iVES OENO One vine & wine

DOI: https://doi.org/10.20870/oeno-one.2026.60.1.9593

OPEN ACCESS

VITICULTURE SHORT COMMUNICATIONS

Systemicity of fungicides in grapevines assessed using ^{14}C radiolabelling

Paulo Sérgio José dos Santos[1] and Marcel Bellato Spósito[2,*]

[1] Basf SE, APM/VS – LI554 67117, Limbrurgerhof, Germany
[2] Escola Superior de Agricultura Luiz de Queiroz (ESALQ), Universidade de São Paulo (USP), Piracicaba, Brasil

Article number: 9593

*correspondence:
mbsposito@usp.br

Associate editor:
François Delmotte

Received:
29 August 2025

Accepted:
14 December 2025

Published:
12 January 2026

This article is published under the **Creative Commons licence** (CC BY 4.0).

Use of all or part of the content of this article must mention the authors, the year of publication, the title, the name of the journal, the volume, the pages and the DOI in compliance with the information given above.

ABSTRACT

Chemical control is among the most widely used strategies in plant disease management and remains essential in many agricultural pathosystems. Understanding the dynamics of fungicide absorption and translocation within plants is therefore critical for optimising control strategies. This study aimed to evaluate the foliar absorption and translocation of three systemic fungicides, epoxiconazole, pyraclostrobin, and fluxapyroxad, in grapevines. Commercial formulations containing (^{14}C)-labelled molecules were used. Applications were performed with a micro-applicator on specific grapevine leaves, and absorption and translocation were quantified at five time intervals (3, 9, 24, 48, and 72 hours after application) using liquid scintillation spectrometry and autoradiography. The results indicate that fluxapyroxad exhibited the lowest absorption throughout the evaluation period. After 72 hours, 64 % of the fluxapyroxad remained on the grapevine-treated leaf, which was twice the amount observed for epoxiconazole and pyraclostrobin. Therefore, in grapevine leaves, the majority of the absorbed products of all three systemic fungicides remained at the site of application, when intertissue mobility was low, below 0.2 %, with reduced but detectable systemic translocation. These findings contribute to a better understanding of the dynamics of the absorption and translocation of these compounds in grapevines, providing a basis for the development of more effective plant disease management strategies.

KEYWORDS: SDHI, DMI, QoI, translocation, grapevine

INTRODUCTION

Grapevines are highly susceptible to early-season infections caused by pathogens such as downy mildew *(Plasmopara viticola),* powdery mildew *(Erysiphe necator)*, and anthracnose *(Elsinoë ampelina)*, which can significantly impact the development of young shoots, leaves, and inflorescences under favourable environmental conditions. In viticulture under subtropical or tropical climates, rainfall is concentrated in spring and summer, precisely when, after the winter dormancy period, grapevines are pruned, budburst occurs, and shoots grow very rapidly, reaching 4–7 cm per day (Sanchez-Rodriguez & Spósito, 2020). This is precisely the period when susceptible tissues are present, and climatic conditions are favourable for early-season disease outbreaks. Fungicide application remains the primary strategy for controlling grapevine diseases. However, the rapid and continuous growth of shoots and leaves following a spray often exposes newly developing tissues to pathogen infection. Although systemic fungicides can move within vine tissues to some extent, the extent and rate of this movement depend on each molecule's physicochemical properties and the plant's physiological state. Rapid shoot growth can outpace fungicide redistribution, limiting protection of newly formed tissues, particularly given the accelerated growth of grapevines during spring and summer.

From an epidemiological perspective, protection and immunisation are key principles in plant disease control (Kimati, 2011). Fungicide residues remain on the plant surface, awaiting pathogen contact, while the fraction absorbed can translocate within the plant to reach fungitoxic concentrations in healthy tissues. The performance and redistribution within plants are complex and vary widely (Klittich, 2014). Fungicides can be classified by their mobility: systemic fungicides penetrate plant tissues and are translocated via the vascular system, whereas topical fungicides remain on the surface without absorption or translocation (Mueller *et al.*, 2017). In addition to systemic and surface mobility, fungicides may exhibit translaminar movement, where the compound crosses the leaf lamina and redistributes between the upper and lower surfaces without necessarily moving upwards through the vascular system (Klittich, 2014). Most so-called systemic fungicides exhibit limited distribution, primarily through acropetal movement (Oliver & Hewitt, 2014). Among systemic fungicides, differences in fungitoxicity are notable across the demethylation inhibitor (DMI), quinone outside inhibitor (QoI), and succinate dehydrogenase inhibitor (SDHI) groups (Azevedo, 2007). Triazoles (DMIs), such as epoxiconazole, can protect plant tissues when applied before infection, preventing the fungus from establishing itself by reducing hyphal viability and the formation of appressoria by compromising cell membrane integrity. After penetration, triazoles can interrupt sterol biosynthesis when the fungus begins forming new hyphae or reproductive structures within the plant tissue, thus reducing its ability to grow and form new inoculum and limiting new infections. Oomycetes such as *Plasmopara viticola* are insensitive to triazoles because their sterol metabolism differs fundamentally from that of true fungi. QoI fungicides, such as pyraclostrobin, from the strobilurin group are considered to have translaminar movement. When these fungicides are applied, most of the active ingredient is initially retained on or within the plant's waxy cuticle. Some QoI fungicides bind strongly to the cuticle, where most of the active ingredient resides. Although the active ingredients disperse within the leaf blade, their affinity for the cuticle is so strong that they quickly rebind to the cuticle when the chemical reaches the other side of the leaf (Vincelli, 2002). Thus, the fungicide can be found on both leaf surfaces, even if only one is treated (Vincelli, 2002). Carboxamides (SDHIs), such as fluxapyroxad, have a protective effect when applied before the deposition of spores in host tissues, as they inhibit the development of appressoria and germinative hyphae. This fungicide also has a curative effect, interrupting mycelial growth and preventing the colonisation of plant tissues by the fungus as well as the formation of reproductive structures. This property provides the molecule with a pronounced protective effect, in addition to the curative effect.

The systemicity of a fungicide depends largely on its physicochemical properties, such as partition coefficient (log Kow) and acid dissociation constant (pKa), which determine absorption and mobility within plant tissues. The log Kow, a measure of lipophilicity, is generally the most important, as it governs the ability of a fungicide to penetrate membranes and distribute through plant tissues. The pKa complements this by influencing the capacity of compounds to cross specific barriers and remain active intracellularly (Azevedo, 2007; Chen *et al.*, 2016; Pereira *et al.*, 2016). However, systemicity alone does not ensure sufficient protection, as potency (IC_{50}) and metabolic stability must also be considered (Klittich *et al.*, 2020). This interpretation aligns with approaches commonly used in the registration of plant protection products, which take these properties into account when defining application intervals and expected redistribution.

Furthermore, some studies have examined the behaviour and fate of triazole and strobilurin fungicides in plants, including epoxiconazole and related compounds (Lichiheb *et al.*, 2016), providing complementary evidence for limited systemic translocation and partial translaminar movement. Carbon-14 (^{14}C)-radiolabelled compounds have been fundamental for elucidating the movement of fungicides within plants, although the available literature remains limited for grapevines. Therefore, this study aims to evaluate the foliar absorption and translocation of systemic fungicides from three different chemical classes in grapevines. Understanding the dynamics between fungicides and plant physiology can guide safe and effective vineyard applications.

MATERIALS AND METHODS

In this study, grapevines (*Vitis labrusca* cv. Niagara Rosada) grafted onto 'IAC 766' (106–8 Mgt × *Vitis caribaea*) were planted in pots and grown until they had eight expanded leaves. The grapevines were maintained in a greenhouse at the BASF Experimental Station, Brazil (22° 36' 16.3" S 46° 59' 13.1" W, and 612 m altitude).

For the systemicity experiments with fungicides, solutions of epoxiconazole, pyraclostrobin, and fluxapyroxad were used. The working solution was prepared by diluting the radiolabelled fungicides ^{14}C-epoxiconazole, ^{14}C-pyraclostrobin, and ^{14}C-fluxapyroxad with their respective commercial solutions BAS 480 27F, BAS 500 17F, and BAS 700 04F at doses of 25 g of active ingredient (a.i.) ha^{-1}, 100 g a.i. ha^{-1}, and 50 g a.i. ha^{-1}, respectively. All commercial formulations used were concentrated suspensions (SC), thereby eliminating any formulation-related effect on product absorption. The specific activity of each radiolabelled compound was 25–40 µCi µmol^{-1}, with radiochemical purity greater than 98 %.

The fungicide systemicity analyses were conducted at the Ecotoxicology Laboratory of the Center for Nuclear Energy in Agriculture (CENA/USP) in Piracicaba, Brazil. In the grapevines, 40 drops of 1.0 µL of the working solutions containing the fungicides were applied to the third leaf, which was counted from the base of each plant. Applications in leaves were performed using a micro-applicator (Hamilton PB6000 Dispenser, Hamilton Co., USA) to prevent drift. Each 1 µL droplet applied to the leaf contained approximately 0.25–0.30 µCi of radioactivity, corresponding to the field-rate concentration after dilution. After application, the grapevines were maintained in a greenhouse at CENA/USP and were irrigated only through the soil of each pot to avoid water contact with the leaves. Fungicide absorption and translocation were evaluated at 3, 9, 24, 48, and 72 hours post-application, totalling 15 replicates per treatment. After each evaluation period, treated grapevine leaves were excised at the petiole–stem junction with scissors, preserving the two buds. After each application, the treated leaves were washed with 12 mL of a methanol + water solution (50 % *v/v*) to extract the unabsorbed fungicide from the leaf surface. Aliquots of 1 mL of the washing solution were added to 10 mL of scintillation liquid for radioactivity measurement by liquid scintillation spectrometry (Packard 1900 TR). For qualitative studies using radio imaging, the grapevine samples were dried (50 °C), pressed, and then placed in contact with phosphorescent plates (PerkinElmer). Afterwards, the plates were scanned using a radio scanner (PerkinElmer Cyclone). The dried grapevines were divided into the stem below the treated leaf, the stem above the treated leaf, the leaf below the treated leaf, the leaf above the treated leaf, and the treated leaf itself (Figure 1). These grapevine parts were then subjected to combustion in a biological oxidiser (OX 500 R. J. Harvey Instruments). Radioactivity was quantified using liquid scintillation spectrometry (LSS).

Fungicide absorption and translocation were determined by the percentage of radioactivity present within each plant part according to the following equation:

$$\text{Fabs} = (14\text{C tec.ox} \times 100)/(14\text{C tec.ox} + 14\text{C lav}) \quad (1)$$

where Fabs is the percentage of fungicide absorbed by the grapevine, ^{14}C tec.ox is the amount of ^{14}C detected in oxidised tissues (treated leaves and aerial parts), and ^{14}C lav is the amount of ^{14}C detected in the washing solution of the treated leaf (washing liquid + radioactivity within the grapevine).

The results, expressed as percentages of not absorbed, absorbed, and translocated radiation, were subjected to analysis of variance (ANOVA) and mean comparisons using Tukey's test ($p < 0.05$). The analyses were performed using routines generated in SAS® software, version 9.1.3 (SAS/STAT, 1999).

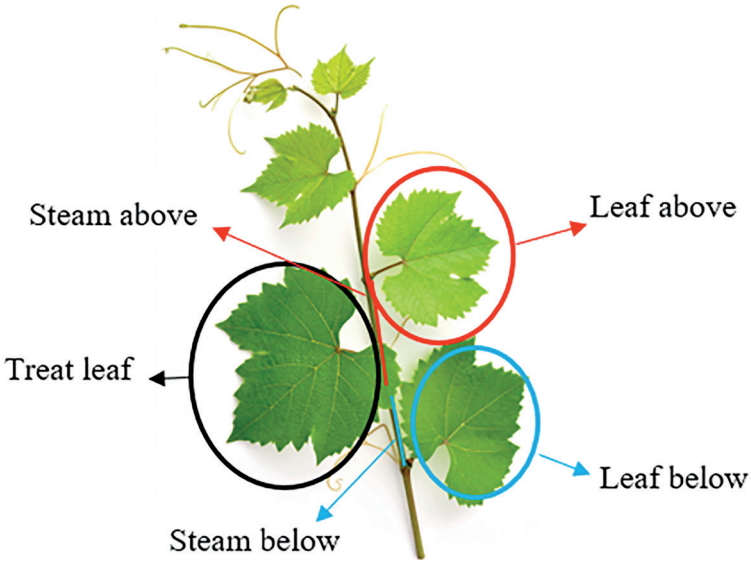


FIGURE 1. Illustration of a grapevine shoot showing the parts used to determine radioactivity within the tissues by liquid scintillation and autoradiography.

RESULTS

In the leaves of the grapevines, the absorption of ^{14}C-epoxiconazole was 10.3 % within the first 3 hours after application, increasing to 40.1 % after 72 hours (Table 1). However, the translocation of ^{14}C-epoxiconazole remained below 0.2 % throughout the entire evaluation period (Table 1).

With respect to ^{14}C-pyraclostrobin, the leaf absorption of the product was 21.8 % at 3 hours, which increased to 53.7 % at 72 hours after application (Table 1). In grapevine leaves, compared with the other fungicides, pyraclostrobin was the product that exhibited the fastest absorption, and it also showed the highest absorption after 72 hours. Pyraclostrobin also exhibited poor translocation and remained restricted to the treated leaves, as observed for the other compounds (Table 2). Like epoxiconazole and fluxapyroxad, the translocation of pyraclostrobin did not significantly vary over time, with values consistently less than 0.2 % of the applied product (Table 1).

Pyraclostrobin is characterised as a surface systemic product with a log Kow of 3.99 (measured at 22 °C and pH 7) and is considered to exhibit moderate systemic activity (BASF, Internal data, 2025). In this study, less than 1 % of the material was translocated to other plant tissues.

The fungicide fluxapyroxad, from the carboxamide group, is also classified as a systemic product (Frac-BR, 2025). With a log Kow of 3.13 (at 22 °C and pH 7), it is considered a fungicide with moderate systemic activity (BASF, Internal data, 2025). ^{14}C-fluxapyroxad was the fungicide with the lowest absorption compared with the other fungicides evaluated, with 19.3 % absorbed and a large portion of the product remaining on the surface of the leaf (64 %), even after 72 hours of application (Table 1). However, ^{14}C-fluxapyroxad was the fungicide that translocated the most to other plant tissues, mainly to the leaves above the treated leaves (Table 2). Fluxapyroxad has a pKa = 12.6 and lacks an acid strength that would allow translocation through the phloem, as demonstrated in this study.

Systemic products require a time interval between spraying and rainfall occurrence to be efficiently absorbed and translocated through the leaf tissues in sufficient quantity for fungal disease control (Lenz *et al.*, 2011; Tofoli *et al.*, 2014). In the grapevine crops analysed in this study, only 10.3 %, 21.8 %, and 7.5 % of epoxiconazole, pyraclostrobin, and fluxapyroxad, respectively, were absorbed after 3 hours of application, increasing to 16.3 %, 36.3 %, and 9 %, respectively, after 24 hours. These results demonstrate the need for repeated applications to ensure effective disease control.

Autoradiographs of grapevine leaves treated with radiolabelled ^{14}C-epoxiconazole, ^{14}C-pyraclostrobin, and ^{14}C-fluxapyroxad revealed high concentrations of radioactivity at the sites of application (Figure 2).

The translocation profiles depicted in the autoradiographs confirm that the majority of each radiolabelled fungicide remained localised in the treated leaf region across all treatments. In several images, intense radiation signals were observed exclusively at the droplet deposition sites, indicating minimal movement from the point of application (Figure 2).

Based on the results of this study, the products' effectiveness, both as a protective and a curative agent, appears to be more evident in the tissue where they were applied. However, the amount of product translocated to other plant tissues is very low.

TABLE 1. Mass balance (%) of not absorbed, absorbed, and translocated fungicides at 3, 9, 24, 48, and 72 hours after the application of ^{14}C-epoxiconazole, ^{14}C-pyraclostrobin, and ^{14}C-fluxapyroxad in grapevine.

	Hours after application – HAA					CV (%)
^{14}C-epoxiconazole	**3**	**9**	**24**	**48**	**72**	
Total not absorbed	76.42 a[1]	60.97 ab	62.65 ab	54.21 b	32.08 c	11.29
Total absorbed	10.27 b	13.79 b	16.35 b	22.06 b	40.14 a	24.97
Total translocated	0.18 a	0.31 a	0.08 a	0.21 a	0.16 a	70.91
^{14}C-pyraclostrobin	**3**	**9**	**24**	**48**	**72**	
Total not absorbed	58.54 a	58.75 a	47.05 ab	28.94 c	32.60 bc	12.92
Total absorbed	21.80 c	26.30 bc	36.31 b	53.94 a	53.71 a	9.83
Total translocated	0.09 a	0.04 a	0.03 a	0.14 a	0.10 a	52.97
^{14}C-fluxapyroxad	**3**	**9**	**24**	**48**	**72**	
Total not absorbed	93.12 a	92.23 a	85.98 a	71.15 b	64.22 b	6.51
Total absorbed	7.48 c	6.22 c	9.03 bc	13.05 b	19.30 a	16.19
Total translocated	0.26 a	0.09 a	0.08 a	0.14 a	0.16 a	63.16

[1] Averages followed by the same letter in the row do not differ from each other according to the Tukey test ($p < 0.05$). CV (%) = coefficient of variation.

TABLE 2. Distribution of absorbed radioactivity (%) by different parts of the grapevine, at 3, 9, 24, 48, and 72 hours after the application of the fungicides ^{14}C-epoxiconazole, ^{14}C-pyraclostrobin, and ^{14}C-fluxapyroxad on leaves.

	Hours after application – HAA				
^{14}C-epoxiconazole	**3**	**9**	**24**	**48**	**72**
Treated leaf (TL)	10.08	13.50	16.29	21.84	39.99
Leaf above the TL	0.05	0.03	0.02	0.10	0.03
Leaf below the TL	0.07	0.02	0.01	0.03	0.10
Stem above of TL	0.03	0.03	0.02	0.01	0.00
Stem below of TL	0.03	0.02	0.02	0.08	0.02
^{14}C-pyraclostrobin	**3**	**9**	**24**	**48**	**72**
Treated leaf (TL)	21.72	26.22	36.18	53.82	53.49
Leaf above the TL	0.01	0.02	0.03	0.05	0.10
Leaf below the TL	0.01	0.03	0.08	0.08	0.12
Stem above of TL	0.05	0.02	0.01	0.01	0.00
Stem below of TL	0.01	0.00	0.00	0.00	0.00
^{14}C-fluxapyroxad	**3**	**9**	**24**	**48**	**72**
Treated leaf (TL)	7.23	6.12	8.94	12.93	19.14
Leaf above the TL	0.23	0.07	0.06	0.12	0.13
Leaf below the TL	0.05	0.02	0.01	0.03	0.08
Stem above of TL	0.03	0.02	0.01	0.00	0.02
Stem below of TL	0.00	0.00	0.01	0.02	0.01

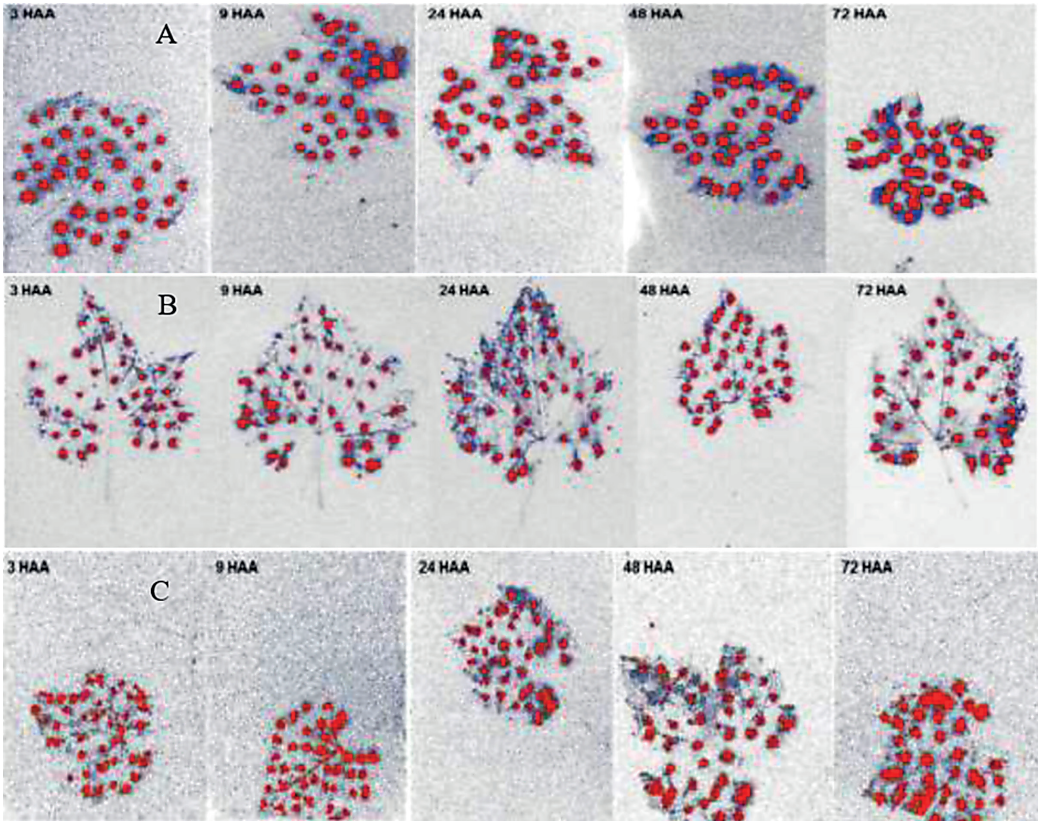


FIGURE 2. Autoradiographic images of grapevine leaves at 3, 9, 24, 48, and 72 hours after the application of ^{14}C-labelled epoxiconazole (row A), pyraclostrobin (row B), and fluxapyroxad (row C).

For diseases such as downy mildew *(Plasmopara viticola),* whose pathogen infects new tissues, the systemic movement of fungicides is important for protecting against and controlling disease in new tissues formed during the days following the application of the fungicide. In grapevines, because these products lack the systemic movement needed to protect newly formed tissues, producers tend to make sequential applications during rainy periods while shoots are growing to protect them from downy mildew (Cappello *et al.*, 2017). In grapevines, shoots continue to grow until tipping, when they reach approximately 1.2 m in length. Until this stage, control measures should be intensified, as new, susceptible growing tissues will be present every day and at risk of new infections. After tipping, as no new tissues are formed, control should focus on ensuring good coverage, with more widely spaced applications, even during rainy periods.

CONCLUSION

Epoxiconazole, pyraclostrobin, and fluxapyroxad, which are used to control grapevine diseases, are systemic fungicides with distinct modes of action. A substantial proportion of the applied product remains on the leaf surface, providing a protective barrier. The fraction absorbed is largely confined to the treated area, regardless of the active ingredient. Translocation to other plant tissues is minimal, which poses a challenge for disease management during phases of vigorous shoot growth.

ACKNOWLEDGEMENTS

The authors would like to acknowledge São Paulo Research Foundation – FAPESP for financial support (grant number 2013/24003-9).

REFERENCES

Azevedo, L. A. S. (2007). *Fungicidas sistêmicos: Teoria e prática*. EMOPI, Gráfica e Editora.

Cappello, F. P., Spósito, M. B., & Osaki, M. (2017). Production costs and profitability of 'Niagara Rosada' table grape grown in different regions of São Paulo state. *Revista Brasileira de Fruticultura, 39*, e-774. https://doi.org/10.1590/0100-29452017774

Chen, Y.-C., Lai, M.-H., Wu, C.-Y., Lin, T.-C., Cheng, A.-H., Yang, C.-C., Wu, H.-Y., Chu, S.-C., Kuo, C.-C., Wu, Y.-F., Lin, G.-C., Tseng, M.-N., Tsai, Y.-C., Lin, C.-C., Chen, C.-Y., Huang, J.-W., Lin, H.-A., & Chung, C.-L. (2016). The genetic structure, virulence, and fungicide sensitivity of *Fusarium fujikuroi* in Taiwan. *Phytopathology*, *106*(6), 624–635. https://doi.org/10.1094/PHYTO-11-15-0285-R

FRAC-BR. (2025). Modo de ação. Accessed 20 February 2025. https://www.frac-br.org/modo-de-acao

Kimati, H. (2011). Controle químico. In *Manual de fitopatologia: Princípios e conceitos*. L. Amorim, J. A. M. Rezende, & A. Bergamin Filho Ed., Ceres edition, Vol. 2, p. 343–365.

Klittich, C. J. R. (2014). Fungicide mobility and the influence of physical properties. In N. A. Satchivi (Ed.), *Retention, uptake, and translocation of agrochemicals in plants* (Vol. 1171, pp. 95–109). American Chemical Society. https://doi.org/10.1021/bk-2014-1171.ch005

Klittich, C. J. R., Wang, N. X., Zhang, Y., & Rowland, L. B. (2020). A revised model of fungicide translaminar activity. *Pesticide Biochemistry and Physiology*, 167:104597. https://doi.org/10.1016/j.pestbp.2020.104597

Lenz, G., Balardin, R. S., Minuzzi, S. G., Tormen, N. R., & Marques, L. N. (2011). Espectro de gotas e idade de trifólios na taxa de absorção e efeito residual de fungicidas em soja. *Ciência Rural, 41*(10), 1702–1708. https://doi.org/10.1590/S0103-84782011005000127

Lichiheb, N., Personne, E., Bedos, C., Van den Berg, F. & Barriuso, E. (2016). Implementation of the effects of physicochemical properties on the foliar penetration of pesticides and its potential for estimating pesticide volatilisation from plants. *Science of the Total Environment* 550, 1022–1031. https://doi.org/10.1016/j.scitotenv.2016.01.058

Mueller, D. S., Wise, K. A., Dufault, N. S., Bradley, C. A., & Chilvers, M. I. (2017). *Fungicides for field crops*. APS Press, St. Paul, MN. https://doi.org/10.1094/9780890545065

Oliver, R. P., & Hewitt, H. G. (2014). *Fungicides in crop protection*. CABI. https://doi.org/10.1079/9781780641669.0000

Pereira, V. J., Cunha, J. P. A. R., Morais, T. P., Oliveira, J. P. R., & Morais, J. B. (2016). Physical-chemical properties of pesticides: Concepts, applications, and interactions with the environment. *Bioscience Journal*, *32*(3), 627–641. https://doi.org/10.14393/BJ-v32n3a2016-31533

Sanchez-Rodriguez, L. A., & Spósito, M. B. (2020). Influence of the trellis/training system on the physiology and production of *Vitis labrusca* cv. Niagara Rosada in Brazil. *Scientia Horticulturae 261*(5). https://doi.org/10.1016/j.scienta.2019.109043

Tofoli, J. G., Domingues, R. J., de Melo, P. C. T., & Ferrari, J. T. (2014). Efeito de chuva simulada sobre a eficiência de fungicidas no controle da requeima e pinta preta da batata. *Semina: Ciências Agrárias*, *35*(6), 2977–2990. https://doi.org/10.5433/1679-0359.2014v35n6p2977

Vincelli, P. (2002). QoI fungicides (strobilurins): Benefits and risks. *The Plant Health Instructor*. https://doi.org/10.1094/PHI-I-2002-0809-02