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*Review*

# Pre-Harvest Fruit Splitting of Citrus

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**Abstract:** Under specific conditions, the fruit on citrus trees will split open. The damaged fruit is unmarketable and provides a habitat for fungal and insect pests that can reproduce and then damage currently marketable fruit. Losses of 30 to over 50 percent of the crop are possible with some cultivars. This is a physiological disorder that starts with nutrient imbalances at flowering that result in mechanically weak areas in the rind. These rupture if interior parts of the fruit expand faster than the peel can stretch. The disconnect between problem initiation and symptom expression provides many challenges to experimental designs and interpretation. Consequently, no solution has been found despite over a century of research into the problem. This is also a problem for growers because they can only see the problem after it is too late to correct. Our goal is to define the problem and highlight successes and failures in finding a solution. The review should help direct continuing research and provide information to extension personnel to help guide growers towards productive solutions.

**Keywords:** physiological disorder; pre-harvest; cracking; bursting; flavedo split



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## 1. What Is Pre-Harvest Fruit Splitting?

Pre-harvest fruit splitting (PFS) is a global problem of physiological origin that affects most citrus cultivars to some degree. Also known as "fruit splitting" [1], "side-splits" or "navel-end splits" [2], "fruit cracking" [3], "fruit burst" [4], and "flavedo splitting" [5], PFS is a physiological disorder manifested as a meridian fissure of the fruit peel, usually at the stylar end [1,6–8]. It is called flavedo splitting because the flavedo of citrus fruit is the colored outer layer of the rind, and the crack typically splits the rind. "Cracking" was defined as a physical failure of the fruit skin, with "splitting" being an extreme form [9]. It was reported that three forms of cracking exist: radial (the most common), transverse, and irregular [10]. This physiological disorder is relatively common in many citrus growing areas of the world. An example from Florida (USA) is shown in 'Murcott' mandarin (Figure 1) with longitudinal cracks (Figure 1A–C), transverse cracks (Figure 1D), tripartite cracking (Figure 1E), and off-center cracking (Figure 1F).

Pre-harvest fruit splitting is not related to fruit creasing (albedo splitting, albedo breakdown) which appears as narrow sunken grooves on the fruit. The albedo of a citrus fruit is the inner white part of the rind between the flavedo and the segments containing the juice vesicles. The grooves are typically irregular [11] rather than transverse or longitudinal [12]. However, if much of the fruit in the grove splits, it may be difficult to distinguish creasing from PFS based on the shape of the crack. It may also be possible to have both issues on the same fruit. However, the flavedo distant from the crack in PFS-affected fruits will appear smooth and not have additional grooves if PFS is the only problem. Finally, fruit can split when subjected to pressure in picking bins and even in stacked, packed fruit containers [6]. However, the focus of this paper is on PFS in the grove.

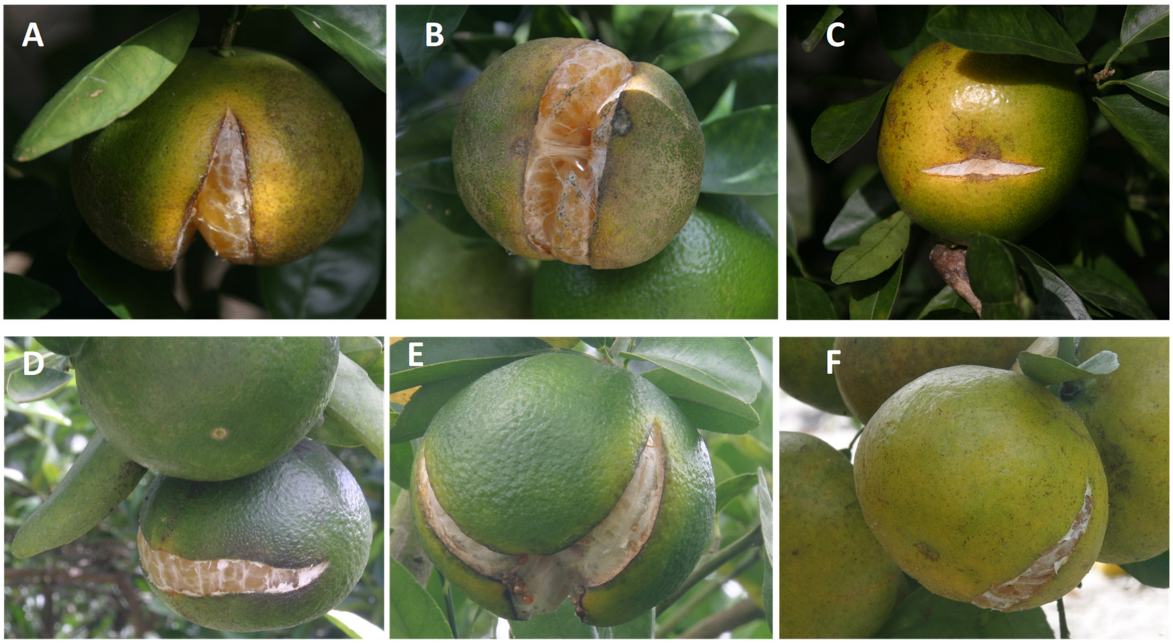


**Figure 1.** Variation in fruit split in Murcott mandarins. The longitudinal splits through navel (**A**–**C**) are common. Transverse splits are less common (**D**), and tripartite splits (**E**) and off-center splits (**F**) are typically uncommon.

## 2. Affected Cultivars

Pre-harvest fruit splitting affects all cultivars, but is a critical problem in some cultivars [13]. Table 1 shows the variability in the problem for different scion and rootstock combinations. Due to the episodic nature of the disorder and differences between years, locations, groves, and even between trees in the same grove, there are insufficient data to allow a precise ranking of cultivars according to their susceptibility to PFS. However, relatively recently released cultivars such as 'Early Pride' (a seedless selection of 'Fallglo') and 'Bingo' also showed apparent propensity to high PFS (A. Schumann, pers.com 12 November 2019). New hybrids under development and commercialization will need to be observed to determine their inherent propensity to develop PFS.

**Table 1.** Incidence of PFS in citrus fruits. This table only considers the control treatment in the cited manuscripts. Only articles that have incidence of PFS expressed as a percentage were included. Rootstock information was not always published.

| Type | Scion | Rootstock | Percentage | Citation |
|---|---|---|---|---|
| Orange | Beibei 447 Jincheng | | 7–16 | [14] |
| | Early Gold | | 0 | [15] |
| | Hamlin | | 0 | [15] |
| | Itaborai | | 10 | [15] |
| | Midknight | | 20 | [15] |
| | Navel | Cleopatra mandarin | 3 | [16] |
| | Navel | FA-5 | 4 | [16] |
| | Navel | C-35 | 9 | [16] |
| | Navel | Carrizo citrange | 8 | [16] |
| | Navelina | | <1–30 | [17] |
| | NewHall | | 27.5 | [18] |
| | Olinda | | 0 | [15] |
| | Rhode Red | | 0 | [15] |
| | Ruby Nucellar | | 0 | [15] |
| | Thompson Navel | *C. aurantium* | 35–45 | [19] |
| | Trovita | | 0 | [15] |

**Table 1.** *Cont.*

| Type | Scion | Rootstock | Percentage | Citation |
|---|---|---|---|---|
| | Valencia | | 3–30 | [6] |
| | Vernia | | 0 | [15] |
| | Washington | | 5.7–6.6 | [20] |
| | Washington | Sour orange | 4.0–9.8 | [21] |
| | Washington | Sour orange | 7 | [22] |
| | Washington | Sour orange | 24–26 | [23] |
| | Washington | *C. volkameriana* | 18–20 | [23] |
| | Washington | | 3.4–5.2 | [24] |
| | Westin | | 10 | [15] |
| Mandarin | Clementina de Nules | | 0 | [13] |
| | Clementine | *Poncirus trifoliata* | 4 | [16] |
| | Clementine | Carrizo citrange | 11 | [16] |
| | Daisy | | 10 | [15] |
| | Ellendale | Carrizo citrange | 14–30 | [25] |
| | Ellendale | | 0 | [13] |
| | Ehime Kashi 34 | | 31 | [26] |
| | Fino | | 0 | [13] |
| | Kinnow | | 0 | [15] |
| | Nova | *C. volkameriana* | 30–55 | [8] |
| | Nova | FA-5 | 5 | [16] |
| | Nova | Carrizo citrange | 17 | [16] |
| | Nova | Carrizo citrange | 1.5–27 | [16] |
| | Nova | *Poncirus trifoliata* | 1.2–7.7 | [16] |
| | Nova | Troyer citrange | 0.10–26 | [27] |
| | Nova | Sour orange | 35 | [28] |
| | Nova | Cleopatra mandarin | 10–40 | [29] |
| | Nova | Troyer citrange | 5–30 | [29] |
| | Nova | | 16–18 | [13] |
| | Nova | | 9 | [30] |
| | Orogrande | | 0 | [13] |
| | Page | | 33–50 | [31] |
| | Pontianak | | 0 | [32] |
| | Shogun | | 52.2 | [11] |
| | Terigas | | 6.8–8.8 | [32] |
| | W. Murcott | | 2 | [15] |
| Lemon | Baramasi | | 31.9–36 | [33] |
| | Baramasi | | 31.9–34.1 | [34] |
| | Baramasi | | 33 | [35] |
| | Baramasi | | 33.5–34.0 | [36] |
| | Baramasi | | 26–34 | [37] |
| | Baramasi | | 37.6 | [38] |
| | Baramasi | | 0 | [15] |
| | Columbia | | 20 | [39] |
| | Eureka | | 0 | [15] |
| | Eureka | | 25.98 | [40] |
| | Eureka | | 22.5–35.0 | [39] |
| | Genoa | | 3.3–10.5 | [39] |
| | Improved Meyer | | 0 | [15] |
| | Italian | | 27.7–35.8 | [39] |
| | Kagzi Kalan | | 47.7–48.9 | [41] |
| | Lisbon | | 0 | [15] |
| | Malta | | 15.8–26.8 | [39] |
| | Nepali oblong | | 5.0–20.0 | [39] |
| | Plant Lemon 1 | | 13.2 | [42] |
| | Punjab galgal | | 0 | [15] |
| | Seedless | | 25.0 | [39] |

**Table 1.** *Cont.*

| Type | Scion | Rootstock | Percentage | Citation |
|---|---|---|---|---|
| Grapefruit | Flame | | 0 | [15] |
| | Marsh Seedless | | 0 | [15] |
| | Rio Red | | 0 | [15] |
| | Red Blush | | 0 | [15] |
| | Star Ruby | | 0 | [15] |
| Lime | Bearss | | 0 | [15] |
| | Local | | 0 | [15] |
| | Mexican | | 0 | [15] |
| Kumquat | *Fortunella* spp. | | 0 | [15] |

PFS poses several problems to citrus growers beyond yield losses. The primary difficulty is that the most effective steps in prevention are required before symptoms become visible [8]. Remediation when fruits begin to split is less effective and may be ineffective. Additionally, split fruit increases the need for grove sanitation. Split fruits were easily invaded by pathogens such as *Alternaria alternata* [43] and *Penicillium* blue and green molds and therefore represented a risk to un-split fruit. Split fruit also attract a variety of insects [3].

## 3. Underlying Mechanisms

The underlying mechanisms start at bloom with the genetic traits that enable mechanically weakened rind at the stylar end of fruits and fruits that are wider than they are tall. The problem is initiated with damage or deformity to the stylar end. This happens with unfavorable weather during flower development through shortly after petal fall or poor nutrition. Once initiated, the symptoms are expressed during periods of rapid expansion of the fruits. Managing fertilizer and irrigation at all growth stages can minimize the problem. Application of plant growth regulators at the right time can also reduce PFS (see Section 7.4).

The propensity of fruit to split is largely determined by genetic factors. The presence of a secondary fruit, or "navel", increased PFS. 'Nova' (a hybrid between 'Fina' Clementine and 'Orlando' tangelo, itself a hybrid of 'Duncan' grapefruit and 'Dancy' tangerine) and 'Ellendale', which is an orange/tangerine cross, both possess a secondary fruitlet ("navel") that impaired the structural integrity of the rind. Cracking problems increased when the navel was large, fruit shape more oblate, and a high rate of morphological differentiation from globose to oblate occurred [3,17]. Cultivars with sub-globose to oblate fruit (i.e., "flat") with an "open" stylar end disrupted by a navel are especially predisposed [13].

Certain cultivars with fruit that do not contain a navel were also prone to PFS. The fruitlets of these possessed a cavity at the base of the style, just below where it abscises following fruit set [8]. Moreover, the styles of flowers of these cultivars were hollow at the base, and stylar abscission occurred above the position of the floral meristem, which itself was conserved or retained in most of the developing fruitlets. Tissues derived from this meristem differed from those of the rest of the rind and caused an empty cavity beneath the stylar attachment zone, instead of solid tissue in this region. This formed a structurally weaker stylar end in most of the fruits. To illustrate this, two 'Murcott' mandarin fruits are shown from the same tree displaying external and internal morphological differences between large and small stylar end openings (Figure 2). This inherent weakness was worsened if an "open hole at the pole of the oblate fruit" existed (Figure 2B–E), and generally gave rise to "star cracking" [13]. Ultrastructural changes in the peel wall also influenced incidence of PFS [5].

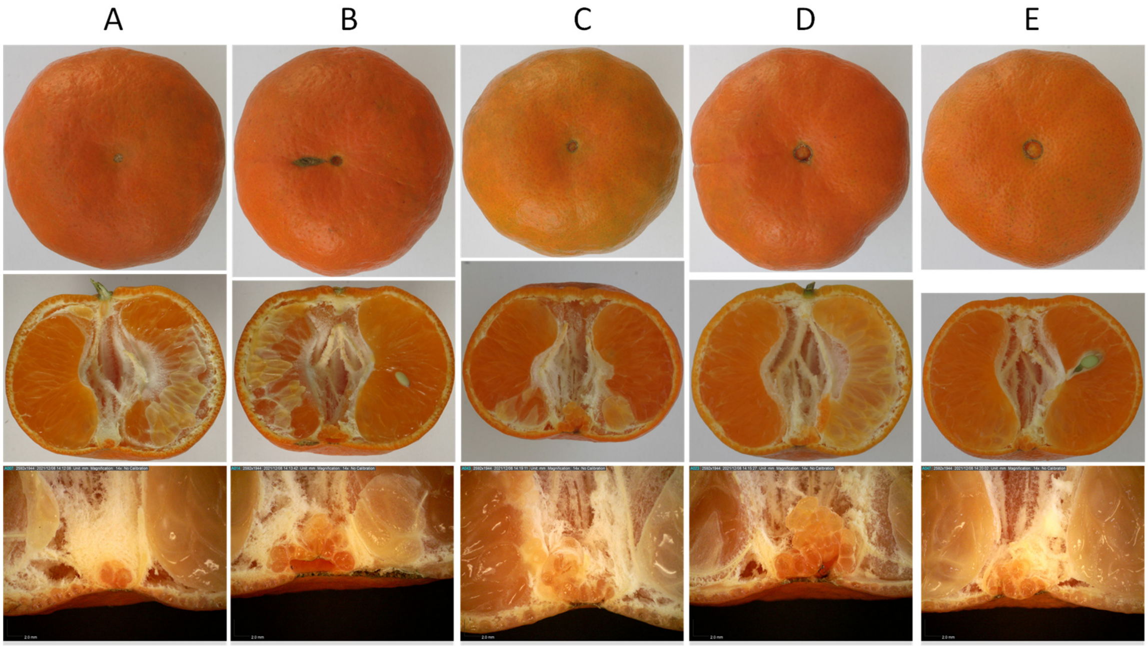


**Figure 2.** Variability in stylar end morphology in 'Dancy' mandarin fruits. The large and morphologically complex navel ends in some fruits are mechanically weaker and subject to greater risk of PFS. (**A**) small stylar end scar on the outside ((**A**), top), with simple internal morphology ((**A**), middle, bottom). (**B**–**E**). Different examples of larger stylar ends with greater complexity and greater risk of PFS. The micrographs of the stylar ends were taken with a Dino-lite camera AM4117MZT (https://www.dino-lite.com/ (accessed on 19 June 2022)).

The progressive change in shape from globose to oblate results in increased internal (structural) stress exerted at the poles of the fruit, notably at the stylar end [3]. PFS increased with "flattening" of the fruit, i.e., as fruit height/equatorial diameter decreased [3,5,13,29,44].

Added to the genetic effect of the scion, the rootstock significantly affects incidence of PFS. This is evident in observations on 'Nova' mandarin where some values are less than 10% while others are over 50% (Table 1). Wide xylem vessels in the fruit peduncles were associated with increased incidence of PFS, with such vessels apparently conferred by the rootstock [16]. The average lumen diameter of xylem elements was greater in rootstocks with high root hydraulic conductance [45], which confirmed results of studies on xylem elements where trees on Rough Lemon and 'Carizzo Citrange' had more and larger xylem elements than those on 'Cleopatra mandarin' and 'Sour Orange', with increased xylem capacity positively related to water uptake rates [46]. One might expect that vigorous rootstocks with larger xylem elements and greater hydraulic conductivity would also favor PFS from rapid fruit expansion when trees are exposed to a transition from water deficit stress to water surplus.

## 4. Initiation

The potential for PFS was determined early in fruit development [6], and detailed studies on fruitlet ontogeny [8,13,29] suggested that in certain cultivars, fruitlet anatomical features around the time of formation of the internal navel played important roles in fruit splitting [8,13]. There was broad agreement that propensity for PFS to develop depends on a range of interacting factors operative during Stage I (S1, cell division stage) of fruit growth (i.e., the cell division stage [3,5,8,47]). In extreme cases, the fruit split during this stage of development [48].

Propensity for PFS was determined from flower bud formation through the time of style abscission of fruitlets [13,29,48]. The occurrence of any stress to trees and/or to fruitlets during the cell division stage was key in determining susceptibility to PFS because it was at this time that the fruitlets' flavedo formed and structural integrity was largely determined [13,43,47]. Any small lesion at the stylar end of the rind was thought to be a starting point for fruit splitting [49]. Observations of the process of stylar abscission in relation to environmental or other conditions may prove worthwhile as an "early warning" for PFS. However, once initiated, symptom expression depends on other factors at play later in fruit maturation.

That the potential for PFS was determined early was supported by observations in the southern citrus producing areas of South Africa during the 2016/17 season on the disruptive effects on floral ontogeny and organogenesis of meteorologically extreme conditions. During flowering, temperatures reached 40 °C (104 °F), relative humidity 8% or less, and wind-speed ca. 30 km/hr. These conditions resulted in abnormally high vapor pressure deficits (i.e., 6 to 7 kPa) at an apparently critical period of flowering and were suggested to cause development of abnormal anatomical features in a range of navel selections and "late" mandarins such as 'Valley Gold', 'Orri', and 'Mor' [48]. Developmental problems in the navel end can be observed in buds in 'Navel' oranges [50], mandarins [13], and lemons [10]. Measurement of vapor pressure deficit may be a potential tool in determination of the risk of PFS.

## 5. Symptom Expression

Many factors appear to affect the propensity of fruit to split and the severity of splitting. The most important of these will be discussed later in this paper, but broadly, the most significant of these are cultivar, climatic factors, soil factors, and such cultural practices as fertilizer application and irrigation. Fluctuating environmental factors (e.g., soil moisture; temperature, relative humidity) that result in rapid expansion of pulp relative to peel lead to PFS [1]. This was described as the effects of "spasms of growth caused by irregularities in culture, irrigations, or seasons" [51]. This disorder is expressed in some cultivars through the entire fruit growth and development period, but is most commonly expressed during the cell enlargement (Stage II) and cell maturation (Stage III) phases of fruit growth [5]. PFS has been quantified in two ways: in absolute terms (i.e., number of fruit split per tree) or relative to fruit set (i.e., percent of fruit splitting [13]).

This disorder develops from a mismatch between growth of fruit rind and pulp. PFS is driven by mechanical stresses resulting from turgor pressure within the fruit. The intensity of the mechanical stresses generated by internal pressures, together with rind resistance and plasticity determining the intensity and location of the splitting [13]. Furthermore, the presence of anatomical features such as a navel or stylar defects may serve as "stress concentrators" [52]. The disorder usually progresses, displaying symptoms as the fruit grows and develops, during the following stages [47].

### 5.1. Fruit Cell Division (Stage I)

In genetically predisposed cultivars where fruits typically possess relatively large or protruding navels and/or "open" stylar regions, the first signs of small, radiating cracks may sometimes be seen during flowering, petal fall, and at stylar abscission [48]. Although different patterns for the development of PFS were described, it usually begins as small cracks (or "microcracks" [3,49]) at the fruit's stylar end [13]. However, in a few cases, it started at the fruit's equator [8,29].

### 5.2. Cell Expansion Stage (Stage II)

An early sign of PFS was a localized yellowing due to loss of chlorophyll in the rind around the fruit's stylar scar, followed shortly thereafter by the formation of radiating longitudinal cracks that increased in size with fruit growth. Splitting was strongly associated with the presence of an aperture in the stylar scar as well as to the size and development of the fruit's navel tissue in cultivars possessing this (e.g., 'Nova,' 'Navelina'). In addition, the time of development of PFS is related to the shape of the fruit. In relatively oblate ("flat") fruit, PFS symptoms were evident one month earlier than in rounder fruits [13].

If the rind did not restart its growth to accommodate pulp expansion, splitting resulted, due to the differing anatomical structure and hence mechanical properties of the rind's two components. The "spongier" albedo cells seem able to stretch to better accommodate increased pulp growth, whilst the flavedo tissue remained more rigid and prone to cracking [7]. Although physical splitting occurs because of increasing pulp volume during Stage II, the potential of incidence of PFS was mostly the result of stress to trees and/or young fruit during the cell division (Stage I) phase of fruit growth [53].

### 5.3. Cell Maturation Stage (Stage III)

As fruit increased in volume any increase in its radius led to a concomitant increase in physical stress applied to the enclosing rind. This effect was more extreme in flatter fruit. Fruit geometric changes occurring in early organogenesis may have little effect on stress distribution at the time when stresses occur, but give rise to intense stresses after further fruit development [52]. The rate of change of fruit shape (in terms of its diameter to height ratio) also affected the time of development of PFS and its symptoms. Further mechanical stresses exerted by the still-expanding juice vesicles of the fruit pulp result in catastrophic splitting. The processes of PFS can be accentuated and accelerated by heavy rainfall before harvest that results in an influx of water into the pulp, thereby increasing the severity of splitting [3,29]. Sampling three months before harvest ('Nova' in Spain) showed that 86% of split fruit had open stylar ends, which were only present in 8% of non-split fruit [29].

## 6. Factors Affecting Severity

### 6.1. Crop Load

Crop load or yield is often described in subjective terms, with no generally accepted quantitative definitions of low, light, normal, average, high, or heavy. The definition may change depending on whether fruit are for processing or fresh market. It is usually expressed as yield per tree or per unit area where fruit is produced for processing or sold to packinghouses on a negotiated per unit volume basis. Where fruit is grown for fresh-fruit markets, a more useful measure would be the number of packed cartons per tree or per unit area, since this integrates two closely linked factors that affect grower income: yield and fruit size.

Separately and in concert many factors affect yield including genetic considerations related to cultivar/rootstock, tree spacing [6,54], climatic factors [55], soil factors (e.g., salinity [56]), tree bearing patterns (expressed as alternate or biennial bearing) [57,58], and management practices, such as fertilizer applications [6,59–62], irrigation, and weed control [6,63].

In the context of PFS, however, both relatively light crops usually result in oversized fruit that may more commonly split, whilst heavy crop loads produce relatively small, thin-skinned fruit with presumably weaker rinds, more predisposed to PFS [3,6,8]. While PFS is initiated early in fruit development, having an average yield will help predisposed fruits avoid splitting.

### 6.2. Fruit Shape

Fruit shape is, as already stated, a genetic characteristic. Citrus fruits followed a sigmoidal growth pattern [47]. The rind (flavedo and albedo) develops mostly in Stage I (cell division) and into the early part of Stage II (cell expansion). The pulp develops mainly during Stage II and Stage III (cell maturation), and at this stage, fruit shape may change from globose to oblate where fruit diameter is greater than the height. This concentrates stress at the poles of the fruit, with the most dramatic effects on the thin-skinned stylar region with its structurally weaker rind [3,64].

### 6.3. Fluctuating Water Status

Regardless of cultivar, PFS was probably mainly a result of "unstable" (i.e., irregular, fluctuating) tree water status, itself an interaction between soil moisture, rootstock, and climatic factors which caused abrupt changes in fruit growth rate [16,17,43,65]. The role of irrigation is to prevent drought–flood cycles to the extent possible given rainfall patterns when used to manage PFS, and this is facilitated by relatively dryer surface layers with wetter soil deeper [17].

### 6.4. Humidity and Light

Other factors reported to affect PFS were light (more PFS was likely on rinds of fruits developing in full sun) and humidity. Of all the environmental factors inducing a thin rind, warm and humid conditions during Stage I of fruit development were most important [3]. High PFS was observed with a "dry spring followed by a wet period in stages II and III", based on the assumption that soil moisture status was the main effect [3,5,6,8–10,16,43].

### 6.5. Peel Quality

Thickness and hardness of peels constituted peel strength, which was directly associated with fruit cracking [13,30,32]. The size of rind oil glands was discussed. Larger rind oil cells might allow the (flavedo) cells between them to bear higher pressures [5].

A relatively recent report investigated the disorganization of rind and fruit pedicel tissues in cracked fruit as compared with other fruits not affected. It was suggested that such disruption might disrupt the flow of water and minerals into fruit [10]. However, this study did not specify the location on the fruits used of the tissues sampled for microscopic examination, most importantly, the proximity to any cracks in the rind. It is possible that the disorganization of tissues described may be the direct consequence of any nearby cracking, therefore raising the question of whether observed anatomical changes are the cause or effect of splitting.

In some cases, PFS damage fails to result in an open wound. In these cases, the damaged flavedo can heal, sometimes leaving a scar, as seen in [66,67] and Figure 3. These are longitudinal scars (Figure 3A,B) that are aligned with intersegmental areas internally (Figure 3C), and may result in microscopic internal defects in the peel (Figure 3D).

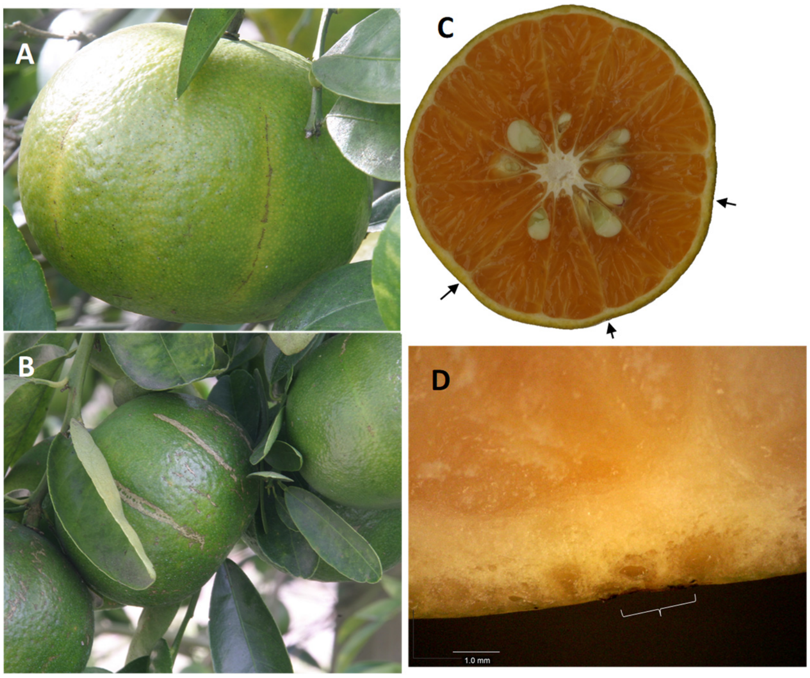


**Figure 3.** Narrow (**A**) and wide (**B**) longitudinal scars in 'Murcott' mandarin fruits. One fruit was cut to show peel below scars (arrows) (**C**). Scars align with section membranes. The sectioned fruit shows variability in peel thickness within a fruit. Closeup of scarred area (**D**) shows slight abnormalities below scar (bracket).

## 7. What Steps Can Be Taken to Mitigate the Effects of PFS?

There is no single solution to this problem, rather a succession of approaches that constitute generally good management practices in any year. Historical trends in production and incidence of PRS are significant in determining nutrient demand in the especially critical pre-bloom stage of the phenological cycle. This is to ensure that trees have the resources necessary to produce healthy fruits. After this pre-PFS initiation period, continued monitoring may be needed to adjust fertilization rates for development of strong peels. The goal through the remainder of fruit growth and maturation is for a consistent growth rate. This is accomplished by applying small doses of fertilizer as needed and irrigating to keep soil moisture consistent regardless of sunny or rainy conditions.

### *7.1. Mineral Nutrients*

Maintenance of leaf nutrient levels within "norms" is standard practice affecting a wide range of physiological processes in all plants. However, the following nutrients have been shown to be important in PFS in citrus.

#### 7.1.1. Boron

B was suggested to be involved in promotion of cell division, synthesis of cell walls, and possibly cell wall integrity and "toughness" [5,68,69]. Boron application reduced cracking in lemon from a 2-year average of 33% in the control to 23.7% [34], and in mandarin the 0.8% foliar boric acid spray reduced splitting from 52% in the control to 8.89% [11]. Boron may play a synergistic effect where calcium applications are made (see Section 7.1.2 below).

#### 7.1.2. Calcium

Assuming that calcium incorporation into cell walls "strengthened" them or increased their plasticity, the best strategy to improve Ca content of fruit was to optimize root uptake and transport via the transpiration stream, as Ca was not readily absorbed from foliar applications nor from fruit surfaces [70]. Any factor hampering Ca transport (e.g., lowered vapor pressure deficit), especially during the critical stages of cell division and growth may lead to reduced Ca levels in the fruit. Such a shortfall could lead to physiological disorders of the rind, including PFS [3].

However, Ca $(NO_3)_2$ foliar sprays (1% concentration) were applied at the start of the cell enlargement stage (Stage II: [47]) to reduce PFS but results were erratic [6,7]. In contrast, a single application of Ca $(NO_3)_2$ applied (2% concentration) as a foliar spray at "70% petal fall" on 'Nova' resulted in reduced PFS [3]. One percent calcium chloride foliar sprays reduced splitting in 'Shogun' mandarin from 52% in the control to 5.56% [11].

Calcium fertilization (foliar spray of 0.5%) resulted in lower cracking rates in Beibei 447 Jincheng orange. Peels of cracked fruits had higher levels of malonaldehyde, polygalacturonase, cellulase, soluble pectin, peroxidase, and polyphenol oxidase, but lowered concentrations of protopectin, superoxide dismutase, and catalase. Calcium fertilization decreased the concentration of soluble pectin, polygalacturonase, cellulase peroxidase, and polyphenol oxidase, but increased the concentration of protopectin, superoxide dismutase, and catalase in the peel. Normal fruits had higher N and Ca. Levels of P were higher in normal fruit in the leaf, peel, and pulp but the difference was not significant. Levels of K were always higher in split fruit, but the differences were not significant [14].

Calcium was incorporated into structural components of the fruit cell walls during cell wall formation (i.e., Stage I, or the cell division stage), at the end of which nearly all the cells present in the fruit have been formed. This includes the rind tissues: flavedo and albedo. Calcium and boron formed a stabilizing complex in the middle lamella of the cell walls [3,5].

The combination of calcium (1% $CaCl_2$) and boron (boric acid at 0.8%) foliar sprays applied 4 months after fruit-setting reduced fruit splitting in 'Shogun' mandarin to under 10%, compared with 52% fruit splitting in the water-sprayed control [11]. The reduction in fruit splitting from calcium alone, boron alone, or the combination appeared to be roughly equivalent.

#### 7.1.3. Nitrogen

No involvement of nitrogen in PFS has been published. However, the effects of nitrogen fertilization on increased fruit set and thereby on fruit size and rind thickness [61,71] might suggest that endogenous nitrogen levels may affect expression of PFS.

#### 7.1.4. Phosphorus

The effects of relatively high leaf phosphorus levels in inducing thinner, smoother rinds are well documented [3,5,6,43]. To reduce PFS, nutritional programs must balance peel thickening and/or strengthening elements (e.g., K, Ca), with peel-thinning phosphorus. There is a strong negative correlation between rind thickness and PFS in lemons [30]. There is also a correlation between phosphorus and rind thickness where both low and high P produce thin peels [72]. However, there is no direct field data showing that elevated phosphorus increases PFS despite frequent claims of the association.

#### 7.1.5. Potassium

Incidence of fruit drop caused by PFS ('Hamlin' orange in Florida) correlated strongly with both leaf (−0.896 **) and fruit K content (0.946 **). The number of split fruits decreased sharply where leaf K levels exceeded 1.25% [73]. In 'Valencia' orange (Malelane, South Africa), leaf K levels gave inconsistent results for PFS severity although indications were that leaf K levels <0.8% were associated with increased propensity for PFS, whilst K levels > 0.9% were associated with reduced PFS [6]. Note that these norms were determined based upon analysis of leaves from fruit-bearing terminals.

Foliar $KNO_3$ spray (4%) after the end of physiological fruit drop was a recommendation followed by growers intended to increase fruit size at harvest [3,6]. Low peel content of both K and Ca seemed to be associated with increased PFS [8]. $KNO_3$ at 6% application at full bloom reduced splitting from 7% in the controls to 2% and was as effective as an application later (fruit 1.5 to 2 cm) or an application at both times. However, the later application was more effective than an earlier application at 4%, and at 2%, fruit split was 5.5 to 6% [22].

In 'Page' mandarin, the addition of 1 or 2% $KNO_3$ significantly reduced fruit splitting. The most effective time for the application was at the end of petal fall. Fruit split was reduced from an average of 33% to about 20% [31]. The addition of 8% $K_2SO_4$ reduced PFS in lemon from a 2-year average of 33% in the control to 25% [34]. The addition of 0.2% potassium sulfate reduced splitting from 31% to 15%, and increasing the fertilization rate to 2% $KSO_4$ reduced splitting to 5% in 'Ehime Kashi No. 34' [26]. The reduction in splitting was correlated with an increase in the hardness of the peel relative to the flesh. Trees receiving additional potassium fertilizer also had elevated amino acid levels in the peel, which is relevant because amino acids are used in osmoregulation. Elevated K increased metabolic rates and upregulated/downregulated several metabolic pathways, but the complexity of the interactions make it difficult to directly relate the contribution of each effect to fruit splitting [26].

Combinations of K and Ca have been used to reduce incidence of PFS. Foliar application of 2% $K_2SO_4$ applied at full bloom and when fruit diameter reached 15 to 25 mm, plus 2% $CaCl_2$ applied at average fruit diameter of 84–85 mm (no details were given on the phenological stages represented) resulted in reduced incidence of PFS to 2.6% of total fruit number (half that recorded in water-sprayed control trees) [22]. Moreover, foliar application of 10% $K_2SO_4$ plus 1% $CaCl_2$ reduced fruit cracking of lemon [40].

Potassium fertilization at 4% and 6% increased peel thickness, but fertilization at 2% did not regardless of whether fertilization took place at bloom, when fruits were between 1.5 and 2 cm in diameter or at both times [22].

7.1.6. Zinc

Zn was suggested to play a role in increasing cell enlargement and accelerating fruit growth. The possibility existed that fruit rind-cracking-related gene Cs-cdc48 and cell wall-related gene Ct-Exp1 which were both specifically expressed in "normal" fruit peels, were not expressed in cracked fruit peels. Zn fertilizer application during the cell enlargement stage promoted the upregulation of Cs-cdc48 expression [5].

7.1.7. Ending Remarks

There is a large body of evidence indicating that specific nutrients are important in moderating PFS in susceptible cultivars. There are a few papers that show no effect of fertilization. There was no effect of calcium, magnesium, or potassium fertilization [32].

Fertilization can correct a deficiency or a nutrient imbalance where a surplus of one nutrient results in a deficiency of another even though soil analysis suggests that the other nutrient is at sufficient levels. For example, excess manganese levels are antagonistic to calcium, iron, and magnesium, and increase IAA oxidase activity. This led to reduction in IAA levels, and a possible adverse effect on cell wall extension [5].

Fertilization to prevent PFS needs to start before bloom so that the plants have time to absorb the nutrients and move essential components to the developing buds. Plants should be monitored thereafter to adjust fertilization in support of strong peels. Late season fertilization can be reduced as the benefit is minimal and there is risk of inhibiting color break in fruits.

*7.2. Water (Rainfall, Irrigation, Flood, or Drought)*

Irrigation and unexpected late rain affected PFS. A dry spring period followed by a wet period during Stage II (cell expansion) and early Stage III (cell maturation) resulted in high PFS [3]. Enhanced irrigation at 200% of normal resulted in excessive expansion of the fruits' pulp and thereby to increased PFS [8], whilst reduced irrigation reduced PFS [6,8]. Although regulated deficit irrigation (RDI; i.e., using 50–60% of "normal" irrigation) reduced PFS [8], any reduction in irrigation should not result in stress to trees or fruitlets especially during "early stages of fruit development" [3].

No positive correlation was reported between seasonal rainfall patterns and PFS [53]. However, several studies have shown that irrigation schedules can affect PFS [16,65,74]. Irrigation schedules include any factor that influences water availability and would include the type of irrigation (subsurface flooding to drip irrigation) and temporal distribution based on calendar or soil moisture probes. We suggest that the irregular nature of rain events makes it difficult to detect the link between soil moisture and PFS. Furthermore, this link with irrigation is strongest in sand-dominated soils [16].

One factor strongly affecting irrigation and ultimately propensity to PFS is soil type. Irregularities in tree water status, due to interaction between soil moisture, rootstock, and climatic conditions lead to substantial changes in fruit growth rate, which may contribute to PFS. A close relationship existed between cracking and soil texture, with severity of PFS inversely correlated to soil clay and silt content, and positively with sandiness. Under 85% sand-soil conditions, slight changes in soil moisture due to fluctuations in temperature, evapotranspiration or water supply changed fruit growth patterns with a few hours, and induced splitting. Under extreme sand-soil conditions, trees became highly sensitive to tree-water-status variations, such that, at the end of summer, a single 5 mm rain day induced continuous fruit growth for >40 h, resulting in a fruit–pulp hydrostatic pressure that might exceed the rind's ability to contain it, thereby causing fruit to split [16].

*7.3. Regulation of Crop Load*

PFS was worse where trees set large numbers of fruit [25]. Efforts to increase yield through girdling or the application of $GA_3$ resulted in increased PFS [25,27]. Thus, the benefits of increasing fruit set by foliar $GA_3$ applications or girdling must be weighed against the risk of increased PFS. It should also be noted that heavy flowering represents a stress to trees, and one which exists during the sensitive period of cell division.

The number of fruits borne on the tree affects PFS. Where fruit number was excessively high (e.g., where no thinning was done in "on years" of biennial bearers) high competition for water and assimilates between fruit resulted in reduced partitioning of resources between fruit, and thence in smaller, thin-skinned fruit that were more prone to splitting. Where crop load was excessive, the resulting smaller fruits usually possessed thinner skins and an inherently flatter shape, which was apparently a characteristic of foliar $GA_3$ applications to increase fruit set. Conversely, where trees bore too few fruit (after low fruit set or perhaps excessive fruit drop or hand thinning), the resulting excessively large fruit grew faster and hence showed higher PFS [3].

The number of split fruits was unrelated to the number of fruits set and by extension to crop load. Being unrelated to crop load, the % of PFS decreased as crop load increased [29]. However, this conflicted with the observation that severity of PFS was "very much dependent on flower number, % fruit set; and final crop load" [7].

Girdling is an approach to increase fruit load in citrus [75–77]. However, any alteration in inter-fruit competition (e.g., by girdling, or foliar application of GA to stimulate higher fruit set) could lead to fruit with thin and/or "weak" rinds and increased PFS [3].

Achieving an appropriate crop load is an ongoing challenge and a worthwhile area for future research. Cross pollination increases yield in some cultivars and increases seediness [78] but may also reduce PFS [25].

### *7.4. Plant Growth Regulators*

Plant growth regulators influence crop load, fruit shape, and peel characteristics. In turn, plant growth regulators may also influence PFS regardless of the reason for their application. The efficacy of these products is highly dependent on timing the application to specific phenological growth stages of the tree. We suggest that further research in this area would benefit more growers and the scientific community if application timing was based on fruit size rather than calendar date. This would adjust for year-to-year variability within a grove and for groves in different areas.

#### 7.4.1. Gibberellic Acid (i.e., Gibberellins, GA, $GA_3$, or A3)

The use of GA was recommended to reduce incidence and severity of a variety of problems including creasing, watermark [79], oleocellosis, and general improvement in rind quality. While GA has no effect on internal quality, it may delay external (rind) color development [79]. The possibility exists that delayed rind color may predispose fruit to higher levels of oleocellosis [80].

Application of GA to 'Washington' navel orange (50, 100 ppm at full bloom and/or when fruits were up to 2 cm diameter) significantly reduced cracking, though the application at bloom was less effective than the later spray. There was no difference between the later application and an application made at both bloom and when fruits were 1.5 to 2 cm diameter [22]. GA applications to 'Thompson navel' reduced cracking from 35–45% in the control to about 10% in the highest rate of GA (100 mgL) [19].

Application of GA to lemons at 10 ppm reduced cracking from 37.8% in untreated control to 17% which was slightly better than the performance of GA at 5 or 20 ppm [38].

Despite the benefits of GA, the required timing and application (dose, pH < 8, crop phenology, time of day, adjuvants) can make efficacious GA application difficult [79].

The reduction in PFS sometimes achieved with gibberellic acid foliar spray may be due to its effect on reducing pectin methylesterase activity as demonstrated in 'Valencia' oranges [81,82].

#### 7.4.2. 2,4-Dichlorophenoxyacetic Acid (2,4-D)

2,4-D alone reduced fruit splitting from about 33% to under 15% at 100 mg/L rate. There was an effect of application time where the application at the end of petal fall was slightly more efficacious than applications at full bloom or the end of the June fruit drop [31]. 2,4-D was applied to 'Newhall Navel' and 'Washington Navel' oranges at 15, 25, and 35 mg/L at full bloom and petal drop. The timing was more important than concentration. Application at full bloom was more effective at reducing the size of navels and increasing the percentage of fruit with closed navels. However, the percentage of split fruit was not reported [83]. Application of higher rates of 2,4-D (10 to 20 mg/L) decrease splitting from 35–45% in the controls to 25–30% at the highest rate when applied to 'Thompson Navel'.

2,4-D (one application of 40 mg/L at 10 L/tree) applied to 'Nova' mandarin on sour orange rootstock significantly reduced fruit split from 35% to 25% when the application was to trees when fruit were on average 13 mm [28]. In 'Marisol' Clementine, foliar 2,4-D (10 mg/L, applied directly after physiological fruit drop) increased rind thickness [3,13], strength (expressed as puncture resistance), and rind coarseness such that PFS incidence was reduced [44].

Use of 2,4-D increased peel thickness, especially at the stylar end, such that it was the same as at the fruit median [29]. However, stylar peel thickness may not be the only determinant of splitting: peels were thicker in split, 2,4-D-treated fruit than some untreated, non-split control fruit [13].

One other effect of 2,4-D (10 ppm after physiological fruit drop) was increased sink strength of fruits, due to increased effectiveness of transport of water, nutrients, and assimilates by increased capacity of the vascular system between source (leaves) and sink (fruits). Fruit pedicels were thicker due to increased thickness of the central xylem cylinder [84,85]. 2,4-D application post-drop reduced PFS [25].

There are several chemical forms of 2,4-D that are available: acid, butoxyethyl ester, dimethylamine salt, isooctyl ester, and isopropyl ester. At least amongst these five forms of 2,4-D, there was little difference in their ability to control pre-harvest fruit drop [85]. Based on this result, we would assume that use of 2,4-D to manage splitting would also be little affected by the form of 2,4-D. While the isopropyl ester is sold in the USA for use as a plant growth regulator in citrus, most of these forms are only sold as herbicides and the only legal application must follow label guidelines.

Tank mixed 2,4-D: 2,4-D is combined with other products to further improve efficacy. For 'Page' mandarin, the most effective application was 100 mL $L^{-1}$ 2,4-D and 2% $KNO_3$ which reduced splitting from about 33% to under 10%. All treatments followed a pattern where the most effective application was at the end of petal fall [31]. When applied to 'Thompson Navel' the application of up to 20 mg/L 2,4-D plus 100 mg/L GA had the lowest rate of fruit split (<10% compared to 35–45% in controls) [19]. Within the tested rate range for GA (0, 50, 100 mg/L) and 2, 4-D (0, 10, 20 mg/L), GA had a greater effect at reducing splitting, though at all rates, the addition of 2,4-D had additional benefits [19].

#### 7.4.3. Other Plant Growth Regulators

A variety of these have been used. These include 1-naphthaleneacetic acid (NAA), S-abscisic acid (S-ABA), aminoethoxyvinylglycine (AVG), 1-methylcyclopropene (1-MCP), and 3,5,6-trichloro-2-piridil oxyacetic acid (3,5,6-TPA). Few studies have been conducted that relate the use of these products to an effect on PFS. One study included NAA, S-ABA, and 1-MCP but found no effect on fruit splitting. Foliar application of NAA to lemons at 40 ppm reduced cracking from 37.6% in the control to 13.4%. Applications of NAA at 10 and 20 ppm also reduced cracking but to a lesser extent [38]. Foliar application of 40 ppm NAA reduced fruit cracking in lemon, though further improvement was observed with the addition of 8% $K_2SO_4$ and 1% borax [34]. NAA (300 mg/liter at 10 L/tree) applied to 'Nova' mandarin on sour orange rootstock significantly reduced fruit split from 35% to 21% when the application was to trees when fruit were on average 26 mm but not in an earlier application when fruit were 13 mm [28]. In addition, application of 3,5,6-TPA (15 mg/L at 10 L/tree) significantly reduced cracking from 35% to 17% [28].

7.4.4. Combinations of Plant Growth Regulators

Combinations of foliar $GA_3$ and/or 2,4-D (two foliar applications of each) reduced PFD [3,5], an effect attributed to increased peel resistance to puncture rather than to increased skin thickness [7,43]. However, two foliar applications of 20 ppm 2,4-D (at full bloom and at petal fall) altered fruit shape (increased fruit length) and increased rind thickness especially at the stylar end [13,49]. The resulting thicker rind showed development of solid, compact tissue under the stylar-end flavedo tissue and reduced PFS. Timing of GA application is important as GA application at bloom to increase fruit set can result in increased fruit split to nearly double untreated PFS levels while GA application post-drop decreased PFS [25].

Application of 3,5,6-TPA (15 mg/L, 10 L/tree) significantly reduces splitting when applied to older fruits (26 mm average size). The application of 3,5,6-TPA when fruits averaged 13 mm significantly reduced yield [28].

### *7.5. Pesticides*

We should consider the possibility that sometimes the effect is due to problems associated with pest management sprays at critical times at or near bloom. If this was a major issue it would be more common, but we should not dismiss this possibility. PFS researchers have attributed certain physical deformities of fruit to some pesticide sprays. Sprays of chlorpyrifos resulted in longitudinal ridges in the treated grapefruit [86]. A similar effect was also induced by hydrocyanic acid fumigation of orange (navel, Valencia), grapefruit, and lemon [87]. The most sensitive period was from bud formation through fruits < 2.54 cm in diameter. For chlorpyrifos applications in Californian grapefruit, an application in mid-February caused the most damage with some damage within two weeks either side of this date [86].

### *7.6. Canopy Position*

There was more PFS in "outside canopy", "top of canopy", and fruit located on the sun-exposed row-side, compared with lower hanging fruit borne in "shaded canopy zones" [48]. This might raise the issue of the difference between air temperature (i.e., ca. 40 °C/104 °F) and leaf temperature, which was not recorded. In addition, fruits developing on the outer canopy of unpruned or inappropriately pruned trees were exposed to higher temperatures than "inside canopy" fruits (although temperatures were not measured). The increase in surface temperature of fruit in the outer canopy may trigger physiological processes that result in free radicals which may in turn cause damage to cell membranes, cell death, and hence increased physiological stress [3].

Splitting increased on the south side of trees in South Africa in 'Washington' navel orange, while the west side had the next highest number of split fruits. Furthermore, the low parts of the canopy had more split fruits than upper parts of the canopy [23].

## **8. Summary and Possible Future Directions for Research**

PFS depends upon and is affected by the unique morphology of the citrus fruit, consisting of pulp and rind, with the rind itself made up of the outer, more rigid flavedo, which overlies the spongy albedo. A critical stage is the cell division stage (SI) of fruit growth, a time when the majority of the flavedo tissues are formed and the structural integrity of the rind is apparently determined. Basic anatomical features peculiar to each cultivar, such as presence of a navel or of a hollow space beneath the stylar end compromise the structural integrity of the rind. During the cell expansion phase (SII), pulp expansion occurs as the result of turgor pressure on the juice vesicles. If this expansion is unresolved, and if microcracks are present at the stylar end, especially in "flat" or oblate fruits with thin rinds, fruit splitting will occur. Several environmental factors and cultural practices interact to further affect the propensity for PFS, especially in trees of sensitive cultivars bearing high crop loads under warm and humid growing conditions, with irregular or fluctuating water supply. However, the potential for PFS to manifest itself has its roots in SI of fruit growth. Given damage in SI, subsequent environmental conditions (e.g., heavy late rains) during later stages can increase symptom expression.

Stress during Stage I of fruit development seemed to be the most important factor determining propensity of the grove to PFS. The most important contributory factors were heavy crop loads and stress during the cell division stage of fruit growth. Given the "episodic" nature of PFS, the complexity of interactions between genetic features, environment, and cultural practices, it is likely that the commercial solution will be multifaceted rather than a one size fits all approach. While nutrition is important, the critical nutrient (Ca, Mg, B, etc.) is the one that is deficient in your region based on soil and tissue analyses of nutrient composition (Liebig's barrel or Liebig's law of the minimum as applied to plant nutrition). Water balance is also implicated so irrigation supplies water but also evens out water availability to prevent drought to flood cycles that would promote onset of PFS issues. Monitoring soil water potential as well as assessing plant nutrition pre- and post-bloom will enable the best estimate for PFS severity. However, a couple seasons of data may be necessary to properly interpret the data from an individual grove given the current understanding of PFS.

It was stated that "currently predicting splitting probability at the single fruit level is impossible" [8]. However, light microscopy sections of flowers of "sensitive cultivars" before anthesis show either presence of an open cavity beneath the rind of the stylar end of so-called "non-navel" cultivars or of a secondary fruit (i.e., a navel) in so-called "navel" cultivars. Both features affect PFS, depending on environmental conditions at flowering and again during later stages of fruit growth. Both features may be observed early in the process of fruit growth, hence perhaps giving early indication of the risk of PFS. Observation of the process of stylar abscission may prove useful.

There remain many unanswered questions regarding PFS. A key time in determining fruit health and vigor is at bloom and cell division stages in fruit growth. However, the cellular mechanism(s) remain poorly understood. Plant nutrition (including the movement of nutrients such as calcium in, say, the transpiration stream) and water balance play key roles both at flowering and at symptom development. While nutrition affects rind strength, it is less clear how best to measure that strength as it relates to PFS. Attempts have been made to quantify strength by puncturing [30,49], and resistance to cutting [44]. Other mechanical properties may also be important, such as the ability to stretch [5]. Factors such as peel thickness and the number of cell layers are also important [5] but this would also influence peel strength. We suggest that tensile strength might be important. Overall, the issue becomes more complex as scion/rootstock combinations interact with the abiotic environment and there is no consensus on measurement techniques that would allow meaningful comparisons between results from different researchers. Gaining a better understanding of this issue would enable a more informed selection of cultivar for each growing region, provide a warning for problematic years, and enable a more targeted remediation when problems are expected. A more consistent approach to recording key data between studies would facilitate this process. Identifying those key variables and sample collection issues as it relates to phenological stages of the trees would be a first step in this process.

## 9. Methods

Citations were found searching Web of Science using key words: "citrus (split or splitting)" ($n$ = 254), "citrus (crack or cracking)" ($n$ = 99), or "pre-harvest defects citrus" ($n$ = 1). Citations were also collected from the literature cited sections of relevant papers. This latter step was essential as the electronic search missed some of the older literature. Articles were selected based on title, and full records recovered using Internet resources such as Google Scholar and the University of Florida interlibrary loan service. Using Google Scholar to find pdf versions of articles sometimes turned up additional articles, and some publisher websites made suggestions based on the current search. Non-English titles were excluded except when clearly relevant. A few citations were excluded as conference proceedings later published as a full paper. Additional references were included to fill knowledge gaps within the citrus literature. The research goal was to clearly define preharvest fruit splitting, identify underlying causes, and explore potential remedies. The range in citation dates was 1913 to 2022 (Figure 4). Citations were last searched for on 3 May 2022.

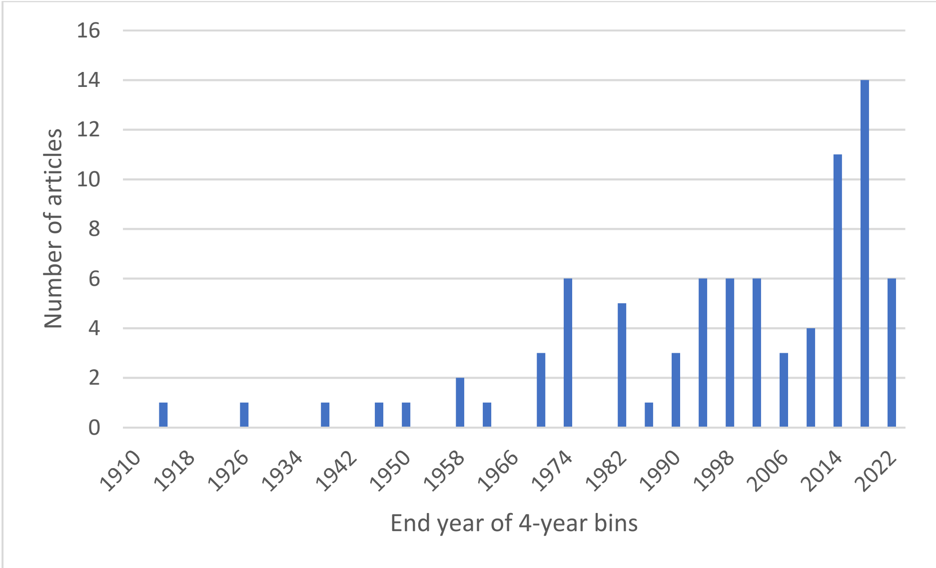


**Figure 4.** The distribution of publication dates of the literature cited in this review. There were 87 articles in total. The Yara website, two anonymous articles, and two web pages were not included. The count from 2022 is incomplete and represents a count from less than half the chronological year.

We typically excluded articles involving PFS issues that did not count split fruit. The size of navel openings or rind thickness are correlated with PFS, but a lack of PFS data makes it difficult to assess the actual benefit of the method for managing PFS.

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