

REVIEW

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Global distribution and management of peach diseases

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Abstract

Peach is a popular and important tree fruit widely produced in the world, and the production of high-quality peach fruit does require management of pests and diseases. In this review, major peach diseases from China, Spain, and USA are described in detail for the benefit of producers, consultants, researchers, and other interested parties. Minor diseases of concern in these countries are also described. Current progress on pathogen resistance to major chemical classes of fungicides as well as current resistance management practices are discussed. Specific cultural practices applied in China, Spain, and USA are also described to provide an overview of peach disease management. A 'Future Outlook' section is included at the end of this review to highlight the challenges and opportunities for disease management in the future.

Keywords: Peach diseases, Fungicide resistance, Integrated management, Brown rot, Bacterial spot, *Armillaria* root rot, Bacterial canker, Powdery mildew

Background

Peach (*Prunus persica* (L.) Batsch) is a deciduous tree or shrub in the family Rosaceae grown all over the world (Zheng et al. 2014). As the birthplace of peach, China also leads in peach production in the world with 15.02 million tons of fruit annually, accounting for 61.12% of global peach production in 2020, followed by Spain (1.31 million tons), Italy (1.02 million tons), Turkey and Greece (0.89 million tons each), Iran (0.66 million tons), USA (0.56 million tons), Egypt (0.34 million tons), Chile (0.31 million tons), and India (0.27 million tons) (FAOSTAT 2020). Besides its usages for fresh fruit, canned fruit, dried fruit snacks, and fruit juice, peach trees are also considered to be ornamental plants attributed to their white, pink, or red flowers during springtime. Commercial peach production is challenging for multiple reasons. One of them involves its susceptibility to many fungal

and bacterial diseases that can significantly affect fruit yield and quality, and some can also impact the longevity of the trees. According to the authors, the most economically important peach diseases in China, Spain, and USA are brown rot caused by *Monilinia* spp., bacterial spot caused by *Xanthomonas arboricola* pv. *pruni* (*Xap*), *Armillaria* root rot, bacterial canker caused primarily by *Pseudomonas syringae*, and powdery mildew caused by *Podosphaera pannosa* (Table 1).

Symptoms, causal agents, and distribution of peach diseases

Brown rot

Brown rot of stone fruits is arguably the number one fungal disease affecting peach fruit worldwide (Fig. 1a). In addition to fruit rot, it can also cause blossom blight (Fig. 1b), and twig cankers (Fig. 1c). In some cases, twig infections progress into branch dieback (Fig. 1d). The infected flowers (i.e. blossom blight) typically turn brown and wilt, followed by the infection and colonization on the shoots. Oftentimes shoot infections lead to cankers and gumming around the infection site. On fruit, circular brown lesions develop rapidly and within a few days the

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Table 1 Top five peach diseases in order of economic importance as judged by the authors

Rank	China	USA	Spain
1	Brown rot	<i>Armillaria</i> root rot	Powdery mildew
2	Bacterial spot	Bacterial canker	Brown rot
3	Gummosis	Brown rot	Leaf curl
4	Peach scab	Bacterial spot	Shot-hole
5	Constriction canker	Peach scab	<i>Phytophthora</i> root and crown rot

entire fruit may be colonized. Brown spore masses are produced on the infected fruit surface to serve as additional sources for multiple secondary infections during the same season. Eventually the affected fruit shrivel up and either drop to the ground or remain on the tree to form fruit mummies.

Peach brown rot can be caused by several *Monilinia* species, including *Monilinia fructicola*, *Monilinia laxa*, *Monilinia fructigena*, *Monilia polystroma*, *Monilia yunnanensis*, and *Monilia mumecola*. Among them, *M. fructicola* is considered to be the most prevalent species in Asia, North America, and South America. *M. laxa* is mainly distributed in Europe, North America, and Australia. *M. fructigena* is mainly found in Europe, representing the predominant species in European countries (EPPO 2021). *M. polystroma* exists in East Asia and Europe (EPPO 2021), while *M. mumecola* and *M.*

yunnanensis have thus far only been detected in Asia (Harada et al. 2004; Hu et al. 2011; Luo 2017). Besides peach and nectarine, *Monilinia* spp. also affect other stone fruits such as plum, apricot, cherry, and loquat (Luo 2017; Yin et al. 2021), and pome fruits such as apple, pear, and hawthorn (Zhao et al. 2013; Zhu et al. 2016).

The fungi overwinter on fruit mummies on the ground or on the tree and in twig cankers, all of which serve as main inoculum sources for blossom blight and green fruit rot (Villarino et al. 2012). The fungus is polycyclic and produces spores through several disease cycles on green and maturing fruit.

Bacterial spot

Bacterial spot is one of the most economically important diseases of stone fruits worldwide (Stefani 2010; Janse 2012). It not only causes damage to peach leaves but also to fruit and branches. The initial symptoms on leaves are the appearance of angular water-soaked lesions (Fig. 2a). As the lesions enlarge, the centers dry out and often detach from the leaves, giving the leaf a “shot-hole” appearance (Fig. 2b). Larger crater lesions on fruit are mainly caused by primary infection early in the season between shuck split and pit hardening (Fig. 2c). On maturing fruit, small and shallow lesions may appear with a mottled appearance (Fig. 2d). They are generally caused by secondary infections after pit hardening. On

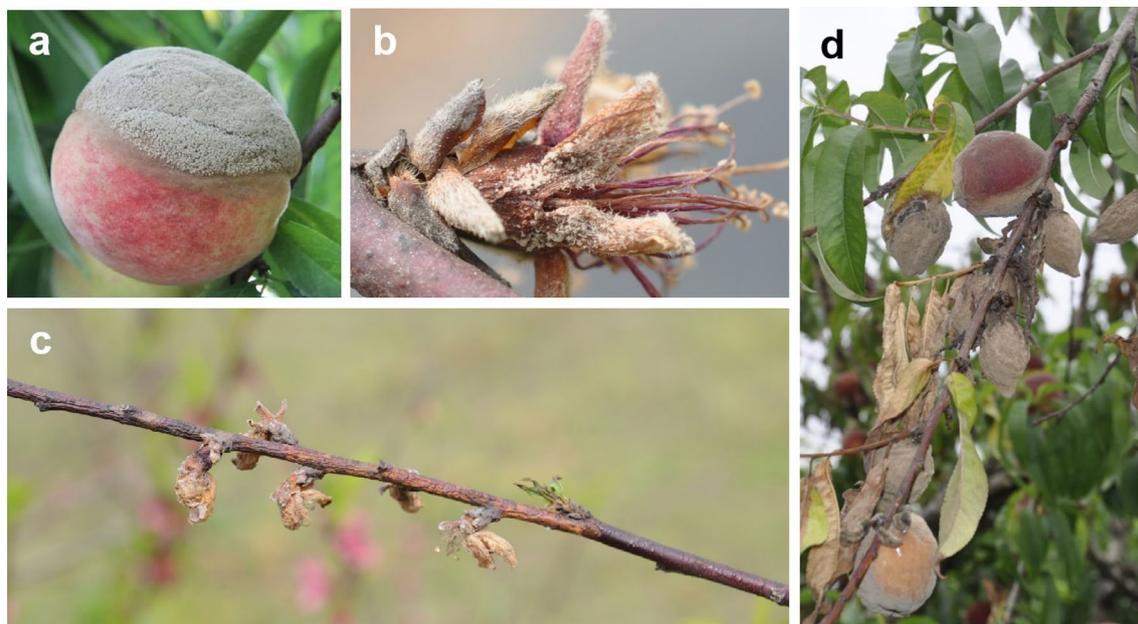


Fig. 1 Symptoms of peach brown rot and blossom blight. **a** Fruit rot with sporulating lesion (Wuhan, 2012). **b** Blossom blight (Wuhan, 2018). **c** Twig canker (Wuhan, 2018). **d** Twig dieback due to multiple infections (Wuhan, 2018)

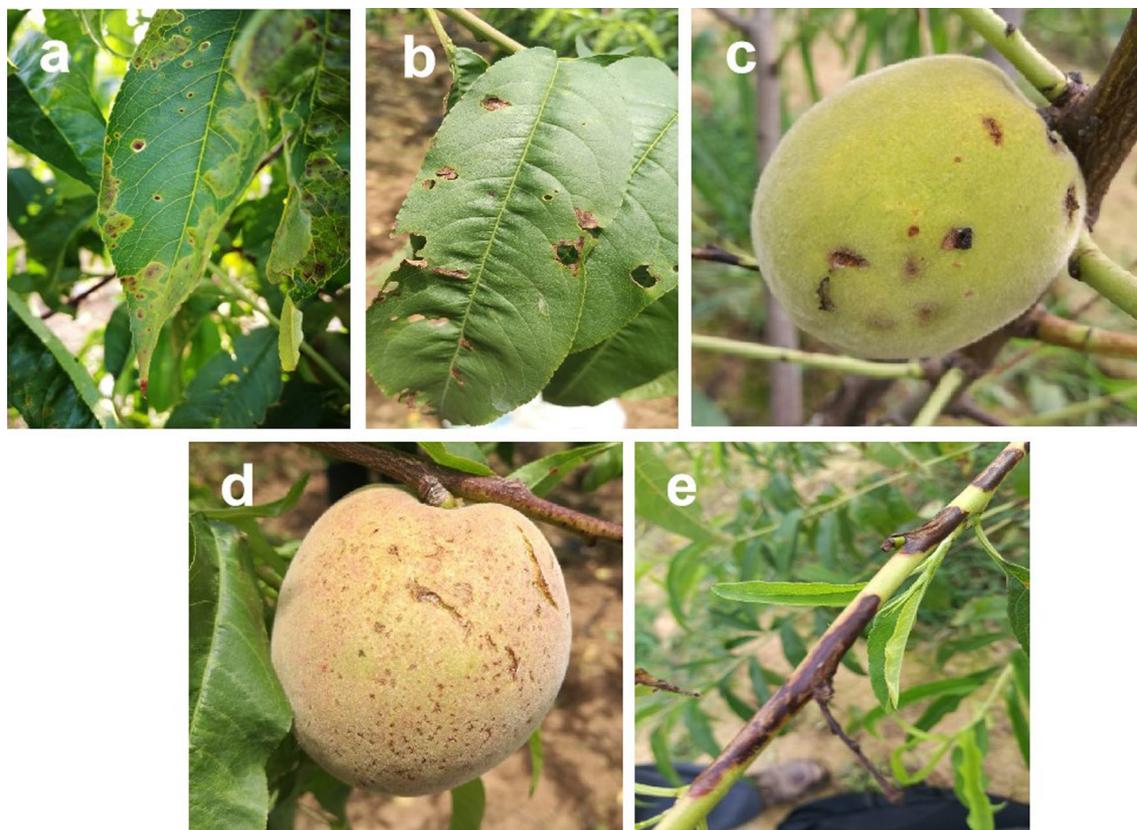


Fig. 2 Symptoms of peach bacterial spot. **a** Water-soaked spots on leaf (Zaoyang, 2018). **b** Shot hole on leaf (Qujialing, 2017). **c** Large crater lesions and surface cracking on fruit (Xiaochang, 2017). **d** Shallow lesions on fruit (Qujialing, 2017). **e** Dark brown cankers on shoot (Xiaochang, 2017)

branches, cankers develop either as raised blisters or dark brown oval lesions (Fig. 2e).

Bacterial spot is caused by *Xanthomonas arboricola* pv. *pruni* (Xap). The bacterium mainly overwinters on cankers, also in buds, cracks in the bark, and leaf scars. Fruit infections are favored by frequent rainfalls, high humidity, and strong winds. Besides peach, it also infects many *Prunus* species including plum, apricot, cherry, and almond, as well as ornamental plants such as *Prunus davidiana* and *Prunus laurocerasus* (Rosello et al. 2012; Tjou-Tam-Sin et al. 2014). This bacterium has been found to damage stone fruits in Asia, Europe, North America, South America, Australia, and Africa (EPPO 2021).

Armillaria root rot

Armillaria root rot (ARR) commonly occurs on sites that were previously forest land with oaks and other hardwoods. Beige to white mycelial fans spread in the bark of roots from the point of infection to the lower trunk where the fungus continues its journey and spreads to other roots. The mycelial fans can be easily seen on a piece of cut bark from affected tissue (Fig. 3a). For some species,

such as *Armillaria mellea*, rhizomorphs explore the soil for hosts. Other species, such as *Desarmillaria tabescens*, move from tree to tree exclusively through root-to-root contact (Sinclair and Lyon 2005). The basidiomycete fungus produces yellow to honey-colored mushrooms after heavy rainfalls in spring, early summer, or fall, providing airborne spores to spread (Fig. 3b). Infected trees may reveal wilting scaffold branches or may collapse suddenly in spring or throughout the year (Fig. 3c).

Multiple fungal species within the genus *Armillaria* as well as *D. tabescens* have been identified to cause ARR worldwide. Specifically, *D. tabescens* is the predominant pathogen in the southeastern US. *A. solidipes* and *A. mellea* are considered to be the main causes of ARR in California, Michigan, and other northwestern states of the US, while *A. gallica* and *A. mexicana* are widely distributed in Mexico (Elias-Roman et al. 2019). Interestingly, these species have been found to vary in their virulence. For example, *D. tabescens* is a primary pathogen and does not require the trees to be stressed by other means (Miller et al. 2020). *A. mexicana* was found to display higher virulence than *A. mellea*. However, the



Fig. 3 Symptoms and signs of *Armillaria* root rot. **a** Mycelial fans on cut bark from affected lower trunk tissue (South Carolina, 2015). **b** Mushroom clusters of *D. tabescens* produced from diseased roots and crown (South Carolina, 2020). **c** Within tree row spread of the disease due to root-to-root contact leading to complete tree collapse (South Carolina, 2015)

virulence of the same species could also vary by different geographic regions (Guillaumin et al. 1991; Baumgartner et al. 2010) and by rootstocks (Guillaumin et al. 1991; Beckman et al. 1998; Beckman and Pusey 2001).

Bacterial canker

If scaffold limbs or entire peach trees do not flush out in spring, there is a good chance that bacterial canker has invaded the tree (Fig. 4a). In spring the affected bark gives off a sour smell, which later in the season tends to fade. Cutting into cankers of scaffold limbs

or trunk sections reveals a clear line between necrotic bark tissue and non-symptomatic bark tissue (Fig. 4b). Infections occur mostly in the fall when leaves drop during rainstorms and abscission zones are infected by the bacteria. Infections can also occur through pruning wounds (Fig. 4b). Young peach trees are more vulnerable to bacterial canker than older trees (Dye 1954; Young 1987). *Pseudomonas syringae*, the causal agent of bacterial canker, is generally a weak pathogen and needs predisposing factors to weaken the tree. The biggest predisposing factor is ring nematode. Bacterial

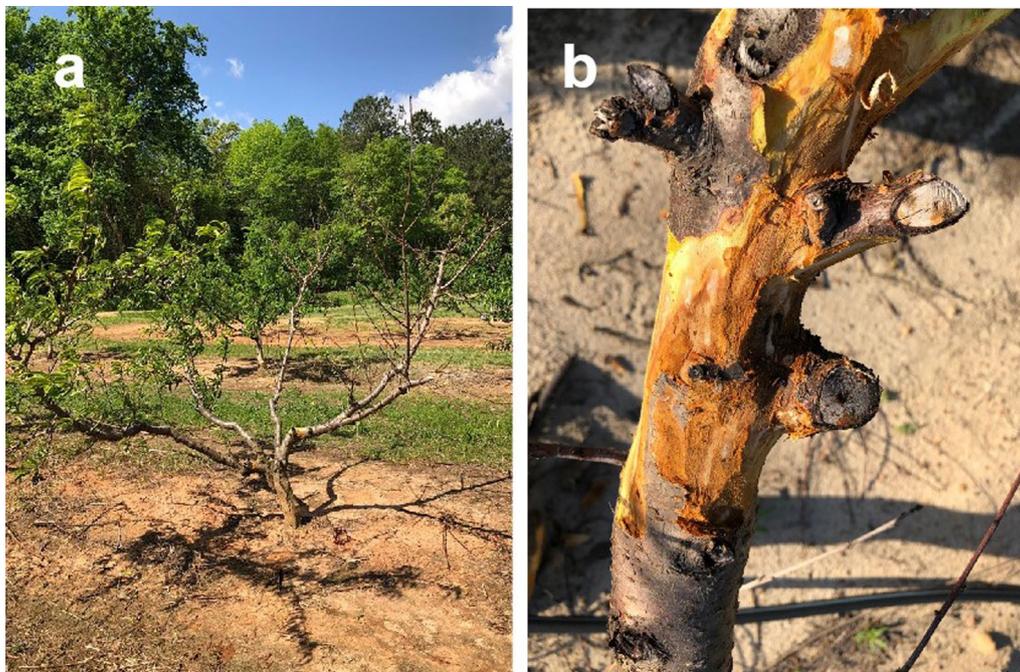


Fig. 4 Symptoms of bacterial canker. **a** Scaffold limb collapse in early spring (South Carolina, 2018). **b** Cankers generated by infection through pruning wounds with a clear line between necrotic bark tissue and non-symptomatic bark tissue (South Carolina, 2018)

canker of peach is caused by two different pathovars, *P. syringae* pv. *syringae* and *P. syringae* pv. *morsprunorum*.

Powdery mildew

Powdery mildew primarily damages the skin of green fruit but can also occur on leaves and young shoots. This disease may cause serious damage during years with cold and humid springs, followed by hot, dry summers. Signs starts as a powdery white coating on infected surfaces that transitions into a brown color with age. Young fruit develop white, spherical spots that may enlarge (Fig. 5a). Infected areas on fruit turn orange-tan and appear rusty (Fig. 5b). Symptoms usually occur on green fruit and disappear as the fruit develops.

Peach powdery mildew is mainly caused by the fungus *Podosphaera pannosa* (Grove 1995). It overwinters on infected twigs, shoots, and buds of peach. A similar symptom with rusty spots on fruit may be caused by *Podosphaera leucotricha*, which is the causal agent of apple powdery mildew, thus removing adjacent apple orchards can reduce rusty spot in peach orchards (Urbanietz and Dunemann 2005).

Other peach diseases

Peach scab

Peach scab is caused by the fungus *Venturia carpophila*. Symptoms on fruit start after pit hardening and consist of relatively small, velvety-brown spots on the fruit surface. They are irregular in shape and corky in appearance. Multiple spots may merge and form bigger lesions. Continuous expansion of the fruit can lead to massive skin cracking. The disease is particularly severe in temperate

climate regions with humid and cool springs, and poor air circulation (González-Domínguez et al. 2017). Scab can result in fruit downgrading and/or rejection if the infection is severe because these blemishes reduce the value of fruit intended for the fresh market (Schnabel and Layne 2004). Much like bacterial spot, peach scab can cause early defoliation. Over time, the tree may become weaker and more susceptible to freezing injuries. The pathogen overwinters as mycelia in twig lesions or as chlamydospores on vegetative tissue or in the bark of 1-year-old shoots. Besides peach, it also affects black plum, apricot, and almond (Fisher 1961; Kim et al. 2017; González-Domínguez et al. 2017; Dar et al. 2019; Zhou et al. 2021c). *V. carpophila* can cause severe damage to peach production in Asia, North America and Europe (EPPO 2021).

Peach constriction canker

Peach constriction canker caused by the fungus *Phomopsis amygdali*, also known as peach shoot blight, causes serious damage worldwide (Daines et al. 1958; Ogawa et al. 1995; Farr et al. 1999; Lalancette and Polk 2000; Lalancette and Robison 2001; Michailides and Thomidid 2006; Dai et al. 2012; Ji et al. 2013; Tian et al. 2018; Froelich and Schnabel 2019). This disease can damage up to 50% of twigs and shoots in individual trees in southern China, but it can also lead to tree death in severe cases (Yang et al. 2022a). Most infections start from abscission wounds during leaf drop and result in cankers that constrict and eventually destroy the vascular system of the entire twig. The disease has also been found on peach fruit, showing sunken and brown lesions. *P. amygdali* was

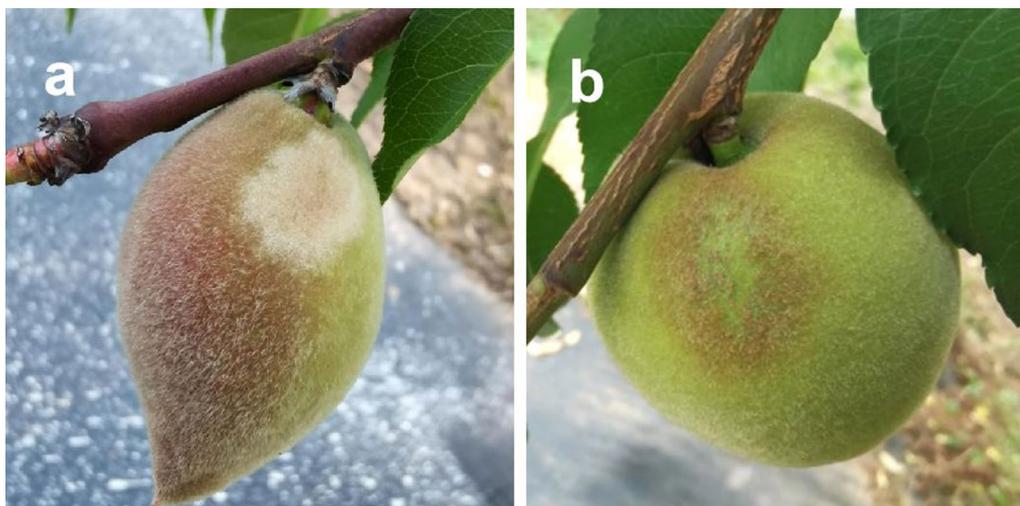


Fig. 5 Symptoms of powdery mildew. **a** White, spherical, and actively expanding spots on young fruitlet (Wuhan, 2022). **b** Older orange-tan, rusty spot on green fruit (Wuhan, 2020)

previously referred to *Fusicoccum amygdali* (Guba 1953). Recently, two new species including *P. liquidambaris* and *Diaporthe eres*, were reported to cause shoot blight (Yang et al. 2022a). In addition to peach, *P. amygdali* can also infect many Rosaceous plants, such as plum, pear, apple, and apricot (Farr et al. 1999; Bai et al. 2015).

Gummosis

Peach gummosis is caused by ascomycete fungi belonging to the *Botryosphaeria* genus, with *B. dothidea* being the predominant species. The earliest symptoms appear as small, raised blisters at natural openings such as stomata and lenticels or near wounds on young shoots. Infected areas on trunks and major branches can exude gummy resins that in severe cases drop to the ground and accumulate next to the tree trunk. Small cankers can coalesce into bigger, rough, and scaly cankerous sections on the bark. Gummosis occurs at relatively warm temperatures primarily on trees predisposed to abiotic or biotic stresses such as herbicide exposure, drought, water logging, and nematodes. The disease gradually increases in severity over the life of the orchard but rarely to the extent of branch or tree death. In addition, *B. rhodina*, *B. obtusa* and *B. ribis* can also cause gummosis. Recently, the fungus *B. parva* (*Neofusicoccum parvum*) was reported to cause peach gummosis in China (Gao et al. 2019).

Shot hole

Peach shot hole is a fungal disease caused by *Wilsonomyces carpophilus*. Fruit and leaf symptoms are small spots, purplish at first, and turn light brown in the center as they enlarge. Leaf lesions may be surrounded by a light green or yellowish zone, generally the brown tissue in the center of lesions will fall out, forming the "shot hole" symptom. The pathogen survives on infected twigs and buds. Spores are produced throughout winter and are spread by splashing water or rain and wind. The disease is favored by prolonged wetness in fall to mid-winter (twig blight). Summer rain or sprinkler irrigation encourages fruit infection. There tends to have more infections lower in the tree canopy where fruit stay wet longer.

Phytophthora root and crown rot

Phytophthora root and crown rot is mainly caused by the oomycetes *Phytophthora cactorum*, *P. cambivora*, *P. megasperma*, and *P. cryptogea*. These oomycetes overwinter and persist in soils as mycelia in infected woods or as thick-walled oospores. When soils are wet, oospores germinate to form thread-like mycelia that can produce sporangia. Zoospores are released from sporangia only when soil is completely saturated with water, infecting susceptible plants. Root and crown rot causes dehydration and death of the bark, which may or may not be

visible (most frequently) under the bark at the soil surface (SEF 2000). Typically, symptoms start a few centimeters below the ground as shades of red of the vascular tissue. The disease development is generally restricted to cankers, with adjacent tissues showing a more or less conspicuous hyperplastic or hypertrophic response. Root rot affects the development of the plants and can lead to whole plant collapse.

Leaf curl

Peach leaf curl is caused by the fungus *Taphrina deformans* (Mix 1935). The pathogen overwinters on the surface of peach twigs. It affects the blossoms, fruit, leaves, and shoots of peaches. The typical symptom is the distorted, reddened foliage in spring. During spring, cool, wet weather slows leaf development and allows more time for leaf curl infection (Fitzpatrick 1934; Mix 1935). If infection is severe, the disease can reduce fruit yield substantially (Pscheidt 1995).

Anthracnose

Peach anthracnose is caused by *Colletotrichum* species, including *C. nymphaeae*, *C. fioriniae*, and *C. godetiae* of the *C. acutatum* species complex, *C. fructicola* and *C. siamense* of the *C. gloeosporioides* species complex, *C. karsti* of the *C. boninense* species complex, *C. truncatum* of the *C. truncatum* species complex, and a singleton species *C. folicola* (Bernstein et al. 1995; Grabke et al. 2014; Hu et al. 2015b; Chen et al. 2016; Tan et al. 2022). Generally, anthracnose is considered a minor disease of peach, however, when the conditions are favorable, it can cause massive economic losses (Hu et al. 2015b; Dowling et al. 2020). The disease mainly occurs on fruit but also leads to leaf or twig lesions. Fruit lesions are generally found on mature or nearly mature fruit but can also be found on young green fruit, which appear as firm, brown, sunken areas and often display concentric rings of small orange acervuli. When leaves are infected, brown lesions with orange acervuli can be observed, and severe twig infections can lead to twig dieback. The fungi overwinter mainly on fruit mummies and in branch cankers as mycelia or conidia. They can also survive on peach debris in soils (Stensvand et al. 2017).

Crown gall

Peach crown gall is caused by the bacterium *Agrobacterium tumefaciens* (de Cleene and de Ley 1976). Rough, rounded galls or swellings occur at or just below the soil surface on the lower trunk or roots (Agrios 2005). The galls disrupt the absorption of water and nutrients, thus weakening and stunting the peach tree over time (Kado 2002). Sometimes the disease becomes systemic and galls are seen above the ground. Galls typically develop

at the site of a wound and new galls may form adjacent to old ones in the following year. The disease is favored by nematode feeding damage, especially in poorly drained or alkaline soils. The *A. tumefaciens* pathogen is a soil-inhabiting bacterium that enters through wounds and starts the infection (Agrios 2005; Kado 2002).

Peach rust

Peach rust is caused by the fungus *Tranzschelia discolor* (Bertrand 1995). Symptoms initiate as pale, chlorotic spots on both leaf surfaces during spring, then form bright yellow and angular lesions (Shin et al. 2019; Vidal et al. 2021). Lesions develop through the summer and into the fall, turning into mature lesions with necrotic yellow halos. Lesions on the lower leaf surface develop rust-brown spore masses. Late in the growing season, lesions may turn dark brown, reddish-to-black with the production of overwintering teliospores. On young shoots, water-soaked lesions appear, then form twig canker with rusty brown masses of urediniospores. On fruit, lesions may develop following leaf symptoms, mainly on later-maturing cultivars. Lesions first appear as small, brownish spots with green halos. When the fruit matures, the lesions are sunken and extend several millimeters in the fruit.

Silver leaf disease

Silver leaf disease is caused by *Chondrostereum purpureum*, a basidiomycete fungus of the Family Stereaceae (SEF 2000). The characteristic symptom is a metallic sheen on the leaves of infected plants. Heavily affected leaves are silvery-grey and curl slightly at the upper edges and may become necrotic. On severely affected plants the foliage is poorly developed and chlorotic; affected shoot and branch sections often show browning of the woody tissue. The appearance of basidiocarps on dead parts of trees is another symptom of the fungus. Trees, or parts of trees, may die within a few months or may, after showing symptoms in spring, recover temporarily or permanently.

Rosellinia root rot

Root rot caused by *Rosellinia necatrix* is a destructive disease observed mainly in Europe and can lead to the wilting of many plants (SEF 2000). There are different types of aerial symptoms that can be observed on fruit trees infected by *R. necatrix*, consisting of defoliation and slow death, or wilting. The symptoms observed in the root system begin with the rotting of small roots by the white mycelia of the fungus, then it invades the large roots, which at first turn brown and then blacken. The invasion spreads through the cortex and cambium of the trunk and progresses upwards, producing sap or gum

exudates on some fruit trees. If the base of the trunk or the roots are peeled back, the typical fan-shaped mycelia can be observed.

Verticillium wilt

Verticillium wilt on peaches is caused by *Verticillium dahliae*. The disease can cause death of trees, especially during their first years of life in isolated trees, which relativizes its economic importance (SEF 2000). Symptoms begin as a wilting that usually affects trees asymmetrically. The leaves at the base of the branch are the first to wither and remain on the tree for some time before falling off. The young leaves at the extremities are the last to do so. Depending on the year, the symptoms of the attacked trees vary in degree, from a normal appearance to a total defoliation and death of the tree at the end of the vegetative cycle.

Identification and detection of peach pathogens

Accurate identification of the causal agent of a given disease is the basis for developing management strategies. In addition to traditional examination of symptoms and signs, molecular tools are available to detect pathogen DNA in host tissues. Polymerase chain reaction (PCR), loop-mediated isothermal amplification (LAMP) (Notomi et al. 2000), recombinase polymerase amplification (RPA) (Piepenburg et al. 2006), and clustered regularly interspaced short palindromic repeats (CRISPR)-associated protein systems (CRISPR/Cas) can identify pathogens to the species level (Sashital 2018; Li et al. 2019). However, none of these methods have been used for routine monitoring.

For peach pathogen detection, several molecular tools have been developed to distinguish *Monilinia* species (*M. fructicola*, *M. fructigena*, *M. laxa*, *M. polystroma*, *M. yunnanensis*, and *M. mumeicola*). For example, *M. fructicola*, *M. fructigena*, and *M. laxa* isolates could be reliably differentiated by the methods of Ioos and Frey (2000), Boehm et al. (2001), Miessner et al. (2010), Hily et al. (2010), van Brouwershaven et al. (2010), Hu et al. (2011), Guinet et al. (2016), Garcia-Benitez et al. (2017). Recently, LAMP and RPA have been gradually developed for peach pathogen detection. For example, the LAMP-based method has been developed to distinguish *M. fructicola* and *M. laxa* on peach and nectarine (Ortega et al. 2019) and to detect *V. carpophila* (Zhou et al. 2021b). Similarly, based on the GME6801 gene sequence, a LAMP-based method has also been developed to detect peach shoot blight fungus *P. amygdali* (Yang et al. 2022b). In 2021, an RPA/Cas12-based method was developed to detect the peach bacterial spot pathogen *Xap*, which could be performed at 37 °C within 2 h (Luo et al. 2021).

Chemical control and fungicide resistance management

Fungicide spray programs

Late dormant stage

In China, lime sulfur is used at bud swell to control overwintering pathogens and pests. In the southeastern US and Spain, copper is applied at that time for bacterial disease, constriction canker (Spain), and leaf curl management.

Bloom and petal fall

In China, pesticides are not recommended during bloom. In USA, sprays begin at full bloom and continue at 10 to 14-day intervals to prevent infections of flowers and young fruit from blossom blight, shot-hole, and peach scab. During bloom only fungicides that do not harm bees are applied and are not used during preharvest season for resistance management. In Spain, non-chemical methods are preferred over chemical methods depending on weather conditions. Conventional fungicides are used only when necessary in very rainy springs. In general, single-site fungicides and fungicides with the least side effects are favored in spray programs.

Shuck split to pit hardening

During early growing season, protectants such as captan, chlorothalonil, and copper are recommended to control peach scab, green fruit rot, shot-hole, powdery mildew, and bacterial spot (copper). Sulfur may be used if rusty spot becomes an issue.

Cover sprays

The period after shuck off to preharvest season is bridged with protectant fungicide applications, typically captan. The use of captan also prevents any inoculum build up for anthracnose disease. Some growers may use sulfur during times of low risk for infection. During this time, at-risk fungicides are not recommended for resistance management purposes.

Preharvest season

In China and USA, single-site fungicides are recommended preferably in mixtures when the fruit turns color from green to yellow and red to manage primarily brown rot. Compared to captan, these at-risk fungicides are more effective in controlling preharvest and post-harvest rots. In areas with high disease pressure, such as the southeastern US, at-risk fungicides are applied in 7-day intervals starting 21–14 days prior to first picking. In Spain, preference is given to non-chemical methods over chemical methods depending on weather conditions. Conventional fungicides are applied prior to rainy

weather. Preference is given to single-site fungicides and fungicides with the least side effects.

Fungicide resistance

Fungicide resistance is a major concern and resistance management practices must be implemented to prolong the effective life span of at-risk fungicides. Resistance management starts with any cultural means to reduce pathogen population size (i.e. sanitation, cultivar choice, pruning, thinning, and orchard floor management, etc.). The use of multisite fungicides such as captan during cover sprays when fruit is the least susceptible is a chemical mean that has the same purpose. At-risk fungicides must be used in moderation and strategically. Single-site MOA (mode of action) type fungicides registered for control of peach diseases belong to the methyl benzimidazole carbamates (MBCs), dicarboximides (DCFs), demethylation inhibitors (DMIs), quinone outside inhibitors (QoIs), and succinate dehydrogenase inhibitors (SDHIs).

Resistance to MBCs

MBCs were first introduced in the late 1960s and proved highly effective specially against brown rot. But by the 1970s resistance to MBCs had emerged in *M. fructicola* and *M. laxa* in USA (Sonoda et al. 1983; Michailides et al. 1987; Zehr et al. 1991; Ma et al. 2003, 2005; Ma and Michailides 2005). Since then, resistance to MBCs has become common in *M. fructicola* and has been reported in New Zealand (Sanoamuang and Gaunt 1995), Korea (Lim et al. 1999), Brazil (May De Mio et al. 2011), Spain (Eguen et al. 2015), and Serbia (Hrustic et al. 2018). Similarly, in China, resistance to MBCs in *M. fructicola* emerged in Beijing, Shandong, and Yunnan provinces (Fan et al. 2009; Chen et al. 2014). Resistance in *M. laxa* to MBCs has also been reported in Spanish (Egüen et al. 2016) and Greek peach orchards (Thomidis et al. 2009; Malandrakis et al. 2012). Mutations at different codons in the β -tubulin gene (*TUB2*) results in different resistance levels to MBCs. In *M. fructicola*, the mutations at codon 6 (H6Y) and 198 (E198A) lead to a low and a high resistance level, respectively (Ma et al. 2003). In *M. laxa*, the mutations at codon 198 (E198A) and codon 240 (L240F) confer the high and low resistance to MBCs, respectively (Ma et al. 2005; Malandrakis et al. 2012).

Resistance to MBCs in *C. acutatum* species complex occurs naturally (Usman et al. 2022) but is acquired in other species. The species *C. siamense* developed resistance to MBCs in USA due to the E198A mutation of *TUB2* (Hu et al. 2015a). In the scab fungus *V. carpophila*, resistance to MBCs was detected in 14 provinces in China and resistance was caused by the E198K and E198G mutations in *TUB2* (Zhou et al. 2021a).

Resistance to DCFs

DFCs were introduced in the late 1970s, and in the 1990s in China (Yuan et al. 1996). Resistance to DCFs in *M. fructicola* was reported in USA (Ritchie 1982), New Zealand (Elmer and Gaunt 1986), Australia (Wherrett et al. 2001), and Spain (Eguen et al. 2015). However, the resistance mechanism is still unresolved. In China, peach anthracnose fungi *C. nymphaeae*, *C. fructicola*, and *C. siamense* are highly resistant to DCFs (Usman et al. 2021, 2022).

Resistance to DMIs

DMIs were first used agriculturally in the 1970s. After more than 2 decades of usage, reports of resistance in *M. fructicola* from Georgia, USA (Schnabel et al. 2004) and from other eastern states were published (Luo et al. 2008). Resistance to DMIs in *M. fructicola* was also described in Brazil (May-De Mio et al. 2011) and Spain as well (Eguen et al. 2015). Overexpression of the 14 α -demethylase gene (*MfCYP51*) was identified to be linked to the resistance (Luo and Schnabel 2008) and a mutation at codon 461 (G461S) of *MfCYP51* was reported from Brazilian isolates (Lichtemberg et al. 2017). The overexpression of *MfCYP51* gene was associated with the 'Mona' element in southeastern populations and isolates from other states (Luo and Schnabel 2008), however, such relationships were not found in populations in Michigan and New York (Villani and Cox 2011; Lesniak et al. 2021).

Interestingly, *Colletotrichum* spp. have differential sensitivities to DMIs. For instance, *C. nymphaeae* was found to be resistant to flutriafol and fenbuconazole, *C. truncatum* was found to be resistant to all tested DMIs, including tebuconazole, metconazole, flutriafol, and fenbuconazole, while some *C. fioriniae* isolates only showed reduced sensitivity to DMIs (Chen et al. 2016).

Resistance to QoIs

QoI fungicides have been used for controlling numerous pathogens on various crops in many countries (Ypema and Gold 1999). In *M. fructicola*, reduced sensitivity to QoIs has been described (Amiri et al. 2010; Chen et al. 2014), but qualitative resistance has yet to be reported. The formation of G143A in the QoI target *Cyt b* gene in this fungus and many others (mostly rust fungi) is impeded by the existence of a group I intron of 1166 bp in size located directly downstream of the codon 143 (Luo et al. 2010). For *Colletotrichum* spp., the evolution and selection of the G143A in *Cyt b* has become a common occurrence. *C. fructicola* developed resistance to QoIs in China, *C. siamense* developed resistance to QoIs in USA, and in all cases resistance is conferred by G143A mutation of *Cyt b* gene (Hu et al. 2015a; Usman et al. 2021).

Resistance to SDHIs

SDHIs were introduced in 2003 for peach disease management in the USA, and soon thereafter, resistance to boscalid in *M. fructicola* emerged in one South Carolina orchard but the mechanism of resistance could not be identified (Chen et al. 2013). For *Colletotrichum* spp., it was found that *C. nymphaeae* is naturally resistant to boscalid (Usman et al. 2022).

Detection of fungicide resistance

Detection of fungicide resistance is crucial for fungicide application and disease management. In general, mycelial inhibition assays are performed by exposing isolates to different concentrations of a fungicide to determine the EC₅₀ value (concentration at which mycelial growth is inhibited by 50%) or MIC value (the lowest concentration at which mycelial growth is completely inhibited (Russell 2003). A rapid method was established to detect DMI fungicide resistance in *M. fructicola* by using Alamar blue or Resazurin as an indicator of respiration (Cox et al. 2009). With knowledge of the molecular mechanisms of fungicide resistance, simple and efficient tools have been developed to detect resistance. Some molecular methods are capable of high-throughput detection and can be used to detect fungicide resistance at low frequencies in pathogen populations. PCR- and sequencing-based methods have been used for detecting fungicide resistance, e.g., AS-PCR for detecting MBC resistance in *M. fructicola* (Ma et al. 2003; Luo et al. 2020), and in *M. laxa* (Ma et al. 2005); PCR-RFLP for detecting MBC fungicide resistance in *M. laxa* (Ma et al. 2005), and DMI fungicide resistance in *M. fructicola* (Luo et al. 2008). LAMP may be the simplest method yet among molecular methods and only requires a *Bst* DNA polymerase and a set of four primers to amplify a target DNA specifically under isothermal conditions (Notomi et al. 2000). The products can be visualized by adding dyes such as SYBR (Pan et al. 2013). A LAMP method has been developed to detect DMI resistance in *M. fructicola* (Chen et al. 2019).

Management of fungicide resistance

In China, peaches are mainly produced by a large number of small farms distributed throughout the country, making it difficult to implement coordinated resistance management practices. In contrast, in southeastern US where the industry is more centralized, resistance is managed by implementation of rigorous resistance management practices. Specifically, MOAs used during bloom are not used preharvest, only multisite fungicides are used during green fruit development, and very specific MOA combinations are used in mixture and rotation during preharvest season. None of the MOAs are used more

than 2 times per season (Schnabel and Brannen 2022). To help with fungicide resistance management, sanitation practices must be implemented to reduce the pathogen's gene pool and the number of sensitive and resistant strains. In Spain, resistance management avoids repeating active ingredients with the same mode of action in the same crop cycle, using active ingredients or mixtures with different modes of action alternately (MAPA 2015).

Continuous farmer education is important for knowledge transfer into the field and to make sure the latest disease and resistance management strategies are implemented. Equally important is researcher education by farmers, who are on the ground day in day out and who have valuable observations on disease and resistance management to share. For this reason, science-based disease and resistance management programs must be implemented by both the researcher and farmer. Regular training programs are important for information exchange on IPM practice implementation, available MOA for disease management, strategy utilization, resistance management, proper disease diagnostics, and more.

In China, a cell phone App using Huizhinongdanjia software has been developed based on deep learning. The content of the cell phone App allows peach growers to recognize peach diseases and to retrieve basic information to make the corresponding management strategies.

In Spain, peach producers are required to minimize the use and risk of pesticides. To achieve this goal, conditions necessary for the implementation of integrated disease management are established, such as advisory services, tools for disease monitoring and decision support systems (Matyjaszczyk 2015).

In the southeastern US, growers follow the Southeastern Peach, Nectarine, and Plum Pest Management and Culture Guide (available at <https://extension.uga.edu/publications/detail.html?number=B1171&%20Nectarine,%20and%20Plum%20Pest%20Management%20and%20Culture%20Guide>) and consult the MyIPM smartphone App (available free of charge from Google Play Store and Apple Store) to diagnose diseases and pests, navigate active ingredients, trade names by FRAC or IRAC codes, look up efficacy ratings, PHI, REI, etc., and learn about non-chemical IPM tools. Farm visits by researchers and county agents, presentations and round table discussions at state-wide and regional fruit grower meetings are additional means for information exchange.

Cultural practices

Many of the above-mentioned diseases can cause serious damage to peach production, however, there are typically only a few causing significant economic losses in any given location. Disease management strategies therefore

differ and are dependent on local climate, the cultivars grown, the production system, and the epidemiology of the local diseases. Nevertheless, there are some disease management principles with value for most locations. Below are some agricultural practices promoting tree health and leading to increased disease tolerance.

Orchard planning

Avoid locations with poor air circulation and poor water drainage. Reduce inoculum sources by removing wild or neglected stone fruit trees nearby. Prior to planting, prepare the soil depending on need. For example, the soil pH may have to be adjusted, nematodes may have to be controlled, organic matter may have to be added to soil, diseased roots from previous trees may have to be raked out, or berms may need to be established on sites with previous ARR problems.

Planting and tree maintenance

Apply proper planting depth (do not bury graft union), optimize fertilization and irrigation, and avoid fall or late spring pruning. Many pathogens able to cause harm to trees enter through pruning wounds. The best time to prune is during dry weather at late dormancy stage. Prune to promote good air circulation will reduce pathogen infection. Avoid pruning immediately before or after a rain. Disinfect pruning tools periodically, especially after cutting trees symptomatic for bacterial canker. Avoid mechanical injuries from equipment.

Orchard sanitation

During pruning, thinning, and harvesting, remove diseased fruit and mummies from the tree and drop to the weed-free ground for rapid decomposition. In China, the diseased fruit is buried to about 30–50 cm depth or moved to a remote location. During winter and summer (if applicable) pruning, cut diseased branches from the tree and either destroy or flail mow pruning cuts soon thereafter.

Fruit wrapping

Wrapping fruit with single or double-layer bags can protect fruits from pathogens and pests, especially for the late maturing cultivars. This practice is commonly used in Chinese commercial orchards but not in the USA or Spain due to labor and cost issues. If the bags are used properly, pesticides are only required prior to bagging.

Resistant cultivars

Planting resistant cultivars is desirable for disease control, however, only some cultivars with resistance to bacterial spot are available. No commercially viable cultivars are resistant to brown rot, scab, anthracnose, or gummosis. Some cultivars, such as Contender and Dahongpao, are less susceptible than others to *Monilinia* spp. infections. Plum/peach hybrid rootstocks are available with resistance to ARR and certain nematodes.

Conclusions

In this review, symptoms, causal agents, and distribution of main peach diseases in China, Spain and USA are described in detail, while other minor diseases are simply introduced. At the same time, identification and detection of peach pathogens are summarized. For better control peach diseases, chemical control and fungicide resistance management, as well as cultural practices are introduced.

Future outlook

Priorities for disease management vary with location. For example, the southeastern US struggles to keep trees alive due to ARR and bacterial canker-caused premature peach tree mortality, while China and Spain are more concerned about managing fruit diseases. Accordingly, the research emphasis in the southeastern US has shifted to breeding for resistance to ARR and nematodes in rootstocks and bacterial spot resistance in cultivars, while in China the emphasis is currently on a better understanding of brown rot disease etiology and epidemiology. Brown rot will remain a major focus of attention worldwide. It did not make the 'top three' list in this publication (Table 1) of economically important southeastern US diseases only because current disease and resistance management practices are strictly followed and are working. In fact, there has not been a single brown rot disease outbreak reported in the entire region for the last 15 years with the exception of orchards that were organically managed. However, the pathogen will eventually adapt and overcome its challenges. Political pressure to reduce and even cancel MOAs from the agricultural markets, especially those with multisite MOA, will force increased use of at-risk fungicides and thus threaten our ability to manage resistance. Single-site fungicides with new MOA are not often produced by companies, and thus the emphasis must be on extending the effective life of MOAs currently registered. Currently there are no routine fungicide resistance monitoring conducted in any country. But technologies such as LAMP-, RPA-based detection kits offer an opportunity for cheaper and faster detection that could be conducted outside the research laboratory.

Bacteria remain very hard to be controlled in peach production due to the lack of effective antibiotics and the ability of the pathogens to adapt. Breeding for bacterial spot resistance is more and more integrated in new selections, however. Future focus could include the role of biofilm in bacterial spot control. Peach surfaces harbor not only pathogens but also beneficial microorganisms that may colonize plants in the same spaces at the same time. Broad spectrum pesticides such as copper may not be desirable because they also reduce beneficial microbes. Future research could target the development of specific pesticides not harming beneficial microbes or promoting a biofilm that protects peach from infection.

Climate change will undoubtedly influence the pest and disease dynamics in the three countries. We expect more weather extremes such as hail, freeze injury in later spring, hotter summers, longer drought spells, more severe thunderstorms, etc., and farmers and scientists will need to adapt in creative ways tailored to their needs and situations, for an improved sustainability.

Abbreviations

ARR: *Armillaria* root rot; AS-PCR: Allele-specific PCR; EC₅₀: The efficient fungicide concentration at which mycelial growth is inhibited by 50%; CRISPR/Cas: Clustered regularly interspaced short palindromic repeats-associated protein systems; *Cyt b*: *Cytochrome b* gene; DCFs: Dicarboximide fungicides; E198A, K, G: Substitutions from glutamic acid to alanine, lysine, and glycine, respectively, at codon 198 of *TUB2*; EPPO: European and Mediterranean Plant Protection Organization; FAOSTAT: Food and Agricultural Organization of the United Nations Statics; FRAC: Fungicide Resistance Action Committee; G143A: Substitution from glycine to alanine, at codon 143 of *Cyt b* gene; G461S: Mutation at codon 461 of *MfCYP51* substituting glycine by serine; IPM: Integrated pest management; IRAC: Insecticide Resistance Action Committee; LAMP: Loop-mediated isothermal amplification; MBCs: Methyl benzimidazole fungicides; MAPA: Ministerio de Agricultura, Pesca y Alimentación; *MfCYP51*: *Monilinia fructicola* *CYP51* gene; MIC: The lowest fungicide concentration at which mycelial growth is completely inhibited; MOA: Mode of action; PCR: Polymerase chain reaction; PCR-RFLP: PCR-restriction fragment length polymorphism; PHI: Preharvest interval; Qols: Quinone outside inhibitors; REI: Re-entry interval; RPA: Recombinase polymerase amplification; SDHIs: Succinate dehydrogenase inhibitors; SEF: Sociedad Espanola de Fitopatologia; *TUB2*: β -tubulin gene; *Xap*: *Xanthomonas arboricola* pv. *pruni*.

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Author contributions

C-X Luo, G Schnabel, M Hu and A De Cal participated in writing the narrative and submitted pictures. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Competing interests

The authors declare that they have no competing interests.

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