RECENT RESEARCH ON PESTICIDES TO MANAGE THE CHIVE MAGGOT, Bradysia odoriphaga YANG ET ZHANG (DIPTERA: SCIARIDAE) IN CHINA

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The chive maggot, Bradysia odoriphaga Yang et Zhang (Diptera: Sciaridae), is a devastating pest for Chinese chive and other vegetables in China. Most farmers take pesticides as their first tool to control this pest. Phoxim, imidacloprid, thiamethoxam, clothianidin and cypermethrin are the common used pesticides but the development of the resistance against these compounds is the main concern, especially phoxim. Insect resistance to thiamethoxam and clothianidin is much lower than that to phoxim although it varies among different area. This issue can be greatly alleviated by rotating the use of the pesticides with different mode of action. Moreover, proper application method can substantially improve control effect. Pesticides with new mode of actions are under intensive investigations and chlorfenapyr has been shown to be a potent alternative pesticide for the control of the chive maggot. The pest shows low resistance to this chemical. Furthermore, many promising pesticides derived from biological products such as plant allelochemicals and microbial metabolites have been discovered and tested for their controlling efficacy. These pesticides are generally environmental-friendly and strongly encouraged in China now. They usually have relatively lower control effect in contrast to the traditional pesticides so they are suggested be used along with the rapid knock-down pesticides. Except for these pesticides, non-chemical methods are also vigorously developed to control B. odoriphaga, among which increasing soil temperature by covering the crop with plastic mulch film in hot days is very effective. This method developed by Youjun Zhang and his colleague has great potential to substantially decrease the usage of pesticides against the chive maggot. Overall, the multiple choices in the toolbox can help suppress the pest population under the economic threshold and greatly reduce the resistance of this pest to pesticides.

Keywords: Bradysia odoriphaga, organophosphates, neonicotinoids, pyrethroids, pyrroles.

INTRODUCTION

The chive maggot, Bradysia odoriphaga Yang et Zhang (Diptera: Sciaridae), is a devastating polyphagous soil pest and its host includes more than seven plant families, such as Chinese chives, Garlic, Welsh onion, Cabbage, Radish, Melon and Celery (Mei et al., 2003). Chinese chive, Allium tuberosum Rottler ex Sprengel, a global grown vegetable, is the most favorite host for this pest (Mau et al., 2001; Imahori et al., 2004; Yabuki et al., 2010; Chen et al., 2017; Zhao et al., 2017). Chinese chive is an important crop, which has high economic value and large planting area in China, with the estimated area of more than 300,000 hm² (Shi et al., 2016b). B. odoriphaga larvae feed on roots and stems of chives and peak damage usually occurs in both spring and autumn. This pest goes through winter mainly in larval form and up to 10 generations can occur each year (Mei et al., 2003). The loss can be more than 60% yield of this crop unless proper controlling actions are taken (Dang et al., 2002; Li et al., 2015). Many techniques have been developed to control B. odoriphaga in Chinese chive industry. The most known, and probably the most successful, is the application of chemical pesticides. In this review, we summarize the current status of pesticide usage in controlling B. odoriphaga and then discuss their proper application in a comprehensive management manner.

Major pesticides used for the control of B. odoriphaga: For the sake of being rapid, efficient and easy to manipulate, pesticide application is a major strategy taken up by most farmers in controlling B. odoriphaga (Ma et al., 2013; Zhang et al., 2016c; Shi et al., 2018). There are five insecticides commonly used, including phoxim, imidacloprid, thiamethoxam, clothianidin and cypermethrin (Shi et al., 2017). Phoxim belongs to organophosphate. Imidacloprid, thiamethoxam and clothianidin are neonicotinoids. Cypermethrin is a type of pyrethroid. Recently, chlorfenapyr was tested and proven to be a promising pesticide with a unique mode of action to control the chive maggot (Zhao et al., 2017). These pesticides have different modes of action and rotating them can greatly reduce the resistance. However, B. odoriphaga has still developed appreciable resistance to them. Studies showed that neonicotinoid insecticides are more efficient in controlling this pest than organophosphate and pyrethroid insecticides (Peng et al., 2014; Zhao et al.,...
Additionally, the major application of chemical insecticides is root irrigation, which can cause the excessive use and seriously environmental pollution. Overuse of these pesticides was ever a huge problem and residues of these chemicals were detected at a high level in marketed Chinese chives in some area mainly because the pests have developed strong resistance (Goh et al., 1990; Na-Na and Yang, 2012; Zhang et al., 2016b; Shi et al., 2017; Zhang et al., 2017; Shi et al., 2018). Therefore, the usages of these pesticides should strictly follow the instructions to keep the residues under limit standard, and it is necessary to monitor and reduce the resistance of *B. odoriphaga*.

**Organophosphates (OPs):** OPs are a class of organophosphorus compounds and usually have a broad insecticidal spectrum. These chemicals rapidly interfere with the neutral signal transmission by phosphorylating the catalytic serine residue in acetylcholinesterase in the nervous system (Rathnayake and Northrup, 2016). Chlorpyrifos and phoxim used to be the mostly used OPs in controlling *B. odoriphaga* (Figure 1). These two chemicals have high soil absorption coefficient and low water solubility, which is essential for root-irrigation to control underground pests. In fact, these two chemicals started to be used in controlling *B. odoriphaga* and other underground pests quite long ago (Feng and Zheng, 1987; Ortiz Saavedra et al., 2008; Arrington et al., 2016). However, chlorpyrifos is not allowed to be used anymore because of its high persistence (http://www.icama.org.cn/). In contrast, phoxim is sensitive to light and the residue can be easily kept below the limit required by the European Union (0.01 mg/kg) (Zhang et al., 2016a; Zhao et al., 2017). In a field study, it was found that the efficiency of phoxim with the active ingredient of 3.6 kg/hm², the recommended concentration used in the field, against *B. odoriphaga* on the 7th, 14th, 21th and 28th day is 74.05 ± 2.23, 77.34 ± 3.58, 76.65 ± 5.66 and 79.62 ± 5.94, respectively, indicating that this pesticide is still effective in controlling this pest. However, the survived population, i.e., more than 20% of the total population, can likely build strong resistance to this pesticide if no pesticide rotation is taken. In a recent study, it was reported that most field collected *B. odoriphaga* populations have developed very high resistance to OPs, more than 100-fold resistance ratio in some cases, in comparison to a laboratory susceptible population so OPs are not recommended for the management of *B. odoriphaga*, given the high resistance in some area (Chen et al., 2017). However, the molecular mechanism of *B. odoriphaga* resistance to organophosphate insecticides is not clear yet.

**Neonicotinoids (neonics):** Neonics are a class of insecticides acting as agonists of the post-synaptic nicotinic acetylcholine receptors, similar to nicotine. Imidacloprid, thiamethoxam and clothianidin are the three commonly used neonics in controlling *B. odoriphaga* (Figure 2), and these pesticides were initially registered to control sap-sucking insects because of their good systemic activity (Chao et al., 1997; Zhang et al., 2010). The efficacy and insect resistance of neonicotinoid insecticides for controlling *B. odoriphaga* were reported after 2010 (Li et al., 2014; Zhang et al., 2014; Hui et al., 2015; Chen et al., 2017). In some area, neonicotinoid insecticides have replaced organophosphorus insecticides as the major pesticide for controlling *B. odoriphaga*. It is reported officially that imidacloprid accounts for more than 60% insecticide registered for the *B. odoriphaga* control since 2016c).
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2013 (www.chinapesticide.gov.cn). The resistance to these chemicals appears much lower (ca, 10-fold) than that for OPs although it varies among different populations (Chen et al., 2017). For example, a lower dosage of thiamethoxam, 0.675 kg/hm² can have similar control efficiency against B. odoriphaga as a high dosage of phoxim, 3.6 kg/hm². The control efficiency can reach up to 100% at day 21 if the higher dosage, 1.125-1.35 kg/hm², was used and this was still much lower than the dosage of phoxim. Obviously, increasing dosage can substantially reduce the resistant population in the field (Shi et al., 2018). In another study, the higher dosage of thiamethoxam (6 kg/hm² and 12 kg/hm²) was used and control effect was also 100%. In the same study, the dosage (3 kg/hm² and 6 kg/hm²) of another neonicotinoid pesticide, clothianidin, was lower than the dosage of thiamethoxam used but the control effect was mostly comparable. The different dosages used in these studies reflected that different B. odoriphaga populations may have developed various resistance to neonicotins. Moreover, application methods are also key factors in using these chemicals efficiently. Double root-irrigation can give a better protection for the crop than the single fixed-point irrigation (Shi et al., 2016a). In another study, it was found that it was relatively easier for thiamethoxam and clothianidin to reach the target by using drip washing method than chemigation method. Interestingly, in spite of the decreasing concentration of thiamethoxam and clothianidin along with soil depth, the concentration was higher in the soil surrounding the root than in the soil between the rows of the plants, likely because they can be systemically transported to the feeding sites underground (Zhang et al., 2015).

The half-lives of thiamethoxam in soil was longer than phoxim, e.g., 27.5 days vs. 6.7 days, so they can provide a longer controlling efficacy than phoxim. (Peng et al., 2016; Zhang et al., 2016b; Zhang et al., 2016c). However, the effect of the residues on human health and other environmental factors should be examined carefully in the future research. Detoxification by P450s is thought to be the major mechanism accounting for imidacloprid resistance in B. odoriphaga larvae, similar as other pesticides resistance (Chen et al., 2017). In contrast to OPs, neonicots are less toxic to birds and mammals but they are harmful to bees, reducing their capacity to establish new populations (Woodcock et al., 2017).

Pyrethroids: Pyrethroids, deriving from the natural pyrethrins produced by the flowers of pyrethrums, are toxic to insects by preventing the closure of the voltage-gated sodium channels in the axonal membranes (Wallace, 2002). Cypermethrin is one type of pyrethroids and widely used for pest management including dipteran pests (Figure 3) (Wei-Long et al., 2012; Wang et al., 2014; Jin et al., 2016). They are preferred pesticides for their low toxicity to mammals and humans. Cypermethrin is also used for controlling B. odoriphaga and shows good knock-down activity to B. odoriphaga adults (Xue et al., 2002). However, moderate to high resistance has appeared (Chen et al., 2017).

![Figure 3. Chemical structure of pyrethroid (cypermethrin) and pyrrole (chlorfenapyr) pesticides in controlling B. odoriphaga. Structure information from PubChem Database is used: cypermethrin (compound ID number = 2912) and chlorfenapyr (compound ID number = 91778).](image)

Other promising pesticides: In spite of relatively high control efficacy of the above pesticides in controlling B. odoriphaga, the increasing usage of these chemicals are significantly causing environmental concern in China. More importantly, we are losing the controlling power when the pest keeps developing their resistance. Therefore, finding new pesticides with different modes of action from the pesticides discussed above is urgent. In the following sections, we review the research progress in the development of new pesticides against B. odoriphaga.

Pyroles: Pyroles refer to a group of heterocyclic aromatic organic compounds which chlorfenapyr belongs to. It has contact and stomach toxicity, and acts as an oxidative phosphorylation uncoupler to disrupt the respiratory chain and proton gradients in mitochondria (Black et al., 1994). This kind of mode of action is different from other pesticides so no obvious cross-resistance appears yet (Hollingworth et al., 1998; N’Guessan et al., 2007; Oliver et al., 2010; Dagg et al., 2019). For example, some study showed that phoxim-resistant B. odoriphaga populations were susceptible to this pesticide.

Chlorfenapyr is a good controlling agent against dipteran pests and it has low toxicity to humans and plants (Figure 3) (Hanafi et al., 2016). The controlling efficacy of chlorfenapyr increases along with the increasing temperature in the range of 8 to 24 °C (Zhao et al., 2017). Moreover, chlorfenapyr has low residues in vegetables, an obvious advantage over the systemic pesticides which tend to exist long in plants (Zhang et al., 2016b). Therefore, this pesticide has been widely and successfully used in controlling many species of insect pests (Yuan et al., 2015).
The toxicity of chlorfenapyr is positively correlated with the activity of P450s because this chemical is converted to the more potent metabolite by P450s. As a result, chlorfenapyr has similar toxicity to the late instars of *B. odoriphaga* as to the early larvae probably because of the higher P450 activity in the former. However, resistance to chlorfenapyr has been reported in some insects and should be monitored (Yoo et al., 2013). Chlorfenapyr not only shows acute toxicity to *B. odoriphaga* but also exhibits sublethal effects. For example, exposure to chlorfenapyr at the concentrations of LC1 and LC20 increases the fecundity of *B. odoriphaga* and the population increased significantly by promoting the larvae feeding under LC1 (Zhao et al., 2017). Therefore, the proper application including insecticide rotation and effective concentration application should be considered comprehensively.

**Insect growth regulator:** Among the four commonly used insect growth regulators, e.g., chlorfluazuron, hexaflumuron, diflubenzuron and cyromazine, chlorfluazuron was the most active one against *B. odoriphaga* (Figure 4) (Zhang et al., 2017). Studies showed that the control efficacy against *B. odoriphaga* can reach 70.2% in the field in 24 days after application (Chen et al., 2005). Chlorfluazuron inhibited the biosynthesis of cuticle chitin so chitin content significantly decreased in the treated *B. odoriphaga* larvae compared to the control ones. In this aspect, immature insects are very sensitive to this pesticide because molting process is interrupted (Perveen, 2010). Chlorfluazuron reduced *B. odoriphaga* population growth significantly at the sublethal LC50 and, interestingly, it stimulated the growth at LC10 (Zhang et al., 2017). The mechanism of the resistance to chlorfluazuron is unclear yet but it has been shown that glutathione S-transferase and mixed function oxidases can metabolize chlorfluazuron (Sonoda and Tsumuki, 2005). Toxic action is slow to *B. odoriphaga* larvae so the rapid knock-down pesticides such as organophosphates, neonicots and pyrethroids are suggested to use along with chlorfluazuron to reduce the development of the resistance (Sonoda and Tsumuki, 2005; Perveen, 2010; Zhang et al., 2017).

**Botanical compounds:** Allyl isothiocyanate (AITC) is an organic compound containing sulfur, i.e., organosulfur compounds (Figure 5). Many plants with pungent taste such as mustard, radish, horseradish, and wasabi have this compound serving as a defensive allelochemical against herbivores. When plant tissues are damaged, for example insect chewing, glucosinolates such as sinigrin are exposed to myrosinase, an endogenous thioglucosidase (EC 3.2.3.1)
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located within the vacuoles. This enzyme mediates the conversion of glucosinolates into AITC and other metabolites (Rungpammetry et al., 2006). AITC is volatile and can be used as a fumigant against insect pests in a closed environment such as greenhouse in which large amount of vegetables including the hosts of B. odoriphaga are grown during winter (Cardiet et al., 2012; Hua et al., 2014; Björnarn et al., 2015). AITC was also an effective contact insecticide (Eltayeb et al., 2010; Shi et al., 2017). This compound showed good control potent against B. odoriphaga and the adults are the most sensitive stage (Shi et al., 2017). But this chemical is phytotoxic especially for the plants at the germination and seedling stages, probably by inhibiting actin-dependent intracellular transport (Björnarn et al., 2015). Therefore, safety tests are required for its usage on Chinese chives.

The mode of action of AITC remains unknown. Some studies indicated that AITC-treated insects showed the symptoms of morphological malformations. Meantime, other studies showed that this chemical acted on the respiratory system, which is consistent with its fumigant activity (Eltayeb et al., 2012).

Garlic essential oil: Many plants in family Liliaceae such as garlic show high resistance to insect pests including B. odoriphaga (Xue et al., 2005). A lot of garlic cultivars have been established in China, providing a good germplasm pool to investigate the variation of resistance among garlic cultivars (Yang et al., 2004). The major biological active chemicals in these plants are the mixture of sulfides, ca. up to 99.9% (Han et al., 1995; Numa Vergel et al., 2011). These phytochemical biomolecules were tested and showed good effects against many pests such as B. odoriphaga, Lycoriella ingenua, Tribolium castaneum (Herbst), Siptotoga cerealella (Lepidoptera: Gelechiidae), Delia radicum (L.), Musca domestica (L.) and Tetranychus urticae (Tetranychidae) (Yang et al., 2010; Feng-Lian et al., 2012). Interestingly, the variation of these chemicals in different cultivars is well correlated with the plant resistance (Prowse et al., 2006; Wang et al., 2010; Attia et al., 2012). Allicin is the main content in the extract of garlic plants but it is not stable. It can be broken down into the stable polysulphide, diallyl disulfide and diallyl trisulfide (And and Shin, 2005; Park et al., 2005; Kimbaris et al., 2010), which are actually the major chemicals in garlic essential oil. In terms of insecticidal activity, these garlic derived chemicals were less potent than the traditional pesticide, phoxim. But they showed better insecticidal activity against B. odoriphaga than sophocarpidine and azadirachtin, two other botany-derived compounds (Choi et al., 2003; Rattan, 2010; Zhu et al., 2017).

Microbial pesticide: Benzothiazole is a microbial secondary metabolite and showed strong fumigation toxicity to B. odoriphaga at various developmental stages (Figure 5) (Chen et al., 2014). Benzothiazole may have multiple effects on different physiological processes such as inhibiting the energy production, reducing nutrient accumulation and decreasing the digestive enzyme activities (Zhao et al., 2016a; Zhao et al., 2016b). B. odoriphaga larvae consume significantly less diet when treated with sublethal concentrations of benzothiazole, i.e., LC10 and LC30, but the insect weight is not affected. More research is necessary to understand the effect of this chemical on B. odoriphaga. Additionally, entomopathogenic agents can be used directly. For example, one entomopathogenic fungus, Beauveria bassiana, is currently registered for controlling B. odoriphaga (www.chinapesticide.gov.cn).

Summary: B. odoriphaga is the major pest in Chinese chive production and high level of the pesticide residue greatly affect the quality of chive and human health. We can find strategies and approaches to reduce the use of pesticides by understanding the resistance mechanism and the effect of sublethal concentrations. Rotating application of the pesticides without cross-resistance is strongly suggested. Moreover, alternative management options are preferred in some cases. For example, new technologies, especially those replacing chemical pesticides, are greatly advocated by the Chinese government in these years. These new methods are mostly environmentally-friendly ones, including entomopathogenic nematodes, colored sticky plates, hormone traps, natural enemies and the promising physical control methods in the integrative pest management system (Yang and Zhang, 1990; Xiang yang et al., 2005; Sun et al., 2004; Ma et al., 2013; Chen et al., 2014; Wang et al., 2014; Chen et al., 2015; Tao et al., 2015; Wang et al., 2015; Wu 2015). Notably, Youjun Zhang and his colleagues have developed a novel method to control et al., B. odoriphaga. They substantially increase soil temperature to kill the pest by covering the crop with plastic mulch film in hot days (Qu et al., 2019). Apparently, the pest has a much lower tolerance to the heat than the crop and the control effect is up to 100%. However, pesticide application seems still an inevitable approach in controlling the pest in greenhouse during winter when it is unlikely to reach such high temperature. In the future, the research on the management of B. odoriphaga should focus on the comprehensive usage of different methods although the usage of pesticides still seems irreplaceable.

Acknowledgements: This work was supported by Shandong Academy of Agriculture Science Foundation Youth Branch (2016YQN44) and the Introduction of Talent Research Start-up Fund of Northwest A&F University (Z111021503).

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Received 07 Oct. 2019; Accepted 18 December- 2019 Published 8 Feb. 2020]