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Review

A review of apple preharvest fruit drop and practices for horticultural management

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ABSTRACT

Preharvest fruit drop is a challenge to apple production, in which fruit abscise from the tree prior to horticultural maturity. Depending on the growing season and the cultivar, yield losses of up to 30% are common by the beginning of harvest and worsen with any delay in harvest. This apple fruit abscission is influenced by developmental and environmental cues. Perception of metabolic changes leads to regulatory changes that promote cell wall degradation, involving the hydrolytic enzymes polygalacturonase and cellulase. Ethylene has a clear association with abscission promotion; whereas, the role of other plant hormones is unclear. The study of plant bioregulators has identified that apple abscission is managed by the ethylene biosynthesis inhibitor, aminoethoxyvinylglycine, and the competitive antagonist for ethylene receptors, 1-methylcyclopropene. This review examines recent progress in understanding preharvest fruit drop of apples, discusses horticultural practices that may alleviate preharvest fruit drop, and provides suggestions for future research.

Contents

1. Introduction

Apples (*Malus domestica* Borkh.) are a popular temperate fruit, consumed both fresh and processed, and they ranked third for global fruit production at 80.8 million tonnes in 2013 (FAOSTAT, 2013). Global production is centered on the high-value freshmarket which requires harvesting at optimum maturity to maintain fruit quality during long-term storage and shipping (Greene et al., 2014; McCluskey et al., 2007).

Fruit drop that occurs in fruit trees during specific developmental stages is a challenge to producers. In the northern hemisphere, there is a period of fruitlet (immature fruits during the cell division phase) drop that occurs 5–6 weeks after full bloom; this is referred to as 'June drop' (Dal Cin et al., 2009a, 2009b). A second period, called preharvest fruit drop (PFD) begins approximately 4 weeks before harvest and will be the focus of this review.

Preharvest fruit drop, in which fruit are shed from the tree early in the ripening phase prior to horticultural maturity, can occur in several important apple cultivars. The severity of drop is cultivar-specific and cultivars have been categorized according to their propensity to drop: less prone, intermediate, and more prone (Irish-Brown et al., 2011). Selection of cultivars by producers is

Abbreviations: ABA, abscisic acid; ACC, 1-aminocyclopropane-1-carboxylate; AVG, aminoethoxyvinylglycine; AZ, abscission zone; 6-BA, 6-benzyladenine; DAFB, days after full bloom; IEC, internal ethylene concentration; NAA, 1-naphthaleneacetic acid; PBR, plant bioregulator; PFD, preharvest fruit drop; PG, polygalacturonase; ROS, reactive oxygen species.

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determined by consumer preference for specific fruit characteristics (i.e., flavour and firmness), rather than for ease of production (Yue et al., 2013). Production challenges are inevitable when cultivar choice depends on consumer preferences rather than ease of cultural management.

Strategies to reduce PFD will help maintain crop yield, an important component of the economic success of an orchard (Bravin et al., 2009). Depending on the growing season and propensity of the cultivar to drop, yield losses of up to 30% are common by the beginning of the harvest period. These losses are worsened with any delay in harvest (Byers, 1997; Schupp and Greene, 2004). A further complication is that PFD in certain cultivars occurs prior to adequate horticultural maturity (Hoying and Robinson, 2010). For apples, physiological maturity occurs when seeds are mature; this precedes the development of colour and flavour properties, which are developed at horticultural maturity (Watada et al., 1984). Picking the apples prior to horticultural maturity in an attempt to avoid fruit drop can be undesirable, given that the fruit are often inferior to horticulturally mature fruit in both taste and colour (Baugher and Schupp, 2010; Wills et al., 2007).

Plant bioregulators (PBRs) influence plant metabolic systems to regulate ripening and PFD. Preharvest fruit drop can be reduced by delaying fruit maturity using PBRs that reduce ethylene biosynthesis, such as aminoethoxyvinylglycine (AVG). In addition to reducing drop, a delay in maturity can help manage commercial harvest operations by widening the picking window of specific cultivars or by extending the time between harvests of multiple-pick cultivars. Labour can be used more efficiently and for pick-your-own operations, a longer harvest period ensures flexibility in managing the harvest season (Byers and Eno, 2002; Byers, 1997; Unrath et al., 2009).

Previous research has focused on the efficacy of foliar-applied PBRs for reducing fruit drop and more specifically their effect on the abscission zone (AZ; the anatomical region on the fruit pedicel where fruit naturally separate from the tree). A greater understanding of the physiology of abscission is required to explain how individual fruit differ in abscission potential, how cultivars differ, and how abscission is induced. Such research will lead to strategies for improved commercial control of PFD.

This review examines recent progress in understanding PFD of apples, discusses horticultural practices that may alleviate PFD, and provides suggestions for future research. To assist investigators that are new to this field or those in search of creative research directions, the literature on apple PFD is evaluated and main concepts are presented.

2. Fruit separation occurs at the abscission zone

When apple fruit prematurely drop approaching harvest, the fruit detach at the AZ located at the pedicel-spur junction (Fig. 1A). The AZ forms in a constriction zone or in the pedicel distal to the constriction zone (Fig. 1A) (McCown, 1943). Fruit separation occurs along a plane of fracture where the cell walls disintegrate without prior division or differentiation (Fig. 1B) (McCown, 1943). The plane of fracture is confined to the width of a few cell layers.

The current anatomical model for abscission includes the following four main events: i) AZ cell differentiation, ii) induction for response to developmental changes in metabolism, iii) cell separation, and iv) development of a protective layer (Estornell et al., 2013). Cell separation is the simplest process to observe based on visual and identifiable changes at the AZ and easiest to study in terms of developmental phase (Sexton and Roberts, 1982). Consequently, more information exists about the cell separation phase, while less is known about the remaining phases. This is particularly true for the inductive phase (also known as the 'lag phase'), the events of which remain largely uncharacterized.

It is hypothesized that perception of changes in metabolism by AZ cells induces abscission, accompanied by hydrolases to initiate cell separation. The stimuli may be molecules (i.e., hormones or elicitors), which bind to receptors on the cell to trigger a signal transduction pathway (Taylor and Whitelaw, 2001). Changes in metabolism that initiate apple PFD may originate from a programmed developmental event or from environmental cues. Currently, the nature and perception of the stimuli that initiate abscission are poorly understood (Estornell et al., 2013; Sexton and Roberts, 1982). Signal perception leads to expression of genes that trigger the formation of cell wall hydrolases (McManus, 2008; Taylor and Whitelaw, 2001). The hydrolases catalyze cell wall breakdown contributing to fruit detachment at the AZ, which leaves the pedicel attached to the fallen fruit (Addicott, 1982; Roberts et al., 2002). Recent work with tomato (*Solanum lycopersicum* L.) leaves and flowers has demonstrated differential gene expression of cell wall hydrolases on opposite sides of the AZ. This finding indicates that abscission processes differ proximally and distally with respect to the AZ (Bar-Dror et al., 2011). This work provides evidence for enzymatic changes that occur at specific locations to coordinate the narrow zone of separation (Bar-Dror et al., 2011).

The preharvest abscission of apple fruit is preceded by the swelling and lengthening of several layers of cells within the AZ (McCown, 1943; Sexton and Roberts, 1982). Intercellular adhesion is overcome by the degradation of pectin in the middle lamella (McCown, 1943). There is evidence suggesting that whether cell separation commences in the pith or the cortex depends on the apple cultivar (McCown, 1943). It appears that the cultivars may have anatomical differences such as tissue composition or enzyme synthesis that have not been analyzed in relation to cultivar abscission potential.

3. Fruit developmental characteristics of size, seeds, and maturity in relation with abscission

Malus (apple) is considered a model species for studying the development of temperate fruit. Apple is especially useful to study during fruitlet abscission since different abscission potentials exist among fruitlets in the same cluster. Because of the greater tendency for the abscission of side ('lateral') fruitlets over the central ('king') fruitlet (Bangerth, 2000; Dennis, 2003), abscising and non-abscising fruitlets can be separated visually during investigation at this developmental stage (Dal Cin and Ramina, 2011; Eccher et al., 2014). Unfortunately, fruit at the preharvest stage do not have abscission potentials that can be identified visually, leading investigators to harvest fruit indiscriminately for analysis (Greene et al., 2014; Li and Yuan, 2008). In an attempt to separate abscising and non-abscising fruit for analysis at the PFD stage, one approach to promote abscission has been to cut apple fruit in half during August and September, prior to harvest (Ward et al., 1999). However, the act of cutting confounds the abscission process by activating wound response mechanisms, and results must thus be interpreted with caution. An ideal approach would be to identify naturally abscising versus non-abscising fruit in order to compare molecular changes associated with PFD.

Marked differences in the PFD abscission potential exist among apple cultivars (Li, 2010; McCown, 1943); however, relatively little research has been conducted to further investigate this topic. Examining cultivars with different drop potentials is one approach for deducing morphological, anatomical, genotypic, and biochemical differences between abscising and non-abscising fruit at harvest.