Fruit Splitting in Citrus

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ABSTRACT

Various citrus cultivars of ‘Navel’ and ‘Valencia’ orange (Citrus sinensis (L.) Osbeck), as well as mandarin and mandarin hybrids (Citrus reticulata Blanco) are prone to a preharvest physiological rind disorder, known as fruit splitting. Similar disorders occur as fruit cracking and/or splitting in other commercially important horticultural crops, most notably in apple, apricot, cherry, grape, nectarine, prune, and tomato. Fruit splitting in citrus differs from other crops due to the unique morphology of a citrus fruit, consisting of the pulp and rind, which is made up of the spongy white internal layer, the albedo (mesocarp), and the external layer, the flavedo (exocarp). Pressure applied by the rapidly expanding pulp during fruit growth leads to the formation of microcracks in the flavedo and initiation of fruit split at the stilar or navel end of the citrus fruit rind. This area of the rind is the thinnest and/or structurally weaker than other areas of the fruit rind. The episodic nature of fruit split is a good indication that certain environmental and/or cultural cues initiate the incidence of fruit splitting. Such factors include nutrient imbalances, specifically low Ca and K and high P, warm and humid climatic conditions, irregular water supply, and heavy crop loads. The unique anatomical features of certain citrus cultivars, such as presence of a secondary fruitlet (navel), weaken the structure of the
primary fruit. In addition, the thin rind of the reticulated mandarin and mandarin hybrids increases the susceptibility to fruit splitting. Current horticultural practices to reduce the incidence of splitting include a combination of crop load manipulation by thinning and \( \text{GA}_3 \) application/girdling, as well as sufficient Ca, K, and P nutrition and consistent irrigation. There is, however, no single commercial technology to consistently reduce the incidence of this disorder. Recent research on mandarin species reported significant reduction of fruit splitting through the application of a synthetic auxin, 2,4-D, as a foliar spray. However, results were erratic when applied to orange cultivars and negative effects on fruit quality, such as increased rind coarseness and reduction in juice content, are some of the major drawbacks of 2,4-D application. This review aims to summarize the unique physiology of citrus fruit splitting, as well as the contributing factors and horticultural practices available to reduce the impact of this disorder.

**KEYWORDS:** fruit splitting; irrigation; nutrient balance; plant growth regulators; rind disorder

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ACKNOWLEDGMENTS

LITERATURE CITED
I. INTRODUCTION

A. Problem and Overview

Fruit splitting is a major preharvest physiological disorder in various citrus species, leading to annual yield losses of up to 30% (Rabe et al. 1990; Barry and Bower 1997). Fruit splitting is caused by pressure resulting from the expanding pulp of an individual fruit on the rind (Erickson 1968; Bower et al. 1992; Almela et al. 1994; Barry and Bower 1997), eventually causing a fissure at the stylar or navel end, and leading to the splitting of the fruit (Fig. 4.1). Split fruit eventually drop from the tree. Not only does fruit splitting negatively affect yield, but it also attracts insects and pathogens that cause decay; subsequently, intense labor is required to sanitize the orchards.

A wide variety of cultural and environmental factors, independent of clonal characteristics, influence and contribute to both the initiation and severity of citrus fruit splitting. These include nutrient imbalances (Erickson 1957; Bar-Akiva 1975; De Cicco et al. 1988), warm and humid climatic conditions (Coit 1915; Almela et al. 1994; Barry and Bower 1997), irregular water supply (Wager 1939; De Cicco et al. 1988; De Cicco et al. 1996; Bower et al. 1997)

Fig. 4.1. Fruit splitting initiates at the stylar end of the fruit as a small fissure of the rind (a). As the pulp starts to expand, the accompanied increase in volume forces the rind to split open (b–e). Split fruit eventually drop from the tree (f). Labor is required to remove split fruit from trees and abscised split fruit from the orchard floor (sanitation).
Goldschmidt and Galili 1992), and heavy crop load (Rabe et al. 1990; Barry and Bower 1997). Secondary to these factors, fruit growth and morphological features of the fruit, such as the thickness of the rind and large navel, also play an important contributing role in the initiation of the disorder (Wager 1939; Lima et al. 1980). The severity of the disorder may vary considerably between seasons (De Cicco et al. 1988; Almela et al. 1994), making it difficult to predict and control.

Most of the studies on the control of fruit splitting focused on increasing the rind thickness and strength of split-prone species by applying preharvest mineral nutrient sprays to the canopy or plant growth regulator (PGR) foliar sprays. Although results were erratic, PGR applications were generally more successful than mineral nutrient applications for reducing splitting. In this regard, the synthetic auxin, 2,4-dichlorophenoxy acetic acid (2,4-D) (Borroto et al. 1981; Almela et al. 1994; Greenberg et al. 2006; Mupambi 2010), and gibberellic acid (GA₃) (Rabe et al. 1990; Almela et al. 1994; García-Luis et al. 1994) were most successful. Calcium (Ca) (Almela et al. 1994; Barry and Bower 1997; Sdoodee and Chiarawipa 2005) and potassium (K) (Bar-Akiva 1975; Borroto et al. 1981; Greenberg et al. 2006) also reduced splitting, but to a lesser degree. Goldschmidt and Galili (1992) focused on the control of pulp expansion during periods of split initiation, using irrigation management, and achieved a significant reduction in the incidence of split fruit.

B. Cultivars Particularly Susceptible to Split

Fruit splitting occurs worldwide as a preharvest problem in mandarin and mandarin hybrids (Goldschmidt and Galili 1992; Almela et al. 1994; Barry and Bower 1997) as well as ‘Navel’ (De Cicco et al. 1988) and ‘Valencia’ orange (Bower et al. 1992) (Table 4.1). Cultivars with genetically thin rinds, especially mandarin and mandarin hybrids (easy peelers), are potentially more susceptible to split than cultivars with thicker rinds. The earliest mandarin species prone to splitting, although at low severity, is ‘Owari’ satsuma. In Clementine, ‘Fino’, ‘Marisol’ (Mupambi 2010), and ‘Nules’ are cultivars known to be susceptible to severe levels of split fruit, while splitting has been reported in mandarin hybrids of ‘Ellendale’ (Rabe et al. 1989), ‘Murcott’ (Goldschmidt and Galili 1992), ‘Nova’ (Almela et al. 1994), and ‘Shogun’ (Sdoodee and Chiarawipa 2005) especially in years of heavy fruit load (Rabe and Van Rensburg 1996).

‘Navel’ orange and certain other mandarin cultivars such as ‘Nova’ and ‘Ellendale’ genetically develop a secondary fruitlet (navel) covered
or protruding at the stylar end of the primary fruit (García-Luis et al. 1994; Rabe and Van Rensburg 1996). The presence of these structures hampers the structural integrity of the fruit rind (García-Luis et al. 1994) and fruit with large secondary fruit (navels) are thus more prone to splitting, as was found with ‘Washington navel’ orange (Wager 1939; Lima et al. 1980; García-Luis et al. 1994). In addition to the secondary fruitlet, certain cultivars such as ‘Navelina’ orange and ‘Nova’ mandarin are more split prone due to their particular oblate shape and the high rate of morphological differentiation from globose to oblate during critical growth periods (De Cicco et al. 1988; García-Luis et al. 2001). ‘Valencia’ orange is the latest maturing orange variety and generally develops fruit with thin rind and increased susceptibility to split. Cultivars of note include ‘Campbell’, ‘Frost’, ‘Midknight’, and ‘Olinda’ Valencia (Borroto et al. 1981; Bower et al. 1992).

The wide variety of influencing factors as well as the complexity of their interactions makes it almost impossible to provide a single commercial solution to the disorder. Therefore, an understanding of the physiology of both the tree and of the most important structural components of the fruit in relation to fruit splitting, namely, the rind and the pulp, is required to combat fruit splitting in citrus.

C. Fruit Splitting in Other Horticultural Crops

Fruit splitting or cracking has been reported for almost every horticultural crop of economic importance. This disorder occurs most notably in apple (Visai et al. 1989), apricot (Benson 1994), cherry (Belmans and Keulemans 1996), grape (Considine and Kriedemann 1972), nectarine (Gibert et al. 2007), prune (Milad and Shackel 1992), and tomato

<table>
<thead>
<tr>
<th>Species</th>
<th>Type</th>
<th>Cultivar</th>
<th>Time of maturity</th>
<th>Prevalence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mandarin</td>
<td>Satsuma</td>
<td>Owari</td>
<td>Early</td>
<td>Low</td>
</tr>
<tr>
<td>Clementine</td>
<td></td>
<td>Fino, Marisol, Nules, Orogrande</td>
<td>Middle</td>
<td>High</td>
</tr>
<tr>
<td>Hybrid</td>
<td></td>
<td>Murcott, Nova, Mor, Orri, Ellendale, Orlando, Ortanique, Shogun</td>
<td>Middle/late</td>
<td>High</td>
</tr>
<tr>
<td>Orange</td>
<td>Navel</td>
<td>Hamlin, Navelina, Washington Campbell, Frost, Leng Midknight, Olinda</td>
<td>Middle/late</td>
<td>High/Moderate</td>
</tr>
<tr>
<td>Valencia</td>
<td>Late</td>
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<td>Late</td>
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Although similarities in certain causal factors as well as certain aspects of the physiological development of the phenomenon exist between these crops and citrus fruit, unique anatomical features of citrus fruit as well as physiology of fruit development separate the phenomenon in citrus from other crops.

Splitting of a fruit is a consequence of cracks developing in the epidermis or in the rind of a developing fruit. In most crops that are prone to cracking or splitting, the spatial distribution of cracks varies. Cracks could develop at the stylar and/or stem end, cheeks, and shoulders of the fruit. Although the tendency to crack is genetically controlled with certain cultivars being crack resistant (Gülşen et al. 1995; Belmans and Keulemans 1996; Sperry et al. 1996), the intensity of the disorder in crack-prone cultivars is episodic, with fluctuations in severity between seasons. This indicates the disorder in other crops to also be induced by either environmental conditions and/or cultural factors (Peet 1992).

Certain causative factors in other fruit crops, namely, cultural and environmental, are also important with citrus. Heavy rainfall during the

<table>
<thead>
<tr>
<th>Crop</th>
<th>Cause</th>
<th>Control</th>
</tr>
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<tbody>
<tr>
<td>Apple</td>
<td>Serious peel russet (Visai et al. 1989)</td>
<td>Foliar GA4 + 7 applications (Byers et al. 1990)</td>
</tr>
<tr>
<td>Apricot</td>
<td>B deficiency (Benson 1994); heavy rainfall during fruit growth (Gülşen et al. 1995)</td>
<td>B application (Benson 1994)</td>
</tr>
<tr>
<td>Cherry</td>
<td>Excessive water supply at harvest (Belmans and Keulemans 1996)</td>
<td>Ca applications (Meheriuk et al. 1991); GA applications (Cline and Trought 2007)</td>
</tr>
<tr>
<td>Grape</td>
<td>High rainfall at onset of ripening (Clarke et al. 2010)</td>
<td>Consistent water supply (Considine and Kriedemann 1972)</td>
</tr>
<tr>
<td>Nectarine</td>
<td>Low crop load (Gibert et al. 2007); increased fruit size (Gibert et al. 2007)</td>
<td>Lowering irrigation during rapid fruit growth (Gibert et al. 2007)</td>
</tr>
<tr>
<td>Prune</td>
<td>Excessive irrigation following water stress (Milad and Shackel 1992)</td>
<td>Consistent water supply (Milad and Shackel 1992)</td>
</tr>
<tr>
<td>Tomato</td>
<td>Excessive irrigation following water stress (Peet 1992); insufficient nutrition (Huang and Snapp 2004); low crop load (increased growth rate) (Peet 1992); harvest at pink stage (late) (Peet 1992)</td>
<td>Use of crack-resistant cultivars (Sperry et al. 1996); consistent water supply (Sperry et al. 1996); GA (Peet 1992) and Ca (Huang and Snapp 2004) application; harvest at green mature stage (early) (Peet 1992)</td>
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</table>
period of rapid fruit growth in apricot (Gülşen et al. 1995), grape (Clarke et al. 2010), as well as tomato (Peet 1992) and at harvest in cherry (Belmans and Keulemans 1996) correlates as a causative factor of the phenomenon in citrus fruit (Wager 1939). In addition, as suggested in citrus (Coit 1915), high-volume irrigation after a period of water stress has been shown to result in the development of cracks in prune (Milad and Shackel 1992), tomato (Peet 1992), and nectarine (Gibert et al. 2007). Cultural practices encouraging excessive fruit growth, such as high irrigation during the period of rapid fruit growth of nectarine (Gibert et al. 2007) as well as pruning and thinning of tomato plants in a similar developmental phase (Peet 1992), can lead to the development of cracks of the fruit surface. In terms of mineral nutrient deficiency, cracks develop due to boron (B) deficiency in apricots (Benson 1994) and calcium (Ca) deficiency in cherry (Meheriuk et al. 1991) and tomato (Huang and Snapp 2004).

Even though similarity exists in causes of splitting between citrus and other fruit, the unique morphology and physiology of citrus fruit indicate additional causes. Citrus fruit is known as a Hesperidian berry, with a leathery rind and internal swollen trichomes and juice sacs (Swingle 1943); these aspects as well as the differences in rind thickness and the presence or absence of secondary fruit add factors that could cause the initiation and splitting of citrus fruit.

II. PHYSIOLOGY OF CITRUS FRUIT SPLITTING

A. Relationship Between Fruit Growth, Resulting Shape, and Splitting

Citrus fruit growth follows a sigmoidal curve as described by Bain (1958), with the rind developing mainly during stages I and II, whereas pulp growth predominantly occurs during stage II. During stage III, very little increase in fruit size occurs as the fruit matures.

García-Luis et al. (2001) linked the chronological development of this disorder with certain morphological changes of the fruit during development, such as an increase in diameter/height ratio ($D/H$ ratio). The physical splitting of the fruit predominantly occurs during stage II of fruit development of split-prone cultivars (Fig. 4.2) (Borroto et al. 1981; Goldschmidt and Galili 1992; García-Luis et al. 1994; Rabe and Van Rensburg 1996). During stage II of fruit development, there is an increase in pulp volume due to the expansion of cells caused by
increase in turgor pressure, resulting in a progressive change in fruit shape.

Fruit shape is classified as the ratio between fruit diameter and fruit height. Fruit with a low diameter to height ratio are generally referred to as globose. During the period of maximum increase in citrus fruit diameter (stage II), fruit transform from globose to oblate in shape (García-Luis et al. 2001) and pressure exerted by the pulp forces the rind to enclose its expanding volume due to the predominant occurrence of the pulp and albedo’s cell growth (Bain 1958). The increase in fruit $D/H$ ratio is accompanied by an increase of internal stress exerted on the poles of the fruit (Considine and Brown 1981), namely, the calyx and the stylar end.

While the large intercellular spaces of the albedo absorb some of the pressure exerted by the rapid pulp expansion (Monselise 1986), the flavedo stretches and becomes thinner. The flavedo of split-prone cultivars cannot accommodate the increase in pulp volume (Erickson 1957; Goldschmidt and Galili 1992; García-Luis et al. 2001), and as a result, fruit split at the stylar or navel end, where the rind is thinner and structurally weaker (Coit 1915).

Although fruit shape is specific to a cultivar, certain factors such as warm temperature, relative humidity, as well as rapid water uptake by the tree (Wager 1939; Lima et al. 1980; Goldschmidt and Galili 1992)
may accelerate fruit growth. This could alter the fruit shape (increase the $D/H$ ratio) to such an extent that the rind is unable to accommodate the increasing pulp volume and the fruit splits (Goldschmidt and Galili 1992). In ‘Navel’ orange, as the $D/H$ ratio reduced, a lower incidence of fruit splitting occurred (De Cicco et al. 1988). In ‘Nova mandarin’, the percentage split fruit reached a maximum when the $D/H$ ratio increased from 1.21 to 1.23 during fruit growth (Fig. 4.3) (García-Luis et al. 2001).

As reported for other crack-prone crops such as tomato (Peet 1992) and nectarine (Gibert et al. 2007), a reduction in irrigation rate during periods of rapid fruit growth, without stressing the tree, holds promise in reducing the likelihood of fruit cracking and splitting. By reducing water supply during stage II of fruit development, fruit splitting was reduced in ‘Murcott’ mandarin (Goldschmidt and Galili 1992).

Although the physical splitting of the citrus fruit occurs as a consequence of increase in pulp volume during stage II of fruit development, the potential for fruit splitting incidence is, to a large extent, a result of any stress to the tree and young fruitlets during fruit development in stage I (Rabe and Van Rensburg 1996). Factors such as nutritional imbalances, water stress during stage I, and high flower number and

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**Fig. 4.3.** Two hundred fruits from ‘Nova mandarin’ trees were tagged and their diameter and height periodically measured until the end of fruit development at which they were then classed as split (solid bars) and nonsplit (hollow bars). Final diameter/height ratio of all tagged fruit ranged from 1.02 to 1.37 with split occurrence at ratios $\geq 1.20$. Source: Adapted from García-Luis et al. (2001).
fruit set hamper sufficient cell division and lead to the development of a weak and thin rind. In addition, fruit shape (known to be genetically influenced) and ambient growing conditions affect the initiation and severity of fruit splitting of the rind. Therefore, finding a successful commercial solution to fruit spitting of citrus will require an understanding of how to manipulate not only fruit growth but, in particular, fruit rind development.

B. Splitting as Related to Rind Characteristics

Although fruit with high $D/H$ ratios are more likely to split, a proportion of fruit from the same tree with similar dimensions or even higher remains structurally intact. Therefore, it could be assumed that additional aspects in the fruit rind development could increase its susceptibility to splitting in reaction to expanding pulp. Cultural as well as environmental factors contribute to the development of citrus fruit with thin or weak rind and, indirectly, the fruit’s propensity to split (Fig. 4.4) (Almela et al. 1994). As cell division in the fruit rind predominantly occurs during stage I of fruit development, contribution of these factors to increased susceptibility to splitting predominantly occurs during stage I of fruit development (Rabe and Van Rensburg 1996).

![Graph](image)

**Fig. 4.4.** As rind/rind thickness of ‘Nova mandarin’ hybrid increases, the percentage of split fruit decreases, indicating an inverse relationship between fruit splitting and peel/rind thickness in ‘Nova mandarin’ fruit. *Source:* Adapted from Almela et al. (1994).
Cultural factors include imbalances of certain mineral nutrients such as K and P (Section III.A.1) (Chapman 1968; Bar-Akiva 1975; Morgan et al. 2005), hormonal imbalances due to production of seedless fruit (Section III.A.2) (Erner et al. 1976; Rabe et al. 1990), and suboptimal irrigation, hampering plant–soil water relations. Any alterations leading to increased interfruit competition in the tree, such as girdling or GA$_3$ treatments that stimulate a higher percentage fruit set, could lead to the development of fruit with a thin or weak rind and an increase in splitting (Rabe et al. 1990). The most important environmental factors leading to development of fruit with thin rind, and thus also susceptibility to splitting, are warm and humid climatic conditions during stage I of fruit development (Cohen et al. 1972).

III. CAUSES OF CITRUS FRUIT SPLITTING

A. Cultural

1. Mineral Nutrition. With regard to citrus fruit splitting, imbalances in potassium (K) and phosphorous (P) can contribute to thin or weak rind and can therefore, at either too high or low rates, indirectly increase the likelihood of splitting (Bar-Akiva 1975; Borroto et al. 1981; Almela et al. 1994; Morgan et al. 2005).

With an increase in P supply and hence increased leaf P content, a decrease in rind thickness of citrus fruit is found (Chapman 1968). In contrast, an increase in leaf K content results in an increase in rind thickness and coarseness (Chapman 1968; Monselise 1986). This concurs with results found on the mineral composition of split ‘Washington navel’ oranges, with the rind of split fruit having significantly higher P content than nonsplit fruit (Erickson 1957). Similarly, a decrease in rind thickness of split fruit was found as the leaf P content increased in ‘Navelina’ orange and a reduced number of split fruit was found as the leaf K content increased (De Cicco et al. 1988). Higher incidence of splitting in trees with low leaf K content was reported in ‘Hamlin’ (Koo 1961) and ‘Valencia’ orange (Gilfillan and Stevenson 1982). Morgan et al. (2005), reporting an increase in rind thickness of ‘Hamlin’ orange with an increase in K nutrition and without evaluating the effect on number of split fruit, hypothesized that an increase in rind thickness could lead to a reduction in fruit splitting of this split-prone cultivar.

One of the aims of fertilizer practices is to ensure an optimum for both P and K in citrus orchards. Optimum for leaf P ranges between 0.10% and 0.16% and for leaf K, between 1.0% and 1.5% (CRI Production
Guidelines 2007). Some orchards with these nutrient levels in leaves still have a high percentage of split fruit. This indicates the involvement of factors other than P and K contributing to the prevalence of this disorder.

2. Hormonal Imbalances. Growth and development of citrus fruit are, to a great extent, dependent on the endogenous hormone content of the fruit. Seeds that develop as a result of pollination serve as a source of these hormones during the critical early development stage of the fruit (Monselise 1977).

However, split-prone mandarin cultivars such as ‘Nova’ and ‘Ellendale’ are weakly parthenocarpic and planted in isolated blocks to avoid cross-pollination and resultant seed formation (Barry and Bower 1997). Production of seedless fruit can lead to reduced fruit set but the lack of seeds has also been correlated with a decrease in rind thickness and a resultant higher occurrence of fruit splitting. Cross-pollinated ‘Ellendale’ mandarin trees had more seeds than noncross-pollinated trees and thus also an increased rind thickness and very few split fruit (Rabe et al. 1990). Pollination and seed formation increase the gibberellin content of weakly parthenocarpic fruit (Ben-Cheikh et al. 1997). It is possible that this increased endogenous gibberellin content leads to an increase in rind thickness. High levels of endogenous GA$_3$ and cytokinin are responsible for the excessive growth of ‘Shamouti’ orange fruit rind, which leads to the development of a very thick and rough rind (Erner et al. 1976).

3. Rainfall and Irrigation. Splitting of citrus fruit is a consequence of the pressure of expanding pulp on the rind of citrus fruit (Goldschmidt and Galili 1992; García-Luis et al. 1994, 2001). It could therefore be reasoned that any factor leading to drastic or excessive pulp expansion could increase the incidence and severity of splitting. The influx of water into the pulp during stages II and III of fruit development could exert undue pressure on the developing rind and lead to the eventual splitting thereof (Coit 1915; Wager 1939; Lima et al. 1980; Goldschmidt and Galili 1992).

Avoiding fluctuations in soil water content as well as avoiding depletion of water from deeper soil layers is of critical importance in avoiding fruit splitting. This was illustrated by De Cicco et al. (1988), who reported a significantly higher severity in fruit splitting of ‘Navelina’ orange when the total available water in the 40–80 cm soil layer was low. With total available water in the 40–80 cm soil layer at an optimum, fruit splitting was significantly lower. In reaction to daytime
drought stress, citrus leaves can withdraw water from the rind (xylem backflow), which leads to cessation of, or decrease in, fruitlet growth (Furr and Taylor 1939; Hilgeman 1977). This is thought to result in a premature strengthening of the flavedo cells, leading to a reduced ability to divide and enlarge as normal (Graebner 1920). Wager (1939) suggested the initiation of splitting of ‘Washington navel’ orange fruit to be caused by a sudden supply of large amounts of water after a period of water stress, during which the prematurely strengthened cells are unable to react to the sudden resupply of water into the pulp. Large tension exerted on the rind leads to eventual failure of the rind tissue. A similar mechanism was proposed to be responsible for splitting of tomato (Peet 1992) and prune (Milad and Shackel 1992).

Citrus produced in the humid, summer rainfall areas of South Africa have a higher propensity to split, presumably due to the frequent and unavoidable natural water supply during periods of rapid fruit growth. However, Rabe and Van Rensburg (1996) failed to correlate the seasonal rainfall pattern positively with fruit splitting.

4. Crop Load. The severity of citrus fruit splitting is very much dependent on flower number, percentage fruit set (Rabe et al. 1989; Rabe and Van Rensburg 1996), as well as final crop load (Gilfillan and Stevenson 1982; Rabe et al. 1990; Barry and Bower 1997). A high percentage of split fruit occurred at very high crop loads and little or no splitting in years of low crop loads (Gilfillan and Stevenson 1984). However, an increase in the disorder was expected at lower crop loads in tomato (Peet 1992) and nectarine (Gibert et al. 2007), which can be explained by the higher growth rate of individual fruit at lower crop loads and an inability of the fruit epidermis to accommodate for the increase in fruit volume created by these higher growth rates. With an increase in the number of fruit per tree, a linear increase in the interfruit competition for water and assimilates is expected. Lenz and Cary (1969) reported a decrease in fruit size and, more importantly, a decrease in rind thickness of citrus fruit with an increased crop load per tree. As crop load increased, the K concentration, a very important contributing agent to the development of a healthy and thick rind, declined in both the leaves and shoots of citrus trees (Lenz 2000).

Cultural practices such as girdling or GA₃ treatments during the blossom period are generally applied to increase fruit set percentage in citrus, especially in weakly parthenocarpic cultivars (Rabe et al. 1990; Rabe and Van Rensburg 1996; Barry and Bower 1997). However, the higher set percentage results in an increased interfruit competition, leading to a significantly higher number of split ‘Nova’ and
‘Ellendale’ mandarin fruit (Rabe and Van Rensburg 1996; Barry and Bower 1997).

5. Canopy Position Microclimate. Growth habit and resulting tree shape of some citrus cultivars as well as ineffective pruning by producers stimulate the development of variation in microclimate within a tree canopy that could lead to the development of fruit that are potentially more prone to physiological disorders such as rind breakdown of ‘Nules Clementine’ mandarin (Cronjé et al. 2011).

However, the fruit in the outer canopy are exposed to higher temperatures than the inside fruit. The high surface temperature of fruit in the outer canopy can cause the formation of free radicals inside cells of the fruit and their high reactivity leads to a loss in membrane integrity and eventual cell death (Wünsche et al. 2004). In ‘Stayman’ apple, fruit in the outer canopy are more likely to crack (Verner 1935). In citrus, the cellular damage due to the high heat leads to sunburn in the flavedo (light yellow to brown discoloration) and has been described by Sdoo-dee and Chiarawipa (2005) as a causal factor of splitting of ‘Shogun’ mandarin in Thailand.

B. Environmental

Climate has a definitive effect on rind thickness as well as the rate of fruit growth, thereby indirectly affecting the propensity of fruit toward splitting. Almela et al. (1994) reported varying intensities of ‘Nova’ mandarin fruit splitting between years and linked the variability to seasonal difference in climate.

1. Temperature. Barry and Bower (1997) reported the splitting of ‘Nova’ mandarin fruit to be less prevalent in cooler production regions. This was in agreement with Coit (1915), who suggested that regions more prone to hot weather are more likely to experience fruit splitting. Reuther et al. (1973) found that ‘Valencia’ orange exposed to warmer climate during the rapid growth period developed thinner rind and thus experienced higher levels of fruit splitting, compared to fruit exposed to lower temperatures. In these hot areas, the growth rate of citrus fruit during every stage of fruit development is also higher than those in cooler areas. This accelerated growth rate, especially of the pulp during growth stage II of fruit development, may lead to higher pressure being applied to the rind and thus initiate fruit splitting. This is similar to what Peet (1992) found in tomato, when fruit are exposed to high temperatures.
2. **Humidity.** Citrus fruit grown in humid production regions develop thinner rinds than those grown in drier regions (Cooper et al. 1963) and are, therefore, more likely to split. Rabe et al. (1989) reported severe fruit splitting of ‘Ellendale’ mandarin specifically in hot and humid citrus-producing regions in Swaziland (Tambankulu) and South Africa (Letaba, Limpopo), compared to regions with lower humidity such as the Western Cape Province of South Africa. However, a high incidence of fruit splitting is often associated with a dry spring followed by a wet period during stages II and III of fruit development.

IV. REDUCING CITRUS FRUIT SPLITTING

A. Foliar Mineral Nutrient Applications

1. **Potassium.** The mineral nutrient most abundant in a citrus fruit is K, and in K-deficient trees, reduction in size as well as number of fruit is expected (CRI Production Guidelines 2007). The most important effect of increased K nutrition on the quality of citrus fruit is a reduction in the juice content and total soluble solids (TSS) as well as an increase in fruit size, total acidity (TA), and rind thickness. Therefore, supplementing split-prone cultivars with K to achieve leaf K levels of between 1.0% and 1.5% (CRI Production Guidelines 2007) will lead to the development of fruit with thicker rind that are less likely to split (Morgan et al. 2005).

   The soil application of K on three-year-old container-grown ‘Valencia’ orange trees reduced fruit splitting and increased rind thickness of K-treated trees, compared with untreated trees that experienced a higher incidence of fruit splitting (Bar-Akiva 1975). Potassium is readily translocated within a citrus tree and soil fertilization is the most effective cultural practice to address nutrient deficiency in citrus trees. Foliar sprays do, however, result in some nutrient uptake and could be used as a method of supplementing trees with K or correcting any deficiency of K. The time of foliar K application affects its efficacy in terms of influencing the incidence of splitting, and Rabe et al. (1989) reported higher numbers of split fruit per tree when 4% KNO₃ was applied prior to physiological fruit drop. In contrast, later application resulted in a significant reduction in splitting. The higher fruit set and increase in interfruit competition as a result from the earlier K application were thought to have led to the higher splitting (Rabe et al. 1990).
2. Calcium. Calcium is one of the most important structural components of cell membranes and walls and plays an important role in the processes of cell division and growth (Hepler 2005). Transport of Ca from the soil to the developing fruit is a passive process, dependent on the flow of the transpiration stream through the plant. Ca is weakly translocated from old leaves or other plant parts/organs to newly developing leaves, meristems, and fruit (Hanger 1979). Therefore, any deficiency of Ca in the soil, or any factor hampering the transport of Ca (e.g., low VPD) especially during critical periods of cell division and growth, will lead to Ca deficiency in the fruit. Such a deficiency or imbalance could lead to physiological disorders involving the rind, namely, rind breakdown of ‘Nules Clementine’ mandarin (Cronje et al. 2011) and fruit splitting of ‘Shogun’ mandarin (Sdoodee and Chiarawipa 2005). The optimum leaf Ca in citrus production is 2.5–5.5% (CRI Production Guidelines 2007).

Cracking of tomato (Peet 1992; Huang and Snapp 2004) and cherry (Meheriuk et al. 1991) is thought to be a consequence of insufficient Ca supply. Multiple foliar applications of CaCl₂ and Ca(OH)₂ reduced the incidence of cracking in ‘Van’ cherry. This concurred with an earlier study by Barry and Bower (1997), in which a single foliar application of 2% Ca(NO₃)₂ at 70% full bloom significantly reduced fruit splitting in ‘Nova’ mandarin, compared with control, untreated trees. Boron (B) and Ca interact to form a stabilizing complex in the middle lamella of plant cells (Blevins and Lukaszewski 1998). By applying these two mineral nutrients in combination as a foliar spray to crack-prone ‘Mountain spring’ tomato, there was a significant reduction in the number of cracked tomato fruit (Huang and Snapp 2004). A similar significant reduction of split ‘Shogun’ mandarin fruit was recorded after the foliar application of either 1% CaCl₂, boric acid or a combination thereof, applied 4 months after fruit set (Sdoodee and Chiarawipa 2005).

B. Foliar-Applied Plant Growth Regulator (PGR) Applications

Foliar applications of PGRs result in varying amounts of success in reducing fruit splitting of split-prone cultivars. PGRs could strengthen the rind of developing fruitlets (Coggins and Hield 1968) or inhibit rind senescence (García-Luis et al. 1994). Application of PGRs in the form of auxin and gibberellin could potentially substitute for the lack of natural endogenous hormones in seedless cultivars and increase the rind strength of these fruit and their resistance to split.

In a study on the effect of applied hormones on the anatomy and splitting of ‘Nova’ mandarin, García-Luis et al. (1994) observed a
decrease in fruit splitting attributed to applied GA₃ successfully inhibiting the senescence of the rind, making the fruit less prone to splitting. The application of the synthetic auxin 2,4-D to cultivars prone to develop thin and/or smooth rinds led to an increase in thickness and rind coarseness (Coggins and Hield 1968), which has subsequently been shown to reduce fruit splitting (García-Luis et al. 2001).

However, in some instances, PGR treatments resulted in contrasting results and either promoted fruit splitting in ‘Navel’ orange (Lima and Davies 1984), had little or no effect on ‘Valencia’ orange (Gilfillan and Stevenson 1982), or reduced the disorder on a number of mandarin species (Borroto et al. 1981; Almela et al. 1994; García-Luis et al. 1994, 2001; Greenberg et al. 2006; Mupambi 2010).

1. Gibberellic Acid (GA₃). Gibberellins are plant hormones responsible for facilitating cell division and enlargement, and therefore the application of GA₃ is used in many crops, such as grape and cherry, to increase fruit size (Cline and Trought 2007). Apart from its effect on fruit size, GA₃ applications also increase firmness of crack-prone cherry (Cline and Trought 2007) and tomato fruit (Peet 1992). In citrus, GA₃ increases rind resistance to pressure and delay of chlorophyll breakdown (McDonald et al. 1987), which is an indication of delaying of rind senescence (García-Luis et al. 1994) and its potential as a possible control measure of fruit splitting in certain citrus species. In ‘Washington navel’ orange, Bevington (1973) reported an increase in rind resistance to puncturing as well as a decrease in physiological disorders of the rind, such as puffing and creasing, with May (Southern hemisphere) applications of GA₃.

In ‘Nova’ mandarin, GA₃ (20 mg L⁻¹) applied after physiological fruit drop was more successful than a foliar spray during full bloom in reducing fruit splitting (García-Luis et al. 1994, 2001). This corresponds with the increase in fruit splitting observed when GA₃ applications at 10 or 20 mg L⁻¹ were made during full bloom on ‘Ellendale’ mandarin (Rabe and Van Rensburg 1996). This can be explained by an increase in fruit set from the earlier application and, therefore, interfruit competition.

2. Synthetic Auxin: 2,4-Dichlorophenoxy Acetic Acid (2,4-D). Expansion of plant cells is facilitated by the important plant hormone auxin, produced in apical meristems and transported to growing tissue (Coggins and Hield 1968). Commercial applications of synthetic auxins in citriculture include 2,4-dichlorophenoxy propionic acid (El-Otmani et al. 1993) and 3,5,6-trichloro-2-pyridyl oxyacetic acid (Greenberg
et al. 2006), and are applied to increase fruit size by facilitating increased cell expansion (Mitchell 1961).

Excessive stimulation of cell expansion can lead to eventual cell and plant death, as is the case with application of the synthetic auxin, 2,4-D as a lethal herbicide. Some crops, such as grape, are very sensitive to this particular PGR and drifts of herbicidal sprays often lead to death of vines (Kasimatis et al. 1968). However, citrus trees are less sensitive to this PGR, and when applied at low rates (≤20 mg L⁻¹), an increase in fruit size is expected due to increased sink strength of treated fruit as well as stimulation of rind growth (Guardiola and García-Luis 1997).

In preliminary studies to reduce the size of navel end opening in ‘Navel’ orange, a significant decrease in fruit splitting of ‘Marisol Clementine’ by foliar application of 2,4-D at full bloom (25 mg L⁻¹) and petal drop (15 and 25 mg L⁻¹) occurred (Mupambi 2010). These treatments, although successfully reducing fruit splitting, negatively increased rind coarseness and led to an increased percentage of fruit with persistent styles. Application of 2,4-D on the same cultivar and site, but at later timing (after physiological fruit drop) and at 15 mg L⁻¹, reduced fruit splitting and produced fruit of acceptable rind coarseness and without persisting styles, indicating that the success of this treatment could be dependent on timing as well as concentration (unpublished). García-Luis et al. (2001) observed a significant reduction of fruit splitting with foliar applications of 20 mg L⁻¹ 2,4-D at full bloom, and attributed it to an increase in rind thickness at the stylar ends of treated fruit.

3. Combination of PGRs and Mineral Nutrients as Foliar Treatments.
The combination of PGRs and mineral nutrients proved successful in reducing the severity of citrus fruit splitting. The disorder was reduced by more than 50%, with a treatment consisting of KCl (150 kg ha⁻¹) and 2,4-D at 10 mg L⁻¹ on ‘Olinda Valencia’ orange trees (Borroto et al. 1981). Greenberg et al. (2006) found a reduction of fruit splitting when 5% Bonus NPK was applied with 2,4-D foliar sprays on ‘Nova’ mandarin. Almela et al. (1994) reported that a foliar spray of 2% Ca(NO₃)₂, 20 mg L⁻¹ 2,4-D, and 20 mg L⁻¹ GA₃ reduced fruit splitting by increasing rind strength, but not rind thickness, which could indicate a possible strengthening effect of the citrus fruit rind.

C. Managing Plant Water Relations
Careful and detailed management of irrigation practices during fruit growth periods, with the aim of avoiding fluctuations in soil water
content, is key in controlling fruit splitting in citrus (Rabe 1988). Goldschmidt and Galili (1992) achieved moderate success in reducing splitting of ‘Murcott’ mandarin when they reduced the normal irrigation during late summer in the period of pulp expansion (stage II) to 50–60% and as much as 30% of normal irrigation, without significantly affecting internal fruit quality. Although deficit irrigation during late stages of fruit development is a standard practice to increase the TSS of early maturing cultivars such as ‘Satsuma’ mandarin, it is important not to stress trees excessively during the early stages of fruit development, as it may negatively affect fruit growth and final fruit size (Hilgeman 1977).

D. Thinning

Splitting of citrus has been particularly prevalent in years of excessive crop load (Rabe and Van Rensburg 1996), where high competition for water and assimilates between fruit leads to a reduction in total partitioning between fruit and the development of small, thin-rinded, and split-prone fruit. Therefore, thinning of flowers or thinning of fruit prior to physiological fruit drop (stage I) in years of expected excessive crop load is suggested as a possible measure to reduce competition between fruitlets for assimilates and water. This can increase partitioning to individual fruit to eventually produce larger fruit with thicker and stronger rind, and an accompanied lower incidence of splitting (Barry and Bower 1997). In addition, in years where a heavy crop load is expected, both irrigation and nutrition should be adjusted to accommodate for the increased fruit set.

However, excessive thinning of fruitlets or thinning during the period of rapid fruit growth (stage II) may result in a low fruit set percentage and, as a result, increase the growth rate of remaining fruit to such an extent that the rinds of these fruit are unable to accommodate for the increased growth rate and result in fruit cracking or splitting. The thinning of young fruit was proposed as a causative factor in the cracking of nectarine (Gibert et al. 2007) and tomato fruit (Peet 1992) due to the resulting increase in growth rate of remaining fruit.

V. CONCLUSIONS

Fruit splitting in citrus differs from other crops due to the unique morphology of citrus fruit, consisting of the pulp and rind, which is, in addition, made up of the spongy white internal layer, the albedo (mesocarp), and an external layer, the flavedo (exocarp) (Monselise 1986).
During stage I of fruit development (cell division), the majority of the flavedo cells are formed whereafter cell division of the flavedo declines and cells of the pulp start to expand in stage II (Bain 1958). The pressure applied by the rapidly expanding pulp leads to the formation of micro-cracks and initiation of splitting at the stylar or navel end of the fruit, the area where the rind is the thinnest and/or structurally weaker than other areas of the rind.

Certain environmental as well as cultural factors lead to the development of rind that is thinner and more split prone. Such factors include nutrient imbalances, specifically low K and P (Erickson 1957; Bar-Akiva 1975; De Cicco et al. 1988), warm and humid climatic conditions (Coit 1915; Almela et al. 1994; Barry and Bower 1997), irregular water supply (Wager 1939; De Cicco et al. 1988; Goldschmidt and Galili 1992), and heavy crop loads (Rabe et al. 1990; Barry and Bower 1997). However, stress during stage I of fruit development seems to be the most important factor determining the susceptibility of an orchard to fruit splitting (Rabe and Van Rensburg 1996). During this stage, the majority of the flavedo cells are formed and its structural integrity is determined. With high crop loads, or by insufficient irrigation or fertilization during this critical period, the potential for fruit to split is increased significantly.

Fruit splitting has been reported in a various ‘Valencia’ as well as ‘Navel’ orange cultivars, which are more prone due to the presence of a secondary fruitlet (navel) that weakens the structure of the primary fruit. Fruit splitting occurrence is more severe in thin-rind, reticulated mandarin and mandarin hybrids (Goldschmidt and Galili 1992; Almela et al. 1994; Barry and Bower 1997). Consumer preference for easy-peeling, low-seeded mandarins of high internal fruit quality, especially relatively new cultivars such as ‘Mucott’, ‘Nova’, ‘Mor’, and ‘Orri’, has led to large-scale planting of these cultivars by producers. However, these cultivars are split prone and large quantities of fruit are lost solely due to fruit splitting, especially in ‘on’ years as these trees are prone to alternate bearing.

Current horticultural practices to reduce the incidence of splitting include crop load manipulation by thinning and GA₃ application/girdling, as well as sufficient Ca, K, and P nutrition and consistent irrigation. However, no single practice consistently reduces the incidence of fruit splitting in a splitting-prone orchard or cultivar.

Recent research on mandarin species reported significant reduction of fruit splitting through the application of a synthetic auxin, 2,4-D, as a foliar spray (Greenberg et al. 2006; Mupambi 2010). Successful reduction of fruit splitting with foliar application of 2,4-D seems more likely
on mandarin cultivars as results were erratic when applied to orange cultivars (Gilfillan and Stevenson 1984; Lima and Davies 1984). Additional negative effects on fruit quality, such as increased rind coarseness and reduction in juice content, are the major drawbacks of 2,4-D application. Successful implementation of 2,4-D application in citrus production in order to reduce splitting would be dependent on elucidating the timing, rate, as well as cultivar sensitivity.

The episodic nature of fruit splitting, however, is a good indication that certain environmental and/or cultural cues initiate the incidence of fruit splitting. The most important causative factors seem to be (1) heavy crop loads and (2) any stress during stage I of fruit development. The goal of future research should be to determine any other contributing factors as well as finding commercially viable methods to manipulate them, to eventually avoid the initiation of the physiological disorder, that is, citrus fruit splitting.

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LITERATURE CITED


