Impacts of Modified Atmosphere Packaging and Controlled Atmospheres on Aroma, Flavor, and Quality of Horticultural Commodities

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SUMMARY. The commercial use of modified atmosphere packaging (MAP) technology provides a means to slow the processes of ripening and senescence during storage, transport, and marketing of many fresh fruit and vegetables. The benefits of MAP and controlled atmosphere (CA) technologies for extending postharvest life of many fruit and vegetables have been recognized for many years. Although both technologies have been and continue to be extensively researched, more examples of the impacts of CA on produce quality are available in the literature and many of these reports were used in development of this review. Storage using MAP, similar to the use of CA storage, impacts most aspects of produce quality although the extent to which each quality attribute responds to CA or modified atmosphere (MA) conditions varies among commodities. Impacts of MAP and CA on flavor and aroma are dependent on the composition of the storage atmosphere, avoidance of anaerobic conditions, storage duration, and the use of fresh-cut technologies before storage.

A number of factors modify the impact of MAP on produce quality. Package gas composition determines the effectiveness of any packaging system. Reduced O_2 and elevated CO_2 concentrations must be sufficiently stringent to slow metabolism and provide shelf-life extension while also being within the tolerance range of the stored commodity to avoid induction of anaerobic stress. Temperature management is critical as gas composition within packages changes with temperature (see Kader et al., 1989). Duration in the package after sealing is also important, as commodity tolerance to atmospheres may change over time (Mattheis et al., 1997). Finally, various processes of produce ripening and senescence do not have the same O_2 and CO_2 optima for maximizing beneficial responses.

Impacts of MAP and CA on quality

Most aspects of produce quality are impacted by MA (Kader et al., 1989; Weichmann, 1986).

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Color changes during produce ripening and senescence are highly impacted by storage atmosphere conditions, particularly the change from green to yellow. Storage in high CO_2 and / or low O_2 results in reduced loss of chlorophyll as well as reduced accumulation of other pigments including anthocyanin, lycopene, xanthophylls and carotenoids (Barth et al., 1993; Barth and Hong, 1996; Salunkhe and Wu, 1973; Wang et al., 1971; Zhuang et al., 1994). Within the tolerance range of O_2 and CO_2, reduced development of browning may also occur (Brecht et al., 1973; Smyth et al., 1998). Outside the tolerance range, particularly for CO_2, browning may be intensified (Brecht et al., 1973; Chen et al., 1981). Undesirable changes in texture are often reduced by high CO_2 and / or low O_2 within the tolerance range (see Weichmann, 1986). This includes reduced softening as well as reduced development of toughness after processing (Lougheed and Dewey, 1966). Outside of the tolerance range, processes of softening may be accelerated (Nanos and Mitchell, 1991; Patterson, 1982). CA and MAP can reduce the use of carbohydrates and titratable acids resulting in slower acid and sugar loss during storage (Salunke and Wu, 1973). Alternatively, loss of sugar and titratable acid can be enhanced if anaerobic conditions develop within the package.

MAP and CA conditions also impact a number of compounds that contribute to produce nutritive value. Ascorbate losses decrease when many commodities are stored under low O_2 conditions at low temperatures (Bangerth, 1977; Delaporte, 1971; Platenius and Jones, 1944). For many fruit and vegetables, as CO_2 partial pressure is increased under low or ambient O_2 partial pressure conditions, ascorbate losses increase but may recover to prestress amounts after storage in air (Weichmann, 1986). Loss of b-carotene in carrots (*Daucus carota* L.) decreases at low O_2 partial pressure but losses increase with the addition of CO_2 (Weichmann, 1986). The response to CO_2 is concentration dependent, below 5% (1% = 1.013 kPa at sea level) losses increase, at 10% losses decrease relative to carrots stored in air.

Impacts of MAP and CA on flavor and aroma

Flavor can also be altered by storage in MA. When CO_2 and O_2 are maintained in the tolerance range, flavor deterioration is slowed by the combination of reduced loss of sugar, acid, and changes in other compounds that contribute to flavor. Flavor may deteriorate at a faster rate if anaerobic conditions develop due to both increased sugar and / or acid loss, and development of off-flavors. Off-flavors result from the accumulation of ethanol and acetaldehyde as well as altered production of other compounds that can contribute to flavor and aroma. Ethanol is used in ester production by fruit (Berger and Drawert, 1984), and increased ethanol present after anaerobiosis can result in increased synthesis of ethyl esters. The increased amount of ethyl esters can alter aroma directly and also due to reduced production of other esters that are produced under normal conditions of fruit ripening (Mattheis et al., 1991).

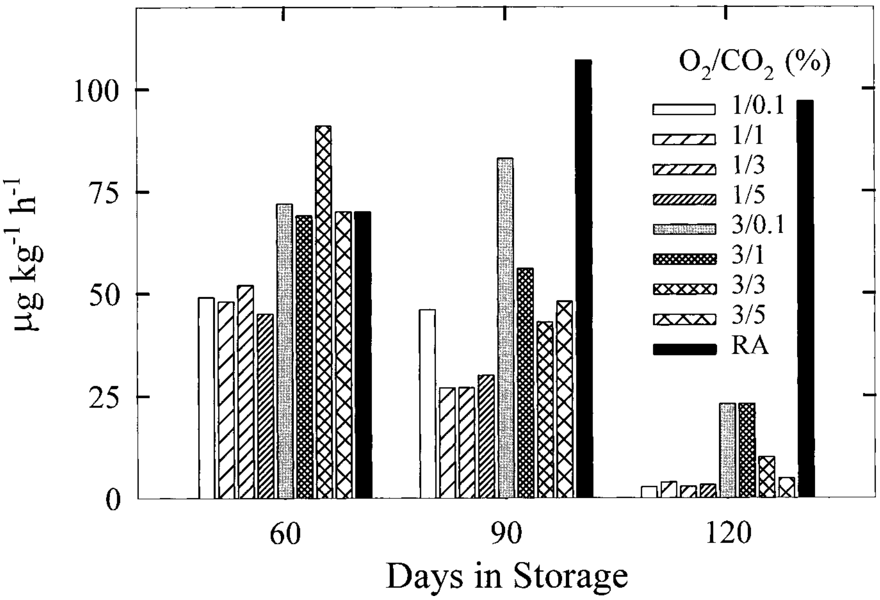

Fig. 1. Production of straight C-chain esters by 'Gala' apple fruit following storage at 0 °C in air or controlled atmosphere. Fruit were removed from storage then held at 20 °C for 7 d before analysis by gas chromatography–mass spectrometry.

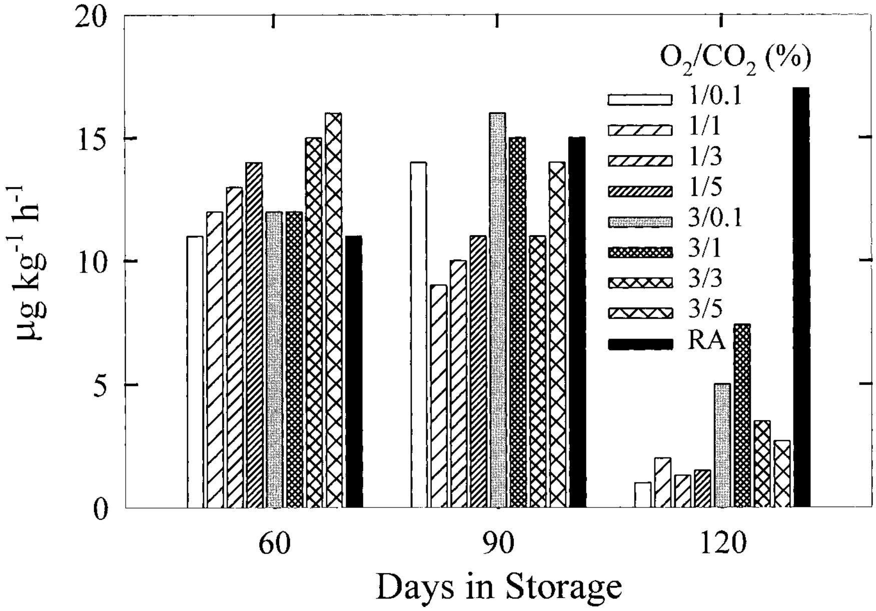

Fig. 2. Production of branched C-chain esters by 'Gala' apples following storage at 0 °C in air or controlled atmosphere. Fruit were removed from storage then held at 20 °C for 7 d before analysis by gas chromatography–mass spectrometry.

The excessive production of sulfur compounds following storage under anaerobic conditions contributes to off-flavor development in broccoli (*Brassica oleraceae* L. Italica Group) (Forney et al., 1991). Reduced production of compounds that contribute to aroma in the absence of anaerobic conditions can occur following storage in low O_2 / high CO_2 atmospheres (Guadagni et al., 1971; Patterson et al., 1974).

Responses to low O_2 and / or high CO_2 partial pressures that impact fruit aroma vary with commodity, cultivars and storage conditions. Aroma of minimally processed honeydew melons (*Cucumis melo* L. var. *inodorus* Naud.) deteriorates when melon pieces are stored in air at 5 °C (41 °F) (Portella and Cantwell, 1998). Storage of these pieces in air plus 15% CO_2 reduces aroma deterioration as indicated by higher taste panel ratings after 12 d storage. Although storage in 15% CO_2 reduced firmness loss in only one of the 4 cultivars evaluated, aroma scores for all 4 cultivars were higher compared to pieces stored in air. Strawberries (*Fragaria* ×*ananassa* Duch. 'Pajaro') stored in 20% CO_2 contain higher amounts of acetaldehyde, ethanol and other ethylesters compared to fruit stored in air over a 12 d period (Larsen and Watkins, 1995). Accumulation of these compounds occurs gradually during storage, and off-flavor development occurs coincident with this accumulation. Storage in air after removal from high CO_2 reduces the detection of off-flavors depending on the duration of anaerobiosis. Off-flavors detected in fruit stored 6 d in 20% CO_2 were no longer present after an additional 6 d storage in air. Ethyl acetate and ethyl butanoate are typically produced by 'Pajaro' strawberries in small amounts. Production of both increased following storage at 20% CO_2. Of these two compounds, ethyl butanoate has a lower odor threshold, therefore production of ethyl butanoate may have contributed to the loss of off-flavors by masking the presence of other compounds, particularly ethyl acetate, that contribute to off-flavor development. Concentrations of other volatiles that contribute to strawberry flavor and aroma were impacted less, if at all, by high CO_2. For example, concentrations of *E*-2-hexenal, g-decalactone, 2,5-dimethyl-4-methoxy-3(2*H*)-furanone and 2,5-dimethyl-4-hydroxy-3(2*H*)-furanone, all of which contribute to the flavor of strawberries (Larsen et al., 1992) were similar in fruit stored in air or high CO_2.

Storage atmosphere and storage duration are important factors determining volatile production by sweet cherries (*Prunus avium* L. 'Bing') (Mattheis et al., 1997). Storage in nonanaerobic conditions (5% O_2 with up to 10% CO_2) for 12 weeks at 0 °C (32 °F) did not impact production of benzaldehyde and *E*-2-hexenal, two compounds that contribute to sweet cherry aroma and flavor (Schmid and Grosch, 1986). Storage in 5% O_2 with 0.1% CO_2 resulted in an accumulation of 2-propanol although no off-flavor developed. Sweet cherries produce only trace amounts of ethanol and ethyl esters under normal storage conditions, however, these compounds accumulated in fruit stored 12 weeks in 5% O_2 with 15 or 20% CO_2, indicating tolerance of 'Bing' sweet cherries to high CO_2 environments changes with storage duration.

Production of volatiles that contribute to apple flavor and aroma can be negatively impacted by storage atmospheres that do not induce anaerobiosis. As O_2 and CO_2 partial pressures are reduced and increased, respectively, fruit volatile production following removal from storage is reduced (Streif and Bangerth, 1988). The degree to which volatile production is reduced increases with the duration of CA storage. Volatile production can increase after a period of air storage following removal from a controlled atmosphere, however, the amount of recovery decreases with increased duration of CA storage. Apple volatile concentration is also reduced in the package in a low oxygen MAP system (Song et al., 1997).

A differential impact of O_2 and CO_2 partial pressures on the types of esters produced by apples (*Malus sylvestris* Mill., *M. pumila* Mill., *M. domestica* Borkh.) has been reported (Brachmann et al., 1993). At 1% O_2 with 1% CO_2, production of straight C chain esters is reduced while storage in 1% O_2 with 3% CO_2 also impacts production of esters with branched C chains. Results from a storage experiment (J. Mattheis, unpublished) using 'Gala' apples further illustrate the importance of atmosphere composition and storage duration on poststorage volatile production. Apples were stored for up to 120 d at 0 °C in air or CA at 1 or 3% O_2 with 0.1% to 5% CO_2. Fruit were held in air at 20 °C (68 °F) for 7 d following removal from CA, then volatile emissions were characterized. A reduction in straight C chain ester production was observed after 60 d storage only in fruit stored in 1% O_2 (Fig. 1). Production of branch chain esters was not altered by any of the CA treatments after 60 d (Fig. 2). After 90 d, straight chain ester production decreased with the addition of CO_2 to either O_2 treatment, while CO_2 addition reduced branched chain ester production only for fruit stored at 1% O_2. The impact of storage CO_2 partial pressure on straight and branched chain ester production after 120 d storage is evident only for fruit stored at 3% CO_2. As CO_2 partial pressure increases, ester

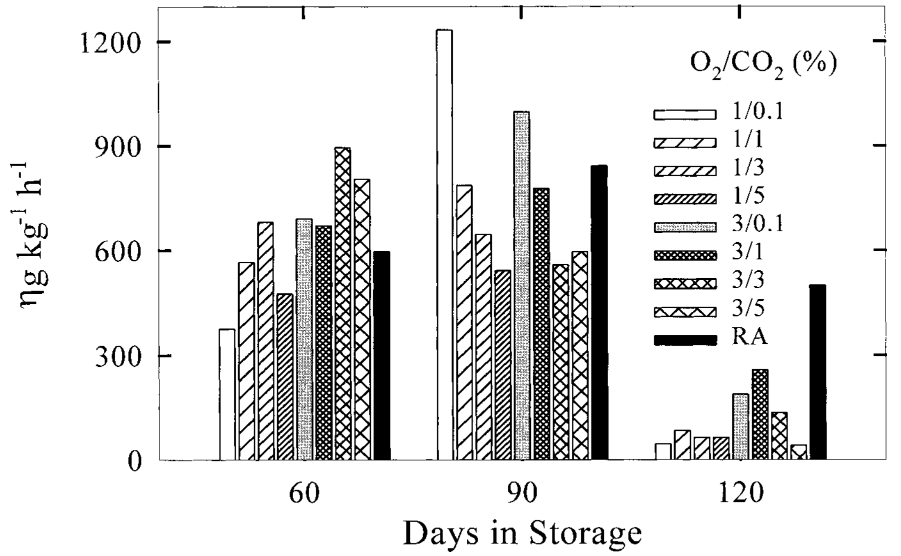

Fig. 3. Production of 4-allylanisole by 'Gala' apples following storage at 0 °C in air or controlled atmosphere. Fruit were removed from storage then held at 20 °C for 7 d before analysis by gas chromatography–mass spectrometry.

production is reduced. At 1% O_2 ester production is low regardless of CO_2 concentration. Impacts of CA conditions on production of 4-methoxyallylbenzene, a product of the shikimic acid pathway (Manitto et al., 1974) that imparts a spicy character to apple aroma (Williams et al., 1977), were also related to O_2 and CO_2 partial pressures and duration of storage (Fig. 3). Production of 4-methoxyallylbenzene decreased with increased CO_2 partial pressure after 90 d storage, however after 120 d this CO_2 response was evident only for fruit stored at 3% O_2.

The use of MAP may also impact flavor and aroma directly by the nature of interactions between aroma compounds and packaging materials. Films slow movement of volatile aroma compounds but the solubility coefficients and diffusivity of volatile aroma compounds varies for different polymers (Charara et al., 1992). This variability may result in differential movement of aroma compounds through packaging films and the potential for change in aroma and flavor. Aroma transfer through methylcellulose-based films increases with the water vapor transfer rate (Debeaufort and Voilley, 1994), therefore packaging that is optimized for a high rate of water movement also provides for higher transmission of aroma compounds. Restricted movement of volatile compounds through packaging materials can also be used to increase concentrations of exogenous volatile materials to enhance flavor and / or reduce development of decay (Song et al., 1997).

Conclusions

The impact of MAP and CA on flavor and aroma is dependent on a number of factors. Temperature management is critical to avoid induction of anaerobic metabolism that leads to off-flavor development and loss of quality. Atmospheres that reduce the rate of quality deterioration while avoiding induction of anaerobiosis may still result in reduced production of other compounds that contribute to flavor and aroma. Reduced production of aroma compounds develops over long storage periods typical of CA applications, however, impacts on flavor development after short-term storage have not been well characterized. The potential for flavor enhancement and decay reduction by introduction of exogenous volatile materials into packages provides another tool to manipulate fruit and vegetable quality by the use of MAP.

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