

# The Role of Calcium and Nitrogen in Postharvest Quality and Disease Resistance of Apples

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The role of calcium and nitrogen on postharvest physiology of pome fruit has been extensively studied, as these elements are known to be more involved in various fruit quality factors than other mineral elements. The major emphasis has been to extend storage life of fruit and delay fruit ripening through a better understanding of the physiological and biochemical role of Ca and N.

Calcium affects fruit senescence and quality by altering intracellular and extracellular processes, and the rate of fruit softening depends on fruit Ca status (Fallahi et al., 1987; Lidster and Porritt, 1978; Mason et al., 1975; Poovaiah, 1988). Calcium also plays a regulatory role in various processes that influence cell function and signal transduction (Marme and Dieter, 1983; Poovaiah, 1988).

## FUNCTION AND INTERACTION OF CA IN CELL WALLS

At least 60% of the total Ca in the plant is associated with the cell wall fraction (Rossignol et al., 1977). The structure of the cell wall is composed of cellulose microfibrils embedded in a gel-like matrix composed of several noncellulosic polysaccharides and glycoproteins (Fry, 1986). In this matrix, the pectic polysaccharides consist of a rhamnogalactosyluronic backbone with covalently linked side chains of arabinose and galactose (Dey and Brinson, 1984). In the cell wall of apple (*Malus domestica* Borkh.) fruit, regions of unbranched galactosyluronic residues (homogalacturonan) have been identified (Barrett and Northcote, 1965). Hank and Northcote (1974) reported that most polysaccharides and glycoproteins of the cell wall matrix are synthesized intercellularly, secreted through the plasma membrane and released in a soluble form. Insolubilization of these polymers in the cell wall involves the formation of crosslinks (Fry, 1986). Galactosyluronic residues of the pectic fraction contain a carboxyl group that may be involved with methyl, acetyl, and phenolic esterification or ionic modifications (Fry, 1986), and these modifications influence the physical property of pectic material, and thus the textural properties of the tissue (Poovaiah et al., 1988). Pectic polymers are able to form a gel when Ca is added (Grant et al., 1973). Formation of a gel in this process depends upon the chemical and structural properties of pectin. Pectins with a high degree of esters do not form cross-links or gel when Ca is added (Yamaoka and Chiba, 1983).

Pectic polysaccharides are abundant in the middle lamellar region (Hall, 1976) and make up about 35% of the primary wall of dicots (Darvill et al., 1980). Calcium serves as an intermolecular binding agent that stabilizes pectin-protein complexes of the middle lamella (Dey and Brinson, 1984). Calcium also plays an important role in the cell membrane by inducing rigidification at the membrane surface of apple fruit tissue (Legge et al., 1982).

## CALCIUM AND FRUIT FIRMNESS IN APPLES

Cell wall degradation results in softening in apple fruit (Diehl and Hamann, 1979). Sams and Conway (1984) reported that Ca delays softening in apples by delaying degradation of cell wall polymers. Calcium also plays a major role in cell-to-cell adhesion, and this phenomenon is important in the textural quality of apples. Apple fruit at harvest have a high degree of cell-to-cell contact. Calcium-treated fruit that have been stored for several months retain their firmness and cell-to-cell contact, while untreated fruit soften during storage and cell walls swell and eventually separate (Poovaiah et al., 1988).

Cell wall hydrolases are involved in softening of climacteric fruit and this process has been reviewed by Huber (1983) and Dey and Brinson (1984). Solubilization and degradation of hemicellulose and insoluble pectins contribute to the pool of monosaccharide substrates for respiration (Dey and Brinson, 1984). Polygalacturonase (PG) enzyme activity results in degradation of pectic rhamnogalacturonan in most fruit, and this dissolution of pectic polymer is the primary cause of tissue softening (Dey and Brinson, 1984; Huber, 1983). Kertesz (1951) reported that pectin methylesterase (PME) is a pectin-degrading enzyme that can be found in many fruit. PME could stimulate depolymerization of pectin by activation of PG (Pressey and Avants, 1982). Pressey and Avants (1976) identified two types of PG. Endo-PG cleaves the rhamogalacturonan chain, but exo-PG removes galacturonosyl residues sequentially from the nonreducing end of the chain.

Apple leaves contain more Ca than fruit tissue (Fallahi and Simons, 1993a 1993b; Green and Smith, 1979; Hanger, 1979; ). Most cultural practices that stimulate vegetative growth, such as excess pruning or N application, could result in more partitioning of Ca in the leaf rather than fruit tissue. Calcium application increases fruit tissue Ca and decreases Ca-related disorders (Scott and Wills, 1977; Wills and Trimazi, 1977). Administration of calcium chloride with vacuum infiltration in apple fruit retards fruit softening (Fallahi et al., 1987; Poovaiah et al., 1988). Calcium content of apple fruit is directly linked to incidences of bitter pit, internal breakdown, watercore, and poststorage disease resistance.

## BITTER PIT IN APPLE FRUIT AND THE ROLE OF CA AND N

Bitter pit in apple fruit was first believed to be caused by persistence of starch (Carne et al., 1929), viral infection (Atanasoff, 1934), and chemical toxicity (Smith, 1926). Delong (1936), Smock (1941), and Garman and Mathis (1956) were among the first researchers who found that bitter pit results from fruit Ca deficiency. Smock and Van Doren (1937) described the first sign of bitter pit, and reported that cell walls of affected fruit collapse and plasmolysis occurs. When cell walls collapse, pit cavities are formed. Simon (1978) proposed that fruit tissue becomes water-soaked, either through the influx of external water into the free space, or loss of vacuolar fluid as a result of the loss of membrane permeability due to Ca deficiency.

Comprehensive reviews on bitter pit are reported by Garman and

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Mathis (1956), Faust and Shear (1968), Perring (1986), and most recently by Ferguson and Watkins (1989). Fruit Ca content correlates more strongly to bitter pit than does leaf Ca (Askew et al., 1960; Fallahi et al., 1985). Preharvest Ca sprays (Baxter, 1960; Bramlage et al., 1985; Garman and Mathis, 1956) and postharvest infiltration (Fallahi et al., 1987) have been shown to reduce bitter pit in apple fruit.

Minerals other than Ca, such as Mg and K, are also associated with bitter pit incidence in apple fruit (Faust and Shear, 1968). The involvement of these elements could be due to the synergistic or antagonistic effects of Ca rather than to the effects of these nutrients per se. Fallahi et al. (1987) observed severe bitter pit-like symptoms in 'Golden Delicious' apple fruit infiltrated with Mg, which was due to a high Mg/Ca ratio. Calcium and Mg will exchange for each other (Ferguson and Watkins, 1981a, 1981b), and Mg will reduce Ca uptake into fruit tissue (Ferguson and Watkins, 1981b). High N fertilizer can also increase bitter pit in apples (Faust and Shear, 1968). Nitrogen also influences yield and fruit size; therefore, it is difficult to distinguish the direct effects of N on bitter pit. Trees supplied with ammonium source N are more susceptible to bitter pit than those with nitrate nitrogen (Martin et al., 1970). Boron has also been associated with Ca and corking disorders in apple fruit and reduction of bitter pit (Faust and Shear, 1968).

### ROLE OF N AND CA IN APPLE FRUIT WATERCORE INCIDENCE

High levels of N are believed to lead to watercore (Bothe 1912; Harley, 1934), particularly in susceptible cultivars injected with N (Hill and Davis, 1936). However, field experiments have shown that high (but not excessive) levels of N can actually decrease watercore (Fisher, 1923). Heinicke (1934) proposed that if N is applied before the shoot growth has ceased, shoots can compete with fruits for photosynthates. After shoot growth stops, even more photosynthates can be partitioned into the fruit sink, leading to watercore (Marlow and Loescher, 1984). In an experiment with 'Fuji' apple, various levels of ground-applied N did not affect the incidence of watercore (Fallahi, unpublished data).

Calcium-deficient fruit have been reported to have lower Ca and higher K and Mg (Sharples, 1967). Some reports indicate that watercore in apple was reduced by Ca sprays (Beyers, 1963; Fukuda, 1977; Sharples, 1980), and by dipping fruits in  $\text{CaCl}_2$  solutions while they were still on the tree (Bangerth, 1973).

Watercore is a serious problem in 'Fuji' apple, although certain markets prefer fruits with watercore. In 1993, when the growing season was cool, incidence of watercore was high in most 'Fuji' growing-areas in the northwestern United States. However, in 1994, when the growing season was unusually warm, watercore incidence was very low (Fallahi, unpublished data). Gergely et al. (1980) and Stebbins and Dewey (1972) reported that a decrease in transpiration would lead to a decrease in Ca movement to the leaves. These observations suggest that weather patterns or soil water deficits that produce reduced evatranspiration could result in an overall deficit of Ca in apple trees. This could be most important about 5 weeks after anthesis when the fruits are undergoing cell division.

### PREDICTION OF POSTHARVEST FRUIT QUALITY BY PREHARVEST N AND CA

Although leaf analysis is a diagnostic tool for optimizing mineral nutrition in fruit trees, it correlates weakly with fruit quality; thus, fruit analysis is more useful in estimating quality (Fallahi et al., 1985; Sharples, 1980) and storage disorders (Bramlage et al., 1980; Sharples, 1980). Mineral analyses of leaf and fruit tissues have become more popular in recent years because of the advances in analytical equipment, allowing multi-element analyses at a fraction of the time and cost traditionally associated with mineral analyses. Understanding relationships between postharvest quality and preharvest mineral nutrients and orchard practices makes various management decisions, such as storage strategies, easier. An early identification of fruit likely to be low in soluble solids concentration (SSC) or titratable acidity (TA) after storage also will assist in developing marketing strategies.

A perfect identification and prediction of fruit quality is neither possible nor necessary. If the apple industry can predict and categorize fruit likely to be low or high in some postharvest quality attributes before storage, profit can be enhanced. Sharples (1980) presented fruit mineral standards for 'Cox's Orange Pippin' apples, suggesting that the performance of fruit in storage can be predicted by fruit analysis immediately before harvest.

Fallahi et al. (1985) studied the relationships between seasonal fruit and leaf contents and fruit quality in 'Starkspur Golden Delicious' apple. They developed regression equations from seasonal leaf and fruit mineral analyses to predict fruit quality attributes at harvest and after storage. Soluble solids concentration, skin ground color, and TA were strongly predicted as early as June or July. However, an August analysis was most predictive. For TA, a combination of leaf and fruit minerals produced stronger predictions than leaf or fruit minerals alone in each individual year. Soluble solids concentration, skin color, and bitter pit were more accurately predicted by fruit analyses. Fruit N and Ca concentrations correlated negatively to fruit skin yellow color and SSC. Fruit size was important in regression equations for firmness, but was not essential for other variables. In this report (Fallahi et al., 1985), although between-year predictions were not as good as within-year predictions, regression equations could successfully place fruit in high or low categories for most quality characteristics.

Fallahi et al. (1988) developed a procedure to strengthen fruit quality prediction between years. In their diagnostic procedure, leaf and fruit mineral levels were ranked from 0 to 100 (percentile), and mineral nutrient factors limiting apple and pear (*Pyrus communis* L.) fruit quality were identified. In this procedure, an individual can decide which quality attributes are important and whether minimum, maximum, or intermediate values for these quality characteristics are most desirable. Also, multiple regression equations were used to predict relative rankings for each quality attribute. Fallahi et al. (1988) used a simple sorting program to allow the operator to use these rankings to choose desirable categories of fruit. This ranking procedure was tested with various sets of data on apples and pears. This percentile approach allows meaningful interpretation despite large differences in fruit mineral concentrations reported for diverse locations and years by a range of analytical laboratories. The procedure is flexible, and fruit could be categorized successfully according to several definitions of optimum quality.

Bramlage et al. (1983, 1985) studied the relationships between mineral nutrients and postharvest disorders of 'McIntosh' apple over several seasons. They reported that Ca was the most variable element among samples within seasons and this element correlated negatively with breakdown, rot, and scald. In their report, susceptibility of fruit to breakdown was predicted from mineral analysis of fruit 2 weeks before harvest (Bramlage et al., 1985). In another study on 'McIntosh' (Marmo et al., 1985), relationships among nutrients and fruit quality attributes with fruit breakdown were studied. Results indicated that fruit Ca, starch concentrations, and fruit diameter accounted for significant variations in fruit breakdown after storage.

The ratio-based Diagnosis and Recommendation Integrated System (DRIS) of mineral nutrients has been used in apple to study the associations between fruit minerals, particularly Ca and N, with only a limited success (Fallahi and Righetti, 1984).

### PREHARVEST TREE SPRAYS WITH CA TO REDUCE POSTHARVEST DECAY

As was previously discussed, Ca is often considered to be the most important mineral element determining fruit quality, especially in apples and pears, where it has been shown to reduce metabolic disorders. Because the fruit flesh concentration that is necessary to reduce diseases and disorders is usually higher than that obtained through the usual fertilizer regimes, several studies have investigated the effects of the direct application of calcium salts to fruit and the resulting effects on storage quality. Foliar sprays can increase the Ca content of apple fruit (Drake, et al. 1979). The initial research involving Ca sprays to reduce postharvest decay by increasing tissue Ca concentration was conducted by Sharples and Johnson (1977). Tree sprays with  $\text{Ca}(\text{NO}_3)_2$  reduced internal breakdown and bitter pit as well

as decay caused by *Gloeosporium perennans* Zeller et Childs. 'Nittany' apple trees were sprayed or fruit were dipped into solutions of  $\text{CaCl}_2$  or liquid  $\text{CaCl}_2$  (Stopit 6, Shield Brite, Kirkland, Wash.) to determine the resulting effect on fruit tissue Ca concentration, postharvest decay caused by *Alternaria* spp., bitter pit, and firmness (Biggs et al., 1993). Tree sprays significantly increased the Ca concentration of the fruit peel and the flesh immediately under the peel when analyzed after 5 months' storage. However, the Ca concentration of the layer of flesh 1–4 mm under the peel was not significantly increased. Calcium chloride, applied either as a tree spray or as a postharvest dip, reduced the incidence and severity of *Alternaria* rot. In one year of this investigation, one postharvest treatment of 4%  $\text{CaCl}_2$  appeared as effective in reducing *Alternaria* rot, as did 9 seasonal sprays when the fruit were examined after 3 months of storage.

Calcium chloride sprays are widely used in Pennsylvania orchards on 'York Imperial', and in the northern United States on 'Delicious', 'Fuji', and 'Golden Delicious' apples to reduce bitter pit and cork symptoms and have been shown to improve fruit firmness and conditions in storage on other cultivars. In a study to determine the uptake of Ca from seven sprays throughout the 1992 growing season in Pennsylvania, 4 apple cultivars, 'Golden Delicious', 'Nittany', 'York', and 'Delicious' fruit were analyzed for Ca content after  $\approx 4$  months in storage at 0 °C (Hickey et al., 1995). The fruit tissue analyzed for Ca concentration was the layer 2–4 mm beneath the peel. The Ca concentration (dry weight basis) in 'Golden Delicious' fruit was increased by 80% (from 89  $\mu\text{g}\cdot\text{g}^{-1}$  to 159  $\mu\text{g}\cdot\text{g}^{-1}$ ), that in 'York' by 33% (83  $\mu\text{g}\cdot\text{g}^{-1}$  to 110  $\mu\text{g}\cdot\text{g}^{-1}$ ), and that in 'Delicious' fruit by about 25% (123  $\mu\text{g}\cdot\text{g}^{-1}$  to 153  $\mu\text{g}\cdot\text{g}^{-1}$ ). There was no significant increase in the tissue Ca concentration of 'Nittany' fruit ( $\approx 110 \mu\text{g}\cdot\text{g}^{-1}$ ). However, there was not enough of an increase in fruit Ca concentration to significantly maintain fruit firmness in any of the cultivars during storage. At the same time that the fruit were removed from storage for Ca and firmness analyses, another lot of similarly sprayed fruit were wound-inoculated with *Botryosphaeria obtusa* (Schwein.) Shoemaker (black rot), *Glomerella cingulata* (Stonem.) (bitter rot), and *P. expansum* (blue mold). The effects of the Ca treatments in reducing the level and severity of the fruit rot infections were sporadic and generally not significantly different. A similar experiment was conducted in 1993 and once again there were not significant treatment effects on reducing decay caused by wound inoculations with the three pathogens (Hickey et al., 1995).

To significantly affect fruit firmness or decrease fruit decay caused by postharvest wound pathogens, it is necessary to raise the level of flesh Ca (dry weight basis) to 800–1000  $\mu\text{g}\cdot\text{g}^{-1}$ . Concentrations significantly higher than 1000  $\mu\text{g}\cdot\text{g}^{-1}$  can result in surface injury to the fruit (Conway and Sams, 1985; Sams and Conway, 1984). Bitter pit, however, can be alleviated with a flesh tissue concentration of only about 250  $\mu\text{g}\cdot\text{g}^{-1}$ . So, while various spray programs may not be able to raise the tissue Ca level high enough to affect firmness or decay by pathogens through wounds, these programs may be able to increase the Ca concentration enough to prevent bitter pit.

## SUFFICIENT N FOR OPTIMUM YIELD AND QUALITY IN APPLES

Nitrogen fertilizer is the most commonly used fertilizer on fruit trees. However, since N can influence most fruit tree growth processes, particularly fruit size and color, precise timing and amount of N fertilizer in each fruit growing area could have a major influence on the success or failure of fruit production. The role of a good N balance has become even more important now that Alar (2,2-dimethylhydrazide) is no longer available to delay harvest to improve fruit color. Also, nitrate contamination of ground water is a major environmental concern in most fruit-growing areas.

In a long-term experiment, the proper time and amount of N (urea, 46% N) application for optimum yield, fruit quality, fruit respiration, ethylene evolution, and maturity in 'Redspur Delicious' on M.7 rootstock and 'Fuji' on several rootstocks were studied (Fallahi, unpublished data). Nitrate movement following nitrogen applications to 'Redspur Delicious' at several times and in various amounts was also monitored. Time of N application did not have significant effects on 'Redspur Delicious' yield, fruit respiration, or major fruit quality

attributes. In this cultivar, yield and fruit size in the very low N (45 g actual N/tree) and those receiving the highest amount of N (589 g actual N/tree) were decreased compared to the other amounts. The gradual yield and fruit weight reduction in the high N treatment over time may be due to suppression of minerals such as K by repeated applications of N. Our preliminary results showed a reduction of leaf and fruit K in the high N treatment. Therefore, leaf K should be closely monitored every year, particularly when N is applied yearly, to prevent yield and fruit weight reduction.

Fallahi (unpublished data) observed that fruit red pigmentation in 'Redspur Delicious' apple was reduced with every incremental increase in N application because leaf and fruit N were increased by these applications. In this cultivar, firmness of fruit from the trees with 45 g actual N/tree was higher than the firmness of apples from treatments with higher N at harvest and after 6 months of 0 °C storage (Fallahi, unpublished data). In this experiment, fruit Ca was not affected by various N application in some years; thus, firmness reduction in fruit from trees with high N applications was due to higher fruit N content rather than lower Ca content, as proposed in other reports (Sharples, 1980). High N application tended to increase ethylene evolution and respiration rate in 'Redspur Delicious' apple fruit (Fallahi and Fellman, unpublished data). This observation has a major impact on apple growers. Because high N delays color development, growers would delay harvest to improve color, but respiration and ethylene evolution of fruit would continue. This delay may lead to fruit decay in storage.

Fellman and Fallahi (unpublished data) found that the N status of 'Redspur Delicious' apple determines the amount and nature of flavor volatiles present in fruit flesh. Esters are major contributors to the perception of fruit flavor. Flath et al. (1967) reported olfactory thresholds of 0.066 and 0.005 v/v for butyl acetate and 2-methyl-1-butyl acetate, respectively. Measurements of acetate esters purged from fruit flesh showed that a split-application of N increased 2-methyl butyl acetate and butyl acetate in 'Redspur Delicious' apple. Levels of 2-methyl butyl acetate and butyl acetate were highest in the fruits from trees with 589 g actual N/tree and 453 g actual N/tree, respectively, (Fellman and Fallahi, unpublished data).

Monitoring nitrate movement in a 'Redspur Delicious' apple orchard showed that application of high level of N ( $\approx 589$  g actual N/tree) led to nitrate leaching away from the root zone (Fallahi, unpublished data), possibly endangering ground water purity. In this orchard, application of low to moderate N (45 to 181 g actual N/tree) did not appear to contaminate ground water.

Fallahi (unpublished data) in an experiment with 'Fuji' apple on three rootstocks and 5 ground-applied urea, observed that 'Fuji' trees on M.9 were the most precocious, followed by those on M.26 EMLA and M.7 EMLA. The early results of this long-term experiment showed that 'Fuji' yield efficiency declined when high N (304 g actual N/tree) was applied to young trees repeatedly every year. Fruits were smaller (weight basis) in the lowest N (32 g actual N/tree) and the highest N (304 g actual N/tree) treatments. 'Fuji' fruit red pigmentation was reduced with every incremental increase in N application. 'Fuji' fruit firmness at harvest tended to be higher in the trees with the lowest N (32 g actual N/tree) application. The short-term result of this experiment indicated that, considering yield and quality characteristics, 32 g actual N/tree seemed to be insufficient, while 304 g actual N/tree was excessive for young 'Fuji' trees. Based on this early evaluation, applications of up to  $\approx 100$  g actual/tree seemed to result in optimum yield and fruit quality in 'Fuji' under the conditions of this experiment (Fallahi, unpublished data). It should be noted that the needs for N may change with tree age; therefore, further data need to be gathered to determine these needs.

Fallahi et al. (1996) made an extensive yield, growth, and fruit quality comparison between ground application and foliar applications of urea for 'Fuji' apple. In summary, foliar application alone for newly established 'Fuji' trees was not sufficient and a ground application was essential for better tree growth and higher production.

## CONCLUSIONS

Calcium and N play important roles in all aspects of apple tree physiology, including postharvest fruit quality. Calcium affects fruit

softening because it is an essential part of the cell wall structure and it also influences cell membrane integrity. Preharvest Ca sprays of apple trees did not increase total or cell wall Ca concentration sufficiently to reduce decay due to postharvest wound inoculations, or maintain fruit firmness. However, these sprays previously have been shown to have some 'fungicidal' effects on decreasing the incidence of natural decay in the field. Combining Ca sprays with reduced fungicide concentrations needs further study. Also molecular aspects of N- and Ca-related problems, such as bitter pit, watercore, and internal breakdown, require further investigation. Nitrogen influences fruit color, firmness, and SSC of apple fruit. With an increasing trend toward high-density orchard systems, and public concern about nitrate contamination, the precise N requirement for each cultivar/rootstock combination needs to be evaluated to assure optimum fruit quality without ground water contamination.

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