microbial growth have been reported in fresh-cut melon [9*, 11], potatoes [101], salad savoy [29*], mixed lettuce [102], grated celery [102] and bell peppers (Capsicum annuum L.) [102]. Treatments that inhibit microbial growth also reduced the development of off-odours. Off-odours and decay of fresh-cut honeydew melon were prevented by a 15% CO₂ atmosphere during 12 days of storage at 5°C [11]. Chlorine dips of cantaloupe and honeydew melons, prior to and following cutting maintained acceptable odour and flavour following 20 days of storage in MAP, while undipped fruit did not [9*]. This loss of flavour and odour quality was associated with increases in log₁₀ microbial counts, which reached 6.7 (aerobic plate count), 7.4 (total plate count), 3.4 (mould) and 3.6 (yeast) in undipped melons compared with 3.1, 3.8, 1.1 and 1.0, respectively, in chlorine dipped melon. Off-odours developed in fresh-cut potatoes held at 6°C in MAP for 7 or 14 days, but were reduced when held at 1°C or treated with the antimicrobial compounds 5% erythorbic acid/1% citric acid or 1% diethylenetriamine pentaacetic acid [101].

**Conclusions**

The flavour of fresh-cut fruits and vegetables is a complex and dynamic trait. Causes of flavour loss are confounded by the interactions of multiple factors affecting flavour, including its diverse chemical nature, complexity of human perception, and multiple mechanisms driving loss. The two primary mechanisms responsible for flavour loss during postharvest handling are metabolic changes of flavour compounds and...
diffusional loss of volatile compounds. Fresh-cut processing stimulates flavour loss by removing natural diffusion barriers and altering normal metabolism. MAP can alter metabolism of flavour compounds by altering package atmosphere composition, which can inhibit flavour compound synthesis. Under extreme atmospheres, the production of off-flavours can be induced although fresh-cut products appear to be more tolerant to low O₂ and high CO₂ concentrations than whole produce. Polymer films used in packaging, as well as edible coatings, can either inhibit or stimulate diffusional loss of volatile flavour compounds. The barrier properties of packaging or coating materials can substitute for the natural barriers removed during processing and reduce diffusional flavour loss. However, nonpolar polymers, such as polyethylene and polypropylene that are commonly used for packaging, have a strong affinity for many nonpolar flavour volatiles. This has the potential to cause flavour loss through scalping. Various postharvest chemical and physical treatments used to extend shelf-life of fresh-cut produce also may affect product flavour by preventing flavour degradation, inhibiting microbial activity or inducing off-flavour. To date, of the studies that have characterised flavour change in fresh-cut produce, few have attempted to assess underlying mechanisms. Understanding mechanisms and factors that affect flavour retention in fresh-cut produce could lead to new technologies for the preservation of flavour quality.

References

Papers of interest have been highlighted as:

* Marginal importance
** Essential reading


*An informative review of the interactions of physicochemical, physiological and psychological effects on flavour perception.


*This article discusses the relationship between flavour chemical composition and sensory properties of fresh fruits and vegetables and their change during market-life.


*This article describes the effects of fruit maturity and storage on the sensory quality and texture of fresh-cut cantaloupe.


*The effects of washing with hypochlorite solutions on sensory quality of fresh-cut cantaloupe and honeydew melon are presented.


*Descriptive sensory analysis of flavour changes in four cultivars of fresh-cut cantaloupe during storage for up to 14 days.


**This article evaluates the effect of atmosphere modification on the quality and ripening of fresh-cut tomato fruit during storage. Changes in fruit composition, flavour, physiology and microbial quality were measured.


*This article assesses the effects of blade sharpness on physical damage, physiological stress and microbial growth of carrots held in MAP. Sensory analysis of appearance and aroma was conducted.


**An excellent overview of the underlying principles of flavour loss from processed food products, including a discussion of diffusion and mass transfer in food systems.


**An extensive study on the post-cutting changes in volatile flavour compounds in fresh-cut cantaloupe of variable maturity during storage.


24. Voon YY, Hamid NSA, Rusul G, Osman A and Quek SY. Volatile flavour compounds and sensory properties of minimally processed durian
*Loss of volatile flavour composition of fresh-cut durian fruit held in MAP during storage was described and related to sensory properties. The shelf-life and quality of fresh-cut tomatoes held in three types of MAP were assessed. Interactive effects of storage temperature, time and atmosphere on sensory, microbial and compositional quality was determined. The release of volatile flavour compounds from model food systems was studied and the rates of release were related to viscosity and molecular size. Mathematical models for the release of flavour compounds in model food systems are presented. This review presents basic principles that affect human flavour perception of food products.

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* Studied the effects of postharvest treatments and MAP on the composition and sensory quality of fresh-cut mango fruit.


* The end of storage life of fresh-cut pineapple was correlated with a rise in CO2 production. Atmospheres were defined that preserved fruit quality and pineapple tolerated atmospheres of <1 kPa O2 and 15 kPa CO2.


* Demonstrates that 0°C is the best storage temperature for sliced tomatoes for reducing microbial counts and maintaining aroma. Tomato slices also tolerated modified atmospheres that reached 2 kPa O2 and 20 kPa CO2 after 10 days and reduced microbial counts.


* Atmosphere composition in MAP that induced off-flavours of snow peas were identified.


* Descriptive sensory analysis was used to characterise sensory changes in fresh-cut carrot quality during storage in various MAP packages.


** An extensive study that evaluated three postharvest treatments on the quality and storage life of fresh-cut apples. The study assessed changes in both flavour chemistry and sensory characteristics.


** Chemical and sensory changes of fresh-cut mango were evaluated providing a good assessment of the effects of fruit maturity and MAP on product shelf-life.


* The benefits of flashing MAP on the flavour retention of fresh-cut cantaloupe were reported.


64 Soliva-Fortuny RC and Martín-Belloso O. Microbiological and biochemical changes in minimally processed fresh-cut Conference pears. European Food Research and Technology 2003: 217:4–9.


* The effects of high O2 MAP and equilibrium MAP on microbial and sensory quality of several fresh-cut vegetables were compared.


** This paper addresses the occurrence and effects of anaerobic atmospheres in packed fresh-cut salads and the resulting effects on product quality and marketability.


** Study characterises sensory and chemical changes in fresh-cut apple during storage in MAP.


* This study characterises the tolerance of a variety of fresh-cut Brassica vegetables to anaerobic atmospheres and identifies those that produce objectionable off-odours.


** An extensive review of the interaction of packaging films with volatile flavour compounds and the principles underlying diffusion and mass flow of these compounds.


* A review of the process of flavour scalping by packaging materials from food products that outlines factors affecting this process.


** An in-depth review of flavour scalping by polymer films that addresses how the chemical properties of flavour compounds and packaging films determine degrees of scalping. External factors that affect rates of scalping are also discussed.


** Describes the permeation of trans-2-hexenal through different polymer packaging films and effects of humidity on transmission properties of different films.

78 Fayoux SC, Seuve AM and Voilley AJ. Aroma transfers in and through plastic packagings: orange juice and d-limonene. A review. Part II: overall sorption mechanisms and parameters. Packaging Technology and
A review addressing the mechanisms of d-limonene sorption from orange juice by plastic packaging films. This review provides some insights into the process of flavour scalping.


This paper describes the development of a model predicting gas diffusion through microperforations, which is useful in predicting MAP atmosphere composition.


**The effects of microperforations on the loss of flavour volatiles from pack-aged fresh fruit are discussed.**


This book chapter provides a review of the use of edible coating on fresh fruits and vegetables to preserve product quality.

Baldwin EA, Malundo TMM, Bender R and Brecht JK. Interactive effects of harvest maturity, controlled atmosphere and surface coatings on mango (Mangifera indica L.) flavor quality. HortScience1999: 34:514.


This paper describes the several effects of edible coating on the flavour of fresh-cut mango using sensory analysis.


**The effects of MAP and edible coatings on the quality, chemical composition, and sensory quality including aroma and flavour of fresh-cut carrots are described.**


**The microbial and sensory quality of fresh-cut potato strips was determined following treatments with a variety of traditional and non-traditional sanitising solutions and storage in passive MAP and vacuum packaging.**


**The impact of hexanal fumigation on the microbial quality and aroma of fresh-cut apple slices was determined. Hexanal was shown to be metabolised by the apple tissue and enhance aroma.**


**Heat treatments of cantaloupe melons prior to cutting increased the desirable flavour of the fresh-cut product.**


**Exposure of fresh-cut cantaloupe to UV radiation was shown to inhibit rancidity and maintain texture during storage. Treatments effects on fruit biochemistry were also assessed.**


**Relationships were established among microbial quality, sensory quality and non-volatile flavour compounds in four types of fresh-cut products held in MAP.**