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DISEASE CONTROL

Control efficacy of the systemic acquired resistance (SAR) inducer acibenzolar-*S*-methyl against *Venturia nashicola* in Japanese pear orchards

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Abstract

Scab caused by *Venturia nashicola* is one of the most serious diseases of Asian pears, and conventional fungicides used to control scab can lose their efficacy when fungicide-resistant strains develop. In contrast, the efficacy of systemic acquired resistance (SAR) inducers, such as acibenzolar-*S*-methyl (ASM), is regarded as stable because they have complex, orchestrated modes of action. Here, field efficacy and phytotoxicity of ASM on scab were tested during the growing season and after harvest for 3 years. The high efficacy of ASM indicated that it has promise for controlling scab in the field without an unacceptable level of phytotoxicity.

Keywords Acibenzolar-*S*-methyl · Pear · Phytotoxicity · Scab · Systemic acquired resistance · *Venturia nashicola*

Scab, caused by the ascomycete fungus *Venturia nashicola*, is one of the most serious diseases of Asian pears such as Japanese pear (*Pyrus pyrifolia* var. *culta*) and Chinese pears (*P. bretschneideri* and *P. ussuriensis*) (Ishii et al. 2020). *V. nashicola* is a distinct species from *V. pyrina* (= *V. pirina*), the pathogen causing scab of European pear (*P. communis*) (Tanaka and Yamamoto 1964; Ishii and Yanase 2000; González-Domínguez et al. 2017). Very recently, a new interspecific commercial pear cultivar (cv.), Yutaka, with excellent fruit quality was bred to carry high resistance to scab, black spot (pathogen: *Alternaria alternata* Japanese pear pathotype), and anthracnose (caused by *Colletotrichum gloeosporioides* sensu lato) (Ishii and Kimura 2018). However, almost all of the popular Japanese pear cultivars, e.g., Kousui (= Kosui), Housui (= Hosui), and Niitaka are highly susceptible to scab. Therefore, various classes of fungicides are commonly used to control this disease, but frequent fungicide sprays have resulted in the development of strains resistant to benzimidazole (MBC) and sterol demethylation inhibiting (DMI) fungicides (Ishii et al. 1985; Kwon et al. 2010; Ishii 2012; Kikuhara et al. 2018).

To avoid such problems with fungicide resistance, the use of non-antifungal systemic resistance inducers is promising (Ishii et al. 2019). Their modes of action are complex and orchestrated in plants, suggesting that the plant defense mechanisms that are induced will rarely be overcome by pathogens. The synthetic compound acibenzolar-*S*-methyl (ASM, *S*-methylbenzo[1,2,3]thiadiazole-7-carbothiate), an analogue of the defense-related plant hormone salicylic acid, is well known to induce systemic acquired resistance (SAR) against diverse pathogens on various plants (Bektas and Eulgem 2015; Faize and Faize 2018). For fruit trees, the efficacy of foliar ASM applications against scab of Japanese pear was earlier shown in a small trial carried out during the growing season in an experimental field (Ishii et al. 2002). Additionally, ASM was suppressive against fire blight of apple caused by *Erwinia amylovora* (Brisset et al. 2000; Percival et al. 2009; De Bernonville et al. 2014; Johnson and Temple 2016, 2017), and apple scab caused by *V. inaequalis* (Marolleau et al. 2017), bacterial canker of kiwifruit (*Pseudomonas syringae* pv. *actinidiae*) (Reglinski et al. 2013), and powdery and downy mildews of grapevine (*Erysiphae necator* = *Uncinula necator* and *Plasmopara*

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viticola, respectively) (Campbell and Latorre 2004; Dufour and Corio-Costet 2013).

ASM has been registered as Actigard® to control various fungal and bacterial diseases in many countries (Leadbeater and Staub 2007) and is now used to control apple fire blight in the United States and kiwifruit bacterial canker in New Zealand (Wurms et al. 2017). However, phytotoxicity, manifested as growth inhibition, chlorosis and necrosis of leaves of treated plants, is the main limiting factor of resistance inducers for practical use, and of ASM in particular (Ishii et al. 2019). Phytotoxicity of ASM has not been tested on Japanese pear so far and must be carefully assessed when its control efficacy is tested in the field.

Ascospores on fallen leaves and conidia on bud scales serve as the primary source for infection the following spring (Umemoto 1990a, b, 1991; Eguchi and Yamagishi 2008). In addition to regular foliar applications of fungicides during the pear growing season, two to three fungicide sprays of trees are thus recommended after fruit are harvested to decrease pathogen populations that overwinter in orchards. The objectives of the present study were to confirm the control efficacy of ASM on scab after spray applications during the pear-growing season (spring) or after harvest (autumn) in commercial Japanese pear orchards and to assess the potential risk of chemical injury caused by ASM on pear trees.

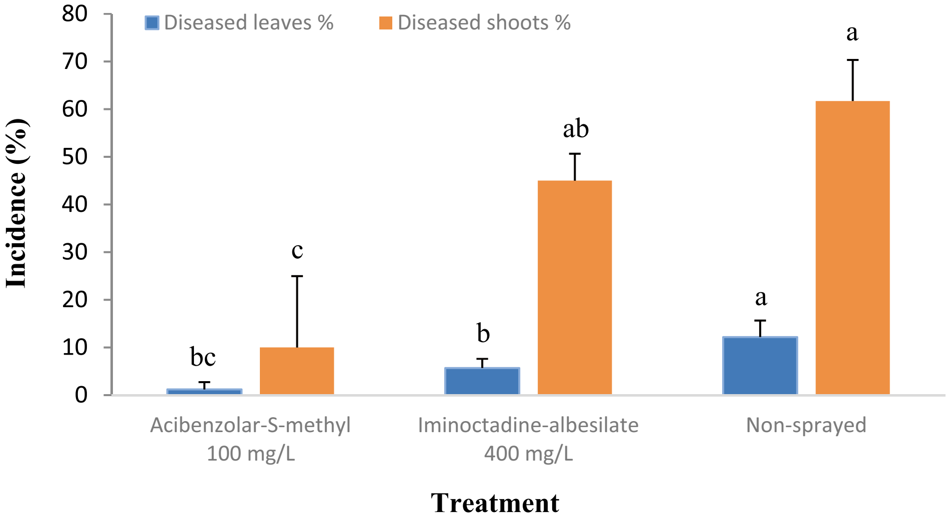
Control efficacy of ASM against pear scab

Tests were conducted in commercial orchards in Hita City, Oita Prefecture, Japan. Experiment (1): in 2016, 15-year-old trees of cv. Niitaka, the third most important in terms of acreage planted in Japan, were tested in three replicates with each of the following three treatments: 50% (active ingredient [a.i.]) water-dispersible granular (WG) of ASM (Actigard®, supplied courtesy of Syngenta) at 100 mg a.i./l, commercial formulations of 40% wettable powder of iminoctadine-albesilate (Bellkute®, purchased), a reference fungicide at 400 mg a.i./l (labeled concentration), and non-sprayed control. Iminoctadine-albesilate is a broad-spectrum fungicide with low risk for resistance development in pathogens, so it is widely used on horticultural crops including Japanese pear by itself or in a mixture with another class of fungicides such as DMIs.

Fungicides were applied after harvest with a speed sprayer three times on October 10, 20 (100 l each spray), and 30 (55 l each spray). No scab symptoms were found on the leaves of Niitaka at the time of the first spray. On November 10, before leaf fall, scab was very noticeable on leaves at the shoot tip. Thus, 15 leaves from the tip to the base of each 20 shoots, 300 leaves in total per replicate, were examined for scab to evaluate the efficacy of the treatments as follows: Diseased leaves % = (Number of leaves diseased/Number of leaves assessed) × 100, Diseased shoots % = (Number of shoots diseased/Number of shoots assessed) × 100, Disease control efficacy % = (Diseased leaves % for non-sprayed treatment − Diseased leaves % for sprayed treatment)/Diseased leaves % for non-sprayed treatment × 100 or (Diseased shoots % for non-sprayed treatment − Diseased shoots % for sprayed treatment)/Diseased shoots % for non-sprayed treatment × 100. Tukey's multiple range test was then used, unless otherwise mentioned, to determine the statistical significance of any difference in means of Diseased leaves % or Diseased shoots % among treatments using R version 3.4.3 (https://cran.r-project.org/bin/windows/base/old/3.4.3/).

As shown in Fig. 1, the average scab incidence on non-sprayed trees was 12.2% (diseased leaves) and 61.7% (diseased shoots), but the three applications with ASM at 100 mg a.i./l gave high control efficacy against scab, 90.2% and 83.8% based on the percentage of diseased leaves and

Fig. 1 Control efficacy of acibenzolar-*S*-methyl against scab disease on Japanese pear (autumn 2016). Different letters among treatments for either leaves or shoots indicate a significant difference according to Tukey's multiple range test ($P < 0.01$ for acibenzolar-*S*-methyl and $P < 0.05$ for iminoctadine-albesilate)



shoots, respectively, and the incidence on ASM-sprayed trees was significantly different from that on non-sprayed trees ($P < 0.01$). On the trees sprayed three times with the reference fungicide iminoctadine-albesilate at 400 mg a.i./l, the average scab incidence on leaves was 5.7% and 45.0% on shoots. Incidence on leaves differed significantly from that on non-sprayed trees ($P < 0.05$). However, the control efficacy of iminoctadine-albesilate was much lower than that of ASM, 53.3% for leaves and 27.1% for shoots. The following spring in 2017, mature pseudothecia of the fungus formed in fallen leaves after the treatment with iminoctadine-albesilate in 2016 and after the non-sprayed treatment. In contrast, pseudothecia formation was largely suppressed in ASM-treated leaves (data not shown). No chemical injury was seen on ASM- or iminoctadine-albesilate-treated trees throughout the trial.

Removal of pear leaves from the ground as a source of ascospores of *V. nashicola* (Umemoto 1990a, b; Eguchi and Yamagishi 2008) to limit infection is important for scab control in the field. As mentioned, pear trees routinely receive two to three fungicide sprays after harvest to suppress bud infection in practice, but interestingly, we first found that ASM treatment reduced lesion development on leaves in the autumn (Fig. 2a, b) and inhibited pseudothecia formation, thus decreasing the primary source for infection the following spring. Some resistance inducers including ASM are known to affect significantly negative impact on plant growth (Yamashita 2004; Heil 2007). In apple and European pear, systemic inducers caused damage to flowers when applied at full bloom and treatment at this growth stage was omitted from the tests (Percival et al. 2009). Early applications of ASM made before transplanting of tobacco caused significant phytotoxicity resulting in reduced plant growth and some mortality. In contrast, established, vigorous plants were not adversely affected by ASM (Csinos et al. 2001). Therefore, spraying ASM after harvest is also a good practice because the potential risk of phytotoxicity from this chemical is lower when leaves and shoots are less active physiologically compared with those actively growing in spring or summer.

Experiment (2): in 2017, three 35-year-old trees each of cvs. Kousui and Housui, first and second most important cultivars in Japan, received one of the following treatments: ASM at 50 mg a.i./l, reference fungicide iminoctadine-albesilate at 400 mg a.i./l, and non-sprayed. Chemicals were sprayed on May 1, 11, and 18 when scab incidence was low, then again (25 l each spray) on May 25, June 1 and 9. Only the main branch was sprayed; the rest of the trees were not sprayed because the trees were so large. Five 2-year-old branches per three replicates, more than 1 m long and bearing abundant axillary flower buds, had been marked previously. On June 19, scab incidence was assessed on the leaves from the first 10 buds from the branch tip because scab is generally found on leaves from sprout base near the tip and on whole fruit on the branches. The number of leaf clusters, whole leaves, fruit clusters, and whole fruit examined is shown in Table 1.

In the non-sprayed plot, scab incidence was low to moderate on Kousui, 1.3% on leaves and 7.3% on leaf clusters (Table 2). On Housui, the incidence was moderate, 6.4% on leaves and 27.0% on leaf clusters. When comparing scab control efficacy, ASM applied at 50 mg a.i./l was almost

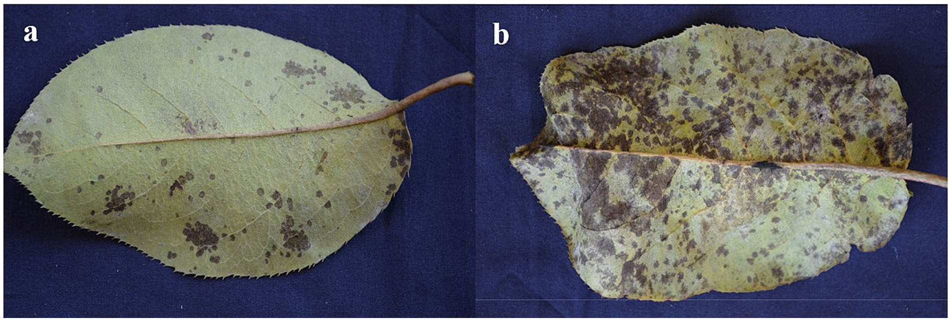


Fig. 2 Autumun-type lesion formation by scab fungus on leaf of Japanese pear **a** sprayed and **b** non-sprayed with acibenzolar-*S*-methyl

Table 1 Number of leaves and fruit examined for scab development in 2017 after treatment with acibenzolar-*S*-methyl, iminoctadine-albesilate or no spray

Treatment	Concentration (mg a.i./l)	Leaf clusters		Whole leaves		Fruit clusters		Whole fruit	
		Kousui	Housui	Kousui	Housui	Kousui	Housui	Kousui	Housui
Acibenzolar-*S*-methyl	50	150	150	1327	1165	98	58	281	129
Iminoctadine-albesilate	400	150	150	1371	1195	116	74	425	135
Non-sprayed	–	150	150	969	1301	124	86	253	187

Table 2 Control efficacy of acibenzolar-*S*-methyl and iminoctadine-albesilate against scab on Japanese pear leaves and fruit in June 2017

Treatment	Concentration (mg a.i. /l)	Cultivar	Incidence on leaves (%)[a]	Efficacy (%)	Incidence on leaf clusters (%)[a]	Efficacy (%)	Incidence on fruit (%)[a]	Efficacy (%)	Incidence on fruit clusters (%)[a]	Efficacy (%)
Acibenzolar-*S*-methyl	50	Kousui	0.9 ± 1.27ab	30.8	2.0 ± 2.26b	72.6	1.5 ± 2.18	83.3	2.2 ± 2.29	76.6
		Housui	0.0 ± 0.00b	100.0	0.0 ± 0.00b	100	0.0 ± 0.00	100.0	0.0 ± 0.00	100
Iminoctadine-albesilate	400	Kousui	0.4 ± 0.39b	69.2	2.0 ± 2.26b	72.6	0.7 ± 0.66	92.2	3.0 ± 2.99	68.1
		Housui	2.4 ± 3.09ab	62.5	14.0 ± 10.37ab	48.1	4.2 ± 4.11	0.0	5.7 ± 6.01	0.0
Non-sprayed	–	Kousui	1.3 ± 0.50ab		7.3 ± 2.61b		9.0 ± 7.34		9.4 ± 6.96	
		Housui	6.4 ± 4.94a		27.0 ± 9.71a		2.1 ± 2.28		4.2 ± 4.22	

There was no significant difference among treatments for incidence on fruit or on fruit clusters

Different letters between means in a column indicate a significant difference according to Tukey's multiple range test ($P < 0.05$ and $P < 0.01$ to 0.05 for incidence on leaves and on leaf clusters, respectively)

[a] Means ± 95% confidential interval are given

equal or superior to iminoctadine-albesilate sprayed at 400 mg a.i./l (Table 2). On Kousui sprayed with ASM, disease control was 30.8% for leaves and 72.6% for leaf clusters, whereas the efficacy was 100% on Housui. On fruit of Kousui, ASM was highly effective, with disease control of 83.3% on fruit and 76.6% on fruit clusters (Table 2). This level of control is acceptable in practice when compared with that for iminoctadine-albesilate (92.2% and 68.1% efficacy, respectively). On Housui, ASM also gave 100% control on fruit and fruit clusters. In contrast, for some reason, the reference fungicide was not effective; scab levels were equivalent to those on the non-sprayed control. Leaf hardening and rippling of leaf margins were seen on both pear cultivars immediately after the first spray of ASM on May 1 (Fig. 3a, b), but this injury gradually became inconspicuous. Such phytotoxicity was not seen after the sprays on May 11 and 18, suggesting that leaves are more resistant to chemical injury as they age. In this study, scab incidence on leaves and leaf clusters of non-sprayed Kousui might have been too low to evaluate the efficacy of ASM. The low incidence on fruit and fruit clusters of non-sprayed Housui also made it uncertain to judge the efficacy. Regarding this, however, ASM showed 93.9% and 78.1% efficacy when sprayed at 50 mg a.i./l four times during the growing season under higher disease pressure in two field trials where scab incidence was 31.1% and 11.5%, respectively, on leaves of non-sprayed Kousui (Ishii et al. 2002). On the basis of all these results, a spray of ASM at 50 mg a.i./l during the growing season was determined to be practical to control pear scab in the field.

Experiment (3): in the autumn of 2017, Experiment (1) was repeated to confirm the reproducibility of the high ASM efficacy found in 2016 when applied after harvest. Three 16-year-old trees of Niitaka each received one of the following treatments: ASM at 50 mg a.i./l, the reference fungicide iminoctadine-albesilate at 400 mg a.i./l, and non-sprayed plots were prepared. Concentration of ASM was reduced from 100 to 50 mg a.i./l, which was high enough to control scab in the tests in the spring as mentioned above. Because harvest of Niitaka fruit was delayed 10 days or so compared with a typical year, trees were sprayed on October 21 and 30 and November 6 and 13. Because scab incidence was extremely low in early November 2017, we extended the spray schedule to four applications instead of three as in 2016. As before, 100 l was sprayed per treatment, enough to cover the plots. On November 24, all attached leaves on 15 shoots per replicate were assessed using a loupe because autumn-type lesions bearing only few conidia were abundant on leaves of non-sprayed plots. Scab incidence was grouped into two types based on the lesion type, spring-type bearing abundant conidia and autumn-type (Table 3), although it is well known that formation of spring-type lesions is low in autumn (Tanaka and Yamamoto 1964). Control efficacy by ASM was 75.6% against spring-type lesion formation and

81.8% against autumn-type lesions. In contrast, iminoctadine-albesilate gave 73.3% and 93.1% control, respectively, of the two lesion types.

Experiment (4): to confirm the high efficacy of ASM when sprayed during the pear-growing season, Experiment (2) was repeated in 2019. Two cultivars Housui and Kousui (37-year-old both) were used. ASM (100 mg a.i./l) and 30% flowable iminoctadine-albesilate (200 mg a.i./l, labeled concentration) were first sprayed on March 29, then every 7 days until May 4 (six sprays total). Ishii et al. (2019) reported the longevity of ASM efficacy on cucumber powdery and downy mildew control in a plastic greenhouse. Pear scab was also controlled well by ASM sprays at 4-week intervals in an experimental field in Ibaraki, Japan (Ishii et al. 2002). Therefore, one additional plot received ASM sprays at 14-day intervals (three sprays total). The spray history and phenological stage of the pear trees are described in Table 4; the results are shown in Table 5.

The 7-day-interval sprays with ASM at 100 mg a.i./l gave very high scab control (98.4%) equivalent to that of iminoctadine-albesilate (98.5%) at 200 mg a.i./l. The 14-day-interval sprays with ASM at 100 mg a.i./l still showed high efficacy (84.0% control) with a significant difference in scab incidence compared with the incidence in non-sprayed

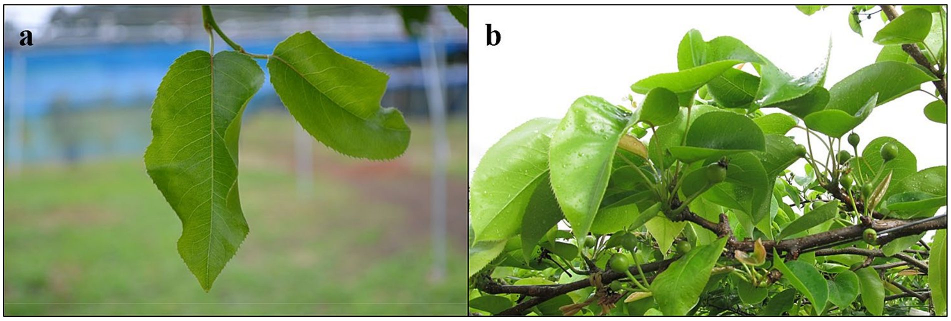


Fig. 3 **a** Leaf hardening and rippling of the leaf margins of Japanese pear (cv. Kousui) 10 days after one spray with acibenzolar-*S*-methyl at 50 mg a.i./l in May 2017. **b** Healthy leaves of Japanese pear

Table 3 Control efficacy of acibenzolar-*S*-methyl and iminoctadine-albesilate against scab disease on Japanese pear leaves in autumn 2017

Treatment	Concentration (mg a.i./l)	Incidence of spring-type lesions (%)[a]	Efficacy (%)	Incidence of autumn-type lesions (%)[a]	Efficacy (%)
Acibenzolar-*S*-methyl	50	1.1 ± 1.14	75.6	10.0 ± 3.68b	81.8
Iminoctadine-albesilate	400	1.2 ± 0.36	73.3	3.8 ± 3.36bc	93.1
Non-sprayed	–	4.5 ± 4.36	–	55.0 ± 15.35a	–

There was no significant difference among treatments for incidence of spring-type lesions

Different letters between means in a column indicate a significant difference according to Tukey's multiple range test ($P < 0.01$ and $P < 0.001$ for acibenzolar-*S*-methyl and iminoctadine-albesilate, respectively, for incidence of autumn-type lesions)

[a] Means ± 95% confidential interval are given

Table 4 Spray history and phenology of pear trees used in the tests (spring 2019)

Treatment	Concentration (mg a.i./l)	Spray interval (d)	Spray[a]					
			1st (29 March)	2nd (6 April)	3rd (13 April)	4th (20 April)	5th (27 April)	6th (4 May)
Acibenzolar-*S*-methyl	100	7	×	×	×	×	×	×
	100	14	×		×		×	
Iminoctadine-albesilate	200	7	×	×	×	×	×	×
Non-sprayed								
Phenological stage of pear trees		Housui	Bud scale deatachment	20% Blossom	Full blossom	80% Petal falls	Fruit set	
		Kousui	Bud scale deatachment	5% Blossom	Full blossom	80% Petal falls	Fruit set	

[a] ×: sprayed

Table 5 Control efficacy of acibenzolar-*S*-methyl and iminoctadine-albesilate against pear scab on leaves in spring 2019

Treatment	Concentration (mg a.i./l)	Spray interval (d)	Number of leaves assessed	Number of leaves diseased	Incidence (%)	Efficacy (%)	95% confidential interval of risk ratio[a] (lower and upper limits)
Acibenzolar-*S*-methyl	100	7	3975	2	0.1	98.4	0.004 and 0.065
Acibenzolar-*S*-methyl	100	14	4395	22	0.5	84.0	0.102 and 0.250
Iminoctadine-albesilate	200	7	4154	2	0.0	98.5	0.004 and 0.062
Non-sprayed	–		4462	140	3.2		

[a] Against non-sprayed control

control, but the sprays were slightly inferior to the 7-day-interval sprays with ASM or the reference fungicide. No phytotoxicity was seen on leaves or fruit throughout the experiment.

Potential risk for phytotoxicity of ASM

In 2018, two experiments were conducted at a commercial orchard located in Hita to evaluate various concentrations of ASM for phytotoxicity after only one or two applications in the spring. Experiment (5): three side branches of one tree each of cvs. Kousui, Housui (both 36-years-old), and Shinko (about 50-years-old) were used. On April 13, whole leaves and fruit were sprayed individually until run-off with ASM at 8.3, 12.5, 16.7, 25, 50, or 100 mg a.i./l using a hand sprayer. Non-sprayed side branches were used as the control. Presence or absence of phytotoxicity was assessed visually on April 16, 22, and 26 and May 1 and 15 (3, 9, 13, 18, and 32 days after treatment, respectively). A slight chemical injury-like syndrome, that is, tiny black spots, was observed only on young fruit of Housui (Fig. 4a–c) on May 1, regardless of treatment including the non-sprayed control, and no further development of the syndrome was seen. The spots were thus judged not to be chemical injury.

Experiment (6): one side branch of Kousui and Housui was sprayed with ASM at a concentration ranging from 16.7 to 1000 mg a.i./l on April 26 and May 11. Branches were assessed on May 1, 11, 15, and 29. Tiny black spots were found only on the fruit of Housui after the first spray of ASM at all concentrations used, but again the black spots were also found on non-sprayed controls. They were not distinguishable on mature fruit, and fruit quality was not affected.

Experiment (7): in 2018, the test in Experiment (6) was extended to three side branches for each treatment at an experimental orchard in Oita Prefectural Agriculture, Forestry and Fisheries Research Center, Usa, Oita, Japan using cv. Niitaka (about 50-years-old). ASM was applied at 16.7, 50, 100, 250, and 1000 mg a.i./l on April 28 as above and phytotoxicity examined on May 1 and 11 (3 and 13 days after treatment, respectively). Only a slight chemical burn was seen on the tip of the soft leaves at the shoot apex (Fig. 5a–c), but it was judged to be no practical problem.

Taken together, ASM sprays gave high control efficacy against Japanese pear scab caused by *V. nashicola* when applied to trees either during the growing season in spring or postharvest in autumn. Percival et al. (2009) reported the effectiveness of a foliar spray application of three resistance inducers including Rigel, a salicylic acid derivative (chemical structure unknown), on the control of apple and European pear scab with no phytotoxicity found except when the

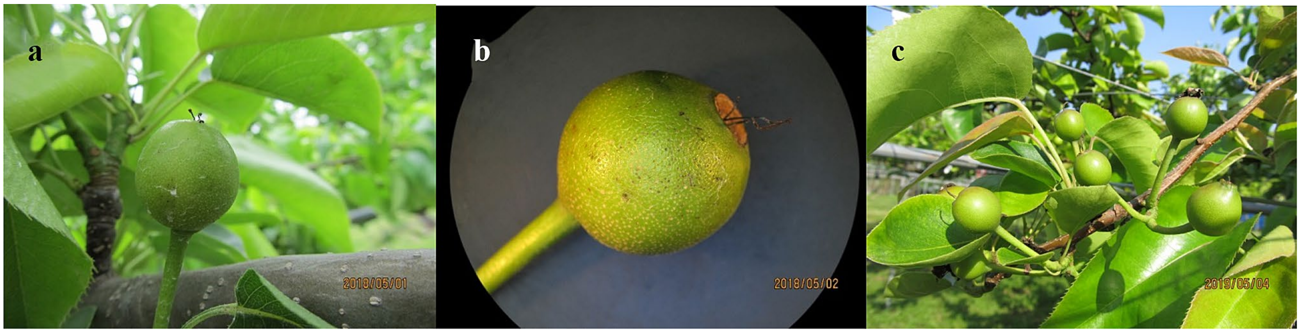


Fig. 4 Tiny black spots observed on the young fruit of Japanese pear (cv. Housui) **a** 18 days and **b** 19 days after one spray with acibenzolar-*S*-methyl at 50 mg a.i./l in April 2018. **c** Healthy fruit of Japanese pear

Fig. 5 **a**, **b** A slight burn seen on the tip of the soft leaves at the shoot apex of Japanese pear (cv. Niitaka) 4 days after one spray with acibenzolar-*S*-methyl at 1000 mg a.i./l in April 2018. **c** Healthy leaves of Japanese pear

treatment was applied at full bloom. They applied this chemical at four growth stages (from bud break to early fruitlet) of tree development in two fields. In the current study, the tests were carried out in Hita City, Oita Prefecture about 890 km from Tsukuba City, Ibaraki Prefecture where the first field study of ASM on scab control was reported (Ishii et al. 2002). Thus, the control efficacy of ASM is reproducible in regions with differing climatic conditions such as temperature and precipitation. Regarding the concentration of this compound, 100 mg a.i./l is suitable for spraying after harvest and 50 mg a.i./l for spraying during the growing season. Phytotoxicity caused by ASM was noted when applied at 50 mg a.i./l in the spring, but the level of toxicity did not seem to be problematic in practice. In addition, phytotoxicity was not apparent when ASM was sprayed at 100 mg a.i./l in autumn. Application in spring is expected to minimize the number of autumn-type lesions on leaves and the number of conidia produced on them. In addition, application after harvest is a promising strategy in particular because the density of ascospores from fallen leaves and conidia from bud scales will also be reduced in the following spring. Marolleau et al. (2017) found that two successive applications of ASM were far more effective than one application in terms of level and duration of protection against apple scab. Therefore, before introducing ASM in the management strategy for pear, optimal spray conditions such as application number, timing, interval, cultivar specificity, and age of trees need to be tested in further experiments.

SAR is a highly desirable form of resistance that generally provides long-lasting and broad-spectrum resistance in plants (Kachroo and Robin 2013; Ishii et al. 2019). From the intensive studies of the mechanisms of ASM-induced resistance in the Japanese pear—*V. nashicola* pathosystem, the expression of resistance results from multiple, complex mechanisms as described below. Thus, these mechanisms will be difficult for the pathogen to overcome. Treatment of Japanese pear with ASM induces and potentiates the expression of defense-related genes that are involved in the signal network, including leucine-rich repeat receptor-like protein kinase (*LRPK*), a non-expresser of pathogenesis-related protein 1 (*NPR1*), a respiratory burst oxidase homologues (*RBOH*), and a mitogen-activated protein kinase (*MAPK*), after inoculation with the fungus (Faize et al. 2004, 2007, 2009). Transmission electron microscopy showed that growth of *V. nashicola* was suppressed in leaves of ASM-pretreated pear trees (Jiang et al. 2008). ASM-induced scab resistance might be associated with proteins secreted from pear because the activity and/or production of pectin-degrading enzyme from fungal hyphae is inhibited after ASM application, and gene expression for polygalacturonase-inhibiting protein (PGIP) is highly and rapidly activated in resistant pear cultivars (Faize et al. 2003). In addition, PGIP extracts from resistant pears inhibit the activity of polygalacturonase produced by *V. nashicola*, suggesting that PGIP might be responsible for the restricted fungal growth typical in resistant cultivars (Faize et al. 2003).

In field trials in Korea, ASM was used instead of a conventional fungicide four times in the middle of a 10-spray schedule, and its control efficacy on pear scab was equivalent to that of the conventional programme (Kim et al. 2018). Thus, ASM can control scab and be used to establish an effective programme. Resistance inducers can be introduced into integrated crop management rather than used as alone, and higher levels of protection from several diseases are expected (Reglinski et al. 2007). The success of ASM when integrated into apple scab management during the primary infection period seems to allow a significant reduction of fungicides (Marolleau et al. 2017). Such approaches are particularly important to reduce the number of applications of single-site fungicides, which carry a high risk of resistance development by the pathogen (Ishii et al. 2019). In March 2020, a commercial formulation of ASM (Actigard® 50WG, Syngenta) was released in Japan to control bacterial diseases in cabbage and Chinese cabbage and is now undergoing official trials for registration to control pear scab based on our study.

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Declarations

Conflict of interest We declare that there are no conflicts of interest.

Human and animal rights This article does not contain any studies with humans or animals.

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