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Calcium Treatment of Apples and Potatoes to Reduce Postharvest Decay

Economic losses caused by postharvest pathogens are greater than is often realized, and the avoidable losses between the farm gate and the consumer are cause for concern. Fresh fruits and vegetables, because of the added cost of harvesting and handling, increase several times in value when they are moved from the field to the consumer. The economic necessity for reducing storage losses and extending the storage life of these commodities adds to the more basic consideration of reducing world hunger and malnutrition.

Treatments such as heat, chemicals, and irradiation effectively reduce populations of microorganisms on various fruits and vegetables and reduce postharvest losses, but in certain cases the resulting injury limits the value of such treatments. Enhanced consumer awareness of chemical residues and a fear of the effect of ionizing radiation on fresh produce are also prompting the development of alternative methods of protection. For some pathogens, particularly pathogenic bacteria, no practical chemical controls have been developed, and many fungal pathogens have developed resistance to commonly used chemicals. To continue to reduce postharvest losses and improve the quality of stored produce, natural mechanisms of resistance to pathogens might be exploited to reduce dependency on chemical treatments.

Certain physiological disorders and diseases of storage organs such as fruits and vegetables are related to the calcium content of their tissues (22,34). Calcium deficiency results in serious economic losses in vegetable and fruit crops, including potatoes and apples (15,44). Calcium helps regulate the metabolism in apple fruit, and adequate concentrations maintain fruit firmness and lower the incidence of such disorders as water core, bitter pit, and internal breakdown (1,17,26,31). Ripening generally is delayed when calcium is increased, and fruit maintain their quality longer. In potatoes, calcium content has been associated with physiological disorders such as internal brown spot in tubers (40) and subapical necrosis of sprouts (15). Decay, whether caused by *Erwinia carotovora* (Jones) Bergey et al in potatoes (27,28) or by fungal pathogens in apples (6,33), also is effectively reduced with applications of calcium.

In this paper we discuss the effect on postharvest decay of increasing the calcium content of apple fruit and potato tubers. Research on the effect of enhanced calcium levels has been conducted along parallel but independent lines for both commodities. The units of measurement for reporting calcium content (micrograms of calcium per gram dry weight for apples and percent dry weight for potatoes) used in the cited papers are also used in this paper.

The similarity of the calcium effect on apples and potatoes may be explained by current knowledge of movement of the calcium ion in plants. Although intracellular concentrations of potassium may range between 20 and 100×10^{-3} M, concentrations of calcium within cells must be maintained between 10^{-5} and 10^{-8} M to prevent interference with cellular functions. Because calcium is actively excluded from living cells of the phloem, very little moves there (4). Movement instead is primarily in the xylem and preferentially toward meristematic and transpiring tissues. In apples and potato tubers, calcium that is present initially in a cell is greatly diluted when the cell enlarges rapidly with flow of nutrients from phloem tissue. Once deposited in tissue, calcium is not redistributed, and in both apples and potatoes, tissues may differ widely in concentrations of calcium. For example, whereas apple leaves may contain 0.2–4.0% of calcium dry weight, the internal concentration of calcium in fruit may range from 150 to 300 μg per gram of dry weight (0.015–0.030%) (9–11). Medullar tissue in potatoes may contain 0.014–0.075% calcium (41).

Methods of Calcium Treatment

The calcium concentration in apples and potato tubers necessary to reduce decay significantly usually is higher than can be obtained with standard fertilization practices (16). Soils may contain adequate levels of calcium, but most of what is taken up by plants is distributed to the leaves. Calcium sprayed directly on apples on the tree can increase the calcium content of fruit, but dipping the fruit in solutions of $CaCl_2$ is more effective (14,32). Vacuum or pressure infiltration of $CaCl_2$ has been superior to dips for control of bitter pit in Australia and New Zealand (32). Experimentally, pressure infiltration with solutions of $CaCl_2$ for 2 minutes at 68.95 kPa can increase the calcium concentration of fruit more effectively than vacuum infiltration for 2 minutes at 33 kPa or dipping for 2 minutes (Table 1) (9).

Similarly, on an experimental basis, the calcium content of potato tubers may be increased by vacuum infiltration of

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Table 1. Calcium concentration in apple cortex after application of $CaCl_2$ solutions

Treatment method[y]	Calcium concentration (%)				
	0	2	4	8	12
Dip	250 a[z]	300 b	350 c	450 d	700 e
Vacuum	250 a	550 b	650 c	1,400 d	1,500 e
Pressure	250 a	1,100 b	1,475 c	2,100 d	3,250 e

[y] Fruit were dipped in each solution for 2 minutes, vacuum-infiltrated for 2 minutes at 33 kPa, or pressure-infiltrated for 2 minutes at 68.95 kPa.
[z] Within rows, numbers followed by the same letter are not significantly different ($P = 0.01$) according to Duncan's multiple range test. Treatment methods were significantly different at $P = 0.01$.

Fig. 3. Golden Delicious apples picked at prime harvest and inoculated with *Penicillium expansum* 4 months after pressure infiltration with calcium chloride solutions. Area of decay (top row) was significantly less than in nontreated fruit, but amount of superficial injury (bottom row) expanded with increasing concentration of calcium chloride.

Table 2. Calcium concentration in potato tuber peel and medulla after application of $Ca(NO_3)_2$ solutions[y]

Calcium (mg/L)	Calcium concentration (% dry weight)	
	Peel	Medulla
0	0.102 a[z]	0.022 a
250	0.165 b	0.034 b
500	0.164 b	0.036 b
1,000	0.246 c	0.046 c
2,000	0.268 d	0.048 c
3,000	0.327 e	0.052 d
6,000	0.371 f	0.063 e
12,000	0.508 g	0.075 f

[y] Tubers were immersed for 2 hours, the first under vacuum (13 kPa).
[z] Within columns, numbers followed by the same letter are not significantly different ($P = 0.05$) according to Duncan's multiple range test.

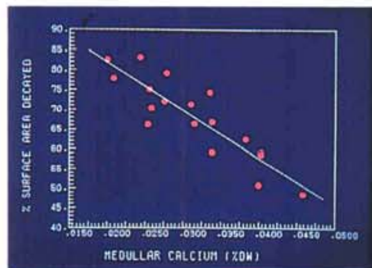

Fig. 1. Percentage of potato surface area decayed in relation to percentage of tuber medullar calcium. Tubers were immersed for 20 minutes in an inoculum suspension containing 10^6 cfu ml^{-1}, then incubated in a mist chamber at 20 C for 96 hours.

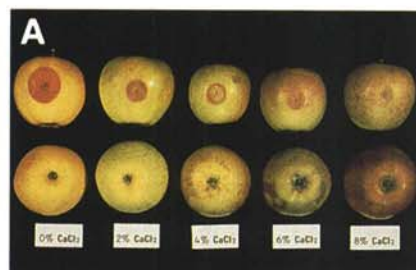

Fig. 2. Decay of potato tubers caused by *Erwinia carotovora* pv. *atroseptica*, with decayed portion removed to show amount of maceration. Decay amount decreased as calcium concentration in tubers increased (left to right). Tubers were incubated in a mist chamber at 20 C for 96 hours.

Fig. 4. Golden Delicious apples picked 2 weeks after prime harvest and inoculated with *Penicillium expansum* 4 months after pressure infiltration with calcium chloride solutions. High calcium concentration in the fruit (A) decreased the area of decay (bottom row), but (B) severe injury extended well into the cortex of the fruit.

calcium solutions. Calcium nitrate was more effective than calcium chloride, calcium sulfate, or calcium gluconate in increasing the calcium content of peel tissue up to five times and medullar tissue three times that of untreated tubers (Table 2) (27). No apparent injury to the tuber resulted from calcium infiltration. Increasing the concentration of calcium in the medulla from 0.022 to 0.063% decreased the percentage of surface area decayed by *E. c. atroseptica* from 93 to 15% when tubers were held for 60 hours in a mist chamber (Figs. 1 and 2) to simulate conditions that may develop in storage facilities. Mist covers tubers with a film of water, reducing the oxygen content and enhancing bacterial infection. In commercial settings, however, vacuum infiltration of potato tubers with calcium is not feasible at present.

Unlike the effect with apples, the calcium content of potato tubers can be increased to some extent through fertilization. The tuber absorbs some calcium directly from the soil solution (24), and uptake can be enhanced by certain environmental conditions (43). Fertilization is the optimum method of increasing calcium in tubers because extra handling and costly equipment necessary for postharvest treatment are eliminated. When $CaSO_4$ and $Ca(NO_3)_2$ were applied, calcium uptake by potato plants (cv. Russet Burbank) increased from 0.057 to 0.277% dry weight in the peel and from 0.011 to 0.062% in the medulla (27). This increase in tuber calcium was also correlated with a decrease from 43.5 to 19.4% in surface area decay.

Factors Affecting Uptake

Control by calcium of physiological and pathological disorders in stored fruits and vegetables is related to the amount deposited within the treated organ. Cultivar, maturity, and permeability of the peel affect absorption of calcium by apple fruit from preharvest sprays or postharvest treatments. Although calcium applied after harvest presumably enters the fruit primarily through lenticels (3), cracks in the cuticle and epidermis may also be important pathways, especially when fruit are picked late in the season (5). Cracks in the cuticle and skin are especially prevalent in the cultivar Golden Delicious early in the growing season (29). Severity of cracking varies yearly (19), and the number and width of cracks also increase as fruit develop (18).

Apple maturity as related to calcium uptake and postharvest decay caused by *Penicillium expansum* Link were studied in Golden Delicious fruit harvested at different maturities (10). Fruit were picked at 2-week intervals just before, at, and after the predicted prime or nor-

Fig. 5. Potato tuber vacuum-infiltrated with a rhodamine B dye solution to indicate points at which calcium solution enters through lenticels and wounds.

Fig. 7. Apples wound-inoculated with *Botrytis cinerea* after pressure infiltration with calcium chloride solutions.

Fig. 9. Golden Delicious apples after pressure infiltration with calcium, magnesium, or strontium chloride solutions and storage for 5 months at 0 C. Magnesium treatment caused severe injury.

Fig. 6. Golden Delicious apples inoculated with 10^4, 10^5, or 10^6 spores per milliliter of *Penicillium expansum* 6 months after pressure infiltration with calcium chloride solutions. Amount of decay decreased as calcium concentration increased and inoculum concentration decreased.

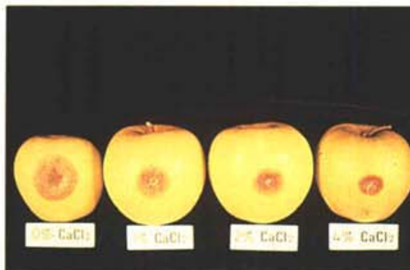

Fig. 8. Golden Delicious apples wound-inoculated with *Glomerella cingulata* 6 months after pressure infiltration with calcium chloride solutions.

mal harvest period and immediately pressure-infiltrated (2 minutes at 68.95 kPa) with 0, 2, 4, 6, or 8% $CaCl_2$ solutions. After 4 months of storage at 0 C, each lot of fruit was wound-inoculated by dipping in a conidial suspension (10^6 spores per milliliter) of *P. expansum* and assayed after 7 days at 20 C for decay and calcium in the flesh.

Results indicated a direct relationship between calcium uptake, inhibition of decay, and time of harvest. Infiltration with 8% $CaCl_2$ of apples picked 2 weeks before prime harvest doubled the calcium concentration of the flesh without causing surface injury but reduced decay only 25%. Infiltration of the same calcium solution into fruit picked at prime harvest increased the calcium concentration of apple flesh to five times that of untreated fruit and reduced decay 57%. These changes were not significantly different from those resulting from infiltration of 4% $CaCl_2$, but discoloration of the peel was greater at 8%. A 2% $CaCl_2$ solution infiltrated into fruit of the prime harvest was optimum (Fig. 3). Pressure infiltration of an 8% $CaCl_2$ solution into fruit picked 2 weeks after prime harvest increased the calcium concentration of the flesh almost seven times over that of untreated fruit, with 67% less decay (Fig. 4A). As with the previous harvest, increasing the $CaCl_2$ concentration above 4% did not suppress decay further and also resulted in more injury than occurred in fruit from the prime harvest (Fig. 4B). Whereas injury to fruit picked at prime harvest was primarily limited to the peel surface, the brown discoloration resulting from infiltration of 6 and 8% $CaCl_2$ into late-harvested fruit extended 10 mm into the cortex. These apples were unsuitable for both the fresh market and processing.

Fruit maturity at the time of harvest can significantly affect the benefits of calcium infiltrated into apple flesh. If the fruit is harvested and treated too early, insufficient $CaCl_2$ solution is taken into the fruit and does little to inhibit decay. If the fruit is harvested too late, more calcium is taken up than is needed for optimum decay control, and severe fruit injury may result.

Calcium deposition in potato tubers is similarly affected by cultivar, maturity, and damage to the epidermis. Tubers of cultivars harvested late in the season frequently have higher amounts of calcium than do those harvested early. Russet Burbank, for example, may contain 0.025% calcium in the medulla and 0.109% in the peel, whereas Norchip may average 0.016% in the medulla and 0.077% in the peel (41). When vacuum infiltration is applied to tubers, solutions enter at lenticels and wounds (Fig. 5). "Cured" tubers (i.e., the outer epidermal layers have been replaced with a thick periderm) are also more resistant to movement of solutes into the inner tissues.

Diffusion of calcium into potato tubers is affected by cultivar, soil type, fertilization practices, and weather. Most soils, with the exception of those derived primarily from sand, contain sufficient calcium for plant growth. But calcium may be unavailable or its uptake impeded by competing cations such as Mg^{++}. Fertilization with calcium is greatly influenced by the potential of calcium to enter the soil solution. Thus, small particles are preferred. In the loamy sand soil of central Wisconsin, a preplant strip application of sieved $CaSO_4$ consistently increased tuber calcium, improved quality, and reduced susceptibility to bacterial soft rot (35,36).

Calcium nitrate is an alternative source of soluble calcium. Placing the calcium directly into the hill where tubers form is effective because calcium can enter the tuber directly through the epidermis (36). Results with calcium fertilization may differ, however, under various environmental conditions (43). High air temperature and low humidity, which increase transpiration, may increase amounts of calcium in the foliage. If tubers have formed on plants, such conditions also can result in the movement of water out of the tubers. With lower temperatures at night, high humidity, and ample soil moisture, the water deficit in the tuber can be restored by comparatively high solutions of calcium entering from the roots. Cycles of such extreme conditions may cause the tuber to alternately expand and contract, resulting in an increase in calcium during each cycle.

How Calcium Reduces Decay

Calcium is a normal constituent of the cell wall and middle lamella. The relationship between calcium ions and the cell wall partially explains the increased resistance to invasion by certain microorganisms prompted by calcium. Calcium ions bind to pectins in the cell wall (12). Pectins are composed of chains of polygalacturonic acid residues with rhamnose insertions that cause marked kinks in the chain (30). The resulting bunched configuration of the polygalacturonic acid chain allows spaces for insertion of cations. All such

spaces may be filled, since binding of one ion causes a chain alignment that facilitates binding of the next ion (20). Cation bridges between pectic acids or between pectic acids and other acidic polysaccharides hinder accessibility to enzymes produced by the fruit that cause softening and to enzymes produced by fungal or bacterial pathogens that cause decay.

In a study by Conway et al (8), calcium applied by pressure infiltration into Golden Delicous apples became bound to cell walls. Cell walls of control fruit contained a calcium concentration of about 550 $\mu g\ g^{-1}$ (0.055%), whereas the concentration in those of fruit treated with $CaCl_2$ solutions of 0, 1, 2, or 4% steadily increased to 1,900 $\mu g\ g^{-1}$ (0.190%) at the highest level. The increase was not proportional to the concentration of $CaCl_2$ applied, perhaps because binding sites in the pectin are of limited number. When other fruit similarly treated were inoculated with spore suspensions of *P. expansum*, the relative effectiveness of the increased calcium in the cell wall increased as the spore numbers in the inoculum decreased (Fig. 6). Decay was reduced 52, 37, and 28% with 10^4, 10^5, and 10^6 conidia per milliliter, respectively, in fruit treated with the 4% $CaCl_2$ solution compared with control fruit.

Later, polygalacturonase was purified from the decayed tissue of untreated apples that had been inoculated with *P. expansum* (7), and cell wall samples with varying calcium content were used as substrates for the enzyme. Significantly less product, in the form of uronic acid, was released from high-calcium cell walls than from low-calcium walls. This indicated that reduction in decay caused by *P. expansum* was due, at least in part, to a decrease in maceration of cell walls by polygalacturonase, presumably following improved structural integrity proceeding from an increase in calcium content.

Calcium-induced resistance in apples affects several pathogens (12). Endogenous calcium in apples added by postharvest pressure infiltration with $CaCl_2$ solutions also reduced decay caused by *Botrytis cinerea* Pers.:Fr. (Fig. 7) and *Glomerella cingulata* (Stoneman) Spauld. & H. Schrenk (Fig. 8). *B. cinerea* and *G. cingulata* also produce polygalacturonase, and calcium might reduce the severity of decay by these fungi in a similar manner. It appears, however, that calcium may affect each pectolytic enzyme differently. Decay is reduced least in fruit inoculated with *P. expansum*, a relatively fast-growing pathogen, but most in fruit inoculated with *G. cingulata*, a relatively slow-growing pathogen. Whether the effect is always inhibition of polygalacturonase activity, as with *P. expansum*, or whether the mechanism is different remains to be proved.

Investigations into the mechanism by which increased tissue calcium reduces bacterial soft rot of potato tubers parallel those using apple and *P. expansum*, but *E. c. atroseptica* produces several forms of pectate lyase in addition to polygalacturonase. Potato tubers (cv. Superior) were produced with high and low concentrations of medullar calcium (28). When tubers were inoculated with serial dilutions of the bacterial pathogen, the relative effectiveness of calcium in reducing decay was increased as inoculum decreased. Injection with a partially purified culture filtrate from *E. c. atroseptica* with pectate lyase and polygalacturonase activity resulted in decay as with live bacteria. Maceration diameters were consistently higher in low-calcium tubers than in those having high medullar calcium. Mixing tuber cell walls and a purified pectate lyase produced significantly slower release of uronides from high-calcium walls than from low-calcium walls (25). Thus, the role of calcium in resistance may be one of interfering with the activity of pectolytic enzymes.

The susceptibility of potato tubers to bacterial soft rot also has been associated with tissue membrane permeability and electrolyte loss (23). When peel and medullar tissues were immersed in solutions containing polygalacturonase and pectate lyase activity, the rate of electrolyte loss was greater from low-calcium tubers than from high-calcium ones (28). Calcium binds anionic groups of all membranes to form bridges between structural components, thereby maintaining selective permeability, structural integrity, and cellular compartmentalization.

Calcium also directly affects the activity of pectolytic enzymes. A polygalacturonase was extracted from apples infected with *P. expansum*, and millimolar amounts of calcium were added to the enzyme-substrate mixture and allowed to incubate. As the calcium concentration increased, the enzyme activity, measured by the formation of uronic acid, was reduced significantly (Conway and Sams, *unpublished*). In apples, the amount of calcium bound to cell walls reached a maximum with the 4% solution, even though total calcium continued to increase after treatment with the 8% solution. Decay decreased, however, indicating that the additional free calcium may have a direct effect on polygalacturonase activity (Conway and Sams, *unpublished*).

Calcium, then, inhibits polygalacturonase activity at relatively low concentrations, as is shown in tests with the enzyme extracted from *P. expansum*. In contrast, pectate lyase in *Erwinia* is stimulated by $CaCl_2$ at concentrations from 2×10^{-5} to 1×10^{-3} M. Concentrations above 10^{-3} M in vitro resulted in precipitation of the sodium-polypectate substrate and a decrease in the reaction rate of the lyase (37,38).

Other Cations and Decay

Carboxylic acid groups of pectic materials have a high affinity for calcium ions, and the resulting effect of cross-linking on physiological and pathological processes is greater than for other cations present in plant tissues (39). The middle lamella exists as a gel; calcium very efficiently promotes gel formation in a pectic solution, whereas manganese and magnesium have almost no effect (39). When ion exchanges occur between cell walls, between calcium and either monovalent cations or magnesium, there is a marked preference for calcium (13,39). Barium and calcium in bean tissue infected with *Rhizoctonia solani* Kühn decreased tissue maceration by polygalacturonase (2). Maceration was inhibited less with magnesium and was not significantly influenced by potassium or sodium. As Golden Delicious apple fruit mature, monovalent cations are exchanged for polyvalent cations, particularly calcium. Therefore, the pectic substances are less extensively cross-linked and become more susceptible to decay (42).

When apple fruit were pressure-infiltrated with solutions of calcium, magnesium, or strontium (11), the concentrations of all cations were increased and all cations reduced decay. Calcium, however, was significantly more effective than magnesium or strontium, which had similar effects. Injury in the form of brown, circular, sunken lesions on the fruit surface with the $MgCl_2$ treatments (Fig. 9) was characteristic of the physiological disorder bitter pit (21). When potato tubers were infiltrated with salt solutions of monovalent and divalent cations and inoculated with *E. c. atroseptica*, the severity of bacterial soft rot was significantly less in the calcium-treated tubers (27). Magnesium and strontium reduced the severity of tuber decay, but not as effectively as calcium, and all divalent cations were more effective than sodium or potassium.

Problems and Prospects

The use of synthetic chemicals to control plant diseases is becoming more restricted, especially for postharvest treatments. The added costs of harvesting and handling make postharvest losses even more important economically than preharvest losses. Increasing the resistance of storage organs to decay by elevating the tissue concentration of calcium enables use of a natural, internal mechanism of resistance. Since calcium increases resistance to microbial enzymes by stabilizing plant cell walls and cell membranes and does not act directly on the pathogen, resistant strains of the pathogen may not develop or resistance may be delayed. But increasing the calcium content in host tissue to a level that reduces postharvest losses is difficult.

For apples, fertilizer regimes or liming practices have not increased calcium because the ion is not absorbed well and distributed to the fruit. Fertilization can increase the calcium content of potato tubers, but solubility and soil type are important considerations. Sandy soils with a low cation exchange capacity seem to produce tubers that are especially susceptible to postharvest losses from pathovars of *E. carotovora*. Fortunately, potato plants grown in this type of soil respond well to calcium fertilization, and a significant increase in tuber tissue calcium is possible. Tubers from plants grown in other types of soil may not respond as readily with increased resistance to decay, however.

The direct application of calcium to the storage organ seems to be the most efficient method for increasing calcium for both potatoes and apples. Vacuum infiltration of calcium into potato tubers reduces bacterial decay and does not produce the injury associated with apples but is not applicable commercially. For apples, pressure infiltration is effective, but dipping alone cannot move sufficient calcium into fruit to resist decay. Optimum maturity of fruit is very important. Immature fruit take up too little calcium and are not benefited, whereas overmature fruit take up so much that injury results. Sanitation is also necessary for calcium treatment to be beneficial. Any fungal spores that infest the fruit or the infiltration solution are forced into the fruit, and injuries create new infection courts for the pathogens. Until these problems can be overcome, pressure infiltration of calcium into apples remains in the experimental stage.

Treatment of storage organs with calcium alone or in conjunction with fungicides or biological control agents can reduce the concentration of the control agent. The proper use of calcium, either alone or in combination with other treatments, can reduce storage losses of either pathological or physiological origin and result in a product of higher quality for the consumer.

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