PLANT DISEASE FEATURE

Sustainable Apple Disease Management in China: Challenges and Future Directions for a Transforming Industry

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Abstract

Apple trees are grown worldwide, and consuming fresh apple fruit is associated with many health benefits. China produces about half of the world's apple supply. However, apple growing in China differs sharply from that in western countries in terms of the prevalent diseases and corresponding management strategies. For instance, family-owned small-scale orchards dominate China's apple industry, and manual bagging of fruit has been a long-standing practice for controlling fruit diseases. In recent years, rural labor shortages have been increasingly challenging the traditional production system, and China's apple industry is experiencing a rapid transition to much larger-scale enterprises featuring high-density orchards with advanced automation and mechanization. Associated with this transition are new challenges and grower demands that are changing the face of apple disease management. This Feature Article summarizes the ongoing transformation of China's apple industry in the context of sustainable disease management.

Keywords: apple, China, etiology, fruit crop diseases, fungi, tree fruits, Valsa canker

Apple is one of the most widely cultivated and consumed fruit around the globe. According to FAOSTAT (https://www.fao.org/faostat/en/), world apple production in 2019 was 87 million metric tons (MMT), which ranked after only banana and watermelon among all consumed fruit. China is the world's leading apple producer. In the 2019–20 crop year, China's apple production reached around 41 MMT, compared with the European Union (11.5 MMT) and the United States (4.8 MMT).

Compared with the European Union (EU) and United States (U.S.), the apple industry in China has many distinctive features in terms of prevailing diseases and orchard management practices. For instance, fire blight, a devastating bacterial disease in both the EU and U.S., has not been reported in China, and the causal agent *Erwinia amylovora* is still under strict import quarantine. Fruit diseases such as sooty blotch and flyspeck (SBFS) and bitter rot, which are common in many other apple-producing regions, are minor concerns in China due to the prevalence of a simple but effective practice—manual bagging of fruit throughout most of the fruit development period. Another distinction is in the scale of individual orchard enterprises; most orchards are considerably smaller than their western counterparts, and typically feature higher inputs of labor and lower levels of mechanization. In recent years, however, a steady decline in China's rural labor force has increasingly challenged the sustainability of this family-owned small orchard system. This workforce shift to urban from rural areas is driving the transformation of China's apple industry toward more mechanized, large-scale production, which has created new disease management challenges and grower demands. This short review summarizes the prevailing diseases, management challenges, and opportunities in China's transforming apple industry.

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China's Apple Production Is Dominated by Small-Scale Family-Owned Orchards

Apple orchards in China were estimated to cover 1.98 million ha in 2019 (the National Bureau of Statistics, China; http://www.stats.gov.cn/). The Loess Plateau Area and Bohai Gulf Area are the dominant apple-producing regions (Fig. 1). The two regions encompass seven provinces: Shaanxi, Gansu, Shanxi, Henan, Shandong, Liaoning, and Hebei. In 2019, the total orchard area in the seven provinces was 1.63 million ha and apple production was 37.3 MMT, which comprised 82.4 and 87.9%, respectively, of the totals in China. Shaanxi is the most important apple-producing province; it included 0.61 million ha of orchards (31.1%) that produced 11.4 MMT (26.8%) of apple fruit. Shandong followed Shaanxi, with 0.25 million ha (12.5%) producing 9.5 MMT (22.4%). 'Fuji' is the dominant apple cultivar in China, with the planted area and total production exceeding 50 and 70%, respectively, in 2015 (Editorial Board of China Agriculture Yearbook 2015).

There was an enormous surge in apple orchard establishment in China during the 1980s and 1990s. From 1958 through most of the 1970s, farming activity in China was organized by a 'People's Commune' system, in which land was collectively owned at the village level and produce was divided among farmers. Fruit production was not encouraged during that period. From 1978 onward, the Commune system was abandoned and replaced with a 'responsibility system', in which land cultivation was subcontracted to single families or individuals. The new system gave farmers more incentives to work hard. Meanwhile, private markets were opened and diversification of agriculture was encouraged. At the same time, consumer demand for fresh fruit rose rapidly. Economic returns from fruit production were considerably higher than for staple crops such as wheat and corn, which had been the mainstays of many family-owned farms during the 1980s. Between 1984 and 1996, apple-planting area in China jumped from 0.75 to 2.99 million ha, mostly from the creation of small-scale orchards. Yuan et al. (2011) estimated that around 80% of current apple orchards in China were established during that period. Due to a sharp drop in market price for apple fruit, the planted area fell rapidly from 1996 to 2002. From 2002 until now, the area of apple orchards in China has stabilized at around 1.9 million ha.

Today, family-owned small-scale orchards still dominate apple production. In the Loess Plateau and Bohai Gulf Areas, over 80% of apple orchards are less than 10 Mu (1 Mu = 667 m^2 = 0.165 acres) (Ma and Li 2020). These small-scale orchards have two features in common. First, their level of mechanization is low. Many of these small-scale farmers are reluctant to upgrade their orchard facilities, and often lack the capital for major equipment purchases. Instead, these orchards are generally managed in a very labor-intensive manner. Drip or spray irrigation is rare. In each growing season, farmers accomplish multiple tasks manually: tree pruning, thinning of fruitlets, fruit bagging and debagging, pesticide spraying (often with a backpack or small hydraulic sprayer), and harvesting (Fig. 2). Second, tree health is often suboptimal. A long tradition of clean-tillage practices and insufficient organic fertilizer application has caused many apple orchard soils to contain insufficient organic matter. In the Loess Plateau, the situation is made worse by extensive soil erosion in the region that leaches away soluble organic matter. A recent investigation showed that the average content of soil organic matter in Shaanxi apple orchards was only 1.26% (Yang et al. 2016). Nutritional imbalances that often result from apple cultivation in such highly mineralized soils are sometimes associated with susceptibility to certain diseases. For instance, potassium (K) deficiency considerably increases the susceptibility of apple trees to Valsa canker, a trunk disease predominantly caused by *Cytospora mali* (synonym *Valsa mali*) (Peng et al. 2016). Major diseases and specific pathogens are listed in Table 1 and described in more detail in the text below. Tree structure and tree age are also factors attenuating tree health. Unlike in the EU and the U.S., where over 70% of apple trees have fully dwarf or semidwarf rootstocks, around 90% of apple orchards in China are planted using vigorous local seedling rootstocks (Shao 2014; Wang et al. 2011; Wang et al. 2019). These trees are often trained using a central leader system and have vigorous growth. The typical spacing between trees and between rows is 3 and 4 m, respectively. As these trees grow older, a closed canopy forms, which can trap moisture and slow canopy drying, thus favoring foliar disease development. A high percentage of these orchards also exhibit significant damage by trunk diseases, particularly Valsa canker and Botryosphaeria canker (caused by *Botryosphaeria dothidea* and *B. kuwatsukai*). Highly mineralized soil and trunk diseases undermine tree vigor and economic returns which, in turn, weaken farmers' incentive to invest in orchard maintenance and improvement. This downward spiral is further exacerbated by a steadily worsening and apparently irreversible shortage in rural labor supply in the 21st century (Shao 2014).

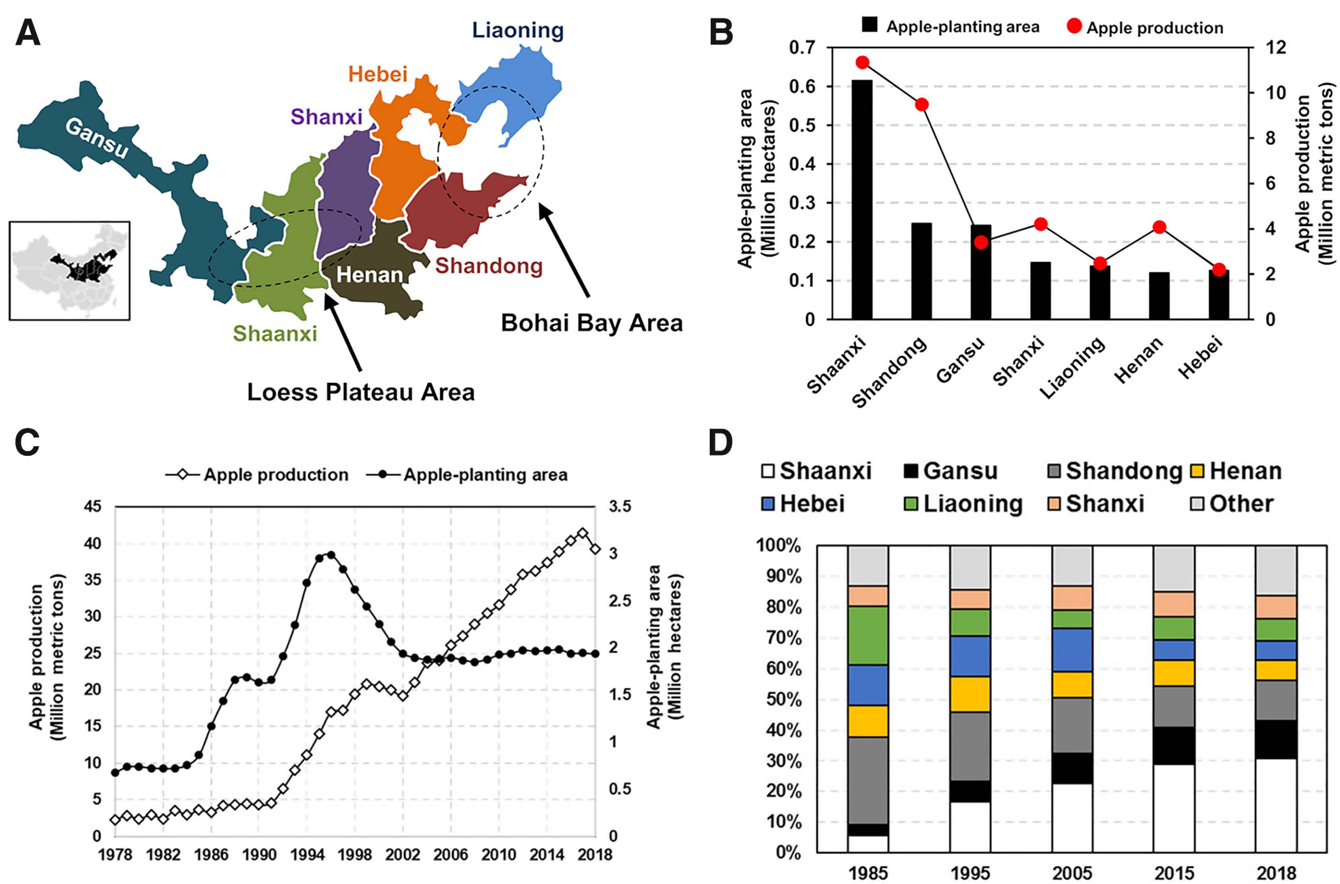

Fig. 1. Summary of apple production in China. **A,** Map showing the two main apple-planting regions (in circle) and the included seven provinces. **B,** Apple production and apple-planting area of the seven provinces in 2019. **C,** Yearly apple production and apple-planting area in China from 1978 to 2018. **D,** Changes in relative frequency of apple-planting area of the seven main apple-planting provinces from 1985 to 2018. Note the steady increases for Shaanxi and Gansu provinces and the steady decreases for Shandong and Liaoning provinces. Data for B, C, and D were derived from the National Bureau of Statistics, China (http://www.stats.gov.cn/).

Apple Diseases Prevalent in China Are Distinct from Those in the EU and the U.S.

Unlike the EU and the U.S., where fire blight and apple scab occur commonly, fire blight has not been reported in China and apple scab occurs only rarely. In addition, due to the wide application of fruit bagging, fruit diseases such as SBFS and bitter rot are minor concerns. Diseases of considerable grower concern include Marssonina blotch (caused by *Diplocarpon mali* [synonym *Marssonina coronaria*]) and Alternaria blotch (caused by multiple *Alternaria* spp.), which cause premature defoliation; Valsa canker and Botryosphaeria canker, which damage the trunks and scaffold branches; fruit spot (multiple causal agents) and moldy core and core rot (multiple causal agents), which damage fruit; and viruses and viroids, which can weaken or kill trees (Table 1).

Foliar Diseases

Premature defoliation occurs commonly in both the Loess Plateau and Bohai Gulf areas. Defoliation reduces tree vigor, fruit yield, and fruit quality, and causes considerable economic loss. Without proper disease management, it is common for Fuji orchards to reach more than 80% defoliation in early September (Dang et al. 2017; Zhang

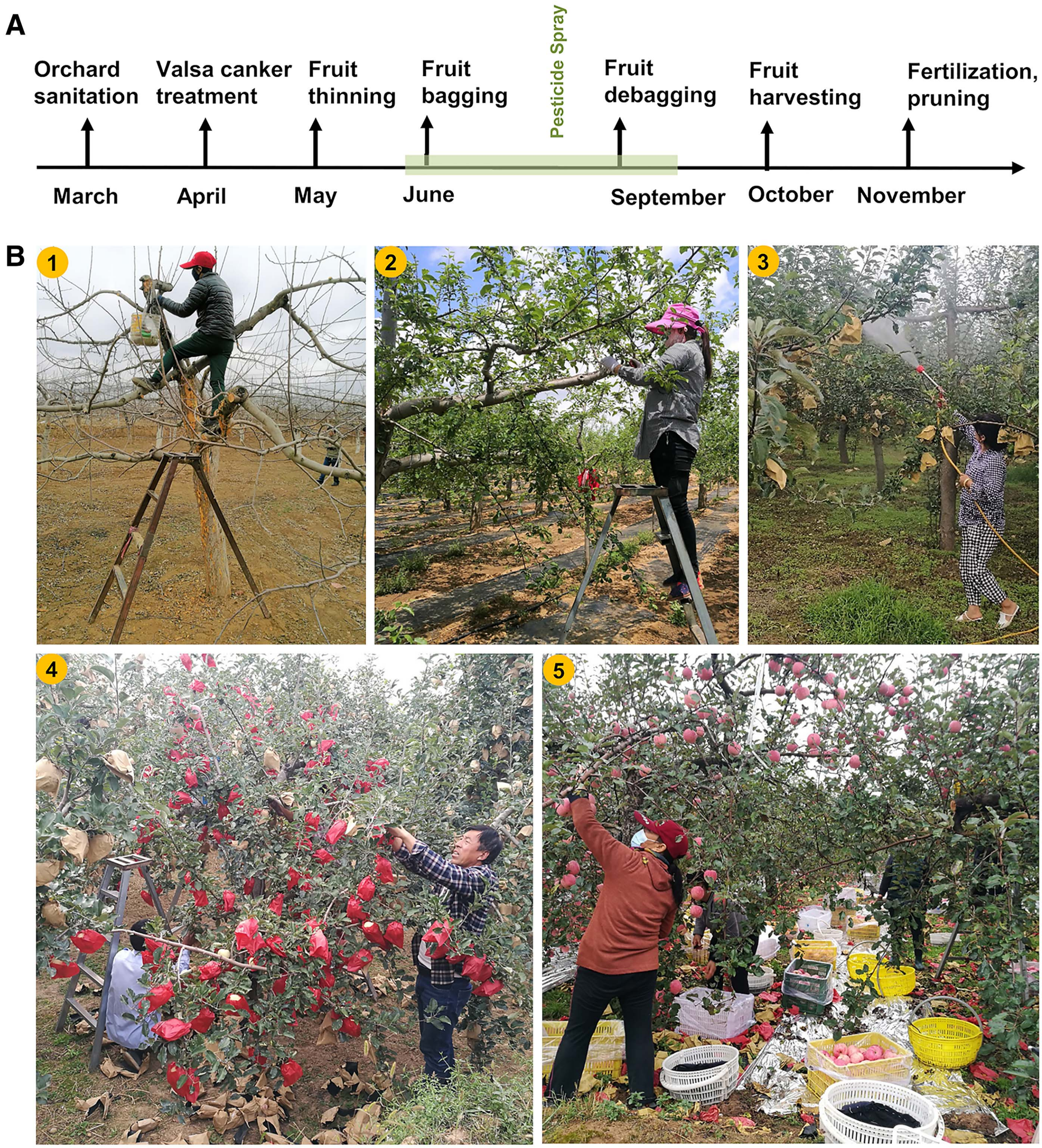

Fig. 2. Labor-intensive apple management practices in family-owned small-scale orchards in China. **A,** Timeline for orchard management practices in a growing season. **B,** 1. Removing fungal cankers on trunk. 2. Fruit thinning. 3. Pesticide spraying in summer. 4. Fruit debagging. 5. Fruit harvest.

et al. 2018), which is 1 month before fruit harvest. Premature defoliation typically results from infection by Marssonina blotch and Alternaria blotch, caused by the ascomycete fungi *D. mali* (synonym *M. coronaria*) and *Alternaria* spp., respectively (Harteveld et al. 2014; Sawamura 1962; Zhao et al. 2013) (Figs. 3 and 4). Both diseases are favored by rainfall and high humidity, which trigger conidial release and secondary infection (Hu et al. 2006; Lian et al. 2021). Thus, to efficiently control both diseases, timely spraying of protectant fungicides is critical. The genus *Alternaria* contains many closely related species (Woudenberg et al. 2013, 2015). Worldwide, several *Alternaria* spp. have been associated with apple leaf blotch. Rotondo et al. (2012) reported three species (*Alternaria arborescens*, *A. tenuissima*, and *A. alternata*) in Italy, whereas Harteveld et al. (2014) reported four species groups (*A. arborescens*, *A. alternata*/*A. tenuissima* intermediate, *A. tenuissima*/*A. mali*, and *A. longipes*) in Australia. In China, Yan (2021) reported four species groups: *A. alternata, A. longipes, A. arborescens* and *A. gaisen*. The pathogenicity of the associated isolates, however, was not tested experimentally. Dang et al. (2018) reported that *A. malicola,* belonging to the Ulocladioides section, could cause leaf blotch, moldy core, and fruit spot following artificial inoculation. Pathogens causing Alternaria blotch are thus diverse in China as well as other apple-producing regions.

During the past decade, Glomerella leaf spot (GLS) (González and Sutton 1999; Sutton and Sanhueza 1998) has emerged and spread rapidly in China (Ma et al. 2018). In China, this foliar disease was first documented in 2010 in Henan Province (Song et al. 2012). However, by 2015, it had been reported in almost all apple-producing provinces. The disease has a very short latent period (2 to 3 days) and quickly causes leaf necrosis and defoliation under warm and high humidity conditions (Fig. 5) (B. Wang et al. 2015; W. Wang et al. 2015). GLS can also damage apple fruit, causing small sunken necrotic lesions on the fruit surface. Unlike Marssonina blotch and Alternaria blotch, GLS has a strong cultivar specificity. Fuji apple is resistant whereas certain cultivars, including 'Gala', 'Golden Delicious', and 'Jonathan', are highly susceptible (W. Wang et al. 2015). Genetic analysis showed that a single recessive genetic locus controls GLS resistance in Fuji apple (Liu et al. 2016).

Worldwide, GLS was first documented in the 1970s. Its occurrence is still limited to a few countries, including Brazil, Uruguay, the U.S., and China (González and Sutton 1999; Sutton and Sanhueza 1998; Taylor 1971; Velho et al. 2018). In Brazil and Uruguay, six GLS species were documented, including one member (*Colletotrichum fructicola*) belonging to the *C. gloeosporioides* species complex (CGSC), four members (*C. melonis*, *C. nymphaeae*, *C. paranaense*, and *C. limetticola*) belonging to the *C. acutatum* species complex (CASC), and one species (*C. karstii*) belonging to the *C. boninense* complex (Moreira et al. 2019; Velho et al. 2015, 2018). Among them, *C. nymphaeae* and *C. fructicola* are the most common species. In the U.S., GLS pathogens have been historically grouped with CGSC or CASC based on morphology (González and Sutton 1999; González et al. 2006; Sutton and Sanhueza 1998); however, accurate species differentiation below the species complex level has not been reported. In China, four CGSC species, including *C. fructicola*, *C. aenigma*, *C. siamense*, and C. *gloeosporioides* sensu stricto, have been identified as causal agents of GLS (Naklumpa 2019; Wang et al. 2012b; B. Wang et al. 2015; W. Wang et al. 2015; Zhang et al. 2021). Among them, *C. fructicola* and *C. aenigma* are the most common species (Naklumpa 2019; W. Wang et al. 2015).

On apple, *Colletotrichum* fungi also cause fruit rot, known as apple bitter rot (ABR), during fruit maturation and storage. The disease occurs worldwide and has been recorded for more than a century (Sutton 1990). More than 20 ABR-related species, belonging to either CGSC or CASC, have been reported (Dowling et al. 2020; Khodadadi et al. 2020; Martin et al. 2021). In the U.S., seven CGSC species (*C. chrysophilum*, *C. noveboracense*, *C. siamense*, *C. fructicola*, *C. henanense*, *C. theobromicola*, and *C. gloeosporioides* sensu stricto) and two CASC species (*C. fioriniae* and *C. nymphaeae*) can cause ABR, among which *C. fioriniae* is the prevalent species (Khodadadi et al. 2020; Martin et al. 2021; Munir et al. 2016). In China, a systematic study identified six ABR species (Fu 2014), including four CGSCs (*C.

Table 1. Apple diseases of major grower concern in China

Disease	Damage	Causal agents	Control measures
Marssonina blotch	Leaf spot, premature foliar drop, reduces yield and tree vigor	*Diplocarpon mali* (syn. *Marssonina coronariae*)	Bordeaux mixture, triazole fungicides
Alternaria blotch	Same as above	*Alternaria* spp.[a]	Same as above
Glomerella leaf spot[b]	Same as above	*Colletotrichum* spp.[c]	Bordeaux mixture, pyraclostrobin
Valsa canker	Bark soft rot, death of twig, limb or entire tree	Mainly *Cytospora mali* (syn. *Valsa mali*)[d]	Physical surgery, fungicide treatment
Botryosphaeria canker	Canker of twig, limb or entire tree, reduces tree vigor	*Botryosphaeria dothidea, B. kuwatsukai*	Same as above
Moldy core and core rot	Core browning, moldy core, or core rot	*Alternaria, Botryosphaeria, Cladosporium, Colletotrichum, Epicoccum, Fusarium, Penicillium, Phoma, Spencermartinsia*, and *Trichothecium* spp.	Antibiotic sprays during flowering
Fruit spot	Brown or black spots	*Acremonium*, *Alternaria*, *Cylindrosporium*, *Phoma*, *Sarocladium*, and *Trichothecium* spp.	Fungicide spray prior to fruit bagging
Viruses and viroids	Reduces tree vigor; several viroids damage fruit directly	ACLSV, ASGV, ASPV, ApNMV, ASSVd, ADFVd[e]	Virus-indexed planting stock
Replant disease	Reduces tree growth	Diverse soil microbes	Soil disinfestation

[a] Five associated species (*Alternaria alternata*, *A. longipes*, *A. arborescens*, *A. gaisen*, and *A. malicola*). *A. malicola* can cause leaf blotch, moldy core, and fruit spot (Dang et al. 2018), whereas a pathogenicity test for the other four species was not performed (Yan 2021).
[b] Glomerella leaf spot disease damages only cultivars closely related to 'Gala' or 'Golden Delicious'.
[c] Four associated species (*Colletotrichum aenigma*, *C. fructicola*, *C. siamense*, and *C. gloeosporioides* sensu stricto), all confirmed by pathogenicity test (Naklumpa 2019; W. Wang et al. 2015; Zhang et al. 2021).
[d] Diverse *Cytospora* spp. are associated with *Malus* spp. and *Cytospora mali* is the main agent causing Valsa canker (Pan et al. 2020; Wang et al. 2020).
[e] Apple chlorotic leaf spot virus (ACLSV), Apple stem grooving virus (ASGV), Apple stem pitting virus (ASPV), Apple necrosis mosaic virus (ApNMV), Apple scar skin viroid (ASSVd), and Apple dimple fruit viroid (ADFVd).

fructicola, *C. siamense*, *C. alienum*, and *C. gloeosporioides* sensu stricto) and two CASCs (*C. nymphaeae* and *C. orientalis* [a novel species]), among which *C. siamense* was the most common one. Notably, the widely applied practice of fruit bagging has been highly efficient in controlling ABR and other fruit diseases in China.

Trunk diseases: Valsa canker. Compared with premature defoliation, Valsa canker is far more damaging (Figs. 6 and 7), because it kills limbs, trunks, and, in severe cases, entire trees (Yin et al. 2015). Valsa canker is the most destructive apple disease in China and has been called the cancer of apple trees (Cao et al. 2009). Diverse *Cytospora* (teleomorph: *Valsa*) spp. can cause Valsa canker and more than 20 species have been reported from *Malus* spp. worldwide (Pan et al. 2020; Wang et al. 2020). In China and other East Asian countries, apple Valsa canker is predominantly caused by *Cytospora mali* (Wang et al. 2020). *C. mali* conidia penetrate bark tissue mainly through natural or mechanical injuries (e.g., frost injury, sunscald, and pruning scars), after which hyphae proliferate within host phloem and xylem tissue (Ke et al. 2013). Diseased bark

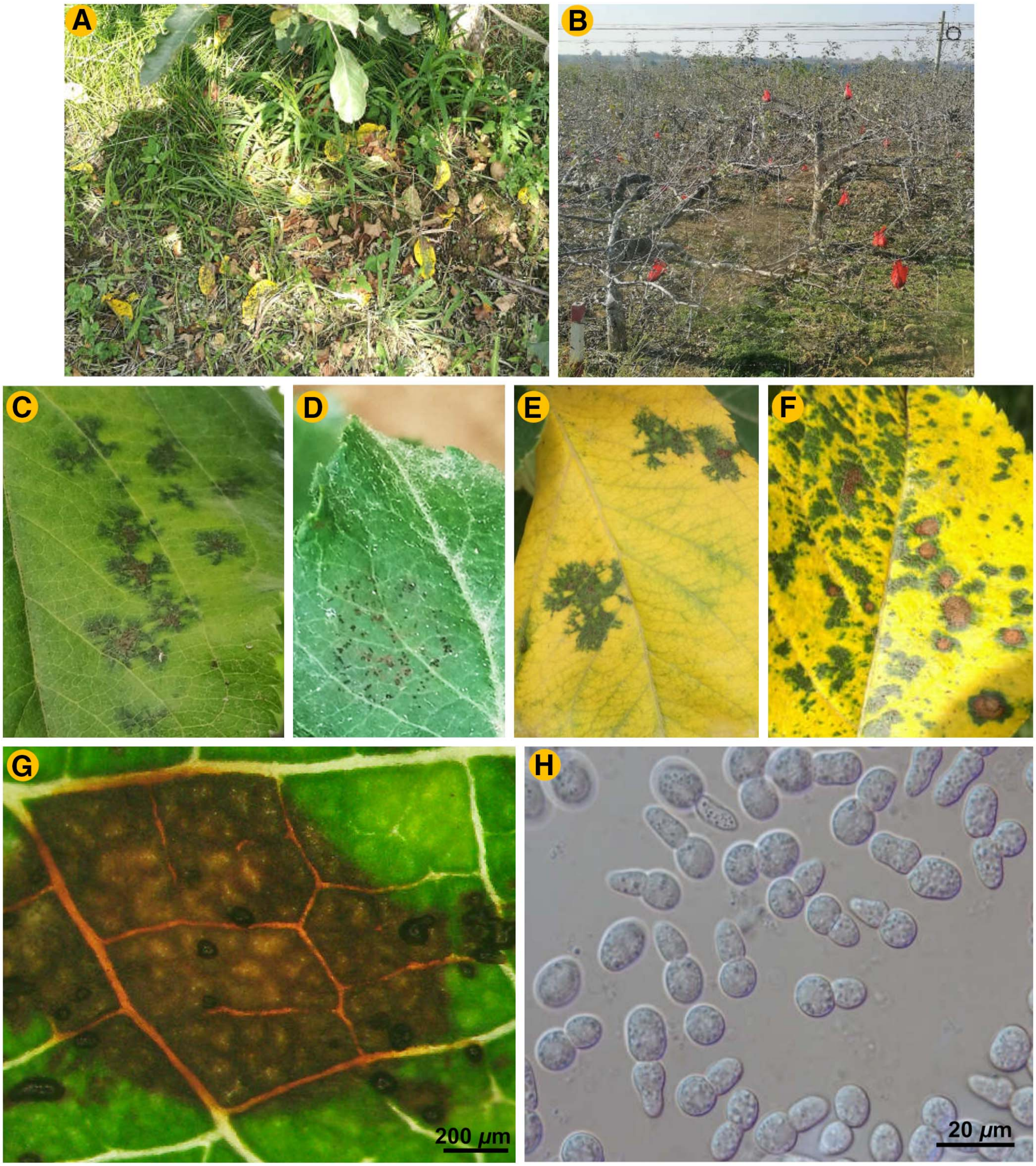

Fig. 3. Marssonina leaf spot. **A,** Leaf yellowing and drop in August. **B,** Severely defoliated orchard in October. **C and D,** Early symptoms, localized necrosis, acervuli formation, and dark-green islands. **E and F,** Extensive leaf yellowing in late infection. **G,** Acervuli under dissecting microscope. **H,** Two-celled conidia.

tissue softens and lesions expand rapidly, reaching diameters >10 cm in a matter of days (Chen et al. 2016). Without intervention, Valsa canker lesions can rapidly encircle a trunk, killing the tree. In the field, *C. mali* conidia are prevalent on dead or pruned twigs (which are usually left on the ground close to the orchard), and epiphytically on healthy tree surfaces (Zang et al. 2012). Field studies support the view that *C. mali* is more prone to damage weak and old trees than young and vigorous ones (Cao et al. 2009; Wang et al. 2012a). In the orchard, canker lesions usually show up first in late February and expand rapidly in March and April. From May onward, the lesions gradually cease expansion. In September, the lesions expand again, but more slowly than in early spring. The pathogen overwinters within tree bark.

Valsa canker is widespread in China. In 2008, Cao and others (Cao et al. 2009) conducted a broad survey of its prevalence in China, examining 3,675 apple trees in 147 orchards across 10 major apple-producing provinces. They noted that Valsa canker had damaged up to 52.7% of the trees they examined. In another investigation in Yantai city in 2011 (Wang et al. 2012a), 68.2% of the investigated trees were damaged, with an average of 2.36 cankers per tree. All commercial apple varieties are susceptible, precluding resistance-based disease control (Liu et al. 2011). Control efforts based solely on chemical fungicide sprays are also ineffective because the fungicide cannot penetrate the outer bark to form a protective layer in noninfected woody tissue. In many orchards, disease management relies heavily on surgical removal of cankers and post-surgical fungicide treatment (Fig. 7), which is usually performed in early spring (March to April). Commercial products with a combination of wood tar, flusilazole, peracetic acid, and humic acid copper are commonly used for canker treatment; these compounds kill the pathogen and promote wound healing (Cao et al. 2009). Arch grafting is another common practice used to mitigate damage from Valsa canker (Fig. 7). These labor-intensive practices, however, fail to prevent canker recurrence during the next growing season. Many

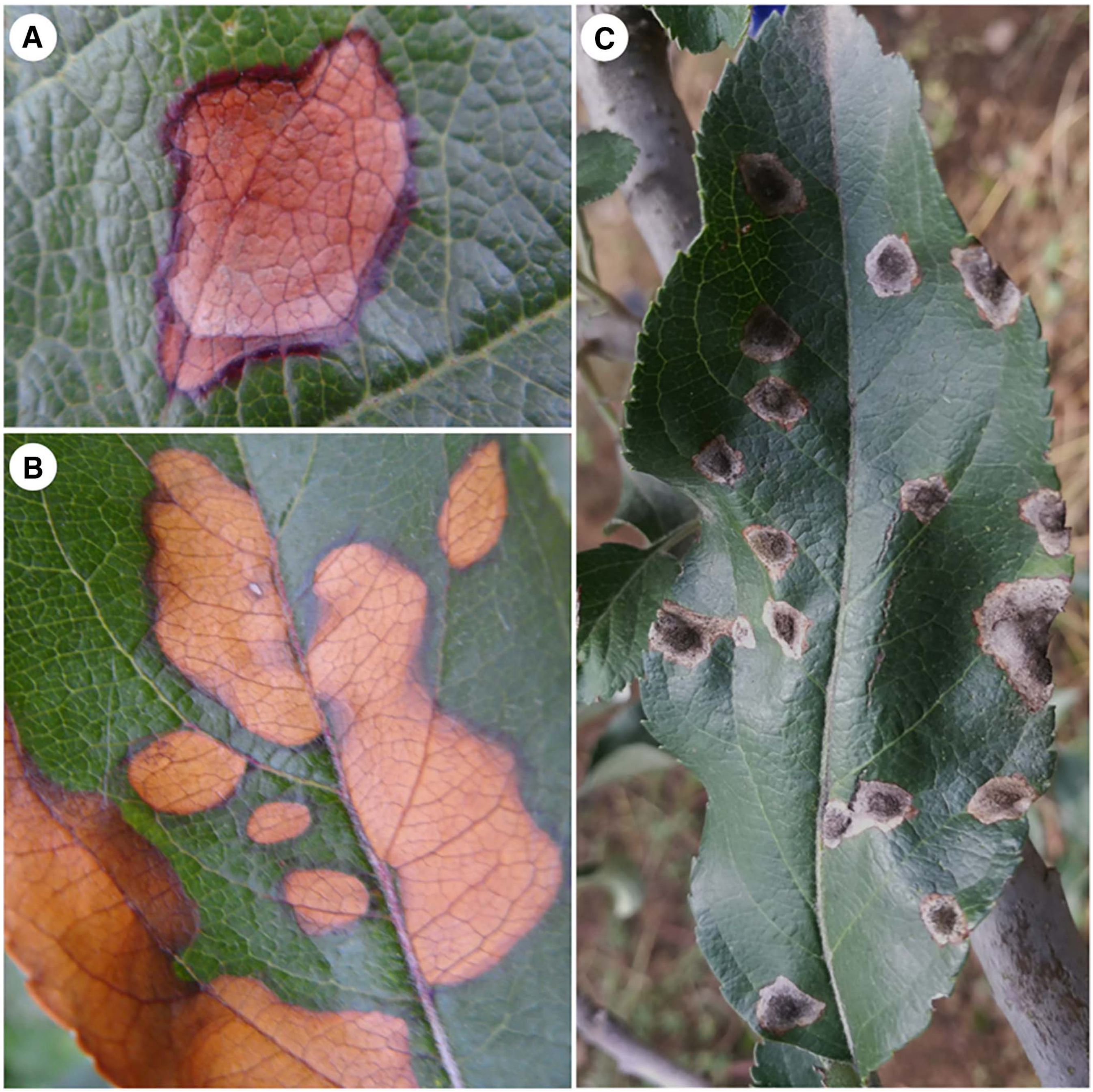

Fig. 4. Alternaria leaf spot. **A and B,** Leaf necrosis in early infection. **C,** Dark-gray conidia-bearing spots in late infection.

orchards in China have been abandoned due to severe Valsa canker damage.

A study by Peng et al. (2016) indicated that the prevalence of Valsa canker in China might be related to tree vigor decline caused by nutritional imbalance, especially K deficiency. The study showed that incidence of Valsa canker had a strong negative correlation with foliar K content. An et al. (2004) measured leaf K concentration across 460 orchards in Shaanxi Province and found that the average level (0.86 ± 0.24%) was considerably lower than the optimal range (1.2 to 1.9%) (Shear and Faust 1980). Greenhouse and field fertilization trials showed that increased K fertilization sharply reduced the incidence and severity of Valsa canker (Peng et al. 2016). Unlike the U.S. and EU, regular foliar analysis is uncommon among small-scale apple orchards in China. A balanced fertilization scheme based on nutrient analysis may be essential for suppressing Valsa canker disease in China.

Trunk diseases: Botryosphaeria canker. Botryosphaeria canker is another important and prevalent trunk disease in China. Symptoms include cankers or warts on branches and trunks (Fig. 6), which considerably reduce tree vigor and fruit yield. A survey of 2,200 trees in 88 orchards located in seven provinces found incidence of Botryosphaeria canker as high as 77.6% (Guo et al. 2009). Two species, *B. kuwatsukai* and *B. dothidea*, have been documented to cause Botryosphaeria canker in China (Xu et al. 2015). *Botryosphaeria* pathogens are stress associated and can infect latently. Symptom expression is typically associated with the presence of biotic stresses such as drought and physical damage (Marsberg et al. 2017), which may explain why old and weak apple trees are more prone to cankering (Guo et al. 2009). Branch or trunk infection can produce cankers or warts (the latter due to hyperplasia and suberization of bark tissue at the infection site). The wart symptom is considered to be a form of host defense response which restricts fungal growth and expansion (Dong et al. 2021). The wart tissue, however, is an important reservoir for fungal sporulation and inoculum release (Xue et al. 2021). Surgical removal of both wart and canker tissue is an important practice in controlling Botryosphaeria canker.

Fig. 5. Glomerella leaf spot. **A,** Contrasting levels of cultivar susceptibility. Gala apple (right) is highly susceptible, whereas Fuji apple (left) is resistant. **B and C,** Typical symptoms and signs on leaf. The tiny spots in C are acervuli. **D and E,** Typical sunken lesions on fruit.

Fruit Bagging and Associated Fruit Diseases

Apple fruit bagging is a very common production practice in China, particularly on cultivars that ripen in mid- to late season. Fruit bagging provides many benefits (Fig. 8) (Frank 2018): (i) improves fruit finish and coloration, which significantly improves commercial value for fresh-market sale; (ii) prevents inoculation by many pathogens, which almost eliminates the necessity for pesticide sprays targeting traditional fruit diseases; (iii) prevents damage caused by insect pests, birds, and mechanical scratches; and (iv) reduces the deposition of pesticide residues on fruit surfaces.

Although fruit bagging is highly effective against apple ring rot (caused by *Botryosphaeria* spp.), Colletotrichum bitter rot, and SBFS, it has unexpectedly given rise to a new fruit disease: fruit spot (Fig. 9). This disease is specifically associated with bagged apple fruit. Damaged fruit are covered with circular, sunken lesions 2 to 20 mm in diameter, especially on the epicarps surrounding sepals (Dai et al. 2019; Hou et al. 2019; Li et al. 2014). In China, fruit spot was first reported in Gansu Province in 2000 (Xu et al. 2000) and, later, in Shaanxi, Shandong, and Hebei provinces. Disease incidence varied among orchards and was as high as 90% (Guo et al. 2005). Apple fruit spot can be caused by a wide range of fungal species, and the symptoms vary with the causal agents and apple cultivars. Six fungal genera (*Trichothecium*, *Alternaria*, *Acremonium, Cylindrosporium*, *Phoma*, and *Sarocladium*) have been reported to be causal agents, and the spot color can be brown, black, or greenish brown (Hou et al. 2019). Changes in the microenvironment on the apple surface, particularly extended periods of environmental wetness, may play an important role in promoting spore germination and pathogen infection (Hou et al. 2019).

In fruit spot caused by *Trichothecium roseum* (Dai et al. 2019), conidial germination requires exogenous nutrients in addition to high humidity, which may explain why Trichothecium black spot is more prevalent in the calyx region, where petal- or pollen-derived nutrients are available. In addition, maturing fruit are more vulnerable to disease damage. Fruit expansion may promote nutrient extrusion around lenticels and inhibit defense reactions, boosting symptom development (Dai et al. 2019).

Apple moldy core and core rot also cause significant economic damage in China. Symptoms include premature fruit drop, core rot, and moldy core on mature fruit (Fig. 9). Diseased fruit are normal in outward appearance, making it difficult to separate them from healthy ones but, in storage, diseased fruit can decay. Moldy core and core rot are disease complexes, each with a range of associated fungal pathogens. Moldy core and core rot are important concerns on cultivar ‘Delicious’ in Gansu Province, where incidence is commonly 40 to 50% at harvest (Dai et al. 2020). In China, moldy core is commonly associated with *Alternaria* and *Cladosporium* spp., whereas core rot is mainly associated with *Trichothecium*, *Epicoccum*, *Phoma*, *Fusarium*, and *Penicillium* spp. (Dai et al. 2020; Gao et al. 2013). Fruit anatomy strongly influences the field incidence of apple moldy core and core rot. Fruit with relatively wide sinus openings (sinuses refer to passageways between the core cavities and the calyx tube) are more prone to infection. Histological observation with *T. roseum* infection confirmed an infection route from style to stylar fissure to open sinus to carpel cavity (Dai et al. 2020). The moldy core pathogen remains quiescent within fissures after style entry but fruit ripening triggers the formation of an open sinus which facilitates carpel cavity entry. Cultivar, weather conditions, and management practices (e.g., crop load and fruit bagging) can all affect the degree of fruit sinus opening and, thus, disease incidence. The latent-infection nature of apple moldy core and core rot poses a considerable challenge for effective disease control.

Viruses and Viroids

Four main types of viruses affect apple production in China: Apple chlorotic leaf spot virus (ACLSV), Apple stem grooving virus (ASGV), Apple stem pitting virus (ASPV), and Apple necrosis

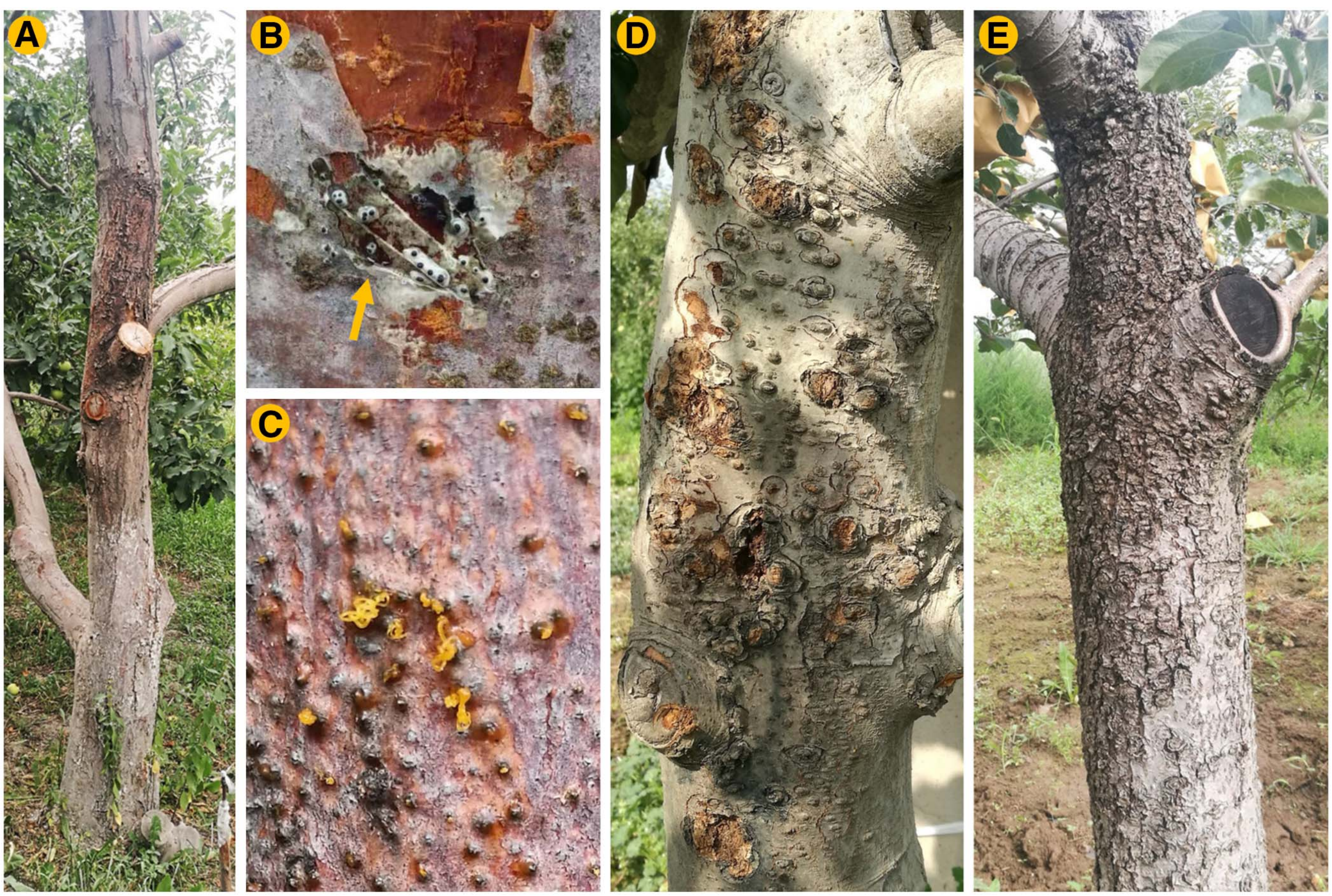

Fig. 6. Symptoms of **A to C,** Valsa canker and **D and E,** Botryosphaeria canker. **A,** Trunk canker. **B,** Pycnidia (arrowheads). **C,** Spore tendrils. **D,** Botryosphaeria warts. **E,** Cracks in tree bark due to *Botryosphaeria* infection.

mosaic virus (ApNMV) (Dong et al. 2020). ACLSV, ASGV, and ASPV are latent viruses, not causing obvious symptoms. However, these viruses significantly inhibit tree growth, vigor, and yield. The prevalence of ACLSV and ASGV in Chinese orchards is estimated to exceed 60% and the prevalence of ASPV in orchards is generally higher than 20% (Dong et al. 2020). Apple leaf mosaic disease is prevalent in all apple-producing regions in China (Fig. 10). Disease incidence in orchards has been documented to be as high as 62.7% (Li et al. 2002). An apple disease causing leaf mosaic and mottle symptoms, as well as reducing photosynthesis, tree vigor, and yield was hypothesized to be caused by Apple mosaic virus and Prunus necrotic ringspot virus but was recently demonstrated to be caused mainly by ApNMV (Shi et al. 2020; Xing et al. 2018). Based on high-throughput sequencing, novel latent viruses such as Apple-associated luteovirus, Apple geminivirus, and Apple hammerhead viroid-like RNA have also been identified in Chinese apple trees or fruit (Liang et al. 2015; Shen et al. 2018; Zhang et al. 2014).

In addition to viruses, apple production in China is also affected by two main types of viroids, Apple scar skin viroid (ASSVd) and Apple dimple fruit viroid (ADFVd) (Fig. 10). ASSVd and ADFVd severely affect fruit quality and gradually reduce tree vigor, and lead to declining yield and, ultimately, tree death. Symptoms of ASSVd and ADFVd are obvious on fruit but not on branches or leaves. ASSVd has been reported in all apple-producing regions whereas the occurrence of ADFVd is restricted to Shandong and Xinjiang (Dong et al. 2020). Because apple is a vegetatively propagated crop, viral contamination can occur readily during rootstock production. Therefore, maintaining virus-free nursery stock is critical to prevent virus and viroid diseases. In the U.S., the apple industry has benefited significantly from the continuous development of virus-free stocks through national programs incorporating virus detection, virus elimination, and virus-free rootstock promotion. In China, however, the prevalence of small-scale orchards has limited the enforcement of a strong national certification program.

Reinventing Disease Management Practices in the Move to Industrialized Farming

Urbanization, aging of rural populations, and worsening labor shortages are increasingly challenging the traditional mode of family-owned small-scale orchard system. In response, there is a rapidly developing trend toward larger-scale, highly automated and mechanized production systems. In both the Loess Plateau and Bohai Gulf areas, high-density plantings of fully dwarfed trees are increasingly prevalent. In Shaanxi Province, the planting area of dwarf orchards has reached 160,000 ha (2.4 million Mu) in 2020, equivalent to 27% of all apple orchards in the province (Li 2020). Compared with traditional orchards, high-density dwarf plantings offer some significant advantages (Yuan et al. 2011) (Fig. 11). For example, tighter tree spacing facilitates drip fertigation and mechanized management practices,

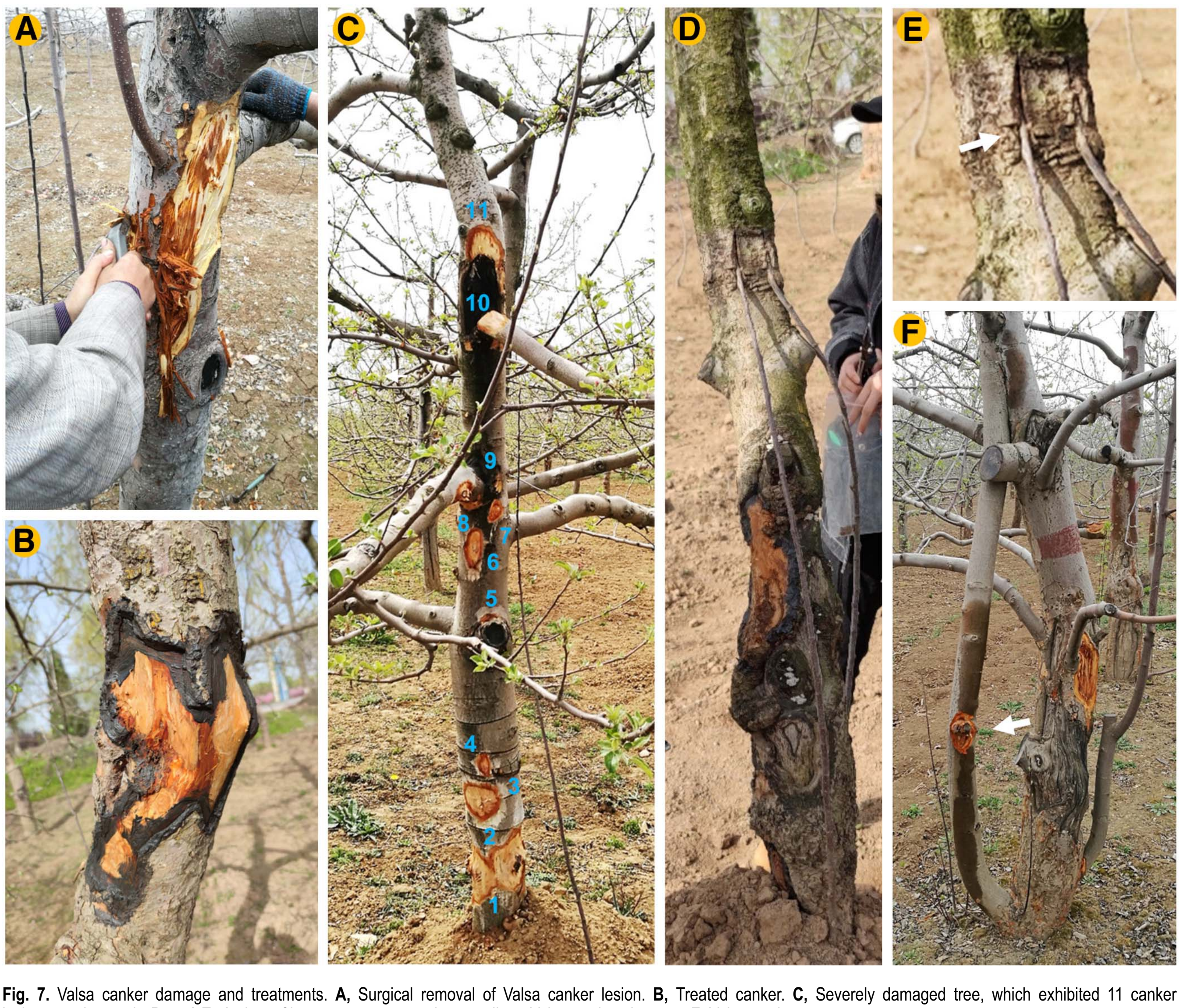

Fig. 7. Valsa canker damage and treatments. **A,** Surgical removal of Valsa canker lesion. **B,** Treated canker. **C,** Severely damaged tree, which exhibited 11 canker lesions on the trunk. **D and E,** Arch grafting, a common practice to relieve Valsa canker damage. **F,** Valsa canker recurrence.

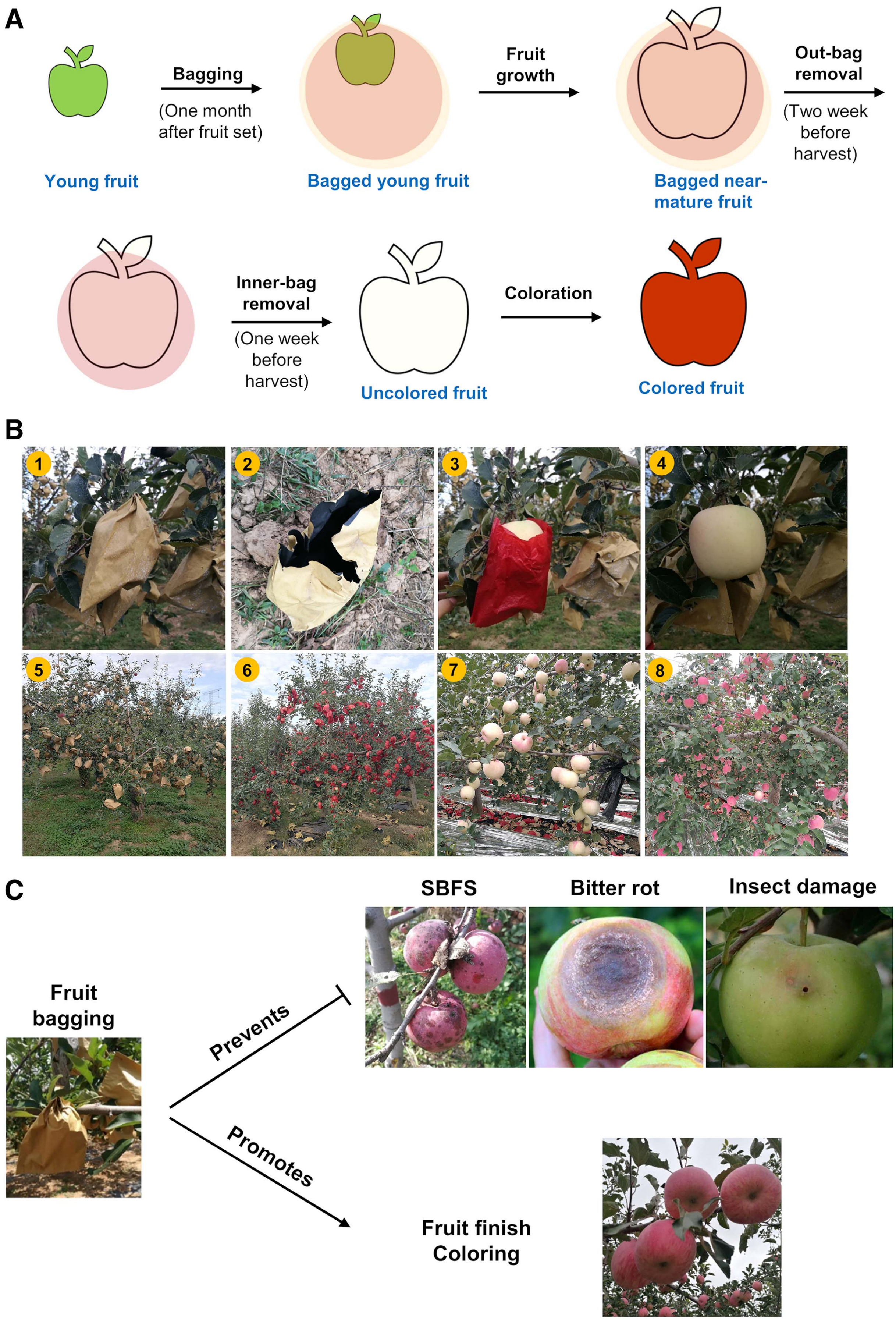

Fig. 8. Bagging for fruit disease control. **A,** Flow chart of the fruit bagging process. **B,** Fruit bag organization (1 to 4) and field aspects (5 to 8). A typical paper fruit bag 1 to 4 contains two layers: the outer layer has a black inner side and prevents light penetration, whereas the inner layer is red in color. 5. Bagged fruit. 6. Exterior layer of bags has been removed. 7. Inner layer of bag has been removed. Note reflective plastic film on the ground, which promotes fruit coloration after bag removal. 8. Fully colored fruit. **C,** Beneficial effects of fruit bagging. SBFS = sooty blotch and flyspeck.

which saves considerable labor cost. In addition to the advent of high-density orchards, certain growers have reconfigured their existing orchard blocks by removing every other tree in each row and pruning radically to facilitate light penetration and access by large-scale equipment.

The transition from traditional to industrialized farming raises many new research questions regarding orchard disease management. Below, we focus on several specific cases to discuss this transition and to highlight the research and extension issues associated with this ongoing transition.

The fading of the fruit bagging era. Fruit bagging remains a very popular production practice in China and is highly efficient in controlling traditional fruit diseases. However, the practice is not without its disadvantages (Jun and Cao 2017). Fruit bagging negatively affects fruit flavor and the accumulation of sugars, dry matter, and micronutrients in the fruit. In addition, fruit bagging reduces wax accumulation on the fruit surface, thus making fruit more prone to desiccate during storage. Fruit bagging generates paper and plastic waste, and has also prompted the emergence of fruit spot disease. Most importantly, economic realities have increasingly challenged the continuation of fruit bagging. For instance, the total bag and labor cost associated with the use of two-layer paper bags in the Loess Plateau region is between 0.3 and 0.5 yuan (equivalent to U.S.$0.05 to 0.08) per fruit, which comprises more than one-third of the total input cost (Jun and Cao 2017). With fewer and fewer rural laborers, it is foreseeable that fruit bagging will gradually fade away.

The transition from bagged to nonbagged apple production has considerable implications for apple disease management. Prior to the fruit bagging era, apple ring rot, bitter rot, and SBFS caused considerable fruit damage in China. Over the past two decades, fruit bagging has effectively controlled these disease problems. In the absence of bagging, the risk of these diseases is likely to increase, particularly for traditional orchards with densely spaced and weak trees. Spraying pesticides with high efficacy, low residue at harvest, and minimal damage to fruit surface finish will be extremely important for producing nonbagged apple fruit. In addition to chemical fungicide sprays, integrated disease control practices combining cultural, biological, and physical measures will also be important to meet consumer demands for safe, good-looking, and delicious fruit.

Globally, apple fruit bagging is uncommon outside of China. In Korea and Japan, bagged-apple orchards take up only 5 and 10%, respectively, of production (Zhang et al. 2020). In the EU, U.S., and New Zealand, apple fruit bagging is even less prevalent. Most of the fruit from outside China is produced in high-density dwarf orchards, the environment and ecology of which differ dramatically from the standard orchards that remain prevalent in China. From this perspective, it is critical to conduct field trials to test and develop practical guidelines for nonbagged apple production in traditional Chinese orchards.

Different schemes for foliar disease control. Diseases causing leaf necrosis and premature defoliation, including Marssonina blotch, Alternaria blotch, and GLS, are all polycyclic. That is, these diseases progress exponentially in a growing season; thus, disease control can unravel rapidly. In traditional small-scale Chinese orchards, these foliar diseases are controlled by fungicide sprays but the process is inefficient for several reasons. First, the dense canopy of traditional orchards creates a moist microenvironment favoring pathogen infection. Second, dense foliage limits pesticide deposition on leaves within the inner canopy. Third, farmers managing small-scale orchards are generally knowledge limited, and their pesticide spray programs are prone to being arbitrary and suboptimal. These sprays are generally performed without regard to weather-associated disease risks, and too-long or too-short intervals between applications are common. In some cases, the chosen pesticide may have low efficacy against the targeted pathogens. Fourth, spray equipment used by these farmers is generally outdated backpack or hydraulic units, which reduces pesticide deposition efficiency. Finally, profit-driven recommendations from local pesticide

Fig. 9. Symptoms of apple fruit spot (left) and moldy core (right).

Fig. 11. Comparison between traditional and dwarf orchards. Compared with dwarf orchards (right), traditional orchards in China (left) typically have a closed canopy, which impedes light penetration, airflow, and access by large equipment.

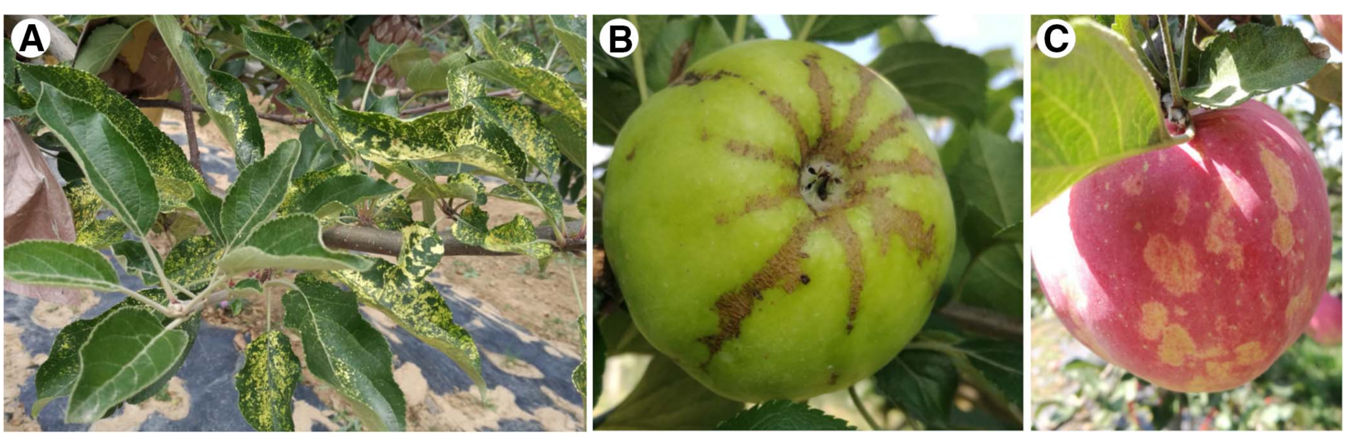

Fig. 10. Apple viruses and viroids. **A,** Apple necrosis mosaic virus (ApNMV). **B,** Apple dimple fruit viroid (ADFVd). **C,** Apple scar skin viroid (ASSVd).

retailers can lead to unnecessary fungicide sprays. In China, Plant Protective Stations (PPS) established in individual counties play important roles in disease control extension. These are small-scale units (around 10 staff persons each) with combined duties of disease investigation and forecasting, disease control recommendations, and enforcement of plant quarantine regulations. The enormous number of small-scale orchard growers (for example, more than 10,000 in a single county) and their personalized orchard management habits have created significant workloads for PPS in disease control extension.

Relative to traditional family-scale orchards, high-density dwarf orchards have improved orchard structure and are managed in a more standardized and organized manner. These orchards generally have a tighter focus on control efficacy and cost effectiveness. Furthermore, growers of larger-scale orchards are often more motivated to learn about disease biology and disease control measures. In the future, there is likely to be increasing grower demand for disease control guidance based on accurate disease surveillance and risk modeling, and for extension specialists who are familiar with integrated disease control strategies.

Potential pitfalls in transitioning to large-scale, higher-tech orchards. The high-density dwarf orchard model is an ongoing trend in new orchard establishment, and using high-quality germplasm is pivotal for its success. At present, however, the apple germplasm market in China is heterogeneous, with less emphasis on purchasing planting stock that has been certified as disease-free than in some other apple-producing countries. Contamination of propagative material by viruses and viroids is widespread and poses a considerable threat to sustainable orchard management. Thus, there is an urgent need for stricter regulations concerning virus elimination and sanitation of planting material. To ensure quality of planting material, many companies have chosen to import grafted material from certified foreign sources. Such activities, however, increase the risk of importing quarantined diseases (e.g., fire blight). Fire blight has been reported in several countries that neighbor China, including South Korea, Kyrgyzstan, and Kazakhstan (Zhao et al. 2019), which poses a significant threat to the Chinese apple industry.

Apple replant disease (ARD) is a factor restricting new orchard establishment. ARD is the result of several pathogens, including nematodes and fungi, and causes severe growth suppression after planting apple on the same site where apple trees have been planted before. ARD severely reduces tree growth and causes losses in fruit yield and quality. Thus far, there is no accepted practice in China for controlling ARD.

Associated with industrialization of apple production, changing market demands are increasingly driving cultivar diversification, which would benefit significantly from integrated breeding programs. In China, universities and public research institutes conduct apple breeding but the coordination level among these units is still low. In addition, it is common for breeders to prioritize yield and quality traits (e.g., ripening period, fruit size and shape, and flavor) over disease resistance traits during breeding selection. Strong nationwide strategic coordination in apple breeding is still in a nascent phase even though several national coordinative systems (e.g., the National Apple Breeding Initiative in 2004 and Apple Industry System in 2007) have been established (Cong et al. 2018).

Conclusion and Future Directions

Driven by worsening rural labor shortages, the largest apple-producing country in the world is experiencing a massive transformation toward industrialized apple production. This transition means that orchard management practices are going to change dramatically compared with traditional small-scale orchard systems. The demand for effective and environmentally friendly disease management guidance is going to surge. For researchers and extension specialists, several prioritized research directions are highlighted here: (i) virus and viroid eradication programs and nursery stock health improvement, accompanied by ready access to virus-free planting stock, is critical for the success of the entire industry; (ii) resistance mining and utilization of genetic resistance against prevalent field diseases should be considered as important as fruit quality and yield during the breeding process, and disease resistance evaluation should be integrated into the early phase of current breeding schemes; and (iii) field trials on the pesticide control of foliar and fruit diseases should be performed in a more systematic manner so that reliable, grower-oriented guidelines for integrated disease control can be formulated and disseminated.

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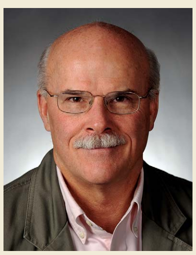

Mark Gleason

Dr. Mark Gleason has been on the Iowa State University faculty for 36 years, doing research, teaching, and extension on disease management of horticultural crops, mainly fruits and vegetables. His apple research has emphasized ecology, diversity, evolution, and management of the sooty blotch and flyspeck fungal complex. He has collaborated in research with Drs. Sun and Zhang since 2002.

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