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REVIEW
Water-Soaked Brown Flesh Disorders in Peach Fruit (*Prunus persica* (L.) Batsch)

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Abstract

Water-soaked brown flesh disorder of peach (*Prunus persica* (L.) Batsch) fruit, which occurs in unpicked fruit near harvest time, has been a problem in Japan since the 1990s. The affected fruit share the characteristics of more mature fruit in that the fruit are large, sweet, and soft. It has also transpired that high-quality; high-value fruit are more sensitive to the disorder, which exacerbates economic losses. The most susceptible regions of the fruit are those with high sugar content, although the symptoms are not clearly linked to specific cultivars. Investigations into the cause(s) of water-soaked brown flesh disorder of peach fruit have just started, and reports are limited to Japan. In this review, published information about the disorder is reviewed, and a hypothesis for the occurrence of water-soaked brown flesh disorder in peaches is presented.

Discipline: Horticulture
Additional key words: browning, fruit quality, physiological disorder, watercore

Introduction

Water-soaked brown flesh is a physiological disorder that emerges just before peach fruit reach optimum maturity. The symptoms resemble "watercore" of apples (Marlow & Loescher 1984); whereby affected tissues appear water-soaked and translucent, initially associated with the main vascular bundles but capable of extending to other cell layers. Fruit with the disorder are not easily visible unless severely affected, whereby the affected tissue extends nearly to the fruit skin. Unlike apple watercore, water-soaked tissues in peach fruit are often accompanied with brown discoloration and the smell of alcohol. This renders the affected fruit unmarketable, leading to direct economic losses.

In Japan, awareness of the problem of water-soaked brown flesh disorder of peach fruit has soared since the 1990s. However, although a few reports about this disorder have been published in Japan, all were in Japanese. No reports exist concerning the disorder in other peach-growing countries, perhaps because peaches cultivated in Japan are very large and harvested at a more mature stage than in other countries. In this review, investigations to date on peach water-soaked brown flesh disorder will be summarized, and a hypothesis for the occurrence of water-soaked brown flesh disorder in peaches will be presented.

Symptoms and definitions

Disorders in peach fruit often appear around the main vascular bundles of the flesh and then spread into surrounding cells (Fig. 1). The affected tissues are watery and look translucent. The disorder is observed more frequently on the apex side of the fruit, on the side opposite the fruit suture, and in both cheeks. Infrequently, the disorder occurs on the flesh near the suture and the peduncle. Takata et al. (2005) reported that the most susceptible regions of the fruit are those with high sugar content. Brown discoloration often accompanies the other symptoms, and the browning tissue smells of alcohol fermentation.

The water-soaked brown flesh disorder occurs during the final stages of fruit maturation, near harvest. Since the frequency of the disorder is unchanged at harvest and after several days' storage, the disorder was initially thought to occur in unpicked fruit (Fujimaru et al. 2005, Takata 2006), but the symptoms will evolve spatially and intensify, even after harvest. Furuya et al. (2011) demonstrated how the incidence of water-soaked brown tissue increased during storage of 2-3 days at 25°C, while the frequency of fruit

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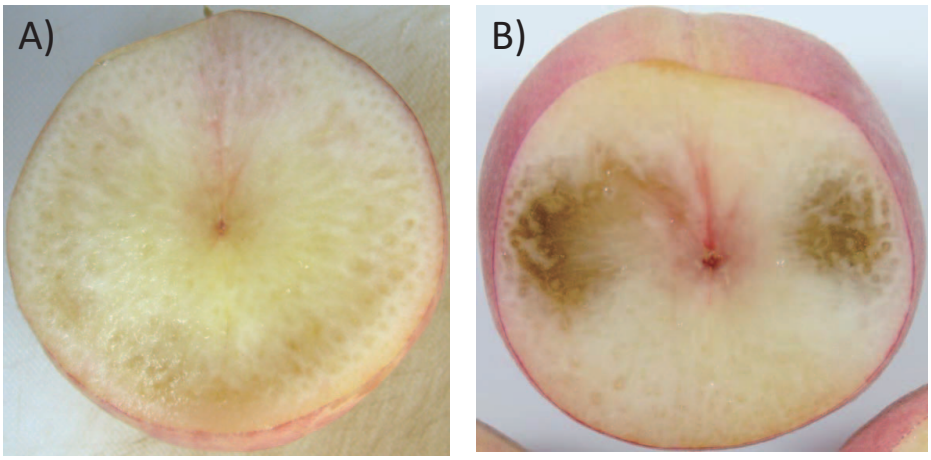

Fig. 1. Symptoms of water-soaked brown flesh disorder of peach fruit. Watery tissues are translucent (A) and often accompanied by brown discoloration (B)

with water-soaked translucent tissue decreased. This result suggests that watery tissue becomes brown during storage.

The water-soaked brown flesh disorders of peach fruit are described using several terms. The term mainly used in Japan is "watercore" (Fujimaru et al. 2005, Furuya et al. 2011, Iwatani et al. 2009, Saito et al. 2002), because the symptoms resemble the watercore of apples (Marlow & Loescher 1984). Furthermore, "internal browning", or "flesh bruises" have also been used (Yasukawa & Kukizaki 2006, Higashi & Okada 2001), because the affected tissue is often accompanied by brown discoloration. Although the physiological mechanisms triggering these symptoms may differ, the symptoms observed are very similar. Accordingly, Takata et al. (2005) suggested that these symptoms are the same disorder and proposed "water-soaked brown flesh" disorder as a common descriptive term. This is the term used throughout this review; although it should be noted that the watery tissue does not necessarily become brown at harvest time.

Cultivar susceptibility

Cultivar differences are observed in the susceptibility to the disorder. However, since these incidences are significantly affected by years or individual trees, the differences are not clearly established. Hagihara et al. (2014) have investigated the disorder frequency in 20 varieties, mainly cultivated in Yamanashi prefecture, and reported that cultivars with high sugar content (over 12.5 °Brix) and firm texture, such as 'Beni Kunimi', 'Reiho', and 'Natsuotome', tended to be affected more easily. Yamane et al. (2010) also reported that sugar content and water-soaked brown flesh disorder frequency were positively correlated in a study of 44 peach cultivars/breeding selections over 3 years. Conversely, reports of resistant cultivars are inconsistent. Some reports noted that 'Shimizu Hakuto' was resistant or impervious to the disorder (Yamane et al. 2010, Takata 2006), although it is affected in other reports (Fujii et al. 2011, Ooura et al. 2011). It is highly likely that any fresh peach cultivar commonly cultivated in Japan could be susceptible to the disorder.

Factors behind the occurrence of water-soaked brown flesh disorder

1. Fruit quality

The affected fruit are larger, with a higher °Brix and less firm flesh than unaffected fruit (Table 1). In addition, the affected fruit produce more ethylene, a ripening-related plant hormone, which is particularly evident when the symptoms are more severe. Many reports correlate with these disorder characteristics (Fujimaru et al. 2005, Saito et

Table 1. Characteristics of peach fruit affected by water-soaked brown flesh disorder ('Akatsuki')

Fruit	Fresh weight (g)	Flesh firmness [z] (N)	°Brix (%)	Ethylene production (nl g^{-1} h^{-1})
Healthy	294.4 b[y]	34.1 a	13.5 b	2.24 c
Moderately affected	299.9 ab	25.8 b	14.3 ab	4.68 b
Severely affected	317.6 a	18.7 c	14.9 a	9.02 a

[z]Flesh firmness was detected with a penetrometer using a flat-tipped cylindrical probe (Ø 8mm)
[y]Values within a column with different letters differ significantly based on Tukey's test at $P<0.05$.

al. 2002, Takata et al. 2006, Yasukawa & Kukizaki 2006). Standard conditions for the frequent occurrence of water-soaked brown flesh disorder have been shown to be > 350 g of fruit, > 13 °Brix, and < 2.0 kg of flesh firmness (detected with a penetrometer using an Ø 8mm conical probe) in 'Kawanakajima Hakuto' (Fujimaru et al. 2005, Saito et al. 2002), and > 12 °Brix, < 2.0 kg of flesh firmness in 'Asama Hakuto' (Saito et al. 2002).

2. Thinning

Promoting fruit size by disbudding and/or early thinning increases the occurrence of the disorder (Yasukawa & Kukizaki 2006) while larger fruit are more susceptible to this disorder as described above. In other instances, when fruit sizes are the same or similar, fruit for which thinning was delayed are more susceptible to the disorder than fruit thinned early (Saito et al. 2002). With delayed thinning, fruit have fewer flesh cells than fruit thinned early, due to active competition for limited nutrients among fruit during cell division. Fruit size is mainly determined by the number and size of cells, so in fruit of equivalent size, the cell size will be larger with delayed thinning. The large cell size may, in turn, increase susceptibility to the disorder.

3. Fruit bags

Fruit cultivated without fruit bags shows a lower incidence of water-soaked brown flesh disorder than fruit using fruit bags. Notably, fruit bags with low gas permeability tend to show increased incidence. High temperatures (Yasukawa & Kukizaki 2006) or fruit transpiration suppression (Yamane et al. 2013) from the use of fruit bags have been suggested as factors which exacerbate the occurrence of the disorder. Furthermore, anaerobic conditions in fruit bags may also induce the disorder.

4. Harvest time

Observations are divided on the effects of harvest time (early or late) on incidences of water-soaked brown flesh disorder. There is a higher proportion of affected fruit in the early maturing fruit of a tree (Takata 2006, Tsutani et al. 2009). Early maturing fruit are located in the outer canopy of trees and tend to be of high-quality, large and containing more sugar. These quality factors may cause water-soaked brown flesh disorder to proliferate. Conversely, two studies reported increased incidence and intensity of the disorder in late-harvested fruit (Hagihara et al. 2009, Iwatani et al. 2009). These investigators noted that late-harvested fruit were more mature, suggesting that over-maturation may cause the increase. Harvesting fruit at optimum maturity is important to alleviate the disorder.

5. Temperature

Ooura et al. (2011) showed that high-temperature treatment of trees in greenhouses for the last 10-20 days before harvest in 'Shimizu Hakuto' (from 100 days after full flowering (DAFF) to harvest), delays fruit maturity for 4 days and causes the disorder to proliferate. Additionally, covering the fruit with black bags to increase its temperature also increased the frequency of disorder, although some reports disagreed with these results. The high-temperature treatment of potted trees during the fruit maturation period did not affect the incidence of the disorder in 'Beni Shimizu' (Takata 2006). There was also no relationship between temperature during the last 10 or 20 days before harvest and the disorder incidence in 'Kawanakajima Hakuto' (Iwatani et al. 2009). Although the reasons for these different observations are not well understood, a delay in fruit maturity induced by high-temperature treatments in 'Shimizu Hakuto' may be related to the increased incidence.

Yasukawa & Kukizaki (2006) noted that in 1998, when the incidence of water-soaked brown flesh disorder in peaches was high, there were particularly high temperatures during the early fruit development. Iwatani et al. (2009) also reported that years with a short fruit developmental period (from flowering to harvesting maturity) showed higher incidence of the disorder in 'Kawanakajima Hakuto'. The fruit developmental period of peaches is shortened by exposure to high temperature during the early fruit development stages (Hayama et al. 2006). Shortening the fruit developmental period may also increase the incidence of water-soaked brown flesh disorder.

6. Water relations

Recently, changes in soil moisture during fruit maturation have also been shown to affect the occurrence of the disorder. Tezuka et al. (2012) showed that the disorder frequency significantly increased when tree soil moisture was repeatedly increased and decreased during the last 2 weeks before harvest in the greenhouse compared to trees receiving stable soil moisture. Fujii et al. (2012) demonstrated that a mulching treatment under the canopy from 40 DAFF to harvest to avoid rapid changes in soil moisture reduced the occurrence of the disorder without affecting fruit quality. Rapid and/or reversible changes in soil moisture during fruit maturation may accelerate the incidence of water-soaked brown flesh disorder.

Physiology of water-soaked brown flesh disorder development

1. Water-soaked symptoms

The water-soaked and translucent appearance of fruit is due to the intercellular spaces of the flesh becoming filled with fluid instead of air. The affected areas of the flesh have different sugar compositions from the unaffected areas; containing more sorbitol, fructose, and glucose, and less sucrose

than the latter (Hayama et al. 2007). Sugars in the intracellular spaces of flesh cells are mostly sucrose (approx. 90%), whereas those in the intercellular spaces contain higher levels of sorbitol, fructose, and glucose. Considering these results, the sugars in the intercellular spaces may accumulate in the affected areas. The water-soaked symptom is mainly observed in large fruit with high sugar content. Furthermore, flesh cell enlargement is hypothesized to increase the incidence (Saito et al. 2002). Flesh cells in a large fruit with high sugar content can accumulate a large quantity of sugars and water in vacuoles and become extremely enlarged by vacuolar expansion. Accordingly, the ability to translocate sugars into the flesh cells may decline, drawing the fluids to the intercellular space and thus triggering the water-soaked symptoms. In addition, such large cells and/or vacuoles considerably hinder the membrane function; meaning membrane activities to translocate sugars into flesh cells and/or vacuoles decrease, and the fluids may accumulate in the intercellular space. This process can be accelerated by cell senescence caused by over-ripening. Since the translocated sugars are supplied while the unpicked fruit remains on the tree, this hypothesis agrees with the observation that the water-soaked symptom only occurs in unpicked fruit. Furthermore, this hypothesis also is consistent with the water-soaked appearance most common around the vascular bundles in more mature fruit.

2. Brown discoloration

Browning occurs due to phenolic compounds being enzymatically oxidized into o-quinones that are very reactive and form brown-colored polymers by polyphenoloxidase (PPO) (Mathew & Parpita 1971, Mayer 1987). PPOs and phenolic substrates are located in different cell compartments in intact cells; generally in plastids and vacuoles, respectively, (Vaughn et al. 1988). Meanwhile, the destruction of fruit cellular compartmentation renders the phenolic substrates accessible to PPOs and triggers the development of tissue browning in plants. This process is probably the same as that occurring in browning flesh of damaged peaches (Lee et al. 1990, Cheng & Crisosto 1995). In short, the membrane function is damaged and cellular compartmentation destroyed in the brown tissue of peach fruit. The browning process in water-soaked flesh occurs in unpicked fruit and also during storage. Storing fruit below 15°C reduces the brown discoloration (Furuya et al. 2011), probably due to a reduction in enzyme activity.

Conclusions

Water-soaked brown flesh affecting peach fruit is a physiological disorder that occurs when unpicked fruit approaches optimum maturity. The translucence and browning of water-soaked tissues are assumed to be the same disorder, and translucent tissue becomes brown tissue in unpicked fruit or after harvest. The incidence and intensity of the water-soaked brown flesh disorder in peach fruit are affected by fruit maturity. Increases in the incidence and intensity of the disorder are particularly characteristic of more mature fruit, namely larger, sweeter and softer fruit. Accordingly, the disorder is possibly a general symptom of over-ripening caused by flesh cell aging, although it is often observed in fruit that remain firm. Excess sugar and water may burden the flesh cells and induce the disorder. Identifying the factors involved in the disorder should more completely characterize the phenomenon and lead to a means to control its incidence.

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