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ORIGINAL ARTICLE

Effectiveness of lime sulphur and other inorganic fungicides against pear scab as affected by rainfall and timing application

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Abstract Pear scab, caused by *Venturia pirina*, is the most significant pear disease, causing economic losses in many pear production areas. In organic pear growing, scab control is based on the protective use of copper, or sometimes wettable sulphur. As the use of copper is subject to European restrictions and wettable sulphur has some phytotoxic effects on the main cultivated cultivars, new control strategies are needed. The aim of this study was to determine, under controlled conditions, the preventive and curative action and the rainfastness of such new fungicide formulations available for organic pear farming. The study shows that protective applications, at 300 degree-hours (DH) before inoculation, of copper hydroxide (0.1%), wettable sulphur (1%), lime sulphur (2%) and potassium bicarbonate (1%) significantly reduced pear scab severity with more than 96% effectiveness. On susceptible cultivars, under high scab pressure, lime sulphur, wettable sulphur and potassium bicarbonate are still effective for pear scab control until 300 DH after inoculation. From 300 to 650 DH after inoculation, effectiveness decreases gradually for all formulations, but lime sulphur still remains the most effective. However, with two successive applications, at 300 and 650 DH after inoculation, the second application did not provide a significant increase in protection. In addition, lime sulphur revealed a high resistance to rain compared to copper, wettable sulphur and bicarbonates, providing effective scab control and rainfastness after a simulation of 30 mm of rain. At the doses tested, no phytotoxic effect was visible for any of the compounds. Phytotoxic effect appears with wettable sulphur and potassium bicarbonate used at 2%. The potential and limitations of protection strategies against pear scab in organic farming are discussed.

Keywords Curative fungicide · Lime sulphur · Organic farming · Pear scab · Potassium bicarbonate · Rainfastness

Introduction

In Belgium and the Netherlands, pear growing is still gaining in importance, and nearly 50% of the top fruit area in these countries is planted with pears. The 'Conference' cultivar (cv) is by far the most important cultivar grown. Pear scab, caused by *Venturia pirina*, is the most significant pear disease, causing economic losses in many pear production areas. Its significance is indicated by the fact that up to 15–20 fungicide treatments per season are applied, mostly to control scab. With modern, integrated disease control strategies the number of treatments could be reduced to 4–7 applications, using curative fungicides after conditions for scab infections are fulfilled [1, 25, 39, 40]. Simulation models based on weather data reliably predict infection periods, but the success of these control strategies strongly depends on the availability of efficient curative fungicides. In integrated pest management production, several chemical fungicides were used until both *V. pirina* and *V. inaequalis* developed resistances against these active compounds [4, 14, 17–19, 26, 30].

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In organic pear growing, protective sprays with copper, sulphur or lime sulphur are usually used for pear scab control. But protective sprays have to be repeated when new leaves unfold, and protective spray schemes depend on the accuracy of weather forecasting methods. Moreover, cv. 'Conference', the main cultivar cultivated in Belgium, is susceptible to wettable sulphur compounds, the leaf and fruit phytotoxic impacts of which make them less usable. Fruit russeting resulting from copper applications as well as European restrictions on copper use also create the need for alternative products for pear scab control. In order to improve the efficacy of treatment timing, organic growers started to apply lime sulphur during the period when the fungus needs to germinate on the leaf surface [13], Kunz and Hinze [21]. The germination period lasts 8–40 h, depending largely on the temperature and the wetting periods, and fungicide applications have to be performed just after rainfall on wet or drying leaves. Through the use of curative control agents, which could be applied after the fungus has established its primary stroma under the cuticle, protective treatments could be avoided and the time span for the application after germination could be prolonged.

Lime sulphur has already been shown to be useful as a curative application for apple scab control [10, 28], but has sometimes also shown phytotoxic effects. In several trials under controlled and field conditions, potassium bicarbonate has been demonstrated as an effective control agent against apple scab, including curative action in some cases [12, 13, 21, 32, 42]. Unfortunately, similar studies focusing on pear scab are seldom performed.

The phytosanitary products usually used against fungus in organic farming are mainly contact fungicides, acting on the upper leaf surfaces, and are not likely to be systemic or curative. They are therefore easily washed off by small amounts of rain. Today, there is a lack of quantitative information regarding the behaviour of alternative fungicides and the levels required to fully protect the pear trees against scab [35]. Usually, for copper and sulphur compounds, 20 mm of precipitation is the threshold recommended by commercial companies before the treatment application has to be renewed. A general rule of thumb that is often used is that 5 mm of rain removes about 50% of the protectant fungicide residue and over 5 mm of rain will remove most of the spray residue [21, 22]. However, newer "sticky" formulations and fungicides applied with spreader stickers may be more resistant to wash-off by rain. Also, fungicides and formulations differ a lot in their ability to adhere to plant surfaces. Therefore, research is needed to describe the effect of rain on wash-off for specific products.

Most rainfastness studies have focused on synthetic fungicides [2, 7, 8, 31, 34, 35, 38, 45, 46]. While the main inorganic fungicides have been used for a long time, very few studies have focused on their rainfastness [9, 29, 33, 41, 44]. These studies are restricted to copper and have never focused on pear trees, although considerable differences in the upper leaf surface characteristics and the retention or rainfastness of the contact fungicides were found among species [5, 8].

It is therefore of great interest to organic pear growers to gain a better understanding of (i) the curative effect of preparations for pear scab control and (ii) the rainfastness of available inorganic products with regard to pear leaves.

The aim of this study was to give answers to such questions by testing under controlled conditions various new fungicide formulations available for organic pear farming, with a view to adapting the timing of treatment applications and reducing the amount of fungicide applications according to the climatic conditions.

Materials and methods

Plant material

As cv. Conference fruits contain very few useful seeds suitable for seedling productions, experiments were carried out on pear seedlings from trees of cv. 'Doyenné du Comice' pollinated with cv. Conference, which is characterised by a high susceptibility to scab. After dry storage, the seeds were stratified in moist peat at 2 °C for 80–90 days. The pear seeds were raised in commercial potting soil mixture under greenhouse conditions at 18 ± 2 °C and 80% relative humidity in a 12-h light regime. Six-week-old plants at the six-leaf stage were used for the experiment.

Controlled inoculation

A mixture of strains of *Venturia pirina* isolated from newly infected fruits and leaves from unsprayed orchards of various cultivars in central Belgium was used for the experiments. The inoculum was prepared as described by Szkolnick [36]. For infection experiments, conidia were collected in distilled water and the suspension was adjusted to 1.5×10^5 living conidia ml^{-1}, using a hemocytometer. Seedling inoculations were carried out with an automatic bench sprayer machine in the laboratory. The conidial suspension was sprayed at the 'just before run-off' stage. Immediately after inoculation, the plants were incubated in a dew chamber at 100% relative humidity for 48 h at 18 °C to provide optimal infection conditions. The treatments were randomised within the mist chamber in a complete block design.

Fungicide application

The chemicals tested included wettable sulphur (Thiovit jet, 80%, Syngenta Agro, Saint Cyr l'Ecole Cedex, France), copper hydroxide (Ko-Plus 40, 40%, Dupont, Wilmington, Delaware, USA), lime sulphur (Curatio®, calcium polysulphide, 23% of elemental sulphur, Biofa AG, Münsingen, Germany), and potassium bicarbonate (Armicarb APC-09CD, 85%, Helena Chemical Company, Collierville, TN, USA). Armicarb is registered in Belgium and labelled as a biocompatible fungicide. The five treatments in both experiments were as follows: (1) water control as untreated control, (2) 1% potassium bicarbonate from Armicarb, (3) 1% sulphur from wettable sulphur, (4) 2% lime sulphur (corresponding to 0.5% sulphur from lime sulphur), (5) 0.1% copper from the hydroxide form. A single spray of fungicide was applied to young pear seedlings, with a hand sprayer machine in the laboratory. The volume of treatment was defined to ensure as many droplets as possible on the leaf while avoiding run-off ('just before run-off'). Thanks to this technique, the volume of treatments applied to seedlings was nearly the same for each experimental object.

Artificial rainfall simulation

Rainwater was used to simulate natural rainfall with a laboratory rain simulator (RS-100, Department of Agricultural Engineering, Walloon Agricultural Research Centre, Gembloux, 1997). The RS-100 rain simulator (length 4.0 m; width 1.4 m; height 2.0 m), with a useful area of 1.8 m^2 (3.0 m × 0.6 m), is equipped with two individually controlled flat-fan nozzles fixed to a mobile horizontal bar. A bench moves the plants very slowly below the nozzles. Rain intensities are achieved by combining nozzle types, water pressure at the nozzles, the interval between bench movements and the movement speed of the bench supporting the plants. The homogeneity of the rainfall was evaluated in the RS-100 testing phases by placing several rain gauges in the effective area. Furthermore, monitoring was performed during the experiments by placing three rain gauges, randomised between the plants. Due to the large distance between the nozzles and plants (0.8 m), the raindrops hit the plant surfaces at a nearly vertical angle. Precipitation was simulated at heavy rain intensity (8 mm/h), with a medium droplet volume diameter of 500 μm. The volume and duration of rain varied according to the objective of the experiment, as described below.

Effect of treatment timing on chemicals' effectiveness for pear scab control

In a first set of experiments, plants were sprayed once up to just before run-off with a freshly prepared solution of wettable sulphur, copper hydroxide, lime sulphur or potassium bicarbonate. The seedling treatments, inoculation and incubation were carried out as described above. The experiment was conducted in a controlled climate greenhouse at 18 °C. The treatment timings, defined as the number of hours multiplied by the mean temperature in degrees Celsius (degree-hours or DH) between the onset of the inoculation and the time of application, were 300 DH before the inoculation or 300 and 650 DH after the inoculation. In one case, treatments were applied twice, at 300 and 650 DH after inoculation. The experimental design included 45 plants (3 replicates of 15 seedlings) per treatment x timing; 900 plants were therefore used for the experiment. Disease incidence and severity were assessed as described below.

Effect of simulated rainfall on chemicals' effectiveness for pear scab control

In a second set of experiments, freshly prepared aqueous solutions containing chemicals were sprayed once onto the upper surface of pear seedling leaves 18 h before artificial rain applications. The drying time of the fungicide deposit was therefore 18 h ($T = 20$ °C, $RH = 70\%$). "Water-treated samples were used as the control". With the objective of evaluating the influence of rain quantity at the same rain intensity (8 mm/h), pear seedlings were subjected to 5, 10, 15, 20, 25 and 30 mm of simulated rain during 0.6, 1.2, 1.8, 2.4, 3.0 and 3.6 h, respectively. Treated seedlings that were not exposed to rain served as a control (0 mm rain). Rainwater was used to simulate natural rainfall with the laboratory rain simulator. After rain exposure, plants were returned to the growth chamber ($T = 20$ °C, $RH = 70\%$) for 3 h, so that leaf surfaces could dry before the seedlings were used for artificial inoculation. The artificial inoculation was scheduled for completion 24 h after the protective treatments. After treatment, the plants were incubated for 48 h in a dew chamber at 100% relative humidity. They were then placed on greenhouse benches at 18 °C and 80% relative humidity for 3 weeks to promote plant and disease development. There were 45 plants (3 replicates of 15 seedlings) per treatment × rain; 1575 plants were therefore used for the experiment. Disease incidence (proportion of infected leaves) and severity (leaf area infected) were assessed 21 days after inoculation by examining five sprayed leaves per seedling [23].

Conidia production and conidia germination rates

Conidia production was measured by adding a wet agar disc (4 mm in diameter) to the leaves approximately at the centre of the scab symptoms (4 weeks after inoculation) for

2 s. Discs were then placed in the dark at 20 °C and 100% RH for 36 h. After this, the total observed and germinated conidia were counted accurately under a light microscope (100× magnification sight). The relative rate of conidia production (%) was calculated by the following formula: (treated disc result/untreated disc result) × 100. The relative rate of conidia germination (%) was calculated by the same formula as above. The experiment was repeated six times for each treatment and timing.

Phytotoxicity study

In this experiment, solutions of the previously mentioned chemicals were sprayed at 50, 100 and 200% of the concentration described above. Each solution was applied with the bench sprayer machine in the laboratory to the upper surface of 40 healthy seedlings until just before run-off. The plants were 5 weeks old at the time of treatment. Visible leaf phytotoxicity (necrotic area) was recorded on the 10th day after treatment. As phytotoxicity on cv. Conference occurs on leaves and fruits, the experiment on seedling leaves has extended value. A qualitative assessment was conducted on the third and fourth leaf of each seedling. Leaf phytotoxicity was scored using the following assessment scale: –, no damage; +, 0–2%; ++, 2–5%; +++, 5–20%; and ++++, >20% of the leaf surface damaged.

Experimental design and data analysis

Each greenhouse experiment was arranged in a completely randomised split-plot design with six replicates of 15 seedlings for each treatment x variable ‘rain quantity’ or ‘timing DH’. Each complete experiment was repeated twice to verify the repeatability of the results. The percentage data were transformed into arcsine angles before performing an analysis of variance. The data were analysed using statistical SAS software, and the Student–Newman–Keuls test was applied as a mean variance analysis. The mean and standard error of the mean for each treatment are given in the figures. All statistical analysis was conducted at a significance level of $p < 0.05$. The Student–Newman–Keuls multiple range test at $p < 0.05$ was used to establish the differences among treatments.

Results

Effect of treatment timing on chemicals’ effectiveness

Artificial inoculation provided heavy disease pressure, as revealed by the high scab infection rates recorded in the untreated controls in both experiments (Figs. 1, 2 and 3). Protective applications of wettable sulphur (1%), lime sulphur (2%) and copper hydroxide (0.1%) significantly reduced pear scab incidence (proportion of infected leaves) and severity (leaf area infected), with 92–98% effectiveness. Protective applications of potassium bicarbonate (1%) reduced scab incidence and severity by 82 and 84%, respectively (Fig. 1). Applications of lime sulphur at 300 degree-hours (DH) after inoculation controlled pear scab severity with 99% effectiveness, but under curative applications at 650 DH, lime sulphur effectiveness was reduced to 70% (Fig. 1). Applications of copper hydroxide after inoculation were less effective than wettable sulphur and potassium bicarbonate. Potassium bicarbonate reduced scab severity by 72 and 50% at 300 and 650 DH respectively. Two applications after inoculation, at 300 and 650 DH, slightly enhanced the effectiveness of wettable sulphur and potassium bicarbonate.

Effect of simulated rainfall on chemicals’ effectiveness

This study showed a great difference of retention between formulations. Among sulphur formulations, lime sulphur showed significantly higher pear scab control in comparison with wettable sulphur formulations whatever the rainfall application rate (Figs. 2 and 3). This indicates that the adhesion capacity of the wettable sulphur formulation was lower than lime sulphur, since both formulations have the same effectiveness under protective applications (Fig. 1). After 30 mm of rainfall, lime sulphur showed better behaviour, showing 85 and 92% effectiveness for scab incidence and scab severity control, respectively. The artificial rainfalls of 5 mm were sufficient to reduce significantly the scab control effectiveness of copper and wettable sulphur. However, after 30 mm of rainfall, copper and sulphur controlled scab severity with 64 and 75% effectiveness, respectively. Concerning potassium bicarbonate, 5 mm of artificial rainfall was sufficient to reduce significantly the control of scab incidence and severity, from 85 and 92% to 32 and 60% effectiveness rates, respectively.

Conidia production and conidia germination rates

The relative rates of conidia production and conidia germination of pear scab were significantly affected by treatments and timing (Table 1). The rates of conidia production and conidia germination were 0% for lime sulphur applied at 300 DH after inoculation in comparison with the untreated control (100%). When lime sulphur was applied at 650 DH, the rates of conidia production and conidia germination were about 29 and 90%, respectively, in comparison with the untreated control (100%). Potassium bicarbonate applied at 300 DH reduced the rate of conidia production by about 70%, but not the conidia

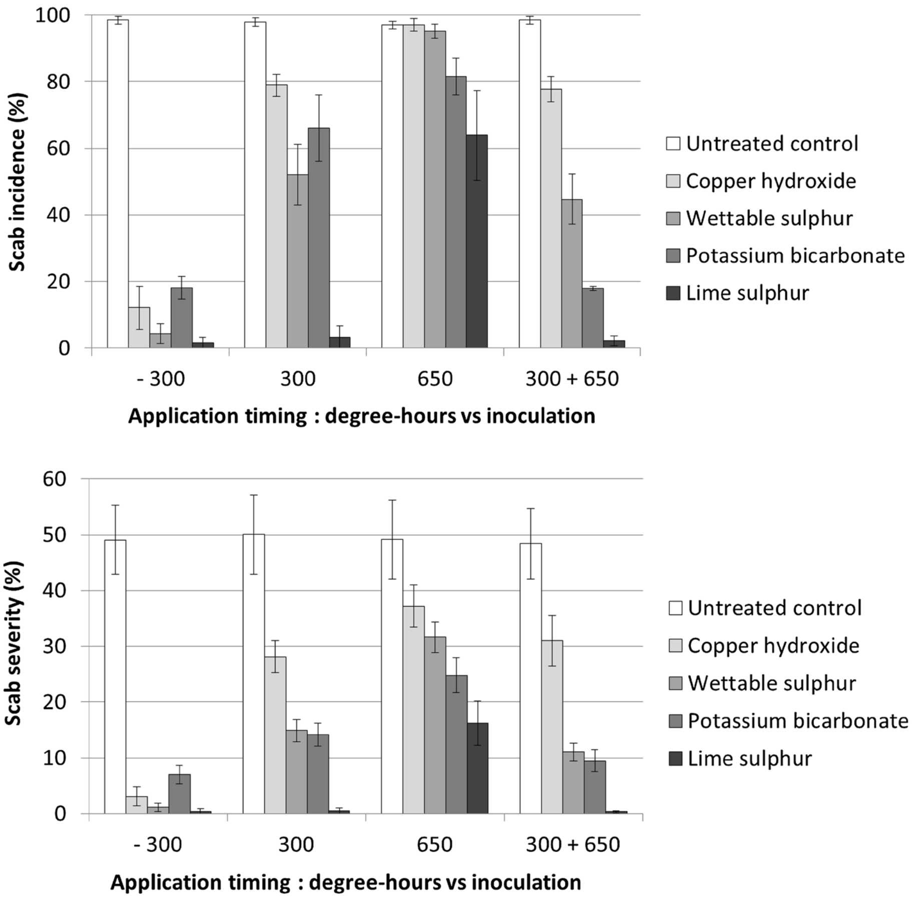

Fig. 1 Influence of application timing (−300, 300, 650, 350 + 650 degree-hours in relation to inoculation) on pear scab leaf incidence and severity. Pear seedlings were treated with a spray solution of sulphur 1%, lime sulphur 2%, copper 0.1% or potassium bicarbonate 1%. The different formulations were sprayed until just before run-off on the upper surface leaf. *Vertical bars* represent the standard error ($n = 6$)

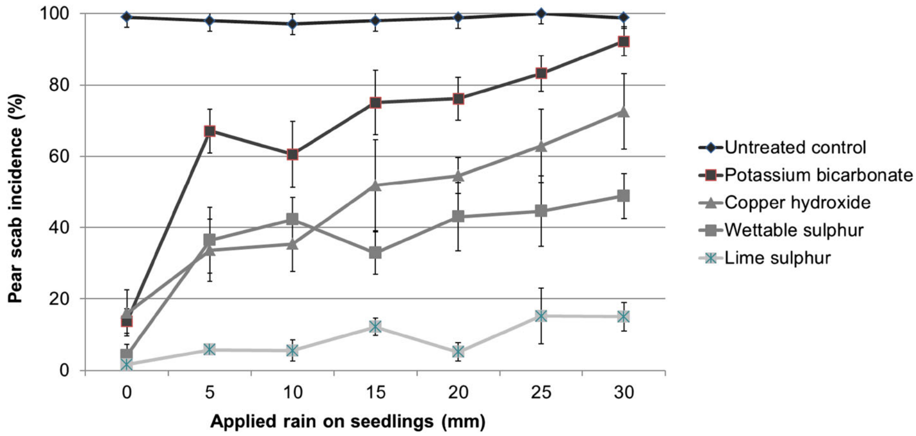

Fig. 2 Influence of applied rain volume (0, 5, 10, 15, 20, 25, 30 mm) on pear scab leaf incidence (proportion of infected leaves) treated with a single foliar spray solution of sulphur 1%, lime sulphur 2%, copper 0.1%, potassium bicarbonate 1%. The different formulations were sprayed until just before run-off on the upper surface of each leaf, 18 h before the applied rain and 24 h before inoculation. *Vertical bars* represent the standard error ($n = 6$)

germination rate. If the treatment was delayed to 650 DH, the rate of conidia production was reduced by only 18% in comparison with the untreated control. Treatment with wettable sulphur or copper hydroxide significantly reduced the rate of conidia production but not the rate of conidia germination.

Phytotoxicity study

With all the treatments, at low concentration rates no damage at all was observed on young leaves (Table 2). A few beige necrotic spots appeared on leaves treated with wettable sulphur at concentrations of 2%. Phytotoxicity in

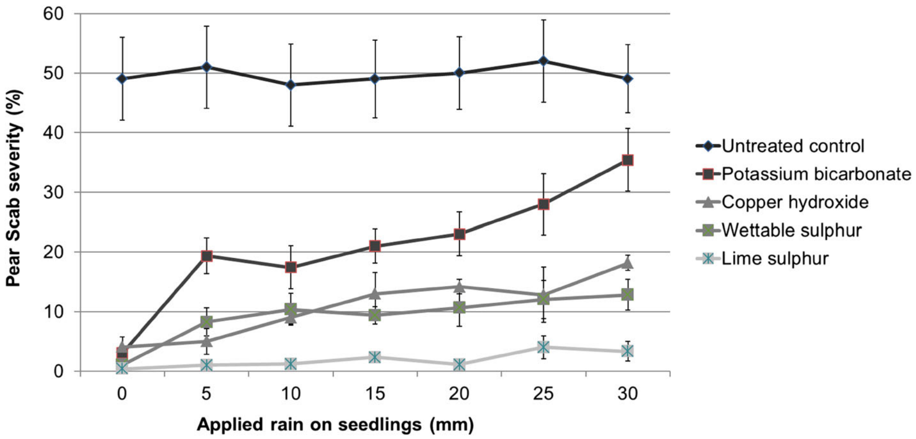

Fig. 3 Influence of applied rain volume (0, 5, 10, 15, 20, 25, 30 mm) on pear scab leaf severity (leaf area infected) treated with a single foliar spray solutions of sulphur 1%, lime sulphur 2%, copper 0.1% or potassium bicarbonate 1%. The different formulations were sprayed until just before run-off on the upper surface of each leaf, 18 h before the applied rain and 24 h before inoculation. *Vertical bars* represent the standard error ($n = 6$)

Table 1 Relative rate of conidia production and conidia germination of pear scab symptoms

Application timing (DH after inoculation)	Treatment	Application rate of active ingredient (%)	Relative rate of conidia production (%)*	Relative rate of conidia germination (%)
300	Lime sulphur	2.0	0.0 (0.0)a	0.0 (0.0)a
	Potassium bicarbonate	1.0	29.5 (5.3)b	98.2 (2.5)b
	Wettable sulphur	1.0	69.8 (11.0)c	84.4 (6.1)b
	Copper hydroxide	0.1	84.6 (8.1)c	89.8 (6.5)b
	Untreated control	–	100.0 (6.9)d	100.0 (8.2)b
650	Lime sulphur	2.0	29.2 (4.8)a	90.1 (4.8)a
	Potassium bicarbonate	1.0	81.9 (9.4)b	97.8 (1.8)a
	Wettable sulphur	1.0	74. (5.1)b	89.2 (4.9)a
	Copper hydroxide	0.1	71.1 (13.6)b	89.1 (4.2)a
	Untreated control	–	100.0 (7.2)c	100.0 (7.5)a

* Figures in brackets indicate the standard error of the mean ($n = 6$). Values in column within the same timing followed by the same letter do not differ significantly

the form of beige to light brownish necrotic areas was noted on healthy pear leaves treated with 2% potassium bicarbonate. Tests with 6-week-old pear seedlings therefore showed that phytotoxicity symptoms were related to the concentration of the bicarbonate salts used. No leaf phytotoxicity appeared either with copper hydroxide or with lime sulphur at any concentration.

Discussion

Scab is one of the key parasites in pome fruit growing. The importance of pear scab is amplified by the fact that it does not only infect fruits and leaves, but also young twig surfaces as well. The presence of twig scab represents a major problem, especially in organic pear growing, as fruit growers lack sufficient measures to control the disease. In organic pear growing, scab control is based on the protective use of copper or sometimes wettable sulphur. As the use of copper is subject to European restrictions and wettable sulphur is very often phytotoxic for the main cultivated cultivars in Belgium and the Netherlands, new alternative control strategies are needed in organic farming. Until now, most research concerning scab disease has been performed on apples and as such, the disease management of pear scab is based on experience with apples. However, it seems likely that the timing of fungicide application for pear scab control could be enhanced and that less fungicide spraying may be needed to control pear scab than usually occurs at present [43].

Exactly where does the inflection point lie between protective and curative application for pear scab control? Today, this question is still open. Within the range of fungicides developed, Szkolnick [36] established two main times for treatment application based on fungicidal

Table 2 Phytotoxicity of four chemicals on pear seedlings under greenhouse conditions

Treatments	Active ingredient dose (%)	Phytotoxicity	Active ingredient dose (%)	Phytotoxicity
Copper hydroxide	0.1	–	0.2	–
Wettable sulphur	1.0	–	2.0	+
Potassium bicarbonate	1.0	–	2.0	+++
Lime sulphur	2.0	–	4.0	–

Phytotoxicity was recorded on the 12th day after treatment on healthy leaves of 5-week-old seedlings. A qualitative assessment was conducted on the third and fourth leaves of each seedling. –, no damage, +, 0–2%, ++, 2–5%, +++, 5–20% of the leaf damaged

efficacy: the first is 'protective', i.e., before infection using contact fungicides, while the second one is 'curative', i.e., after infection using systemic fungicides. The revised Mills criteria for predicting apple scab infection periods [24, 27] define the relationship between temperature and the minimum hours of continuous leaf wetness needed to ensure infection by ascospore of *Venturia inaequalis*. However, this relationship does not define when the infection (in the sense of penetration into the leaf) occurs or when the contact fungicide does not work. In a previous 2-year field study, the mixing of wettable sulphur and copper, two contact fungicides, was very effective for apple scab control under a treatment scheme timed from 125 degree-hours (DH) to 300 DH after the rainfall during which infection occurs [13]. It could mean that the scab infection process in apple ends after this period.

As shown in the present study, lime sulphur is very effective for pear scab control from 300 DH before inoculation to 300 DH after inoculation. From 300 to 650 DH after inoculation, its effectiveness gradually decreases, but it still remains partially effective.

This means that lime sulphur's properties allow it to be used up to 650 DH after ascospore inoculation (the artificial inoculation simulates the start of a rainfall during which infection occurs) even though its activity decreases slowly from 300 to 650 DH. To reach 650 DH requires about 36 h at 18 °C. Lime sulphur treatment applied at 650 DH provides a very significant reduction of the conidia production rate, while earlier application of lime sulphur, at around 300 DH, can reduce the rate to almost 0%. Lime sulphur could therefore be very useful after rainfall during which infection occurs, during primary high infection risk periods in spring, when preventive application could not provide sufficient protection. To simulate practical situations where growers in heavy infection periods often receive advice to spray twice for effective prevention of infection in the orchard, this study also included treatments with two successive applications, at 300 and 650 DH after inoculation. However, the experiment shows that the second application did not provide a significant increase in protection.

Furthermore, lime sulphur revealed a higher resistance to rainfall due to its strong past effect. Good rainfastness and scab control were achieved in this study when up to 30 mm of water was applied after treatment. As infection periods, which usually occur during rainy periods, often include short periods without rain, the retention of the active ingredient on the leaves is of prime importance. Such results show that in practice, sprays of lime sulphur could be applied either before ascospore releases (before the onset of rain) or after ascospore releases, during the germination period from 0 to 300 DH or also curatively, from 300 to 600 DH after the onset of rain. These specific applications could be less difficult to schedule, as the time frame for the application is longer than other contact fungicides, given that in most cases applications have to be made just after rainfall.

Finally, lime sulphur seems to have less phytotoxic effects on pear leaves than wettable sulphur. However, the use of lime sulphur for pear scab control should be limited since (i) phytotoxicity in the case of intensive use on apple trees has previously been reported [10] and (ii) side effects on beneficial arthropods have been reported [3, 13]. Phytotoxic effects on fruits still have to be evaluated, although slight fruit russeting on cv. Conference is well accepted in the organic market.

The effectiveness of bicarbonate salts in controlling apple scab, as reported in previous studies [12], suggests that this simple compound acts as a contact fungicide and is not likely to be systemic. The curative activity of potassium bicarbonate, as recorded in this study, gives growers the opportunity to replace lime sulphur in some situations. From the present trials, it was concluded that bicarbonate has a fungistatic activity and is most effective against pear scab when it is applied during the germination process until around 300 DH after the rainfall during which infection occurs. However, a long-lasting effect of bicarbonates cannot be expected. Bicarbonates are quickly converted into ineffective compounds and are highly water soluble. Our present results showed that they will be washed off leaves by a small amount of precipitation. Frequent spray applications are therefore required, determined by the presence of ascospores in the orchards and the infection risk periods forecasted by modern local warning systems. Effective application timing seems to play a key role. Armicarb is formulated with a surfactant system that seems to increase its coverage ability [12]. Bicarbonate ion concentrations in solution (the active part) are directly related to the pH of that solution. Bicarbonates are ineffective under acidic conditions because carbonic acid predominates in solutions below pH 6.5. H_2CO_3 is unstable and converts into carbon dioxide and water. As the pH increases to pH 8.5, the concentration of bicarbonate increases. Above pH 8.5, bicarbonate concentration decreases and the level of carbonate rises.

Curative applications of bicarbonates were found to be effective in apple scab control [16, 42]. Curative applications up to 432 DH after inoculation were reported to be effective in apple scab control in greenhouse experiments [20]. Bicarbonates were most effective when used in combination with wettable sulphur [6, 37, 42]. Potassium bicarbonate has been found to display variable effectiveness in apple field trials [11, 13, 15]. This could be explained by the difference between the formulations used, the instability of bicarbonates or rainfastness or by the fact that the timing of application has a considerable impact on the efficacy. Several studies show that application during germination process is more effective [13, 42]. Various bicarbonate formulations have shown a higher curative action than lime sulphur [21], although lime sulphur is the only fungicide widely used in organic growing for curative control of apple scab [10].

Bicarbonates could increase apple fruit russet, which indicates that bicarbonates should not be used during bloom and 4 weeks after bloom, but could be useful as curative supplements for scab control before bloom and in summer [21].

Knowledge of behaviour under different weather conditions and in combination with different products should be available for reliable recommendations to pear growers. Further research is necessary to determine the practical effectiveness of sulphur and copper compounds as well as bicarbonate salts under field conditions in experimental pear orchards.

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References

1. Bühler, M., & Gessler, C. (1994). First experiences with an improved apple scab control strategy. *Norwegian Journal Agriculture Sciences, Supplement, 17,* 229–240.
2. Cabras, P., Angioni, A., Garau, V. L., Melis, M., Pirisi, F. M., Cabitza, F., et al. (2001). The effect of simulated rain on folpet and mancozeb residues on grapes and on vine leaves. *Journal Environmental Sciences, 36,* 609–618.
3. Daniel, C., Haeseli, A., & Weibel, F. (2001). The side effects of lime sulphur on predaceous arthropods, i.e. *Typhlodromus pyri* and other leaf occupying arthropods. http://www.fibl.net/archiv/pdf/daniel-etal-2001-lime-sulphur.pdf.
4. FRAC (2013). http://www.frac.info/docs/default-source/publications/pathogen-risk/pathogen-risk-list.pdf?sfvrsn=8.
5. Hall, F. R., Downer, R. A., Cooper, J. A., Ebert, T. A., & Ferree, D. C. (1997). Changes in spray retention by apple leaves during a growing season. *HortScience, 32,* 858–860.
6. Hinze, M., & Kunz, S. (2010). Screening of biocontrol agents for their efficacy against apple scab. In *Proccedings of the 14th International Conference on Organic Fruit-Growing*. Weinsberg: FÖKO e.V., 38–44.
7. Hunsche, M., Bringe, K., Schmitz-Eiberger, M., & Noga, G. (2006). Leaf surface characteristics of apple seedlings, bean seedlings and kohlrabi plants and their impact on the retention and rainfastness of mancozeb. *Pest Management Sciences, 62,* 839–847.
8. Hunsche, M., Damerow, L., Schmitz-Eiberger, M., & Noga, G. (2007). Mancozeb wash-off from apple seedlings by simulated rainfall as affected by drying time of fungicide deposit and rain characteristics. *Crop Protection, 26,* 768–774.
9. Hunsche, M., Alexeenko, A., Damerow, L., & Noga, G. (2011). Rain-induced removal of copper from apple leaves: influence of rain properties and tank-mix adjuvants on deposit characteristics at the micro scale. *Crop Protection, 30,* 495–501.
10. Holb, I. J., de Jong, P. F., & Heijne, B. (2003). Efficacy and phytotoxicity of lime sulphur in organic apple production. *Annals Applied Biology, 142,* 225–233.
11. Ilhan, K., Arslan, U., & Karabulut, O. A. (2006). The effect of sodium bicarbonate alone or in combination with a reduced dose of tebuconazole on the control of apple scab. *Crop Protection, 25,* 963–967.
12. Jamar, L., Lefrancq, B., & Lateur, M. (2007). Control of apple scab (*Venturia inaequalis*) with bicarbonate salts under controlled environment. *Journal of Plant Disease and Protection, 114,* 221–227.
13. Jamar, L., Lefrancq, B., Fassotte, C., & Lateur, M. (2008). A during-infection spray strategy using sulphur compounds, copper, silicon and a new formulation of potassium bicarbonate for primary scab control in organic apple production. *European Journal of Plant Pathology, 122,* 481–493.
14. Jones, A. L. (1981). Fungicide resistance: Past experience with Benomyl and Dodine and future concerns with sterolinhibitors. *Plant Disease, 65,* 990–992.
15. Kelderer, M., Casera, C., & Lardschneider, E. (2006). Erste Ergebnisse mit dem Einsatz von Khydrogencarbonat in Südtirol. In *Proccedings of the 12th International Conference on Organic Fruit-Growing*. Weinsberg: FÖKO e.V., 93–97.
16. Kelderer, M., Casera, C., Lardschneider, E., & Torre, A.L. (2010). Preventative and curative applications of carbonates against apple scab (*Venturia inaequalis*) in organic apple orchards. In Föko e.V., (ed.) *14th International Conference on Organic Fruit-Growing*. Weinsberg: FÖKO e.V., 52–60.
17. Köller, W., Parker, D. M., Turechec, W. W., Avilia-Adame, C., & Cronshaw, K. (2004). A two-phase resistance response of *Venturia inaequalis* populations to the QoI fungicides kresoxim-methyl and trifloxystrobin. *Plant Disease, 88,* 537–544.
18. Köller, W., Wilcox, W. F., & Parker, D. M. (2005). Sensitivity of *Venturia inaequalis* populations to anilinopyrimidine fungicides and their contribution to scab management in New York. *Plant Disease, 89,* 357–365.
19. Kunz, S., Deising, H., & Mendgen, K. (1997). Acquisition of resistance to sterol demethylation inhibitors by populations of *Venturia inaequalis*. *Phytopathology, 87,* 1272–1278.

20. Kunz, S., Mögel, G., Hinze, M., & Volk, F. (2008). Control of apple scab by curative applications of biocontrol agents. In *Proccedings of the 13th Internatinal Conference on Organic Fruit-Growing*. Weinsberg: FÖKO e.V., 62–67.
21. Kunz, S., & Hinze, M. (2014). Assessment of biocontrol agents for their efficacy against apple scab. In *Proccedings of the 16th International Conference on Organic Fruit-Growing*. Weinsberg: FÖKO e.V., 65–71.
22. Kunz, S., & Hinze, M. (2016). Efficacity of biocontrol agents against apple scab in greenhouse trials. In *Proccedings of the 17th International Conference on Organic Fruit-Growing*. Weinsberg: FÖKO e.V., 25–31.
23. Lateur, M., Wagemans, C., & Populer, C. (1999). Evaluation of fruit tree genetic resources as sources of polygenic scab resistance in apple breeding. ISHS. *Acta Horticulturae, 484,* 35–42.
24. MacHardy, W. E., & Gadoury, D. M. (1989). A revision of Mills's criteria for predicting apple scab infection periods. *Phytopathology, 79,* 304–310.
25. MacHardy, W. E., Gadoury, D. M., & Gessler, C. (2001). Parasitic and biological fitness of *Venturia inaequalis*: relationship to disease management strategies. *Plant Disease, 85,* 1036–1051.
26. Michel, M., & Ließ, N. (2006). Wirkstoffresistenz bei Schorffungiziden: zweijährige Ergebnisse aus Mecklenburg-Vorpommern. *Obstbau, 31,* 521–523.
27. Mills, W. D. (1947). Effects of sprays of lime sulphur and of elemental sulphur on apple in relation to yield. *Cornell Experiment Station*, 273, 38 pp.
28. Montag, J., Schreiberg, L., & Schönherr, J. (2005). An in vitro study on the postinfection activities of hydrated lime and lime sulphur against apple scab (*Venturia inaequalis*). *Journal of Phytopathology, 153,* 485–491.
29. Pérez-Rodríguez, P., Soto-Gómez, D., De La Calle, I., López-Periago, J. E., & Paradelo, M. (2016). Rainfall-induced removal of copper-based spray residues from vines. *Ecotoxicology Environmental Safety, 132,* 304–310.
30. Schabi, E., & Ben-Yephet, Y. (1976). Tolerance of Venturia pirina to benzimidazole fungicides. *Plant Disease Reporter, 60,* 451–454.
31. Schepers, H. T. A. M. (1996). Effect of rain on efficacy of fungicide deposits on potato against *Phytophthora infestans*. *Potato Research, 39,* 541–550.
32. Schulze, K., & Schönherr, J. (2003). Calcium hydroxide, potassium carbonate and alkyl polyglycosides prevent spore germination and kill germ tubes of apple scab (*Venturia inaequalis*). *Journal of Plant Disease and Protection, 110,* 36–45.
33. Schutte, G. C., Kotze, C., van Zyl, J. G., & Fourie, P. H. (2012). Assessment of retention and persistence of copper fungicides on orange fruit and leaves using fluorometry and copper residue analyses. *Crop Protection, 42,* 1–9.
34. Smith, F. D., & MacHardy, W. E. (1984). The retention and redistribution of Captan on apple foliage. *Phytopathology, 74,* 894–899.
35. Stewart, T. M., Knight, J. D., Manktelow, D. W. L., & Mumford, J. D. (1998). Spraycheck—A model for evaluating grower timing of black spot (*Venturia inaequalis*) fungicides in apple orchards. *Crop Protection, 17,* 65–74.
36. Szkolnik, M. (1978). Techniques involved in greenhouse evaluation of deciduous tree fruit fungicides. *Annals Review of Phytopathology, 16,* 103–129.
37. Tamm, L., Amsler, T., Schärer, H., & Refardt, M. (2006). Efficacy of Armicarb (potassium bicarbonate) against scab and sooty blotch on apples. http://orgprints.org/8075.
38. Töfoli, J. G., Domingues, R. J., Melo, P. C. T., & Ferrari, J. T. (2014). Effect of simulated rain on the efficiency of fungicides in potato late blight and early blight control. *Semina Ciencias Agrarias, 35,* 2977–2990.
39. Triloff, P. (1994). Moderne Schorfbekämpfung. *Obstbau, 77,* 182–185.
40. Triloff, P. (1999). Elf Jahre biologisch-orientierte Schorfbekämpfung. *Obstbau, 24,* 544–550.
41. Van Bruggen, A. H. C., Osmeloski, J. F., & Jacobson, J. S. (1986). Effects of simulated acidic rain on wash-off of fungicides and control of late blight on potato leaves. *Phytopathology, 76,* 800–804.
42. Van Hemelrijck, W., Croes, E., & Creemers, P. (2012). Potassium bicarbonate: A conceivable alternative control measure towards scab on pome fruits. In *Proccedings of the 15th International Conference on Organic Fruit-Growing*. Weinsberg: FÖKO e.V., 40–46.
43. Van Hemelrijck, W., Ceustermans, A., Creemers, P., Bylemans, D., Martens, D., & Keulemans, W. (2015). Epidemiologic study of pear scab: Early infections of pear fruit. In *Proceedings of the XII International Pear Symposium, ISHS 2015, Acta Horticulturae*, 1094, 457–461.
44. Van Zyl, J. G., Fourie, P. H., & Schutte, G. C. (2013). Spray deposition assessment and benchmarks for control of Alternaria brown spot on mandarin leaves with copper. *Crop Protection, 46,* 80–87.
45. Vicent, A., Armengol, J., & Garcia-Jimenez, J. (2007). Rain fastness and persistence of fungicides for control of Alternaria brown spot of citrus. *Plant Disease, 91,* 393–399.
46. Xu, X. M., Murray, R. A., Salazar, J. D., & Hyder, K. (2008). The effects of temperature, humidity and rainfall on captan decline on apple leaves and fruit in controlled environment conditions. *Pest Management Sciences, 64,* 296–307.