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The importance of acaricides in the control of citrus leprosis mite and factors that interfere with the efficacy

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SUMMARY

Citrus leprosis mite is an important pest to Brazilian citriculture. Due to the potential damage caused by the virus transmitted by this mite, synthetic acaricides are the main management strategy used by citrus growers to reduce the vector population. The current review aims to provide historical data on the use of acaricides to control the citrus leprosis mite and the main factors involved with the efficacy of these products. To get to know the main products that were and have been used to control the leprosis mite, we used scientific papers that studied the toxic effect caused by pesticides on these mites. From 1959 to nowadays, more than 200 papers have been published demonstrating acaricide efficacy on the leprosis mite. Although there are several acaricides registered to control the leprosis mite (abamectin, amitraz, acrinathrin, bifenthrin, fenpropathrin, etoxazole, hexythiazox, flufenoxuron, spirodiclofen, cyflumetofen, chlorfenapyr, fenbutatin oxide, propargite, fenpyroximate, pyridaben, and sulfur), their effectiveness will be determined by factors inherent to the products, application (quality of the spray water, plant coverage by sprayed acaricide, addition of adjuvants, and tank mixture), and biological factors of the pest (biotic potential, short life cycle, reproduction type, initial infestation level, reproduction type, and evolution of mite resistance). The use of synthetic acaricides is a control option that generates short-term results for the citrus grower. However, the association with other control measures will allow more satisfactory results for the pathosystem. Additionally, information on factors that interfere with the effectiveness of acaricides needs to be generated and made available to citrus growers.

Index terms: *Brevipalpus phoenicis, Brevipalpus yothersi, Citrus* spp., Citrus leprosis virus, efficiency, synthetic acaricides.

A importância dos acaricidas no controle do ácaro da leprose dos citros e fatores que interferem na eficácia

RESUMO

Ácaro da leprose dos citros é uma importante praga da citricultura brasileira. Devido ao potencial dano causado pelo vírus transmitido por esse ácaro, o uso de acaricidas sintéticos é a principal estratégia de manejo utilizada pelos citricultores para reduzir a população desses vetores. A presente revisão visa fornecer dados históricos sobre o uso de acaricidas no controle do ácaro da

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leprose e os principais fatores envolvidos na eficácia desses produtos. Como forma de conhecer os principais produtos que foram e têm sido usados no controle do ácaro da leprose, utilizamos trabalhos científicos que estudaram o efeito tóxico dos agrotóxicos sobre esses ácaros. De 1959 até hoje, mais de 200 artigos foram publicados demonstrando a eficácia dos acaricidas sobre o ácaro da leprose. Embora existam vários acaricidas registrados para controle do ácaro da leprose (abamectina, amitraz, acrinatrina, bifentrina, fenpropatrina, etoxazol, hexitiazox, flufenoxuron, espirodiclofeno, ciflumetofem, clorfenapir, óxido de fenbutatina, propargite, fenpiroximato, piridabem e enxofre), a efetividade será determinada por fatores inerentes aos produtos, a aplicação (qualidade da água de pulverização, cobertura da planta pelo acaricida pulverizado, adição de adjuvantes, mistura de produtos no tanque de pulverização) e aos fatores biológicos da praga (potencial biótico, ciclo de vida curto, tipo de reprodução, nível de infestação inicial e evolução da resistência do ácaro). O uso de acaricidas sintéticos é uma opção de controle que gera resultados de curto prazo para o citricultor, porém, a associação com outras medidas de controle permitirá resultados mais satisfatórios para o patossistema. Além disso, informações sobre os fatores que interferem na eficácia dos acaricidas precisam ser geradas e disponibilizadas aos citricultores.

Termos de indexação: *Brevipalpus phoenicis, Brevipalpus yothersi, Citrus* spp., Citrus leprosis virus, eficiência, acaricidas sintéticos.

INTRODUCTION

Phytophagous mites are important pests for citrus plants worldwide. In particular, the mite species belonging to the Tenuipalpidae, Tetranychidae, Tarsonemidae, and Eriophyidae families have potential economic importance for Brazilian citrus orchards, considering the damages, either by direct feeding or by the transmission of plant pathogens (Gerson, 2003; Moraes & Flechtmann, 2008; Vacante, 2010). However, Tenuipalpidae stands out among these families due to the indirect damage caused to citrus plants.

The main reason that citrus growers adopt control measures for these mites is the transmission of plant viruses by some species of *Brevipalpus*. In the management of citrus leprosis, several strategies are recommended to prevent the transmission and spread of the disease in orchards. Among these strategies is the use of healthy seedlings free of viruses and vector mites, the systematic management of the vector, the pruning of symptomatic branches, the use of living fences and windbreaks with plants that do not host mites and virus, and the control of mite and virus-host weeds (Bastianel et al., 2010; Andrade et al., 2013a; Miranda et al., 2017). However, due to the potential damage caused by the virus transmitted by this mite, the use of synthetic acaricides is the main management strategy used by citrus growers to reduce vector population and, consequently, the spread of the disease in orchards (Andrade et al., 2010b; Carvalho et al., 2014; Della Vechia et al., 2018).

Limited information is available on the costs involved in the chemical control of leprosis mite. Worldwide, about 10% of the total volume of the acaricide market is destined for the management of *Brevipalpus* spp. (Van Leeuwen et al., 2015). In Brazil, the costs of acaricides to control these mites correspond to about US$54 million per year (Bassanezi et al., 2019). In addition to the price of acaricides, the cost of the operation is high because excellent external and internal coverage of the trees canopy by the sprayed drops is required. This coverage is obtained by a considerably high spray volume (100 to 150 mL/m^3). Costs may vary according to each region, given the favorable climate conditions for mite development and disease.

Although some studies prove that vector control alone is not a sufficient control measure to control the disease (Bitancourt, 1995; Rodrigues, 2002), this is still the most adopted measure since the identification of the mite association with the virus that causes citrus leprosis. Indeed, synthetic acaricides are an important and effective tool in controlling the leprosis mite. However, several factors can influence the successful use of this tool. The current review aims to provide historical data on the use of acaricides to control the citrus leprosis mite and the main factors involved in the effectiveness of these products in aiding the development of citrus leprosis mite management tactics.

History of the use of acaricides to control the citrus leprosis mite in Brazil

Since the identification of *Brevipalpus* mites as vectors of the viruses that cause citrus leprosis, the use of acaricides has been extensively adopted. To get to know the main products that were and have been used to control the citrus leprosis mite, we used scientific papers that studied the toxic effect caused by pesticides on these mites.

Table 1 shows the acaricides used to control citrus leprosis mite that was studied for some years and are accessible to consult. From 1959 to nowadays, more than 200 papers have been published demonstrating the efficacy of acaricides on the citrus leprosis mite. Of these studies, approximately 10% were published in conference proceedings, while the others were published in papers, scientific journals, and title defense. The acaricides that were or are available for use are in twelve different modes

Table 1. List of acaricides studied between 1959 and 2021 and their mode of action

Mode of action	Active ingredients	Reference
Acetylcholinesterase inhibitors	fenitrothion, carbosulfan, formetanate	Oliveira et al. (1983), Oliveira et al. (1989)
Sodium channel modulators	bifenthrin, acrinathrin, fenpropathrin	Arashiro et al. (1987), Papa et al. (1987), Arashiro et al. (1988), Papa et al. (1989), Scarpellini et al. (1991)
Chloride channel activators	abamectin	Chiavegato & Yamashita (1984), Oliveira et al. (1986a), Scarpellini et al. (1991), Sato et al. (1991a,b), Fernandes et al. (2008), Andrade et al. (2010c), Silva et al. (2011), Silva et al. (2012), Della Vechia et al. (2019)
Mite growth inhibitors targeting chitin synthase	etoxazole, hexythiazox, clofentezine	Motta et al. (1987), Oliveira et al. (1986b), Arashiro et al. (1988), Veloso et al. (1988), Mariconi et al. (1989), Raga et al. (1990), Scarpellini et al. (1991), Oliveira & Oliveira (1991), Chiavegato et al. (1993), Chiavegato et al. (1994), Sato et al. (1995), Moraes & Sá (1995), Raga et al. (1997), Campos & Omoto (2002, 2006), Scarpellini & Santos (2002), Amorim et al. (2006), Celoto (2009), Celoto & Papa (2010), Silva et al. (2011), Prado et al. (2011)
Inhibitors of mitochondrial ATP synthase	azocyclotin, cyhexatin, fenbutatin oxide, propargite, diafenthiuron, tetradifon	Silva et al. (1983), Oliveira et al. (1983), Calafiori et al. (1986), Arashiro et al. (1988), Afférri et al. (1989), Veloso et al. (1988), Raga et al. (1990), Scarpellini et al. (1991), Sato et al. (1991a, b), Oliveira & Oliveira (1991), Sato et al. (1992), Campos Neto et al. (1993), Clari et al. (1993), Ruiz & Matuo (1994), Childers (1994), Sato et al. (1995), Moraes & Sá (1995), Raga et al. (1997), Oliveira et al. (1997), Oliveira et al. (1998), Oliveira et al. (2001), Konno et al. (2001), Scarpellini & Santos (2002), Franco (2002), Oliveira et al. (2003), Amorim et al. (2006), Franco et al. (2007), Fernandes et al. (2008), Martelli et al. (2009), Celoto (2009), Martelli et al. (2009), Celoto & Papa (2010), Andrade et al. (2010a,b), Andrade et al. (2011), Silva et al. (2011), Prado et al. (2011), Silva et al. (2012), Andrade et al. (2013a,b), Sanches et al. (2018), Della Vechia et al. (2019)
Uncoupler of oxidative phosphorylation	chlorfenapyr, binapacryl	Bertolotti et al. (1976), Myazaki et al. (1981), Oliveira et al. (1986b), Arashiro et al. (1987), Raizer et al. (1988), Arashiro et al. (1988), Veloso et al. (1988), Silva et al. (2011), Silva et al. (2012)

Table 1. Continued...

Mode of action	Active ingredients	Reference
Inhibitors of chitin synthesis	flufenoxuron, diflubenzuron, triflumuron, teflubenzuron	Oliveira & Oliveira (1991), Moraes & Sá (1995), Raizer et al. (1988), Scarpellini & Santos (2002), Celoto & Papa (2010)
Octopamine receptor agonists	amitraz	Oliveira et al. (1983), Sato et al. (1995)
Mitochondrial complex I eléctron transport inhibitors	fenpyroximate, pyridaben	Sato et al. (1992), Childers (1994), Sato et al. (1995), Moraes & Sá (1995), Alves et al. (2000), Oliveira et al. (2003), Amorim et al. (2006), Andrade et al. (2011), Silva et al. (2011), Silva et al. (2012)
Inhibitors of acetyl Coenzyme A carboxylase	spirodiclofen	Oliveira & Pattaro (2004a,b), Pattaro (2006), Amorim et al. (2006), Fernandes et al. (2008), Celoto (2009), Martelli et al. (2009), Andrade et al. (2010b), Prado et al. (2011), Silva et al. (2012), Andrade et al. (2013a), Della Vechia et al. (2018, 2019), Andrade et al. (2019), Rocha et al. (2021)
Mitochondrial complex II electron transport inhibitors	cyflumetofen	Silva et al. (2012), Della Vechia et al. (2019)
Compounds of unknown or uncertain mode of action	dicofol, sulfur, lime sulfur, chinomethionat, bromopropylate	Rossetti & Salibe (1959), Rosillo et al. (1964), Suplicy Filho et al. (1977), Caetano et al. (1979), Myazaki et al. (1981), Silva et al. (1983), Chiavegato et al. (1983), Oliveira et al. (1983), Oliveira et al. (1986b), Silva et al. (1986), Motta et al. (1987), Mariconi et al. (1989), Chiavegato et al. (1989), Afférri et al. (1989), Desidério et al. (1989), Mariconi et al. (1989), Raga et al. (1990), Scarpellini et al. (1991), Sato et al. (1991b), Sato et al. (1992), Campos Neto et al. (1993), Clari et al. (1993), Childers (1994), Chiavegato et al. (1994), Sato et al. (1995), Moraes & Sá (1995), Alves (1999), Alves et al. (2000), Omoto et al. (2000), Scarpellini & Santos (2002), Pattaro (2006), Fernandes et al. (2008), Martelli et al. (2009), Casarin (2010), Andrade et al. (2011), Silva et al. (2011, 2012), Andrade et al. (2010b, 2013a, 2020).

of action classified by the Insecticide Resistance Action Committee (IRAC, 2000) (Table 1).

From these studies, we can observe a more significant percentage of information about the efficacy of acaricides between the years 1983 and 2012 (Figure 1). The most extended period in which papers on the effectiveness of acaricides were not published corresponded from 1965 to 1975.

Dicofol, an acaricide of an unknown mode of action, was an effective and widely used acaricide for citrus leprosis mite control for many years until the detection of resistant populations in 2000 (Omoto et al., 2000). Bromopropylate also demonstrated satisfactory efficacy for several years until the detection of the resistant population in 2000 (Alves et al., 2000). Cyhexathin, an inhibitor of mitochondrial ATP synthase, for over 20 years, was

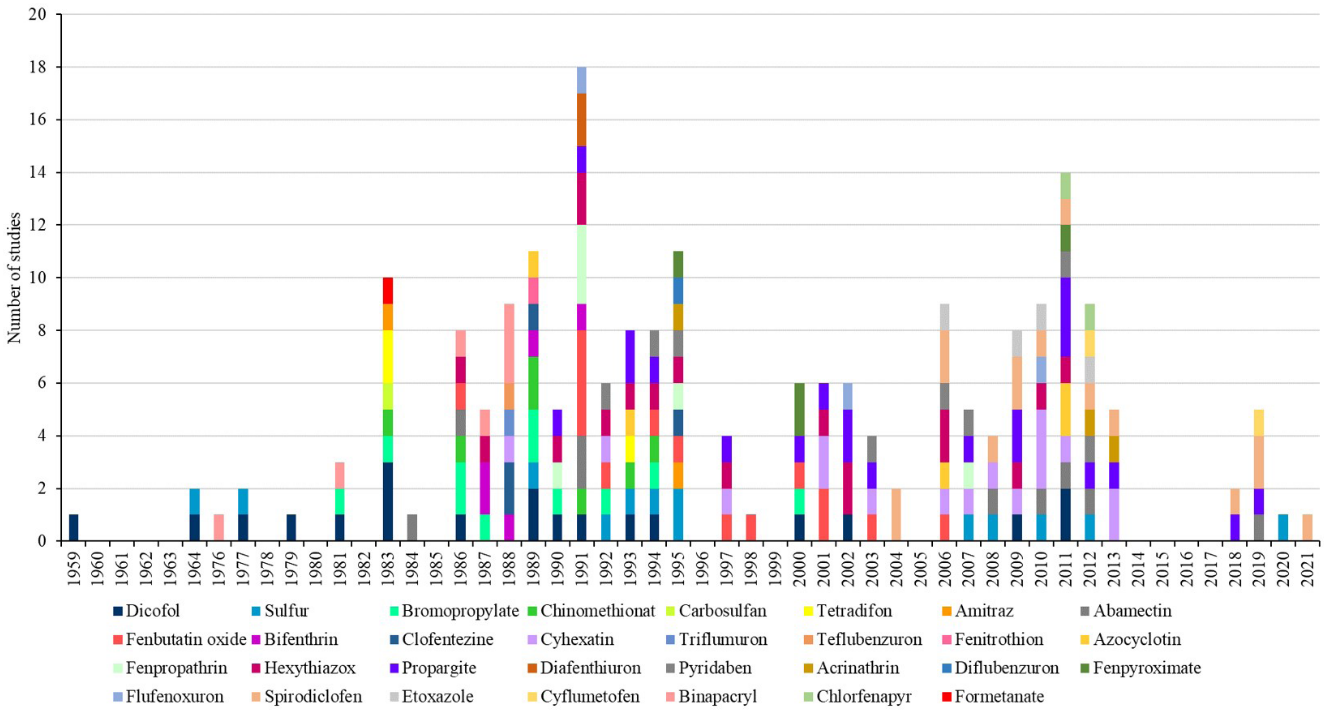

Figure 1. Number of papers published about the efficacy of acaricides in citrus leprosis mite control from 1959 to 2021.

considered an effective acaricide in controlling the citrus leprosis mite. However, in 2007 Franco et al. (2007) detected some populations resistant to this acaricide. Although Alves et al. (2000) have seen a resistant population to fenpyroximate, a mitochondrial complex I electron transport inhibitor, it has still been used and presented satisfactory efficacy (Celoto & Papa, 2010).

Hexythiazox and propargite, a mite growth inhibitor targeting chitin synthase and an inhibitor of mitochondrial ATP synthase, respectively, have been studied since the late 1980s, and resistant populations were detected for both acaricides in 2002 (Campos & Omoto, 2002; Franco, 2002). Despite detecting some resistant populations, both acaricides are still used to control the citrus leprosis mite and have a satisfactory efficacy (Celoto and Papa, 2010; Della Vechia et al., 2019).

Cyflumetofen and spirodiclofen are the newest acaricides registered for citrus leprosis mite control. The mode of action of these acaricides is different from other acaricides, cyflumetofen is a mitochondrial complex II electron transport inhibitor, and spirodiclofen is an inhibitor of acetyl coenzyme A carboxylase. Due to their satisfactory efficacy and control period, citrus growers have extensively used both acaricides. As a possible consequence of frequent use of these products, Rocha et al. (2021) detected resistant populations to spirodiclofen. However, more studies are needed to verify the susceptibility of citrus leprosis mite populations under field conditions to all available acaricides. This information is essential to structure the management program for these mites.

According to published data, the products described in Table 1 were or are still effective in controlling the citrus leprosis mite. Several acaricides were used for years until they were no longer used. Several reasons can be attributed to the reduction or even extinction of the use of a product. Among them is the cancellation of orders by international or national government agencies, low efficacy and/or selection of resistant populations, and the discontinuation of the pesticide by the industry chemistry.

Of the acaricides that have already been used to control the citrus leprosis mite, some of them had their monographs excluded, such as carbosulfan, clofentezine, azocyclotin, cyhexatin, tetradifon, binapacryl, dicofol, chinomethionat, and bromopropylate (Brasil, 2021a). Fenitrothion and triflumuron did not have renewed registration in the European Union (Brasil, 2021a). Propargite was removed from the PIC list (current ProteCitrus – Citrus Protection Products) in 2011 following health and environmental concerns by the Standing Committee on the Food Chain and Animal Health of the European Union. In 2018, the acaricide was once again permitted by the European Union with a maximum residue limit of 0.04 mg/kg in oranges (FUNDECITRUS, 2018).

Currently, the synthetic acaricides registered with the Ministry of Agriculture, Livestock, and Supply (MAPA) for the control of the citrus leprosis mite *Brevipalpus yothersi* (*Brevipalpus phoenicis*) in citrus crops are abamectin, amitraz, acrinathrin, bifenthrin, fenpropathrin, etoxazole, hexythiazox, flufenoxuron, spirodiclofen, cyflumetofen, chlorfenapyr, fenbutatin oxide, propargite, fenpyroximate, pyridaben, and sulfur (Figure 2) (Brasil, 2021b). However, few of them meet the requirements of consuming markets (ProteCitrus), which further limits the number of pesticides available for the orange juice market.

Given these limitations, some alternatives to control the leprosis mite have been studied over the years. An example is the use of *Sophora flavescens* Aiton (Fabaceae) seed extract, registered in MAPA as an oxymatrine-based acaricide. This compound proved to be highly effective in controlling adult females of *B. yothersi* due to its toxicity and repellent effect, despite not having an ovicidal effect (Andrade et al., 2019).

Although several acaricides are registered to control the citrus leprosis mite, their effectiveness will be determined by factors inherent to the products, application, and biological aspects of the pest.

Factors that interfere with acaricide efficacy

The acaricide efficacy can be compromised by several factors, including the quality of the spray water, the plant coverage by sprayed acaricide, the addition of adjuvants, the tank mixture, the level of initial mite infestation, and the evolution of resistance. Some of these factors will be discussed below.

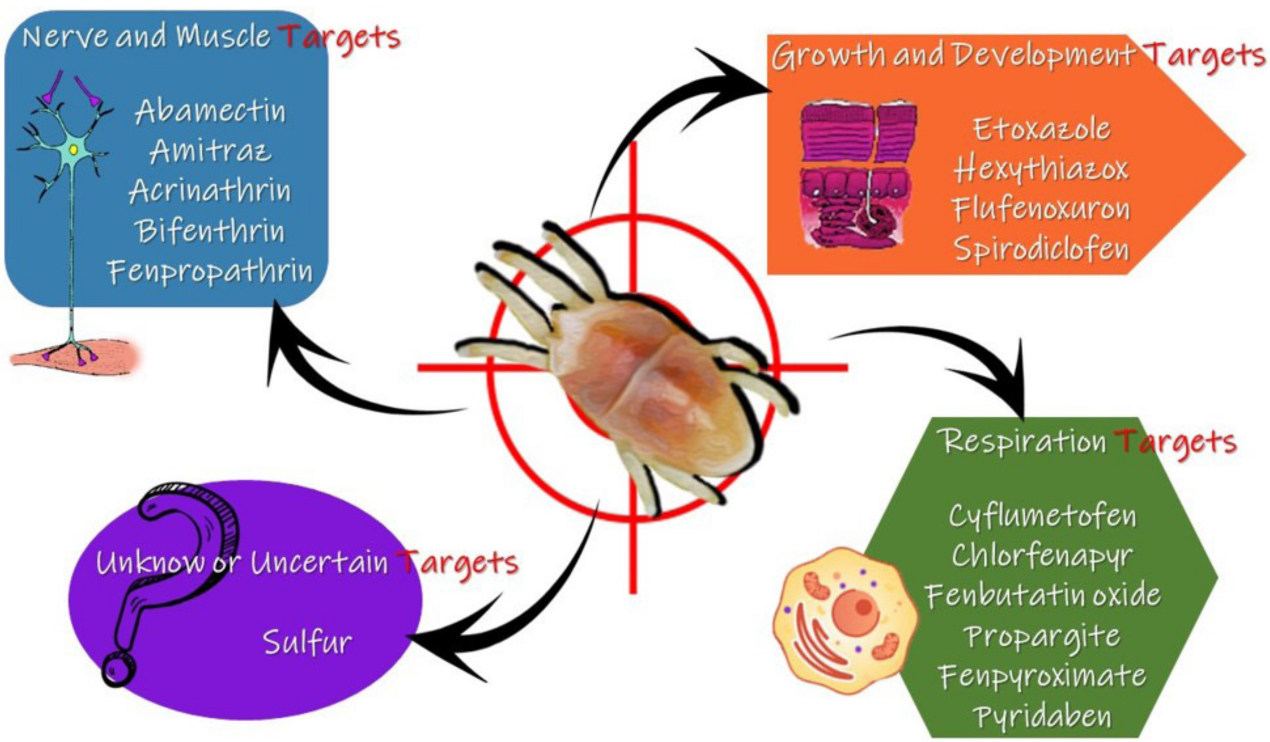

Figure 2. Synthetic acaricides currently used to control *Brevipalpus yothersi* in citrus groves and their mode of action (MoA) classification. **Nerve and muscle targets** (*abamectin:* chloride channel activator; *amitraz:* octopamine receptor agonist; *acrinathrin, bifenthrin,* and *fenpropathrin:* sodium channel modulators); **growth and development targets** (*etoxazole* and *hexythiazox:* mite growth inhibitor targeting chitin synthase; *flufenoxuron:* inhibitor of chitin synthesis; *spirodiclofen:* inhibitor of acetyl coenzyme A carboxylase); **respiration targets** (*cyflumetofen:* mitochondrial complex II electron transport inhibitor; *chlorfenapyr:* uncoupler of oxidative phosphorylation; *fenbutatin oxide* and *propargite:* inhibitors of mitochondrial ATP synthase; *fenpyroximate* and *pyridaben*: mitochondrial complex I electron transport inhibitors); and **unknown or uncertain targets** (*sulfur*).

I) Water quality

The water quality used in preparing the spray solution can influence the action of the acaricide (Andrade et al., 2013b). The presence of dissolved substances in the water and other impurities, depending on the water source, may or may not affect the action of a pesticide (Prado et al., 2011). Thus, the chemical quality of water, such as the hydrogenic potential (pH), salts, and dissolved ions, is a factor to be considered in the phytosanitary treatment.

Andrade (1997) found that the hexythiazox, fenbutatin oxide, and dicofol acaricides were not influenced by the pH of spray solution (3, 6, and 9) as to their acaricidal action on *B. phoenicis*. The water hardness and the hydrogen potential (pH) of the acaricides did not interfere with the effectiveness of propargite, hexythiazox, and spirodiclofen acaricides (Prado et al., 2011). However, water from different sources interfered with the efficacy of propargite and acrinathrin acaricides (Andrade et al., 2013b).

Knowing that factors inherent to water quality can contribute to the efficiency of acaricides and that this may be dependent on the type of acaricide, more research must be done to understand how these factors can influence the efficiency of each acaricide used by citrus growers.

II) Plant coverage by sprayed acaricides

The location, infestation levels, and movement of pests significantly interfere with the phytosanitary treatment, whose effectiveness depends on the distribution of the product through the plant canopy. For targets of low mobility and difficult access to spraying, such as *Brevipalpus* spp., full coverage of the plants by the drops is necessary to increase the probability of contamination of the target pest with the acaricide molecules. In addition to this factor, the mode of action of acaricides on mites (contact and ingestion) requires adequate plant coverage by the sprayed product.

In addition to the behavior of the mite, the dense foliage and the presence of fruit on citrus trees form a compact shield. This makes it challenging to achieve good coverage by spraying, especially inside the canopy, resulting in high volumes of acaricide application (Oliveira et al., 2001).

The leprosis mite usually lays eggs and lodges in sheltered places, such as crevices, citrus scab [symptoms on the fruit epidermis caused by the fungus *Elsinoë fawcettii* (Bitancourt and Jenkins)], and other lesions, scales, and mite exuvial, in addition to dust granules present in the fruits. They are also found on branches and leaves, both external and internal to the canopy (Chiavegato & Kharfan, 1993; Rodrigues, 2000; Bazzo, 2016). Thus, to be successful, sprays with acaricides must cover the entire surface of the fruits, branches, and leaves, both externally and internally, in the plant canopy.

Until the early 21st century, leprosis mite control was associated with a high volume of spray solution. However, the high volume usually results in loss of the spray solution through runoff, resulting in more significant waste and cost (Oliveira et al., 2001). According to Holownicki et al. (2000), the ineffectiveness of many sprays on citrus is attributed to losses in spraying that can be greater than 50% concerning the amount applied, increasing production costs, and contamination of other areas.

Studies have shown that reducing the volume of spray liquid applied to control the mites is possible, as long as some parameters are adequate, such as the number of nozzles and the size of droplets produced by the spray tips, allowing better penetration, distribution, and coverage of spray solution applied inside the plant canopy (Raetano & Matuo, 1999; Ramos et al., 2007; Bazzo, 2016; Sichieri, 2018).

III) Adjuvants

The addition of adjuvants, substances without phytosanitary properties, in the spray solution aims to improve the physicochemical characteristics and, consequently, the efficiency of the sprayed pesticides (Xu et al., 2011). Adopting alternatives that will enhance the coverage of the treated surface or protect the applied solution from unfavorable weather conditions, such as using adjuvants in the acaricide solutions, can contribute to the adequate coverage of the targets (Andrade et al., 2010a).

Some acaricides, such as abamectin or ethion, have often been combined with mineral oils to improve residual activity (Rodrigues & Childers, 2002). On the other hand, adding some adjuvants can negatively affect the efficiency of acaricides in controlling the leprosis mite. Oliveira et al. (2003) observed that adding vegetable oil to pyridaben and cyhexatin acaricides reduced leprosis mite control. Furthermore, results obtained by Vieira (2019) demonstrated that the addition of polyester and silicone copolymer or mineral oil significantly reduced the acute toxicity levels of spirodiclofen and cyflumetofen.

Adding the adjuvant phosphatidylcholine (lecithin) + propionic acid to the acaricide propargite decreased the control efficiency of *B. yothersi*. In contrast, polydimethylsiloxane, associated with the propargite acaricide, did not increase the control efficiency of *B. yothersi* (Sanches et al., 2018).

Decaro et al. (2016) observed that adding polydimethylsiloxane to propargite solution resulted in greater spray solution deposit on citrus leaves, while spirodiclofen the mixture with polydimethylsiloxane or phosphatidylcholine adjuvants reduced spray solution deposit, which possibly would result in lower acaricide efficiency in the leprosis mite control.

The deposit and retention of the sprayed solution on the plant is an important factor in pesticide efficacy and adding adjuvants to the spray solution may influence these characteristics. It is important to emphasize when a high volume of spray solution is used, the use of adjuvants that will promote the spreading of the sprayed droplets will promote excess losses due to run-off.

Since the interaction between adjuvants and pesticides is a complex process that involves several physical, chemical, and physiological aspects (Ramsdale & Messersmith, 2001), it is necessary to know the characteristics of the products and the possible interactions that may occur between adjuvants and acaricides before being used in the field.

IV) Tank mixture

Given possible simultaneous infestations of different pests, mixing pesticides in the spray tank is a common practice among citrus growers to reduce production costs, rationalize the use of water, reduce the demand for spraying equipment and optimize the operational capacity of the production system (Andrade et al., 2013b; Della Vechia et al., 2018; Vieira, 2019). According to Andrade (1997), in a survey carried out in the 1990s with citrus growers, more than 120 product combinations in the spray tank are used, mainly involving acaricides with insecticides, fungicides, foliar fertilizers, and adjuvants.

Some studies were conducted to study the compatibility between the products mixed in the spray tank. Table 2 describes some of the combinations that have already been tested and confirmed compatibility or incompatibility with acaricides, focusing on leprosis mite control.

Although the tank mixture is advantageous, it can also have negative consequences, contrary to the goals of this strategy. Della Vechia et al. (2018 and 2019) found an antagonistic effect in combinations between spirodiclofen and phosmet, imidacloprid, cypermethrin, or bifenthrin, insecticides commonly sprayed to control *Diaphorina citri* Kuwayama (Hemiptera: Liviidae) on Brazilian citrus groves, which reduced the acaricide efficiency by up to 40%. In addition to mixing synthetic pesticides, mixing foliar fertilizers with acaricides is commonly used and may also interfere with the action of the acaricide. Andrade et al. (2013b) found that potassium phosphate, magnesium sulfate, zinc chloride, and manganese fertilizers resulted in lower efficiency of the acaricides propargite and acrinathrin on the leprosis mite. A reduction in the efficacy of propargite, cyflumetofen and spirodiclofen mixed with sulfur has also been reported (Campos-Neto et al., 1993; Andrade et al., 2022).

Given the high cost of controlling the leprosis mite and the possible incompatibilities of pesticides in the spray tank, studies on acaricides and other product mixtures and their implications for citrus leprosis mite management and environmental issues are essential. They should be encouraged to improve citrus production in terms of quantity and quality.

V) Infestation level

The interval between the pest detection and the control action can interfere with mite management. In most cases, these problems result from the reduced number of machines available for operation and the logistics of acquiring the products needed for the application (Bassanezi, 2018). The increase in the interval between detection and control action makes the mite population more significant at the time of application, and, even if the acaricide is efficient, the residual mite population will be larger, consequently, it will take less time to reach the control action level again, resulting in a shorter period of mite control by the acaricide (Bassanezi, 2018; Andrade et al., 2010c).

Also, the use of some insecticides can favor the target-pest resurgence and/or induce the occurrence of population outbreaks of non-target pests, especially of phytophagous mites (Cordeiro et al., 2013; Guedes et al., 2016; Zanardi et al., 2018), which increase the production costs and reduce the environmental sustainability of the system. Della Vechia et al. (2021) found that beta-cyfluthrin, bifenthrin, buprofezin, chlorpyrifos, dimethoate, thiamethoxam, and pyriproxyfen did not promote an increase in the reproduction of *B. yothersi*. However, more studies should be conducted to verify whether this same result is observed when mites are exposed to successive insecticide sprayings, a common practice in the Brazilian citrus groves.

Table 2. Compatibility between acaricides and insecticides or foliar fertilizers in citrus leprosis mite control

Chemical group	Product in mixture	Class*	Acaricide		
			Cyflumetofen	Spirodiclofen	Propargite
Avermectin	Abamectina	A/I	C[1]	C[1]	C[1]
Pyridyloxypropyl ether	Pyriproxyfen	I	C[1]	C[1]	C[1]
Hexythiazox	Hexythiazox	A	-	-	C[1]
Neonicotinoid	Imidacloprid	I	C[1]	I[1]	C[1]
	Thiamethoxam	I	C[1]	C[1]	C[1]
Organophosphate	Chlorpyrifos	I	C[1]	C[1]	C[1]
	Dimethoate	I	C[1]	C[1]	C[1]
	Phosmet	I	C[1]	I[1]	C[1]
Pyrazole	Fenpyroximate	I/A	-	-	C[1]
Pyrethroid	Beta-cyfluthrin	I	C[1]	C[1]	C[1]
	Bifenthrin	A/I	C[1]	I[1]	C[1]
	Cypermethrin	I	C[1]	I[1]	C[1]
Thiadiazinone	Buprofezine	I	C[1]	C[1]	C[1]
Inorganic	Sulfur	A/F	I[4]	I[4]	I[5]
-	$MgSO_4$ + $MnSO_4$ + $ZnSO_4$ + Urea (45% N)	FF	C[2]	C[2]	-
-	Zinc chloride	FF	-	-	C[3]
-	Manganese chloride	FF	-	-	C[3]
-	Urea	FF	-	-	C[3]
-	Potassium phosphite + urea + Cl Zn	FF	-	-	C[3]
-	Cl Zn + magnesium sulfate	FF	-	-	I[3]
-	Cl Mn + magnesium sulfate	FF	-	-	I[3]

C – compatible; I – incompatible. *A – acaricide; I – insecticide; F – fungicide; FF - foliar fertilizer; - without information. [1]Della Vechia et al. (2019); [2]Vieira (2019); [3]Andrade et al. (2013b); [4]Andrade et al. (2022); [5]Campos-Neto et al. (1993).

VI) Acaricide resistance

According to the Insecticide Resistance Action Committee (IRAC), resistance can be defined as a heritable change in the sensitivity of a population, resulting in the repeated failure of a product to reach the expected level of control when used according to the recommendation from the manufacturer. Therefore, there is a selection of genetically predisposed individuals to survive doses that are lethal to most susceptible populations (Li et al., 2007).

The evolution of resistance is influenced by some genetic, bioecological, and operational factors (Georghiou & Taylor 1977a, b). Genetic factors are related to the initial frequency of resistant alleles, the number of alleles involved in resistance, the inheritance pattern of resistance, and the adaptive advantage or disadvantage of resistant individuals. Bioecological factors refer to the mode and rate of reproduction, feeding habits, mobility, refugee for susceptible individuals, and the presence of natural enemies (Georghiou & Taylor, 1977a). Operational factors are linked to chemical characteristics such as persistence, formulation, chemical group, selectivity to natural enemies and application characteristics such as application frequency, control level, pest development stage, dosage, and application mode (Georghiou & Taylor, 1977b).

Brevipalpus resistance to acaricides is identified as one of the main factors responsible for control failures. The reproduction predominantly by thelytokous parthenogenesis (Weeks et al., 2001) and the low dispersal capacity of these mites make a dilution of resistance difficult and, together with the high selection pressure, can accelerate the evolution of resistance (Alves et al., 2005).

Some studies have already reported cases of the evolution of the resistance of populations of Brevipalpus phoenicis lato sensu to acaricides. Omoto et al. (2000) monitored the resistance of populations of *B. phoenicis* from eleven commercial citrus groves in the São Paulo State to dicofol. These authors found high variability in susceptibility among populations, with a resistance ratio of up to 57 times. Alves et al. (2000) found greater susceptibility to fenpyroximate for the dicofol-resistant strain than the susceptible strain, indicating negative cross-resistance between these two acaricides. The absence of cross-resistance between dicofol, fenbutatin oxide, and propargite was also demonstrated (Alves et al., 2000). However, the dicofol-resistant strain was also resistant to bromopropylate, showing positive cross-resistance between these acaricides (Alves et al., 2000).

The susceptibility of *B. phoenicis* to organotin oxide and cyhexatin was studied by Konno et al. (2001). All populations collected by these authors showed similar susceptibility to the susceptible reference strain, except one population showed a 10.7% survival rate to cyhexatin. On the other hand, Campos & Omoto (2002) verified high variability in the response of *B. phoenicis* populations to the hexythiazox, in which the frequency of resistance in the population ranged from 30 to 94%, with a resistance ratio greater than 10,000 times.

Franco (2002) conducted studies to characterize and monitor the resistance of *B. phoenicis* to propargite in populations collected in different citrus groves in the São Paulo State. The author found significant differences in the population susceptibility to this acaricide, with survival percentages ranging from 9.7 to 88.3% and from 0.0 to 63.8% at diagnostic concentrations of propargite, 320 and 720 mg L^{-1}, respectively.

Casarin (2010) evaluated the evolution of resistance of leprosis mite populations from groves with organic and conventional management systems to lime sulfur. Significant differences in susceptibility were detected between populations but not between management systems. The Resistance Ratio found was 5.69 times, and this resistance proved to be stable in the laboratory. In addition, positive cross-resistance was detected between lime sulfur and sulfur.

The most recent report on leprosis mite-resistant populations was carried out by Rocha et al. (2021), who identified a population resistant to spirodiclofen in some regions of the São Paulo State. There was found variability in the population survival to the diagnostic concentration of the acaricide, and a resistance ratio of 10.6 times in the resistant strain was estimated.

Resistant individuals may present a higher fitness cost related mainly to biological and physiological factors than susceptible ones (Kliot & Ghanim, 2012). Thus, in the absence of selection pressure, resistant individuals are expected to have a lower survival and reproduction rate, making them less competitive (Dennehy et al., 1990). A *B. phoenicis* dicofol-resistant strain showed lower fecundity and longevity than the susceptible strain (Alves, 1999). For spirodiclofen, there was a reduction in adult longevity, oviposition days, and fecundity in the resistant strain (Rocha et al., 2021). Furthermore, the resistance of the leprosis mite to hexythiazox was shown to be unstable under field conditions (Campos & Omoto, 2006). This fitness cost associated with resistance is one of the factors responsible for resistance instability, which can help delay the evolution of resistance and revert to susceptibility (Roush & McKenzie, 1987; Alves, 2004; Kliot & Ghanim, 2012). This information can be exploited in citrus leprosis mite resistance management programs aiming to rotate acaricides with different modes of action.

CONCLUSION

The choice of acaricide must follow the recommendations of the Ministry of Agriculture, Livestock, and Food Supply. In addition, for citrus growers who intend their production for exportation, the products to be used must follow the recommendations of the ProteCitrus. In this list, citrus growers find the products authorized for application, with the MRLs (Maximum Residue Limit) defined by the main consumer countries of Brazilian orange juice, with emphasis on the countries of the European Community (FUNDECITRUS, 2021). Additionally, information on factors that interfere with the effectiveness of acaricides needs to be generated and made available to citrus growers.

Using synthetic acaricides is an option that generates short-term results for citrus growers. However, the association with other control measures will allow more satisfactory results for the pathosystem.

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