

Inhibition of Enzymatic Browning in Fruits and Vegetables

Alternative means of controlling enzymatic browning in raw fruits and vegetables are required by the food industry due to restrictions in the use of sulfites by the U.S. Food and Drug Administration. The use of sulfite substitutes and other means of preventing browning are reviewed, and new approaches are presented. Ascorbic acid-2-phosphates are highly effective in preventing browning in cut apple. Sporix acts synergistically with ascorbic acid in apple juice and on cut apple. Ascorbic acid-6-fatty acid esters, combinations of ascorbic acid with cinnamate or benzoate, and β -cyclodextrin are effective browning inhibitors in apple juice but not on cut surfaces. Browning inhibitor performance can be improved if cut apple and potato are treated by pressure infiltration rather than by dipping at atmospheric pressure. Variation in the tendency of potato cultivars to brown can be exploited by using slower browning cultivars in processing situations where sulfites cannot be employed.

Enzymatic browning occurs in many fruits and vegetables when certain phenolic compounds in cut or bruised tissues undergo oxidation to *o*-quinones, a reaction catalyzed by the enzyme polyphenol oxidase, or PPO. Quinones then polymerize to form dark brown, black or red polymers. These reactions, the properties of PPO, and the distribution of this enzyme and its substrates in various commodities have been the subject of numerous investigations and review articles (1-7). The problem of controlling enzymatic browning in fruits and vegetables has been accorded much attention by researchers because of its importance to the food processing industry (1-2, 8-9).

Current Means of Controlling Enzymatic Browning

Sulfites and Ascorbic Acid as Browning Inhibitors. Historically, enzymatic browning was controlled by the application of sulfites

(SO₂, sulfite, bisulfite, metabisulfite), which inhibit PPO and may combine with quinones or reduce quinones to phenols, thereby preventing pigment formation (4, 9-10). Sulfites can produce acute allergic reactions in some asthmatics, however, with serious if not lethal consequences (11-12). Therefore, the Food and Drug Administration has banned the use of sulfites in fruits and vegetables served or sold raw to consumers (13) and has proposed restrictions on the use of sulfites in certain fresh potato products (14).

L-ascorbic acid (AA) and its isomer D-erythorbic acid (EA) (also called D-isoascorbic acid) have been used as inhibitors of enzymatic browning in fruit and vegetable products for at least 50 years, (15-17). These compounds prevent quinone accumulation and subsequent pigment formation by reducing the O-quinones generated from the phenolic substrates of PPO back to O-dihydroxyphenolic compounds (17-18). AA also can act as a PPO inhibitor (19-20). AA and EA are used interchangeably although there are indications that AA is more effective in some systems (21-22).

Alternatives to Sulfites. To meet the needs of the food industry for alternatives to sulfites, a number of browning inhibitor formulations have been marketed. These products are mostly combinations of AA, EA, or their sodium salts with such adjuncts as citric acid, sodium or calcium chloride, phosphates, cysteine and potassium sorbate (23-29). Commercial browning inhibitor formulations vary widely both in AA or EA content and in recommended use levels (Sapers, G. M., Eastern Regional Research Center, Philadelphia, PA, unpublished data). These sulfite substitutes are considered to be less effective than sulfites because they do not penetrate as well into the cellular matrix (11). Furthermore, AA is easily oxidized by endogenous enzymes (18) or by autoxidation, and in the course of its intended role as a browning inhibitor, may fall into a concentration range where it exerts pro-oxidant effects (30). To enhance their effectiveness, the sulfite substitutes may be used in conjunction with modified atmosphere or vacuum packaging (29,31).

Other Inhibitors of Enzymatic Browning. In addition to the aforementioned compounds, a number of other inhibitors of enzymatic browning, including reducing agents such as 2-mercaptoethanol, 2-mercaptobenzthiazole, and thioglycollate; quinone couplers such as glutathione, sodium diethyldithiocarbamate, and benzenesulphinic acid; chelating agents such as cyanide, carbon monoxide, and diethyldithiocarbamate; inorganic ions such as fluoride and borate; aromatic acid inhibitors of PPO such as benzoic acid and various substituted cinnamic acids; polyvinylpyrrolidone (PVP), which binds phenolic compounds; and the enzyme O-methyl transferase, which converts PPO substrates into inhibitors have been described (3-4). Some of these inhibitors are toxic, and none have found commercial application as food additives (4).

Among the more promising compounds showing anti-browning activity are cinnamic and benzoic acids, which were tested

successfully in apple juice (34) and on apple and potato slices (35-36). Cinnamic acid has been shown to inhibit PPO, either competitively or non-competitively, depending on the substrate and treatment of the enzyme (32), while benzoic acid was reported to be a non-competitive inhibitor of the mixed type (33).

Sporix, an acidic polyphosphate which is described as a potent chelating agent (Friedman, S., International Sourcing, Inc., South Ridgewood, NJ, personal communication, 1986), has been tested as a sulfite substitute in apples (36) but is not approved for food use in the U.S. A blend of food grade phosphates with citric acid and dextrose has been marketed as a browning inhibitor for fruits and vegetables (26). A browning inhibitor formulation containing sodium acid pyrophosphate has been introduced by Monsanto (29).

Cyclodextrins (CD's), cyclic oligosaccharides containing 6 or more glucose units with α -1,4 linkages, form inclusion complexes with various organic compounds and have been used to debitter grapefruit juice by removing naringin, a flavanone, and limonin, a terpene (37). Szejtli (38) has observed that the discoloration of some fruits, induced by reactions of polyphenols, may be retarded by CD's. Labuza (39) reported that proteolytic enzymes such as those used in meat tenderizers can prevent enzymatic browning by destroying PPO.

Blanching and Deaeration. Blanching may be used to prevent enzymatic browning in some fruit products (40) since PPO is heat labile (4). Blanching will result in the destruction or loss of flavor components in fruits (40-41), however, and would not be suitable for products expected to have the flavor and texture characteristics of the raw commodity. A process has been described for preparing light colored raisins without sulfiting, which entails a 2 minute dip in 93°C water to inactivate PPO and improve mass transfer of water vapor through the skin (42).

Vacuum deaeration and infiltration techniques have been used as freezing pretreatments to prevent enzymatic browning in apple slices by replacing tissue gases with aqueous solutions of sucrose and/or AA (43-44). Vacuum infiltration of solutions into apple slices resulted in a translucent or waterlogged appearance which would not be acceptable in a raw product (45).

New Approaches to the Control of Enzymatic Browning

A program to overcome the limitations of current alternatives to sulfites and develop new approaches to the control of enzymatic browning in fruits and vegetables was undertaken by the U.S. Department of Agriculture at its Eastern Regional Research Center in 1985. These studies yielded improved quantitative methods to determine the efficacy of browning inhibitors. A number of promising new approaches to the control of browning were identified, including the use of stable AA derivatives, individually or in combination with complexing agents and PPO inhibitors; the application of browning inhibitors by pressure infiltration; and the utilization of slow-browning cultivars of apples and potatoes.

Methodology to Evaluate Browning Inhibitors. In order to evaluate the effectiveness of treatments to inhibit enzymatic browning, quantitative procedures to measure browning were developed (46). These included the use of tristimulus colorimetry (decrease in L- and increase in a-value), spectrophotometry (decrease in percent reflectance at 440 nm), and UV-visible spectrophotometry (increase in absorbance of clarified juice at 420 nm), all of which correlate with the extent of browning. Treatments to control browning were evaluated in two model systems: the raw juice from Granny Smith apples, to which browning inhibitors could be added, and plugs, cut from Delicious apples, Winesap apples or Russet potatoes with a cork borer. Plugs were cut in half so that one half could be dipped in the treatment solution while the other half could be used as a control, receiving only a water dip. Eight pairs of plug halves could be obtained from apples, and 12 from potatoes, permitting replicated experiments that could compensate for the high degree of variability seen in individual fruits and vegetables. Samples were stored for as long as 24 hr at room temperature or several weeks at 4°C, and browning in control and treated juice samples or at the common cut surface shared by treated and control plug halves was measured periodically. In both the juice and plug systems, experimental treatments were compared with standard ascorbic acid treatments, selected to provide partial protection against browning, so that more effective treatments could readily be recognized. The ascorbic acid derivatives were compared with equimolar concentrations of ascorbic acid.

Quantitative estimates of treatment effectiveness were obtained from the data, plotted as a function of storage time (Figure 1). The lag time (interval before the onset of browning), seen as an initial flat region, and the slope of the linear region (browning rate) were determined from such curves. In addition, the changes in L-value, a-value, percent reflectance or absorbance over specified time intervals were calculated. These Δ -values were used to compare treatments by calculating the percent inhibition, a value defined as the difference between the control and treatment Δ -values, expressed as a percentage of the control Δ -value. Treatments that completely inhibited browning would give percent inhibition values of 100, while ineffective treatments would give percent inhibition values near zero. Large negative values would indicate that the treatment induced browning.

Ascorbic Acid-2-Phosphates. Seib and Liao (47) described the preparation of AA-2-phosphate (AAP) and AA-2-triphosphate (AATP), compounds that are stable against oxygen and are not reducing agents per se but release AA when hydrolyzed by a phosphatase. Such compounds might be used as additives in foods or feeds or in pharmacological applications since they would be stable until consumed and converted to AA during digestion. These compounds were evaluated as browning inhibitors for apple juice and plugs with the expectation that they would be less subject to oxidation by oxidases or autoxidation than AA and, if hydrolyzed at a suitable rate, would provide extended protection against browning (50).

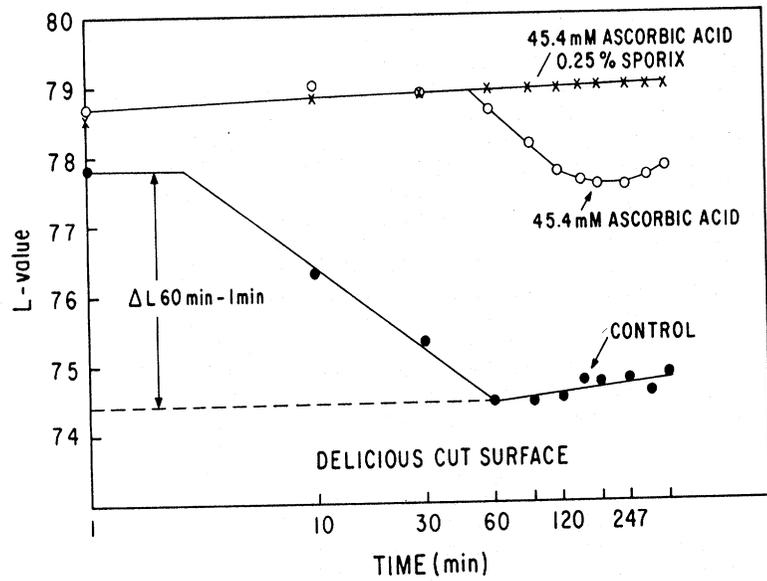


Fig. 1. Reflectance L-value at transversely cut surface of Delicious apple plugs treated with browning inhibitors or untreated (control) and stored at 20°C.

In the juice system AA-2-phosphates gave inconsistent results, and in some cases, were less effective than AA. This failure probably resulted from the loss of endogenous acid phosphatase during juice preparation. Residual acid phosphatase activity would be decreased further by the low pH of Granny Smith juice (3.3), which is substantially less than the optimal pH for acid phosphatase obtained from plant tissues (48-49).

In contrast to the juice results, both AAP and AATP were more effective browning inhibitors than equivalent concentrations of AA when applied to apple plugs. Samples treated with AAP or AATP showed little or no browning after 24 hr at room temperature or 1 week at 4°C (Figure 2). Browning inhibition was not improved significantly by the addition of AA in combination with AAP or AATP. The addition of citric acid to dips had no effect on AAP but decreased the effectiveness of AATP as a browning inhibitor.

The effectiveness of the AA-2-phosphates is due primarily to their stability. AA, applied to the cut surface of apple, may be consumed by reaction with quinones resulting from polyphenol oxidation (18) or by autoxidation (30). Seib and Liao (47) demonstrated that the AA-2-phosphates were much more stable to oxidation by H_2O_2 than was AA. Presumably, sufficient acid phosphatase is present at the cut surface of apple fruit to permit hydrolysis of the AA-2-phosphates at a rate sufficient to prevent browning but not great enough to generate a large excess of AA that would be subject to autoxidation. The poor performance of AATP in combination with citric acid probably resulted from acid inhibition of acid phosphatase, as in juice. Even under favorable conditions, AATP would be hydrolyzed more slowly than AAP (47). The suitability of the AA-2-phosphates as browning inhibitors for commodities other than apple will depend on their acidity and endogenous acid phosphatase activity.

Ascorbic Acid-6-Fatty Acid Esters. L-Ascorbyl-6-palmitate (AP), a fat soluble analog of AA, is an effective antioxidant for vegetable oils and other fatty products (51). AP and other 6-fatty acid esters of AA were shown to function as oxygen scavengers in an aqueous system only if solubilized by adjusting the pH to 9 (51). Because of the possibility that these esters might be more stable than AA and capable of functioning as reducing agents in aqueous systems, they were tested for anti-browning activity in Granny Smith juice.

Experiments with AP, ascorbyl laurate (AL) and ascorbyl decanoate (AD), added to Granny Smith juice at concentrations as high as 1.14 mM (equivalent to 200 ppm AA), demonstrated that these esters were less effective than or similar to AA initially but surpassed AA as browning inhibitors after longer periods of storage (50). The combination of AA with the fatty acid ester had little or no effect with AP and AL but greatly improved the performance of AD, providing protection against browning for at least 24 hr.

Mixed results were obtained when fatty acid esters of AA were applied to apple plugs as dispersions in pH 7 phosphate buffer, stabilized with lipophilic emulsifying agents such as Durkee's EC-25 or Durlac 100. The degree of inhibition was not

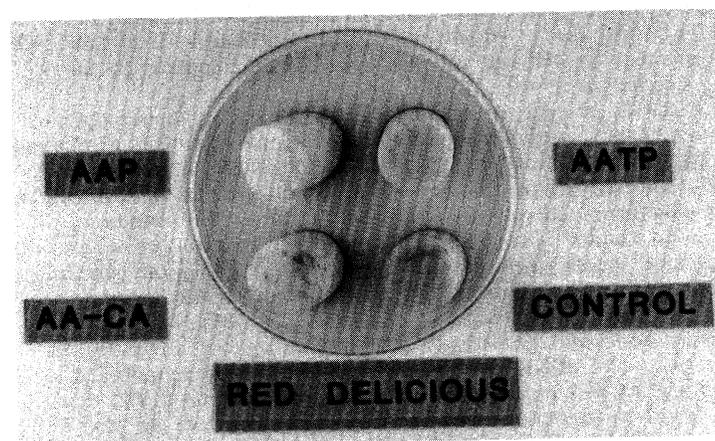
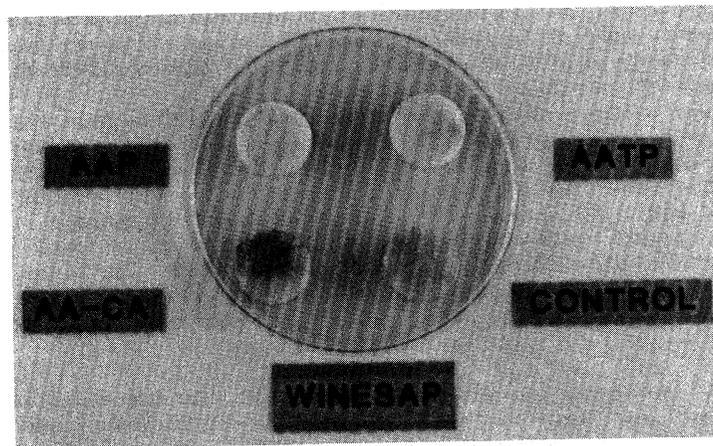


Fig. 2. Apple plugs treated with 56.8 mM ascorbic acid-2-phosphate (AAP), ascorbic acid-2-triphosphate (AATP) or ascorbic acid in 1% citric acid (AA-CA) vs untreated control, stored at 4°C for 1 week.

consistent, probably because of AP precipitation on the cut surface during storage. More stable dispersions could be prepared by substituting AL or AD for AP. Treatment of apple plugs with the former esters tended to induce browning, however. Similar results occurred when AP dispersions were prepared with less lipophilic emulsifying agents such as Tween 60 or Tween 80. These effects may have resulted from the disruption of membranes in cells near the cut surface by the emulsifying agents or esters, causing leakage of PPO and its substrates, and thereby increasing the extent of browning.

Recent patents describe new classes of AA derivatives that are claimed to have antioxidant properties and are recommended for use in high moisture foods: 6-O-phytanoyl-L-ascorbic acid and similar esters of AA or EA with tri- or tetramethyl C15-C17 alkanolic acids (52) and AA ethers in which a methoxy group with an organic residue having a molecular weight of 58 to 400 is attached to the hydroxyl group at carbon 2 (53). It is not evident whether these compounds would be effective as browning inhibitors for cut fruits and vegetables or subject to the same limitations as the 6-fatty acid esters of AA.

Cinnamate and Benzoate. Walker (34) reported that the addition of cinnamic acid to Granny Smith juice at concentrations greater than 0.5 mM prevented browning for over 7 hr. Sapers et al. (50) found that sodium cinnamate inhibited enzymatic browning in Granny Smith juice when added at concentrations between 0.67 and 2.67 mM (114-454 ppm). Combinations of cinnamate with AAP, AP or AA were similar in effectiveness, greatly surpassing AA as a browning inhibitor.

With apple plugs, 10 mM cinnamate inhibited browning for several hours but induced severe browning over extended storage times. The combination of cinnamate with AA in dips was more effective than AA alone; however, the combination of cinnamate with AAP showed no advantage over AAP alone. The tendency of cinnamate to induce browning indicates a potential problem with this compound which may undergo conversion at the cut surface to a PPO substrate by cinnamate-hydroxylase and other enzymes involved in the biosynthesis of polyphenols (54).

Sodium benzoate exhibited anti-browning activity in the juice system, the effect being concentration dependent (50). Combinations of 6.9 mM benzoate (corresponding to 0.1%, the maximum level permitted in foods as a preservative in the U.S. (21 CFR 184.1021) with 1.14 mM sodium ascorbate or AAP inhibited browning to a greater extent than either individual treatment, the effect appearing to be synergistic and due primarily to an increase the lag time.

Dips containing benzoate, alone or in combination with AA, provided short-term protection against browning in Delicious and Winesap plugs but induced browning in samples stored 6 or more hours. Induced browning by benzoate may be an indication of its conversion to a PPO substrate or its stimulation of substrate synthesis by enzymes at the cut surface. Benzoic acid in plants is derived from phenylalanine via trans-cinnamic acid (55-56) which is also a precursor of caffeic acid and other PPO

substrates (54). Benzoate formation in higher plants occurs on the thylakoid membrane; this process is apparently not reversible (56). Zenk (57) demonstrated that the addition of a large excess of benzoic acid to *Catalpa hybrida* leaves stimulated the hydroxylation of cinnamic acid to p-coumaric acid, a PPO inhibitor which might be hydroxylated to caffeic acid, a substrate. Since benzoic acid and cinnamic acid both may induce browning, neither PPO inhibitor is recommended as a component of anti-browning formulations at this time.

Sporix. Sporix, a commercial polyphosphate product, was the most promising browning inhibitor evaluated in the USDA study besides the AA-2-phosphates (50). Sporix is a powerful chelating agent as well as an acidulant (Friedman, S. International Sourcing, Inc., South Ridgewood, NJ, personal communications, 1986) and probably acts by inactivating or inhibiting PPO and by stabilizing added ascorbate, thereby delaying the onset of browning.

In the juice system, Sporix was an effective inhibitor at concentrations above 0.5% or at lower concentrations if combined with AA. Typically, such combinations prevented browning for more than 24 hr in samples that browned within 30 min if untreated or within a few hours if treated with AA alone. The exceptional effectiveness of Sporix-AA combinations resulted primarily from a lag time extension which appeared to be a synergistic effect. The ability of Sporix to control browning in juice was pH-dependent. Adding Sporix to Granny Smith juice decreased the pH from 3.3 to 3.1. When the pH of juice containing a Sporix-AA combination was adjusted to 3.3 by adding NaOH, the percent inhibition and lag time values were smaller than values obtained at pH 3.1 although not as small as values obtained with AA alone.

Sporix was ineffective as a browning inhibitor for apple plugs. Combinations of Sporix with AA were highly effective browning inhibitors, however, preventing browning for at least 24 hr at room temperature. Zent and Ashoor (36) reported that enzymatic browning in apple and potato could be inhibited by treatment with combinations of sodium erythorbate and Sporix.

Browning inhibition by Sporix combinations can be attributed to two effects: a greatly extended lag time compared to that obtained with the individual inhibitors as seen in juice, and a reduced rate of browning once the lag time has been exceeded. The lag time effect probably results from the inhibition of copper-containing oxidases and other copper-catalyzed oxidative processes in apple by Sporix. These oxidative reactions normally would bring about the rapid loss of AA and permit browning to occur once the added AA was depleted (18). Sporix also would inhibit PPO directly by chelation of its copper (3), thereby decreasing the rate of polyphenol oxidation and subsequent browning. The ability of Sporix to exert its effect on enzymatic browning by these two independent mechanisms probably accounts for the apparent synergism obtained with Sporix-AA combinations.

Cyclodextrins. Cyclodextrins (CD's) form inclusion complexes with various aromatic compounds (58), including cinnamic acid (59). Complexation of the phenolic substrates of PPO by CD's might

prevent browning. β -CD, but not α - or γ -CD, was an effective browning inhibitor in apple juice, especially when combined with AA, AA-2-phosphate, or AP (50). Browning in juice could be inhibited for at least 24 hr at room temperature by combinations of β -CD with Sporix or addition of the more soluble branched β -CD (which contains maltosyl branch chains) at a higher concentration than is possible with β -CD (Hicks, K. B., Eastern Regional Research Center, Philadelphia, PA, unpublished data).

PPO substrates in apple presumably can be complexed by β -CD but are too large to fit completely in the cavity of α -CD and too small to be retained strongly by γ -CD. Shaw and Buslig (37) reported that β -CD polymers were more effective than α - or γ -CD polymers in removing naringin and limonin from solution. The effectiveness of β -CD as a browning inhibitor will depend on the equilibrium between free and complexed PPO substrates and the rate of complex formation. Gradual browning of apple juice at all β -CD concentrations tested indicates that complex formation did not go to completion. Browning by the uncomplexed PPO substrates could be controlled by the addition of AA, AA derivatives, or other browning inhibitors.

Attempts to translate the favorable results obtained with juice into a β -CD dipping treatment for apple plugs were not successful. The inability of β -CD to inhibit enzymatic browning in apple plugs can be understood in terms of fundamental differences between the juice and cut surface systems. In the former, PPO substrates, PPO, O_2 , AA and browning inhibitors are all in solution so that the rate of browning is determined by their concentrations, the temperature, stirring conditions, and perhaps the surface to volume ratio. With the cut surface system, juice released from disrupted cell layers at the freshly cut apple surface, which contains PPO, PPO substrates, and other reactants, would be removed by the dipping treatment. Browning would not occur until these species diffused from the interior of the disrupted cell layers towards the surface or reacted in situ, given sufficient dissolved oxygen. An effective β -CD dipping treatment would have to complex PPO substrates before they diffused to the surface or reacted within the disrupted cells. The diffusion of β -CD from the cut surface to the interior of the disrupted cell layers apparently is too slow to allow the complexing agent to compete with PPO for substrates.

Application of Browning Inhibitors by Pressure Infiltration.

One of the disadvantages of conventional sulfite substitutes is their limited penetration into the fruit or vegetable piece, compared to that of sulfite (11). Pressure and vacuum infiltration have been used to increase the penetration of calcium solutions into whole, unpeeled apples to improve their keeping quality during storage (60-62). Pressure infiltration was used successfully to increase the uptake of browning inhibitor solutions into apple and potato plugs (Sapers, G. M., Eastern Regional Research Center, Philadelphia, PA, unpublished data). When Delicious plugs were pressure infiltrated at 5 psi for 5 min, they showed a weight gain of about 5%. This treatment resulted in some initial darkening due to waterlogging, indicated

by a decrease in L (ΔL infiltration), which was partially offset during subsequent storage by an increase in L (ΔL storage) (Table I). With the browning inhibitor formulations tested, the pressure treatment added about 1 week to the storage life of the samples at the higher concentration, and 3 or 4 days at the lower concentration, compared to dipping at atmospheric pressure. Pressure infiltration of Katahdin potato plugs at 15 psi added about 4 days to their storage life, compared to atmospheric pressure dipping, without causing waterlogging. These results are significant because they provide processors with the means to improve the performance of sulfite substitutes that are available now.

Cultivar Variation in Tendency of Apples and Potatoes to Brown.

Cultivar (cv.) differences in the tendency of fruits and vegetables to brown are well known (4) and have been correlated with PPO activity and substrate concentration in various commodities (63-69). Sapers and Douglas (46) exploited such differences in selecting apple cvs. for use in evaluating new browning inhibitors. Among six cvs. compared, Idared and Granny Smith browned the least while Stayman showed the most extensive browning. The use of cvs. with a low tendency to brown in processing situations where sulfites cannot be employed may obviate or minimize the need for sulfite substitutes.

Differences in the tendency of potato cvs. to brown may be used as a rationale for selecting potatoes that can be processed without sulfite or sulfite substitutes. A comparison of Atlantic and related cvs. with Russet Burbank revealed large differences in the extent of browning which were correlated with PPO activity, total phenolics and tyrosine content (68). Atlantic potato browned much more slowly than Russet Burbank potato. A simple dip in water after slicing virtually eliminated browning at the cut surface of Atlantic, while Russet Burbank showed significant browning after dipping. Peeling, especially by steam or abrasion, tends to induce browning at the peeled surface of potato. Atlantic was much less subject to such browning than Russet Burbank.

Future Directions

Studies reviewed herein have demonstrated the potential ability of several new approaches to control enzymatic browning in fruit and vegetable products: the use of novel AA derivatives, polyphosphates and β -cyclodextrin as browning inhibitors; the application of browning inhibitors to cut fruits and vegetables by pressure infiltration; and the use of cvs. having a low tendency to brown. It is likely that one or more of these approaches will be useful as an alternative to sulfites to control browning in affected commodities.

Before commercial application becomes a reality, additional studies are required to optimize the treatments, extend them to other commodities, establish their safety, and demonstrate economic feasibility. Furthermore, because these approaches to the replacement of sulfites address only one function of sulfites,

Table I—Application of Browning Inhibitors to Delicious Plugs by Pressure Infiltration vs Dipping

Formulation	Method of Application ^a	ΔL		Percent Inhibition ^c		
		Infiltration	Storage ^b	Storage (days)		
				4	7	14
4.5% Sodium Erythorbate + 0.2% CaCl ₂	Pressure	-4.0 ^e	2.3 ^d	92 ^d	86 ^d	82 ^d
	Dip	-0.7 ^d	0.6 ^e	93 ^d	84 ^d	66 ^e
2.25% Sodium Erythorbate +0.2% CaCl ₂	Pressure	-3.3 ^d	1.8 ^d	80 ^d	70 ^d	--
	Dip	0.9 ^d	-0.4 ^d	66 ^d	54 ^e	--

^a Immersion for 5 min.

^b 7 days at 4°C.

^c Based on change in a-value.

^{d-e} Means of 4 replicate treatments; means within columns for each formulation, followed by different superscripts, are significantly different at $p < 0.05$ by the Bonferroni LSD test.

Source: Sapers, G. M. Eastern Regional Research Center. Unpublished data.

namely, the control of enzymatic browning, other functions served by sulfites must be dealt with. Among these functions are the inhibition of non-enzymatic browning in dehydrated fruits and vegetables; control of bacteria in wine, grapes and other products; and bleaching of cherries. Since no single approach is likely to meet these needs, research is needed to develop treatments combining several principles of preservation, i.e., use of browning inhibitors in combination with antimicrobials and modified atmosphere packaging. Such treatments would be applied to cvs., selected for their low tendency to brown, and processed under conditions of peeling, cutting, heating and dehydration that minimize the extent of both enzymatic and non-enzymatic browning. Due to the complexity of the problem, a systems approach is suggested to determine the optimal conditions and treatments for any given commodity and product category.

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