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六种新烟碱类杀虫剂和三氟苯嘧啶对黄胸蓟马及南方小花蝽的选择毒性

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摘要：【目的】评估 6 种新烟碱类杀虫剂和 1 种新型杀虫剂三氟苯嘧啶对黄胸蓟马 *Thrips hawaiiensis* 及其天敌南方小花蝽 *Orius strigicollis* 的选择毒性，为杀虫剂与南方小花蝽联合防控黄胸蓟马提供依据。【方法】采用药膜法测定吡虫啉、呋虫胺、氟吡呋喃酮、氯噻啉、烯啶虫胺和噻虫嗪 6 种新烟碱类杀虫剂及三氟苯嘧啶对黄胸蓟马成虫的毒力及对南方小花蝽 5 龄若虫的急性毒性，并评估其对南方小花蝽 5 龄若虫的暴露风险。【结果】供试的 7 种杀虫剂对黄胸蓟马成虫的半致死用量(median lethal rate, LR_{50})均低于田间最大推荐用量。氯噻啉对黄胸蓟马成虫的 LR_{50} 值最低(0.183 g a.i/hm^2)，显著低于其他杀虫剂；氟吡呋喃酮和三氟苯嘧啶对黄胸蓟马成虫的 LR_{50} 值分别为 3.066 和 3.949 g a.i/hm^2，显著高于其他杀虫剂；两种烯啶虫胺制剂(20% 烯啶虫胺可溶液剂和 10% 烯啶虫胺水剂)对黄胸蓟马成虫的 LR_{50} 分别为 0.327 和 0.201 g a.i/hm^2；两种噻虫嗪制剂(70% 噻虫嗪水分散粒剂和 25% 噻虫嗪水分散粒剂)对黄胸蓟马成虫的 LR_{50} 值分别为 0.970 和 0.685 g a.i/hm^2；不同剂型和含量的烯啶虫胺和噻虫嗪对黄胸蓟马成虫的毒力差异显著。测试的 6 种新烟碱类杀虫剂对南方小花蝽 5 龄若虫的 LR_{50} 值均低于田间最大推荐用量，而三氟苯嘧啶对南方小花蝽 5 龄若虫的 LR_{50} 值高于田间最大推荐用量。三氟苯嘧啶对南方小花蝽 5 龄若虫的毒性最低(LR_{50} > 65.736 g a.i/hm^2)，吡虫啉和呋虫胺次之(LR_{50} 值分别为 21.317 和 24.486 g a.i/hm^2)。吡虫啉、呋虫胺、三氟苯嘧啶对黄胸蓟马成虫和南方小花蝽 5 龄若虫具有较高的选择毒性。三氟苯嘧啶和吡虫啉对农田内、农田外南方小花蝽的风险均可接受，氯噻啉和噻虫嗪均不可接受。【结论】黄胸蓟马成虫对 6 种新烟碱类杀虫剂和三氟苯嘧啶均具极高的敏感性，其中以吡虫啉和三氟苯嘧啶对南方小花蝽 5 龄若虫的风险较低；三氟苯嘧啶与南方小花蝽兼容性较高，二者在黄胸蓟马的联合防控中具备良好的潜力。

关键词：黄胸蓟马；南方小花蝽；新烟碱类杀虫剂；三氟苯嘧啶；急性毒性；风险评估

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Selective toxicity of six neonicotinoid insecticides and triflumezopyrim to *Thrips hawaiiensis* (Thysanoptera: Thripidae) and *Orius strigicollis* (Heteroptera: Anthocoridae)

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Abstract:【Aim】This study aims to assess the selective toxicity of six neonicotinoid insecticides and one novel insecticide triflumezopyrim to *Thrips hawaiiensis* and its natural enemy *Orius strigicollis* so as to provide a basis for the combined control of *T. hawaiiensis* using *O. strigicollis* and insecticides.【Methods】The acute toxicity of six neonicotinoid insecticides including imidacloprid, dinotefuran, flupyradifurone, imidaclothiz, nitenpyram and thiamethoxam, and triflumezopyrim to *T. hawaiiensis* adults and the 5th instar nymphs of *O. strigicollis* was determined using the residual film method, and their exposure risks to the 5th instar nymphs of *O. strigicollis* were assessed.【Results】The median lethal rates (LR_{50} values) of these seven insecticides to *T. hawaiiensis* adults were lower than their maximum recommended field application rates. The LR_{50} value of imidaclothiz to *T. hawaiiensis* adults was the lowest (0.183 g a.i/hm^2), significantly lower than those of the other insecticides, whereas those of flupyradifurone and triflumezopyrim were 3.066 and 3.949 g a.i/hm^2, significantly higher than those of other insecticides. The LR_{50} values of the two nitenpyram formulations 20% nitenpyram SL and 10% nitenpyram AS to *T. hawaiiensis* adults were 0.327 and 0.201 g a.i/hm^2, and those of the two thiamethoxam formulations 70% thiamethoxam WG and 25% thiamethoxam WG were 0.970 and 0.685 g a.i/hm^2, respectively. The toxicity of nitenpyram and thiamethoxam in different formulations and with different contents to *T. hawaiiensis* adults was significantly different. The LR_{50} values of the tested six neonicotinoid insecticides to the 5th instar nymphs of *O. strigicollis* were lower than their maximum recommended field application rates, while that of triflumezopyrim to the 5th instar nymphs of *O. strigicollis* was higher than its maximum recommended field application rate. The toxicity of triflumezopyrim to the 5th instar nymphs of *O. strigicollis* was the lowest, with the LR_{50} value of over 65.736 g a.i/hm^2, and that of imidacloprid and dinotefuran followed, with the LR_{50} values of 21.317 and 24.486 g a.i/hm^2, respectively. Imidacloprid, dinotefuran, and triflumezopyrim showed high selective toxicity to *T. hawaiiensis* adults and the 5th instar nymphs of *O. strigicollis*. The risks of imidacloprid and triflumezopyrim to *O. strigicollis* adults were acceptable in two exposure scenarios in- and off-field. However, the risks associated with imidaclothiz and thiamethoxam to the 5th instar nymphs of *O. strigicollis* were unacceptable.【Conclusion】*T. hawaiiensis* adults have extremely high sensitivity to six neonicotinoid insecticides and triflumezopyrim. Imidacloprid and triflumezopyrim exhibit low risks to the 5th instar nymphs of *O. strigicollis*, and triflumezopyrim has high compatibility with *O. strigicollis*. The combination of triflumezopyrim with *O. strigicollis* shows a promising potential for the management of *T. hawaiiensis*.

Key words: *Thrips hawaiiensis*; *Orius strigicollis*; neonicotinoid insecticides; triflumezopyrim; acute toxicity; risk assessment

黄胸蓟马 *Thrips hawaiiensis* 属缨翅目(Thysanoptera)蓟马科(Thripidae),广泛分布于世界各地,是我国最常见的栖花蓟马之一(Atakan, 2015; Marullo and De Grazia, 2017; Fu *et al.*, 2019a)。黄胸蓟马通常以植物幼嫩组织和花粉为食,通过刺穿花朵和果实造成为害(Goldarazena, 2011; Cao *et al.*, 2018),其在我国主要危害芒果、香蕉、柑橘、苹果以及多种园艺植物和蔬菜(Chen *et al.*, 2018; Fu *et al.*, 2018)。化学防治是目前蓟马防控的主要手段(Fu *et al.*, 2019b)。然而,化学农

药的大量使用致使蓟马对吡虫啉、啶虫脒、多杀菌素等杀虫剂产生不同程度的抗性和交互抗性，从而导致防治难度进一步增大（Bao *et al.*, 2015; Wang *et al.*, 2016; Fu *et al.*, 2019b）。同时，噻虫嗪、啶虫脒等杀虫剂在田间施用时带来的雾滴漂移、农药残留等对环境非靶标昆虫产生直接或间接的影响，存在潜在的毒性风险（苍涛等, 2017; Jiang *et al.* 2019; 王烁等, 2020; Lin T *et al.* 2021）。

南方小花蝽 *Orius strigicollis* 在我国主要分布在南方的大部分地区，是茄科、菊科、豆科、葫芦科等作物上的优势天敌，主要以蓟马和叶螨为食（Kim *et al.*, 2015）。南方小花蝽凭借其搜索能力强、捕食量大、滞育率低等优点成为蓟马生防中最具潜力的天敌物种之一（Wang *et al.*, 2001），其天敌产品在温室蓟马的综合防控中的比重逐渐增大（Kim *et al.*, 2004; Yano, 2004）。然而在复杂的农田生态系统中，仅仅依靠天敌昆虫很难完全控制蓟马虫口密度（Cuthbertson *et al.*, 2014; Herrick *et al.*, 2017），强力释放则会大幅增加农业生产成本（Weintraub *et al.*, 2011）。因此，选择利用低风险的杀虫剂联合天敌昆虫防控蓟马被认为是一种高效的综合防控策略（Rocha *et al.*, 2015; Lin QC *et al.*, 2021; Lin T *et al.*, 2021）。

新烟碱类杀虫剂主要作用于昆虫的烟碱乙酰胆碱受体（nicotinic acetylcholine receptor, nAChR），通过扰乱昆虫中枢神经系统，导致个体死亡（Simon-Delso *et al.*, 2015; Bartlett *et al.*, 2018）。近年来，新烟碱类杀虫剂凭借其良好的防效和对哺乳动物安全等特点被广泛应用。新烟碱类杀虫剂在防治蚜虫、蓟马、粉虱等刺、锉吸式害虫中发挥重要作用（Zhang *et al.*, 2016; Jiang *et al.* 2019）。然而，越来越多的证据表明该类杀虫剂能够显著降低农业生态系统中非靶标生物的数量（Douglas *et al.*, 2015），其中以对蜜蜂等传粉昆虫高毒性风险备受关注（Goulson, 2013; Fairbrother *et al.*, 2014）。新烟碱类杀虫剂对捕食性天敌昆虫的毒性风险却因物种的敏感性差异而不同，其对捕食性蝽（Prabhaker *et al.*, 2011; Martinou *et al.*, 2014; Herrick and Cloyd, 2017; Esquivel *et al.*, 2020; Lin *et al.*, 2020; Mahmoudi-Dehpahni *et al.*, 2020）、捕食性瓢虫、蓟马和瘿蚊（Mori and Gotoh, 2001; James, 2003; Yao *et al.*, 2015）等非靶标的天敌昆虫高毒高风险，但对捕食性螨无明显毒性，二者能够很好地兼容（Villanueva and Walgenbach, 2005; Lefebvre *et al.*, 2011; Cheng *et al.*, 2021）。

因此，本研究通过测定 6 种新烟碱类杀虫剂对黄胸蓟马的毒力和对南方小花蝽的急性毒性，比较两种昆虫对不同药剂的敏感性，并对比与该类杀虫剂同样作用于烟碱乙酰胆碱受体的新型杀虫剂三氟苯嘧啶的毒性效应。同时，依据“最差暴露场景”（worst-case scenario）原则（Bostanian *et al.*, 2009），通过不同场景下的预测暴露浓度评估该类杀虫剂对南方小花蝽的毒性风险，明确其对黄胸蓟马和南方小花蝽的选择毒性。研究结果对明确南方小花蝽与新烟碱类杀虫剂在防治中的兼容性，推进杀虫剂与天敌昆虫联合防控策略的实施具有重要意义。

1　材料与方法

1.1　供试昆虫

黄胸蓟马最早从田间采集，在室内饲养参考 Lin T 等（2021）的方法，并做适当改进，在实验室内人工饲养建立试验种群，饲养过程中未接触任何农药。黄胸蓟马成虫饲养在圆台形塑料盒内（顶部直径 8 cm，底部直径 11 cm，高 7.5 cm），塑料盒漂浮于长方形水槽中。塑料盒顶部设置了可自由开启的纱网盖，底部为敞口形，并以拉伸过的封口膜密封。盒中加入花粉以供蓟马取食，每周更换 2～3 次。黄胸蓟马将卵产入水槽内，将水过滤后则卵被收集在滤纸上，后将卵置于方形塑料盒（长×宽×高 = 12 cm × 8 cm × 5.5 cm）中，并放入蚕豆作为黄胸蓟马若虫的食物，待成虫羽化后挑取雌成虫用于试验。

南方小花蝽商品化的天敌产品由福建省农业科学院植物保护研究所提供。将挑取的南方小花蝽若虫集中饲养于上述方形塑料盒中，以盒内黄胸蓟马为猎物，待南方小花蝽若虫发育至 5 龄后用于后续试验。黄胸蓟马和南方小花蝽均饲养在温度 25 ± 1℃、相对湿度 80% ± 5%、光周期 16L∶8D 的人工气候箱。

1.2　供试药剂

供试药剂详细信息见表 1，施药方式均为喷雾。化学农药对非靶标天敌昆虫的毒性试验通常选用乐果（dimethoate，96%，广东广康生化科技股份有限公司）作为参比试验药剂（Cheng *et al.*, 2021; Lin *et al.*, 2021）。

1.3　毒性测定

采用药膜法开展毒性试验。将供试药剂用蒸馏水稀释成 6 个梯度浓度，移取 0.5 mL 溶液至内壁面

表 1 供试杀虫剂详细信息
Table 1 Details of the tested insecticides

杀虫剂 Insecticides	施药次数 Number of applications *n*	施药间隔期 Interval of pesticide application (d)	田间最大推荐用量 Maximum recommended field application rate (g a.i/hm^2)	施用作物 Applicable crops	农药漂移因子 Pesticide drift factor *PDF*	厂家 Manufacturers
10%吡虫啉可湿性粉剂 10% Imidacloprid WP	2	21	60.00	小麦 Wheat	2.38	苏州遍净植保科技有限公司 Suzhou Bianjing Agro-Biochemical Co. Ltd
20%呋虫胺可溶粒剂 20% Dinotefuran SG	2	3	150.00	黄瓜 Cucumber	7.23	日本三井化学 AGRO 株式会社 Mitsui Chemicals AGRO
17%氟吡呋喃酮可溶液剂 17% Flupyradifurone SL	1	–	143.82	番茄 Tomato	2.77	拜耳作物公司 Bayer CropScience AG
10%三氟苯嘧啶悬浮剂 10% Triflumezopyrim SC	1	21	21.91	水稻 Rice	2.77	杜邦公司 DuPont Crop Protection
10%氯噻啉可湿性粉剂 10% Imidaclothiz WP	2	7	45.00	番茄 Tomato	7.23	江苏省南通南沈植保科技开发有限公司 Jiangsu Nantong Nanshen Plant Protection Co. Ltd
20%烯啶虫胺可溶液剂 20% Nitenpyram SL	1	–	112.86	水稻 Rice	2.77	山东鑫星农药有限公司 Shandong Xinxing Pesticide Co. Ltd
10%烯啶虫胺水剂 10% Nitenpyram AS	2	21	112.86	水稻 Rice	2.38	河南丰收乐化学有限公司 Henan Fengshoule Chemical Co. Ltd
70%噻虫嗪水分散粒剂 70% Thiamethoxam WG	1	–	56.70	芦笋 Asparagus	2.77	山东惠民中联生物科技有限公司 Shandong Huiming Vanda Biotechnology Co. Ltd
25%噻虫嗪水分散粒剂 25% Thiamethoxam WG	1	–	80.00	豇豆 Cowpea	8.02	先正达作物保护有限公司 Syngenta Crop Protection AG

WP: 可湿性粉剂 Wettable powder; SG: 可溶粒剂 Soluble granule; SL: 可溶液剂 Soluble concentrate; SC: 悬浮剂 Suspension concentrate; AS: 水剂 Aqueous solution; WG: 水分散粒剂 Water dispersible granule. 表 2 – 4 同 The same for Tables 2 – 4.

积为 36.9 cm^2 的玻璃瓶中，以蒸馏水为空白对照。将玻璃瓶置于室温下水平滚动约 2 h，待溶剂完全挥发后即为药膜瓶。将 20 头黄胸蓟马雌成虫或 10 头南方小花蝽 5 龄若虫分别转移至药膜瓶中，并放入 1 粒蜂花粉作为食物，用棉花塞住瓶口，每个处理重复 3 次。将药膜瓶置于温度为 25 ± 1℃，相对湿度为 80% ±5%，光周期为 16L∶8D 的人工气候箱中。染毒 24 h 后检查试虫的死亡数，即用毛笔尖轻触试虫，3 s 后仍未动则判定其死亡。当试验设置的剂量达到该杀虫剂有效成分单位面积最高施药量即田间最大推荐用量(*AR*)3 倍[即制剂用量 = (3*AR* ×36.9 cm^2)/药剂百分含量]时仍无试虫死亡，则试验终止，并认为 LR_{50} >3 倍田间最大推荐用量为急性毒性结果[LR_{50}，半致死用量(median lethal rate)，指引起 50% 供试生物死亡时单位面积的供试物使用量]。乐果作为参比物质的试验设置与条件同上述；在乐果 LR_{50} 剂量下开展致死试验 10 次，每次设置 5 个重复。

1.4 风险评估程序

1.4.1 暴露分析：根据杀虫剂在田间的施用方式和作物类型预测暴露量(中华人民共和国农业部，2016)：

$$PER_{in} = AR \times MAF;$$

$$PER_{off} = \frac{AR \times MAF \times PDF}{VDF}。$$

式中，PER_{in} 表示农田内预测暴露量，PER_{off} 表示农田外预测暴露量，*PDF* 表示农药漂移因子(表 1)，*VDF* 表示农药植被分布因子，采用默认值 5。*MAF* 表示多次施用因子，计算公式如下：

$$MAF = \frac{1 - e^{-n \times k \times i}}{1 - e^{-k \times i}}。$$

式中，k 表示农药在植株表面的降解速率常数，*n* 表示施药次数，*i* 表示施药间隔期。k 的计算公式如下：

$$k = \frac{\ln 2}{DT_{50}}。$$

式中 DT_{50} 表示农药在植株表面的降解半衰期，采用默认值 10 d。

1.4.2　风险表征：分别用危害商值 HQ_{in} 和 HQ_{off} 进行农田内、农田外的风险表征，计算公式如下：

$$HQ_{in} = \frac{PER_{in}}{LR_{50}};$$

$$HQ_{off} = \frac{PER_{off} \times UF}{LR_{50}}。$$

式中 UF 表示不确定因子，采用默认值 5。当 $HQ \leqslant 5$，表明风险可接受；当 $HQ > 5$，则表明风险不可接受。

1.5　数据分析

数据通过 SPSS 软件进行 Probit 分析，计算供试药剂对黄胸蓟马和南方小花蝽 24 h 的毒力回归方程、LR_{50} 值和 95% 置信区间。若 95% 置信区间没有重叠则认为不同药剂间 LR_{50} 值差异显著；选择性指数为杀虫剂对南方小花蝽的 LR_{50} 值与对黄胸蓟马的 LR_{50} 值之比，指数越大表明药剂对天敌和害虫的选择毒性越大（Lin T *et al*., 2021）。

2　结果

2.1　参比物质的有效性

毒性试验开展前以乐果作为参比物质确定黄胸蓟马和南方小花蝽试验试虫的性状一致性。结果表明乐果对黄胸蓟马和南方小花蝽的 LR_{50} 值分别为 0.448 和 85.831 g a.i./hm^2（图 1），暴露在这一剂量下黄胸蓟马和南方小花蝽的死亡率维持在 50% ~ 80%（图 2）。

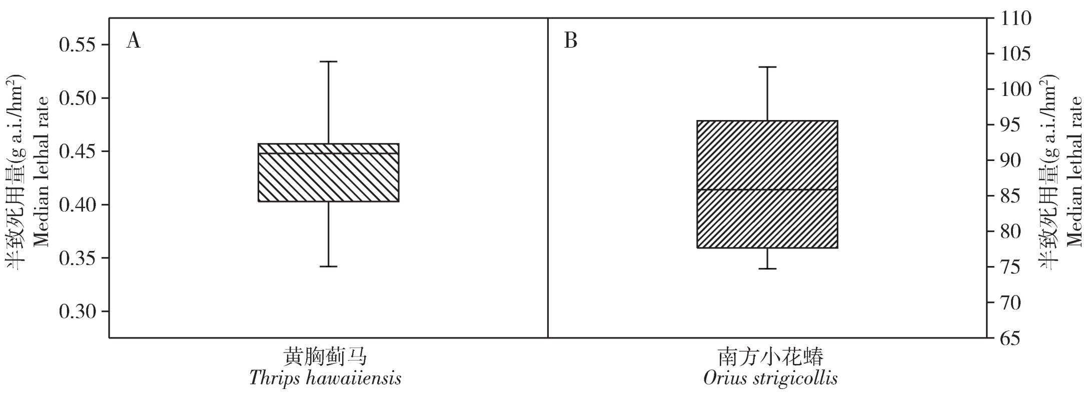

图 1　乐果对黄胸蓟马成虫（A）和南方小花蝽 5 龄若虫（B）的半致死用量（LR_{50} 值）

Fig. 1　Median lethal rates（LR_{50} values）of dimethoate to *Thrips hawaiiensis* adults（A）and the 5th instar nymphs of *Orius strigicollis*（B）

箱式图的中线、顶线和底线分别代表半致死用量（LR_{50}）的中位数、第 25 和第 75 百分位，上边缘和下边缘分别代表最大和最小值。In the box, the centre, bottom, and top lines represent the median value and the 25th and 75th percentiles of LR_{50}, respectively, and the upper and lower bars represent the maximum and minimum values, respectively.

2.2　杀虫剂对黄胸蓟马毒力和对南方小花蝽的急性毒性

供试杀虫剂对黄胸蓟马的 LR_{50} 值均低于田间最大推荐用量。氯噻啉和烯啶虫胺对黄胸蓟马的毒力（LR_{50} 值）显著高于其他杀虫剂，但二者之间的差异不显著（$P > 0.05$）。氟吡呋喃酮和三氟苯嘧啶对黄胸蓟马的毒力显著低于其他杀虫剂（$P < 0.05$），但二者之间的差异不显著（$P > 0.05$）。10% 烯啶虫胺水剂对黄胸蓟马的毒力显著高于 20% 烯啶虫胺可溶液剂（$P < 0.05$）；含量不同的两种噻虫嗪水分散粒剂对黄胸蓟马的毒力也存在显著差异（$P < 0.05$）（表 1 和 2）。除了三氟苯嘧啶外，其他杀虫剂对南方小花蝽的 LR_{50} 值均低于田间最大推荐用量。以三氟苯嘧啶对南方小花蝽的毒性最低，吡虫啉和呋虫胺次之；烯啶虫胺和噻虫嗪对南方小花蝽的毒力无显著差异（$P > 0.05$）（表 1 和 3）。

2.3　杀虫剂对黄胸蓟马和南方小花蝽的选择性

南方小花蝽对两种噻虫嗪制剂的敏感性高于黄胸蓟马，对其他杀虫剂的敏感性均低于黄胸蓟马（表 2 和 3）。噻虫嗪对南方小花蝽和黄胸蓟马的选择性指数小于 1，其余杀虫剂的选择性指数均大于 1，且以吡虫啉对二者的选择毒性最高，呋虫胺和三氟苯嘧啶次之（表 4）。

2.4　杀虫剂对南方小花蝽和黄胸蓟马的选择性指数及风险评估

吡虫啉、呋虫胺和三氟苯嘧啶对南方小花蝽和黄胸蓟马的选择性指数较高（表 4），表明高于其他杀虫剂的选择毒性。在不同场景（农田内、农田外）

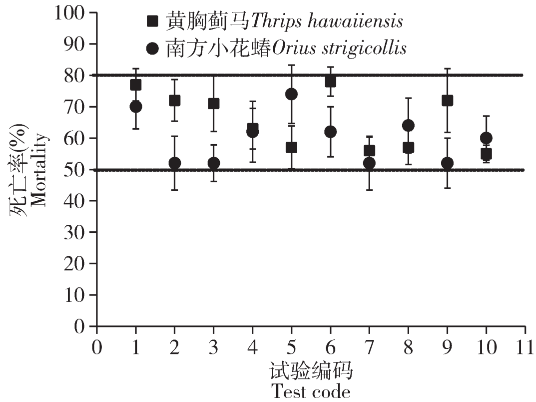

图 2 黄胸蓟马成虫和南方小花蝽 5 龄若虫在乐果半致死用量(LR_{50})下的死亡率

Fig. 2 Mortality of *Thrips hawaiiensis* adults and the 5th instar nymphs of *Orius strigicollis* exposed to the median lethal rate (LR_{50}) of dimethoate

图中数据为平均值 ± 标准误;试验编码的数值代表每种昆虫各自开展参比试验的次数。Data in the figure are means ± *SE*. Test code values represent the number of reference tests conducted for each insect.

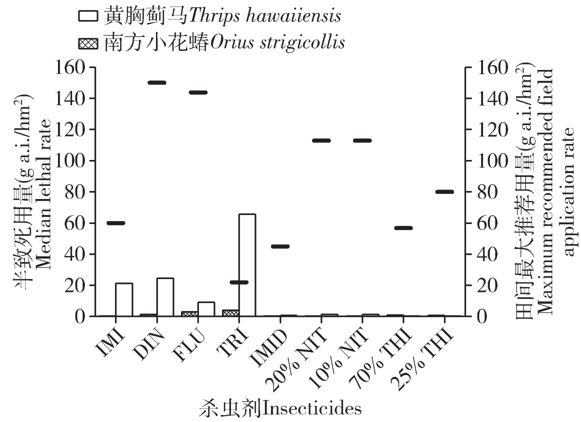

图 3 比较杀虫剂对黄胸蓟马成虫和南方小花蝽 5 龄若虫的半致死用量(LR_{50}值)(立柱)和田间最大推荐用量(黑色短线)

Fig. 3 Comparison of the median lethal rates (LR_{50} values) (columns) and the maximum recommended field application rates (black short bars) of insecticides to *Thrips hawaiiensis* adults and the 5th instar nymphs of *Orius strigicollis*

IMI: 10% 吡虫啉可湿性粉剂 10% Imidacloprid WP; DIN: 20% 呋虫胺可溶粒剂 20% Dinotefuran SG; FLU: 17% 氟吡呋喃酮可溶液剂 17% Flupyradifurone SL; TRI: 10% 三氟苯嘧啶悬浮剂 10% Triflumezopyrim SC; IMID: 10% 氯噻啉可湿性粉剂 10% Imidaclothiz WP; 20% NIT: 20% 烯啶虫胺可溶液剂 20% Nitenpyram SL; 10% NIT: 10% 烯啶虫胺水剂 10% Nitenpyram AS; 70% THI: 70% 噻虫嗪水分散粒剂 70% Thiamethoxam WG; 25% THI: 25% 噻虫嗪水分散粒剂 25% Thiamethoxam WG. 制剂缩写见表 1。For the abbreviations of formulations, see Table 1.

下杀虫剂对南方小花蝽的风险评估如表 4 所示。结果表明,三氟苯嘧啶和吡虫啉对农田内、农田外南方小花蝽的风险均可接受;呋虫胺、氟吡呋喃酮、烯啶虫胺对农田内南方小花蝽的风险均不可接受,对农田外的风险均可接受;氯噻啉和噻虫嗪对农田内、农田外南方小花蝽的风险均不可接受。

表 2 杀虫剂处理 24 h 对黄胸蓟马成虫的半致死用量(LR_{50}值)

Table 2 Median lethal rates (LR_{50} values) of insecticides to *Thrips hawaiiensis* adults in 24 h

杀虫剂 Insecticides	LR_{50} (95% 置信区间 95% Confidence interval) (g a. i/hm²)	χ^2	*P*	*df*	毒力回归方程 Toxicity regression equation	R^2
10% 吡虫啉可湿性粉剂 10% Imidacloprid WP	0.365 (0.331 – 0.402)	0.816	0.846	3	$y = 4.079x + 1.788$	0.995
20% 呋虫胺可溶粒剂 20% Dinotefuran SG	1.359 (1.132 – 1.635)	5.352	0.253	4	$y = 1.941x - 0.258$	0.963
17% 氟吡呋喃酮可溶液剂 17% Flupyradifurone SL	3.066 (2.625 – 3.594)	0.899	0.925	4	$y = 2.269x - 1.104$	0.995
10% 三氟苯嘧啶悬浮剂 10% Triflumezopyrim SC	3.949 (2.907 – 5.535)	3.268	0.514	4	$y = 1.029x - 0.614$	0.951
10% 氯噻啉可湿性粉剂 10% Imidaclothiz WP	0.183 (0.155 – 0.218)	3.718	0.445	4	$y = 2.144x + 1.579$	0.982
20% 烯啶虫胺可溶液剂 20% Nitenpyram SL	0.327 (0.272 – 0.392)	0.758	0.944	4	$y = 1.944x + 0.945$	0.994
10% 烯啶虫胺水剂 10% Nitenpyram AS	0.201 (0.157 – 0.251)	3.050	0.550	4	$y = 1.540x + 1.073$	0.969
70% 噻虫嗪水分散粒剂 70% Thiamethoxam WG	0.970 (0.836 – 1.137)	4.545	0.337	4	$y = 2.230x + 0.030$	0.944
25% 噻虫嗪水分散粒剂 25% Thiamethoxam WG	0.685 (0.583 – 0.806)	3.171	0.530	4	$y = 2.344x + 0.385$	0.982

x 为剂量的对数值,*y* 为死亡几率值。*x* is the logarithm of the dose, and *y* is the probit of death.

表 3　杀虫剂处理 24 h 对南方小花蝽 5 龄若虫的半致死用量(LR_{50}值)

Table 3　Median lethal rates (LR_{50} values) of insecticides to the 5th instar nymphs of *Orius strigicollis* in 24 h

杀虫剂 Insecticides	LR_{50}(95%置信区间 95% Confidence interval) (g a.i./hm^2)	χ^2	*P*	*df*	毒力回归方程 Toxicity regression equation	R^2
10%吡虫啉可湿性粉剂 10% Imidacloprid WP	21.317 (15.278 - 29.835)	0.823	0.935	4	$y = 1.456x - 1.935$	0.984
20%呋虫胺可溶粒剂 20% Dinotefuran SG	24.486 (17.700 - 33.554)	1.041	0.902	4	$y = 1.531x - 2.126$	0.982
17%氟吡呋喃酮可溶液剂 17% Flupyradifurone SL	9.089 (5.703 - 12.980)	0.479	0.975	4	$y = 1.313x - 1.259$	0.987
10%三氟苯嘧啶悬浮剂 10% Triflumezopyrim SC	>65.736	–	–	–	–	–
10%氯噻啉可湿性粉剂 10% Imidaclothiz WP	0.797 (0.589 - 1.087)	1.736	0.784	4	$y = 1.610x + 0.158$	0.977
20%烯啶虫胺可溶液剂 20% Nitenpyram SL	1.432 (1.063 - 1.896)	1.418	0.841	4	$y = 1.745x - 0.272$	0.981
10%烯啶虫胺水剂 10% Nitenpyram AS	1.297 (0.961 - 1.718)	0.012	0.999	4	$y = 1.739x - 0.196$	0.999
70%噻虫嗪水分散粒剂 70% Thiamethoxam WG	0.199 (0.144 - 0.278)	0.612	0.962	4	$y = 1.477x + 1.035$	0.989
25%噻虫嗪水分散粒剂 25% Thiamethoxam WG	0.168 (0.121 - 0.232)	1.576	0.813	4	$y = 1.492x + 1.157$	0.973

x 为剂量的对数值，*y* 为死亡几率值。*x* is the logarithm of the dose, and *y* is the probit of death.

表 4　7 种杀虫剂的制剂对黄胸蓟马和南方小花蝽的选择性指数及风险评估

Table 4　Selectivity ratios and the risk assessment of the formulations of seven insecticides to *Thrips hawaiiensis* and *Orius strigicollis*

杀虫剂 Insecticides	选择性指数 Selectivity ratio	HQ_{in}	HQ_{off}
10%吡虫啉可湿性粉剂 10% Imidacloprid WP	58.403	3.4712	0.0826
20%呋虫胺可溶粒剂 20% Dinotefuran SG	18.018	11.1018	0.8027
17%氟吡呋喃酮可溶液剂 17% Flupyradifurone SL	2.964	15.8235	0.4383
10%三氟苯嘧啶悬浮剂 10% Triflumezopyrim SC	>16.646	<0.3333	<0.0092
10%氯噻啉可湿性粉剂 10% Imidaclothiz WP	4.355	91.2179	6.5951
20%烯啶虫胺可溶液剂 20% Nitenpyram SL	4.379	78.8128	2.1831
10%烯啶虫胺水剂 10% Nitenpyram AS	6.453	107.3132	2.5541
70%噻虫嗪水分散粒剂 70% Thiamethoxam WG	0.205	284.9246	7.8924
25%噻虫嗪水分散粒剂 25% Thiamethoxam WG	0.245	476.1905	38.1905

选择性指数 = 杀虫剂对南方小花蝽的 LR_{50}/黄胸蓟马杀虫剂对的 LR_{50}。HQ_{in} 和 HQ_{off} 分别代表杀虫剂对农田内、农田外的风险商值。当 HQ ≤ 5，表明风险可接受；当 HQ > 5，则表明风险不可接受。Selectivity ratio = LR_{50} of the insectide to *O. strigicollis*/LR_{50} of the insectide to *T. hawaiiensis*. HQ_{in} and HQ_{off} represent the hazard quotients of the insecticides to *O. strigicollis* in the in-field and off-field, respectively. When HQ ≤ 5, the risk is considered as acceptable, and when HQ > 5, the risk is considered as unacceptable.

3 结论与讨论

高防效的化学农药能够与天敌昆虫良好地兼容是有害生物综合治理的主要目标之一。尽管化学农药与天敌昆虫兼容性的确定仍存争议(Stark and Banks, 2003),但其作为一种高效和低风险的害虫防控策略已逐步被认同和应用(Gentz *et al*., 2010; Lin *et al*., 2019; Lin QC *et al*., 2021)。本研究通过测定6种新烟碱类杀虫剂及与其同样作用于烟碱乙酰胆碱受体的新型杀虫剂三氟苯嘧啶对黄胸蓟马的毒力和对南方小花蝽的急性毒性,比较了黄胸蓟马和南方小花蝽对这些杀虫剂的敏感性,确定这些杀虫剂对害虫-天敌的选择毒性,并以杀虫剂预测暴露浓度进一步评估其对南方小花蝽的暴露风险。结果表明,黄胸蓟马和南方小花蝽对氯噻啉、烯啶虫胺和噻虫嗪高度敏感,吡虫啉、呋虫胺和三氟苯嘧啶对黄胸蓟马和南方小花蝽的选择毒性较高,且吡虫啉和三氟苯嘧啶对农田内、农田外南方小花蝽的风险均可接受。

氯噻啉和烯啶虫胺已逐步取代高毒农药,在防治蚜虫、飞虱、叶蝉以及部分鳞翅目害虫中发挥重要作用,但二者对蓟马类害虫的防效并无报道。在本研究中烯啶虫胺表现出对黄胸蓟马明显的高毒力,对南方小花蝽高风险,且不因杀虫剂含量和剂型的改变而降低该风险。然而,前人的研究却表明氯噻啉和烯啶虫胺对不同赤眼蜂的风险均可接受(王彦华等, 2012; Wang *et al*., 2012, 2014; Zhao *et al*., 2012),与寄生性天敌昆虫能够很好地兼容。氟吡呋喃酮和噻虫嗪对蓟马类害虫的防治已取得良好效果(Panthi and Renkema, 2020; Renkema *et al*., 2020; Lin QC *et al*., 2021),但二者对东亚小花蝽 *Orius sauteri* 的暴露风险差异较大,前者低风险,后者为高风险(Lin QC *et al*., 2021);然而,本研究表明氟吡呋喃酮对南方小花蝽也为高风险(表4),这与早期研究其对小花蝽类天敌的高风险(Barbosa *et al*., 2017; Cloyd and Herrick, 2018; Rahman *et al*., 2022)相符。天敌昆虫的种类、发育阶段以及性别等都有可能对其敏感性造成不同程度的影响;毒性测试方法,杀虫剂的预测暴露量、暴露途径以及暴露时间也是影响风险评估结果的重要因素(Lin T *et al*., 2021; Mahmoudi-Dehpahni *et al*., 2021)。

近年来国内陆续开发出不同剂型的吡虫啉、呋虫胺用于防控蓟马类害虫,这可能与该类害虫对两种杀虫剂的高敏感性有关,本研究发现这两种杀虫剂对黄胸蓟马和南方小花蝽具有较高的选择毒性。然而,呋虫胺对农田内的南方小花蝽高风险,以制剂在田间推荐用量下使用仍可导致半数以上的南方小花蝽个体死亡(图3)。因此,呋虫胺对害虫和天敌昆虫的高选择性无助于增强其与南方小花蝽的兼容性,这与前人研究认为呋虫胺与东亚小花蝽兼容差的结论(Lin QC *et al*., 2021)是相符的。但另一些研究却表明吡虫啉对东亚小花蝽、刺小花蝽 *Orius armatus* 低风险(Broughton *et al*., 2014; 何丹等, 2018),并且能够与东亚小花蝽很好地兼容(Lin QC *et al*., 2021)。杀虫剂制剂中的助剂、表面活性剂成分和比例的差异可能是导致其与捕食性天敌昆虫兼容性差异的要素之一(Cowles *et al*., 2000; Herrick *et al*., 2017; Demkovich *et al*., 2018; Chen *et al*., 2019)。

与新烟碱类杀虫剂类似,三氟苯嘧啶同样通过作用于昆虫的烟碱乙酰胆碱受体发挥作用。然而,三氟苯嘧啶主要通过抑制作用,是为烟碱乙酰胆碱受体的拮抗剂(Cordova *et al*., 2016; Liu *et al*., 2020)。三氟苯嘧啶凭借独特的结构和作用机制、高效的杀虫活性以及对非目标生物的低毒性和环境友好而受到越来越多的关注(Liu *et al*., 2020)。其商品制剂在中国于2016年首次获得登记用于防治对新烟碱类杀虫剂产生高抗性的褐飞虱(Zhang *et al*., 2017; Xu *et al*., 2019)。褐飞虱对三氟苯嘧啶的敏感性显著高于对吡虫啉(Zhu *et al*., 2018),但黄胸蓟马却正好相反,其对三氟苯嘧啶敏感性低于对吡虫啉。尽管如此,三氟苯嘧啶对黄胸蓟马的半致死用量仍远低于其田间最大推荐用量(图3),仍然显示极强的毒力。同时,三氟苯嘧啶对南方小花蝽显示出极低的暴露风险,其对黄胸蓟马和南方小花蝽具备高选择毒性(表4)。这种高选择毒性在三氟苯嘧啶对褐飞虱及其天敌中也有明显体现(Zhu *et al*., 2018; Mishra *et al*., 2022)。这可能与三氟苯嘧啶特殊的抑制而不是激活昆虫烟碱乙酰胆碱受体的作用机理有关(Cordova *et al*., 2016),或者与其选择性地影响昆虫酯酶活性有关(Li *et al*., 2020)。

新烟碱类杀虫剂在蓟马类害虫防治中的重要性日益凸显。本研究首次明确了6种新烟碱类杀虫剂和三氟苯嘧啶对黄胸蓟马及其天敌南方小花蝽的选择毒性;黄胸蓟马对供试的杀虫剂均显示高敏感性,其中仅有吡虫啉和三氟苯嘧啶对南方小花蝽的暴露风险可接受,但吡虫啉仍存在导致大量南方小花蝽

死亡的风险。因此，三氟苯嘧啶具备良好的兼容南方小花蝽防治黄胸蓟马的潜力。然而，在国内三氟苯嘧啶相关制剂尚未被登记用于蓟马类害虫防治，其对蓟马类害虫的田间防效，以及对其他非靶标生物的暴露风险仍需要进一步评估。另一方面，对南方小花蝽暴露风险不可接受的新烟碱类杀虫剂，可以探索通过改变剂型或施药方式，例如拌种、土壤撒施等，降低其对南方小花蝽甚至其他天敌昆虫的风险，以提高杀虫剂与天敌昆虫的兼容性，促进协同防控黄胸蓟马策略的有效实施。

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