

蓟马行为调控与诱剂应用研究进展*

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摘 要 昆虫寄主选择行为受寄主气味和光学特点的影响, 在这一过程中, 昆虫的嗅觉和视觉起了重要作用。基于蓟马对视觉和嗅觉信号的行为反应, 研究人员针对蓟马行为调控开展了一系列的研究, 同时衍生出了蓟马行为调控产品, 在农业生产中应用广泛。本文针对国内外的蓟马行为调控研究进行综述, 从植物挥发物和光学特点方面分析了蓟马对寄主植物选择的特点, 从物理调控、化学生态调控和“推-拉”治理策略等方面阐述了蓟马诱控技术的研发概况, 并对蓟马诱剂的应用现状和研发中存在的问题进行了分析, 以期对蓟马的行为调控研究和技术发展提供参考。

关键词 蓟马; 行为; 寄主选择; 物理和化学生态调控; 诱剂研发

Advances in the behavioral manipulation of thrips through the application of attractants

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Abstract Insects primarily use olfactory and visual cues to locate host plants. Understanding these cues has led to the development of products that are now extensively used in agricultural production to manipulate the behavior of pest insects such as thrips. This paper reviews domestic and international research on the behavioral manipulation of thrips and the plant volatiles and optical features used by thrips to locate preferred host plants. It also summarizes research on the physical, chemical and ecological manipulation of thrips, and the use of the “push-pull” strategy in thrip management. Finally, it discusses the effective use of lures to control thrips and problems in lure development.

Key words thrips; behavior; host plant selection; physical and chemical ecology manipulation; research and development of attractants

蓟马(Thrips)是缨翅目(Thysanoptera)昆虫的总称。目前, 全世界记录的蓟马有近 7 000 种 (<https://www.gbif.org/species/1228>), 但对农业造成经济损失的种类不超过 1% (Morse and Hoddle, 2006; Reitz *et al.*, 2011; Wu *et al.*, 2020)。蓟马具有虫体微小、为害隐蔽、繁殖能力强和抗

药性强等特点, 治理起来较为困难, 一旦发生, 很难根除 (Diaz-Montano *et al.*, 2011; Gao *et al.*, 2012; Reitz *et al.*, 2020)。蓟马除通过取食和产卵对植物造成直接危害外, 还可以通过传播植物病毒对植物造成间接危害 (He *et al.*, 2020), 如西花蓟马 *Frankliniella occidentalis* Pergande 可以

*资助项目 Supported projects: 国家重点研发计划 (2017YFD0200900); 国家现代农业产业技术体系专项资金 (CARS-23-D-08)

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收稿日期 Received: 2020-06-30; 接受日期 Accepted: 2020-08-19

传播 11 种植物病毒, 包括凤仙花坏死病毒 (Impatiens necrotic spot orthospovirus, INSV)、番茄斑点萎蔫病毒 (Tomato spotted wilt orthospovirus, TSWV)、番茄褪绿斑病毒 (Tomato chlorotic spot orthospovirus, TCSV) 等 (He *et al.*, 2020)。鸢尾黄斑病毒 (Iris yellow spot virus, IYSV) 以烟蓟马 *Thrips tabaci* L. 为传播载体, 对葱属蔬菜为害严重 (Diaz-Montano *et al.*, 2011)。

蓟马寄主范围广泛, 涵盖了蔬菜、花卉、果树和粮食等作物, 严重威胁着保护地蔬菜和园艺作物的生产 (Diaz-Montano *et al.*, 2011; Reitze *et al.*, 2011, 2020)。深入了解蓟马对寄主植物的利用情况和掌握成熟有效的蓟马早期监测和防控技术对开展蓟马的综合治理研究非常重要。本文重点以西花蓟马和烟蓟马为例, 分析影响蓟马寄主选择的因素, 综述目前对蓟马的行为调控研究, 探讨诱剂研发的方法和影响诱剂应用的因素, 为开展蓟马的生态调控和综合治理提供参考。

1 蓟马对寄主植物的选择行为

蓟马对寄主植物的选择受植物挥发物、植物光学特点的影响, 表现为蓟马对不同植物、不同生育期等的偏好性不同 (Healey *et al.*, 2017; Cao *et al.*, 2018, 2019; Silva *et al.*, 2018)。在田间对开花植物上西花蓟马种群调查发现, 西花蓟马以玫瑰 *Rosa rugosa*、月季 *Rosa chinensis*、万寿菊 *Tagetes erecta* 为寄主时, 种群适合度显著高于以康乃馨 *Dianthus caryophyllus*、非洲菊 *Gerbera jamesonii*、天竺葵 *Pelargonium hortorum* 等为寄主时的种群适合度 (Cao *et al.*, 2019)。黄胸蓟马 *Thrips hawaiiensis* 以栀子花 *Gardenia jasminoides* 为寄主时的种群适合度高于以月季为寄主时的种群适合度 (Cao *et al.*, 2018)。室内蓟马嗅觉行为反应研究发现, 西花蓟马对玫瑰的选择偏好性高于对康乃馨、非洲菊、天竺葵的偏好性, 与田间对寄主植物的适合度研究结果一致, 表明蓟马对寄主植物的适合度与植物挥发物成分存在相关性 (Cao *et al.*, 2019)。Ren 等 (2020a) 田间调查发现, 西花蓟马和烟蓟马在

罗勒 *Ocimum basilicum* L. 和荆芥 *Schizonepeta tenuifolia* (Benth.) Briq. 上的种群数量较低; 室内嗅觉行为反应研究发现, 西花蓟马和烟蓟马对罗勒和荆芥挥发物均表现出驱避性, 但是对花期挥发物驱避性降低。Silva 等 (2018) 调查了澳大利亚棉花产区蓟马对杂草和棉花的利用情况, 发现西花蓟马和梳缺花蓟马 *F. schultzei* 在棉田内数量是否增加与棉花的生育期相关。花期植物合成并释放出大量的芳香物质, 对蓟马具有引诱作用 (Koschier *et al.*, 2000), 影响蓟马的选择定位行为, 且花朵颜色、形状等均能影响蓟马的选择行为 (Prokopy and Owens, 1983; Silva *et al.*, 2018)。

蓟马能识别不同的形状, 偏好花朵形状, 尤其偏好几何形状对称的花朵 (Mainali and Lim, 2008, 2010, 2011)。西花蓟马喜欢在花朵边缘活动, 且在花朵的狭缝中停留时间较长, 如在花朵形状中的停留时间是其它形状 (如矩形、三角形等) 的 4 倍, 有利于蓟马对隐蔽栖境和食物的搜索 (Mainali and Lim, 2011; Reitze *et al.*, 2020)。在草莓种植温室, 花型诱捕器对西花蓟马和花蓟马 *F. intonsa* 的诱捕量分别是矩形粘虫板的 4.1 倍和 5.4 倍 (Mainali and Lim, 2008)。蓟马对形状的选择不受颜色的影响 (Mainali and Lim, 2011; Ren *et al.*, 2020b)。Ren 等 (2020a) 分别测试了西花蓟马对白、蓝、黄色 3 种颜色的矩形、三角形、圆形和花朵形状的选择性, 结果发现, 西花蓟马对 3 种颜色的圆形和花朵形状的选择量均高于对矩形和三角形的选择性。根据蓟马对形状的偏好性, 可用于开发更为有效的诱捕器, 提高对蓟马的监测和防治效果。

2 蓟马行为调控研究

基于对昆虫寄主定位特点和行为调控研究, 目前已经研发出了一系列害虫行为调控技术和措施, 包括昆虫性信息素、昆虫迷向剂、昆虫引诱剂、昆虫驱避剂、诱虫灯、诱虫色板、害虫“推-拉”治理策略 (Push-pull strategies)、害虫“引诱-杀死”策略 (Attract-and-kill) 等。目前, 对蓟马的行为调控研究主要集中在引诱化合物、驱

避化合物和引诱色板等。

2.1 物理调控

随着研究方法和仪器精密度的不断提高, 研究人员对蓟马敏感波长的研究更为精细, 提高了诱虫色板、诱虫灯等对蓟马的专一性。

2.1.1 蓟马趋光性 通过视网膜电图分析发现, 西花蓟马复眼的感光区为 365 nm 的紫外线波段和 540 nm 的黄绿色波段(Matteson *et al.*, 1992)。米娜(2019)利用单色仪研究了西花蓟马和烟蓟马对 340-620 nm 范围波长的反应, 发现这 2 种蓟马在该波段范围的趋光反应均为双峰型, 分别出现在 430 nm 和 498 nm 处。棕榈蓟马 *Thrips palmi* 雌成虫对 483 nm 的蓝光趋性最强(张安盛等, 2015); 室内条件下, 豆大蓟马 *Megalurothrips usitatus* 对反射波长为 440 nm 和 461 nm 的色板趋性最强(唐良德等, 2015)。此外, 饱和度、反射强度等影响视觉图像的形成, 影响昆虫对刺激源的反应(Prokopy and Owens, 1983; Vernon and Gillespie, 1990; 范凡等, 2012; 张安盛等, 2015; 米娜, 2019)。蓟马的光强衰减实验表明, 蓟马对单色光的趋性随光强的减弱而降低(范凡等, 2012; 张安盛等, 2015; Otieno *et al.*, 2018; 米娜, 2019), 蓟马对单色光的避光率则随着光强的增加而降低(张安盛等, 2015)。饱和度对蓟马的诱捕效果因颜色而异(Vernon and Gillespie, 1990)。

2.1.2 影响趋光性的因素 环境因素会影响蓟马的趋光性, 包括温度、湿度、植物种类、光强、背景环境等(Prokopy and Owens, 1983)。在一定温度范围内, 西花蓟马的趋光性随温度的升高而升高。在 15 °C 和 35 °C 下, 西花蓟马对 430 nm 单色光趋性不显著; 在 20-30 °C 下, 西花蓟马对单色光的趋性随温度升高而增加(米娜, 2019)。湿度对蓟马趋光性的影响存在相似的规律。当相对湿度从 30% 增加到 60% 时, 西花蓟马对单色光的趋性增加; 当相对湿度增加到 75% 时, 对单色光的趋性与相对湿度为 60% 时相近, 但当湿度增加至 90% 时, 对单色光的趋性降低(米娜, 2019)。背景颜色也能影响蓟马趋光性, 如通过调整背景颜色, 能增强蓟马对色板的趋性, 如黑色背景显

著增强西花蓟马对黄色的选择性(Mainali and Lim, 2010)。此外, 植物的生育期、植物种类等均会影响昆虫的趋光性(边磊等, 2012), 如植物进入花期后, 由于西花蓟马的栖花性特点和花期植物对蓟马的引诱作用增强, 使得蓟马对颜色的趋性减弱。

昆虫自身的生理因素也会影响蓟马的趋光性, 如性别、营养情况、虫龄等(边磊等, 2012; 米娜等, 2019)。在 430、450 和 562 nm 下, 西花蓟马雌性个体的趋光率显著高于雄性个体, 但在 498 nm 时差异不显著(Vernon and Gillespie, 1990; 米娜, 2019)。短时间的饥饿会提高蓟马的趋光性; 反之, 可降低蓟马的趋光性。西花蓟马饥饿 4 h 对黄色视觉信号的趋性可达到 65%(Davidson *et al.*, 2006), 当饥饿时间延长至 24 h, 对单色光的趋性显著降低(低于 40%)(米娜, 2019)。西花蓟马低日龄成虫对视觉信号的趋性显著低于高日龄成虫。在风洞实验中, 2-3 日龄成虫对黄板的趋性为 38.8%, 而 10-13 日龄成虫的选择率高达 70.4%(Davidson *et al.*, 2006)。

2.1.3 趋光性应用 根据蓟马对不同波长的反应, 相应的诱虫灯、诱虫色板被研发, 在农林生产中得到普遍应用。蓟马对低紫外线反射率的白色、蓝色、蓝紫色和黄色具有显著的趋性(Vernon and Gillespie, 1990), 目前, 常用于蓟马监测和治理的色板包括白色、蓝色、绿色和黄色粘虫板。在温室和田间, 烟蓟马对反射波长为 450 nm 的色板的趋性最强(米娜等, 2019); 吴青君等(2007)研制的反射波长为 438.2-406.6 nm 的海蓝色诱虫板对西花蓟马的诱捕效果最好, 可用于西花蓟马的防治和种群监测; Otieno 等(2018)将蓝色粘虫板与深蓝色 LED 灯(445 nm)联合应用, 增加了西花蓟马对粘虫板的趋性; 浅绿色(RGB: 124, 252, 0)对茶黄蓟马 *Scirtothrips dorsalis* Hood 的引诱效果最好, 柠檬绿(RGB: 0, 255, 0)对茶棍蓟马 *Dendrothrips minowai* Priesner 诱捕量最大(Bian *et al.*, 2016); 白色色板对花蓟马的诱捕效果最好(Mao *et al.*, 2018)。此外, 根据蓟马趋光性特点, Kigathi 和 Poehling(2012)使用具有紫外吸收特点的滤网

和滤膜能有效降低西花蓟马对寄主植物的定位和选择。

2.2 化学生态调控

2.2.1 植物源信息化合物 植物在生长过程中合成并释放出一系列的挥发性物质,其化合物组成和比例构成了植物特有的“指纹图谱”(陆宴辉等, 2008; 梁兴慧和雷仲仁, 2010)。如花期植物合成并释放出大量的芳香物质,对昆虫具有显著的引诱作用,促进昆虫对开花寄主植物的选择(Pan *et al.*, 2013)、提高种群适合度(Wackers *et al.*, 2007)。昆虫利用寄主植物特定的化合物或化合物的特定比例来识别寄主(Bruce *et al.*, 2005)。迄今已报道了多种可以引起西花蓟马行为反应的化合物(表 1),可通过在诱捕器、诱虫板中添加引诱物质,提高对蓟马的诱捕效果。

对西花蓟马具有引诱或驱避作用的化合物包括苯环型、苯丙醛类、萜烯类、脂肪酸衍生物、氨基酸衍生物及吡啶类等物质。Koschier 等(2000)利用 Y 型嗅觉仪系统地评估了多种化合物对西花蓟马的行为反应,包括苯环型化合物(苯甲醛、茴香醛等)、萜烯类化合物(芳樟醇、香叶醇、橙花醇等)、苯丙醛类化合物(丁香酚、苯丙醛等)以及植物精油(玫瑰精油、天竺葵精油)等。研究表明,西花蓟马对苯甲醛、茴香醛、芳樟醇、香叶醇等化合物有显著的趋性(Koschier *et al.*, 2000),而水杨醛、水杨酸甲酯、顺式茉莉酸酮、茉莉酸甲酯、4-烯丙基苯甲醚等化合物对西花蓟马表现出驱避作用(Koschier *et al.*, 2000, 2007; Egger *et al.*, 2014)(表 1)。蓟马对化合物的行为反应是浓度依赖型的,即在不同浓度下,对化合物的行为反应存在一定的差异:如浓度为 10%时,西花蓟马雌虫对芳樟醇表现出极显著的趋性(76.0%),当浓度降低至 1%时,西花蓟马对芳樟醇的趋性(56.0%)降低(Koschier *et al.*, 2000)。

除对植物挥发物具有行为反应外,西花蓟马对吡啶衍生物类化合物也有显著的趋性(表 1),如异烟酸甲酯、烟酸乙酯、异烟酸乙酯等(Koschier *et al.*, 2000; Davidson *et al.*, 2008),其中,异烟酸甲酯对 12 余种蓟马均具有引诱作

用,包括西花蓟马、棕榈蓟马、烟蓟马、梳缺花蓟马、美东花蓟马 *Frankliniella tritici* 等(Teulon *et al.*, 2017)。以异烟酸甲酯为主要成分的商品化蓟马诱剂 Lurem-TR (<https://www.koppert.com/lurem-tr/>),已被应用于农业生产中(Teulon *et al.*, 2007; Davidson *et al.* 2009; Broughton and Harrison, 2012; Broughton *et al.*, 2015)。在玫瑰种植温室中,在黄色诱虫板上添加蓟马诱剂 Lurem-TR,极大地提高了对西花蓟马的诱捕效果(Broughton *et al.*, 2015)。在白色水盘诱捕器中添加异烟酸甲酯,对烟蓟马的诱捕量是对照的 12 倍(Davidson *et al.*, 2009)。

使用驱避化合物或植物精油处理植物,可以探究挥发物或植物精油对蓟马的取食和产卵影响(表 2)。研究表明,使用水杨醛、水杨酸甲酯、香芹酚、百里酚、对烯丙基苯甲醚、顺茉莉酮、茉莉酸甲酯等处理植物叶片,可以减少西花蓟马成虫产卵量。水杨酸甲酯、丁香酚、芳樟醇、马郁兰精油、薄荷精油、薰衣草精油、迷迭香精油等,对烟蓟马具有拒食作用,香芹酚和百里酚可减少烟蓟马产卵量。

2.2.2 昆虫源信息素 蓟马具有聚集行为,聚集信息素常常由蓟马雄性个体合成释放,对雌雄个体均具有引诱作用。Hamilton 等(2005)从西花蓟马雄虫释放出的挥发物中鉴定出了聚集信息素,其主要成分为(R)-薰衣草乙酸酯((R)-lavandulyl acetate)和萘肉基(S)-2-甲基丁酸酯(neryl (S)-2-methylbutanoate),并证明聚集信息素对西花蓟马雌雄均具有引诱作用,单独使用萘肉基(S)-2-甲基丁酸酯或将二者以 1:1 混合与诱虫板结合使用,能显著提高诱虫板对西花蓟马的诱捕量(Hamilton *et al.*, 2005; Sampson and Kirk, 2013),与其相应的蓟马诱剂产品 ThripLine ams (Syngenta)已被研发应用。除此之外,花蓟马(Zhang *et al.*, 2011)、棕榈蓟马(Akella *et al.*, 2014)、丝大蓟马 *Megalurothrips sjostedti* (Niassy *et al.*, 2019)和普通大蓟马(李晓维等, 2019)聚集信息素均已被鉴定。花蓟马聚集信息素与西花蓟马聚集信息素成分相同,均为(R)-薰衣草乙酸酯和萘肉基(S)-2-甲基丁酸酯(Zhang *et al.*, 2011);棕榈蓟马聚集信息素主要成分为

表 1 已报道的能引起西花蓟马行为反应的化合物

Table 1 List of reported chemicals affecting behavior responses to western flower thrips, *Frankliniella occidentalis*

化合物名称 Chemicals names	行为反应 Behavioral response	参考文献 References
苯环型化合物 Benzenoids		
苯甲醛 Benzaldehyde	引诱 Attractive	Koschier <i>et al.</i> , 2000
大茴香醛 <i>p</i> -anisaldehyde	引诱 Attractive	Koschier <i>et al.</i> , 2000; Koschier, 2008
邻茴香醛 <i>o</i> -anisaldehyde	引诱 Attractive	Koschier, 2008
水杨醛 Salicylaldehyde	驱避 Repellent	Koschier <i>et al.</i> , 2007; Koschier, 2008
水杨酸甲酯 Methyl salicylate	驱避 Repellent	Chermenskaya <i>et al.</i> , 2001
苯丙素类 Phenylpropanoids		
丁香酚 Eugenol	引诱 Attractive	Koschier <i>et al.</i> , 2000
3-苯丙醛 Phenylpropyl aldehyde	引诱 Attractive	Koschier <i>et al.</i> , 2000
萜烯类 Terpenoids		
α -蒎烯 α -pinene	引诱 Attractive	张骏等, 2015
桉树脑 1,8-cineole	引诱 Attractive	Chermenskaya <i>et al.</i> , 2001
(+)-香茅醛 (+)-citronellol	引诱 Attractive	Koschier <i>et al.</i> , 2000
香叶醇 Geraniol	引诱 Attractive	Koschier <i>et al.</i> , 2000
芳樟醇 Linalool	引诱 Attractive	Koschier <i>et al.</i> , 2000
顺式氧化芳樟醇吡喃 Cis-linalool oxide pyran	引诱 Attractive	Matsuura <i>et al.</i> , 2006
橙花醇 Nerol	引诱 Attractive	Koschier <i>et al.</i> , 2000
(+/-)-茶螺烷 ($\pm$)-theaspirane	引诱 Attractive	Avellaneda <i>et al.</i> , 2019
β -石竹烯 β -caryophyllene	引诱 Attractive	Avellaneda <i>et al.</i> , 2019
2-乙酸苯乙酯 2-phenylethyl acetate	引诱 Attractive	Avellaneda <i>et al.</i> , 2019
氧化石竹烯 (-)-caryophyllene oxide	引诱 Attractive	Avellaneda <i>et al.</i> , 2019
壬醛 Nonanal	引诱 Attractive	Avellaneda <i>et al.</i> , 2019
马鞭草烯酮(S)-(-)-verbenone	引诱 Attractive	Abdullah <i>et al.</i> , 2014, 2015
(<i>E</i>)- β -法尼烯 (<i>E</i>)- β -farnesene	引诱 Attractive	Koschier <i>et al.</i> , 2000
脂肪酸和氨基酸衍生物 Volatile fatty acid and Amino-acid derivatives		
顺-3-己烯醇 (Z)-3-hexenol	引诱 Attractive	张骏等, 2015
叶醛 (Z)-3-hexenal	驱避 Repellent	张骏等, 2015
1-辛烯-3-醇 1-octen-3-ol	引诱 Attractive	张骏等, 2015
环戊醇 Cyclopentanol	驱避 Repellent	张骏等, 2015
异戊醇 Isopentanol	引诱 Attractive	张骏等, 2015
异戊醛 Isovaleraldehyde	驱避 Repellent	张骏等, 2015
吡啉衍生物 Pyridine derivatives		
异烟酸甲酯 Methyl isonicotinate	引诱 Attractive	Davidson <i>et al.</i> , 2008; Koschier, 2008
异烟酸乙酯 Ethyl isonicotinate	引诱 Attractive	Davidson <i>et al.</i> , 2008; Koschier, 2008
烟酸乙酯 Ethyl nicotinate	引诱 Attractive	Davidson <i>et al.</i> , 2008; Koschier, 2008
4-乙酰基吡啶 Methyl 4-pyridyl ketone	引诱 Attractive	Davidson <i>et al.</i> , 2008

表 2 影响西花蓟马和烟蓟马取食和产卵的化合物和植物精油
Table 2 Feeding and ovipositing of *Frankliniella occidentalis* and *Thrips tabaci*

名称 Names	西花蓟马 <i>Frankliniella occidentalis</i>		烟蓟马 <i>Thrips tabaci</i>	
	取食/产卵 Feeding/Oviposition	参考文献 Reference	取食/产卵 Feeding/Oviposition	参考文献 Reference
水杨醛 Salicylaldehyde	拒食、减少产卵量 Feeding and oviposition deterrence	Koschier <i>et al.</i> , 2007	—	—
水杨酸甲酯 Methyl salicylate	拒食、减少产卵量 Feeding and oviposition deterrence	Koschier <i>et al.</i> , 2007; Allsopp <i>et al.</i> , 2014	拒食 Feeding deterrence	Koschier <i>et al.</i> , 2002
香芹酚 Carvacrol	减少产卵量 Oviposition deterrence	Sedy and Koschier, 2003; Allsopp <i>et al.</i> , 2014	减少产卵量 Oviposition deterrence	Sedy and Koschier, 2003
百里酚 Thymol	减少产卵量 Oviposition deterrence	Sedy and Koschier, 2003; Allsopp <i>et al.</i> , 2014	减少产卵量 Oviposition deterrence	Sedy and Koschier, 2003
丁香酚 Eugenol	—	—	拒食 Feeding deterrence	Koschier <i>et al.</i> , 2002; Riefler and Koschier, 2009
对烯丙基苯甲醚 Allylanisole	拒食、减少产卵量 Feeding and oviposition deterrence	Egger <i>et al.</i> , 2014	—	—
顺茉莉醛 (Z)-jasmone	拒食、减少产卵量 Feeding and oviposition deterrence	Egger and Koschier, 2014; Egger <i>et al.</i> , 2014	—	—
茉莉酸甲酯 Methyl jasmonate	拒食、减少产卵量 Feeding and oviposition deterrence	Egger and Koschier, 2014; Egger <i>et al.</i> , 2014	—	—
芳樟醇 Linalool	—	—	拒食 Feeding deterrence	Koschier <i>et al.</i> , 2002
马郁兰精油 Marjoram oil	—	—	拒食 Feeding deterrence	Koschier <i>et al.</i> , 2002
薄荷精油 Mint oil	—	—	拒食 Feeding deterrence	Koschier <i>et al.</i> , 2002
薰衣草精油 Lavender oil	—	—	拒食 Feeding deterrence	Koschier <i>et al.</i> , 2002
迷迭香精油 Rosemary oil	—	—	拒食 Feeding deterrence	Koschier <i>et al.</i> , 2002

(R)-3-甲基 3-丁烯酸薰衣草酯 ((R)-lavandulyl 3-methyl-3-butenate) (Akella *et al.*, 2014); 丝大蓟马聚集信息素的组成为(R)-3-丁烯酸薰衣草酯((R)-lavandulyl 3-methylbutanoate) (主要成分) 和(R)-薰衣草醇 ((R)-lavandulol) (次要成分) (Niassy *et al.*, 2019); 普通大蓟马聚集信息素主要成分为反式, 反式-金合欢醇乙酸酯 ((E, E)-farnesyl acetate) (李晓维等, 2019)。昆虫源信息化合物具有较强的专一性, 可以显著提高对目标害虫的诱捕效果 (Broughton and Harrison, 2012)。

除蓟马聚集信息素外, 研究人员还发现了蓟马报警信息素、接触信息素等。Teerling 等(1993) 从西花蓟马二龄若虫排泄物中鉴定了以乙酸癸酯和乙酸月桂酯为主要成分的报警信息素, 但由于二者对蓟马的驱避效果较弱, 在应用中受到限制 (Cook *et al.*, 2002; Macdonald *et al.*, 2003)。Olaniran 等 (2013) 从西花蓟马雄性个体中提取的接触信息素 7-methyltricosane, 在蓟马种间识别中具有重要作用 (Olaniran *et al.*, 2013; 刘艳琪和班丽萍, 2020)。美洲棘蓟马 *Echinothrips americanus* Morgan 雄性释放的反性信息素物质

Dimethyl adipate (DBE-6) 和 Dimethyl glutarate (DBE-5), 能避免多次交配, 对蓟马的治理具有潜在应用前景 (Krueger *et al.*, 2016; 刘艳琪和班丽萍, 2020)。

2.3 “推-拉”调控

“推-拉”防控策略是最大限度的利用昆虫行为的可调控性, 降低害虫对主要作物的为害。在“推-拉”系统中, 使用引诱刺激物(拉)聚集害虫或者募集天敌昆虫, 伴随着利用驱避刺激物(推)将主要作物上的害虫向引诱刺激源驱赶, 降低害虫在主要作物上的种群密度 (Cook *et al.*, 2007; Khan *et al.*, 2016), 然后采取措施对引诱刺激源上的害虫进行集中治理 (Attract-and-kill strategy, “引诱-杀死”策略) (Gregg *et al.*, 2018)。引诱和驱避刺激源可以是植物或信息化合物 (Cook *et al.*, 2007)。在非洲东部地区, “推-拉”技术已成熟应用于治理玉米害虫 (Cook *et al.*, 2007; Khan *et al.*, 2016)。银叶山蚂蝗 *Desmodium uncinatum* Jacq 能驱避玉米 *Zea mays* L. 上的亚澳白裙夜蛾 *Busseola fusca* Füller 和玉米螟 *Chilo partellus* Swinhoe, 而象草 *Pennisetum purpureum* Schumach 则起到引诱作用。玉米与银叶山蚂蝗间作, 同时在外围种植象草, 将农田中的玉米害虫聚集到外围象草上, 经济有效地控制了玉米害虫的发生和为害 (Cook *et al.*, 2007; Khan *et al.*, 2016)。

尽管蓟马寄主植物种类繁多, 但对不同植物表现出偏好性, 根据这一特点, 可以筛选出蓟马偏好性强和具有驱避作用的植物。将驱避植物与主要作物间作, 并在主要作物周边种植诱集植物或与引诱物质联合使用, 将蓟马诱集到偏好性植物上, 形成蓟马“推-拉”治理模式, 降低对主要作物的为害。如马郁兰 *Origanum majorana* L.、薰衣草 *Lavandula angustifolia* L.、日本薄荷 *Mentha arvensis* L. 及迷迭香 *Rosmarinus officinalis* L. 精油可以降低烟蓟马对南欧蒜 *Allium porrum* 的为害 (Koschier *et al.*, 2002) (表 2)。将迷迭香与蓟马偏好性强的菊科植物、蓟马引诱物质联合使用, 有效地降低了作物上的蓟马数量, 提高了菊科植物上蓟马密度 (Bennison *et al.*, 2002),

达到了对蓟马集中治理的目的。马郁兰精油、罗勒精油与异烟酸乙酯组成“推-拉”体系, 促使异烟酸乙酯对烟蓟马诱捕量增加, 同时改变了蓟马在作物上的空间分布 (van Tol *et al.*, 2007)。

种植伴随植物可以为天敌昆虫提供栖境, 起到募集天敌昆虫的作用, 有利于开展害虫的生物防治。向日葵 *Helianthus annuus* L. 和三叶草是小花蝽 *Orius insidiosus* Say 的偏好性植物, 在田间种植向日葵、三叶草等, 可以提高小花蝽的种群数量, 提高对蓟马的控制效果 (Bottenberg *et al.*, 1999)。

3 诱剂的研发与应用

引诱剂的研发和应用是将化合物对昆虫行为的调控研究由室内探索到田间应用的推广, 是有害生物绿色防控技术体系的重要组成。

目前, 蓟马诱剂的研发以室内研究为主, 利用昆虫嗅觉仪测定蓟马对化合物的行为反应, 进而确定对蓟马有引诱作用的成分, 常缺乏在温室或田间环境下的效果评估。迄今, 已报道的对诱捕器有增效作用的物质有 13 种 (表 3), 主要为苯环型和苯丙素类化合物、吡啶衍生物类化合物 (表 3), 国外商品化的蓟马诱剂主要为以异烟酸甲酯为主要成分的 Lurem-TR 和以西花蓟马聚集信息素为主要成分的 ThripLine ams; 国内商品化蓟马诱剂主要有蓟马性诱剂 (中捷四方) 和蓟马诱芯 (中捷四方、湖北谷瑞特生物技术有限公司、河南爱树科技发展有限公司等), 与室内筛选出的能引起蓟马行为反应的化合物数量相比, 蓟马诱剂种类较少, 且缺乏蓟马诱剂配方优化评估研究。

在田间化合物能否持续、有效地释放是影响引诱剂应用的重要因素。引诱剂的释放速率和持效期受化合物自身的理化性质、载体材料、环境等因素的影响。如异烟酸甲酯的释放速率随温度的升高而增加 (Nielsen *et al.*, 2019)。在 15 °C 时, 聚乙烯缓释袋中异烟酸甲酯的释放速率为 9.4 mg/d; 当温度升高至 35 °C 时, 释放速率达到 129.3 mg/d。信息化合物在害虫综合治理中的成功应用很大程度上依赖于载体材料的选择和化

表 3 已报道的可增加诱捕器对西花蓟马和烟蓟马诱捕量的化合物

Table 3 Chemicals increasing trap captures of *Frankliniella occidentalis* and *Thrips tabaci*

化合物名称 Chemicals names	参考文献 (西花蓟马) References (<i>Frankliniella occidentalis</i>)	参考文献 (烟蓟马) References (<i>Thrips tabaci</i>)
苯甲醛 Benzaldehyde	Teulon <i>et al.</i> , 1993	Teulon <i>et al.</i> , 2007
2-苯乙醇 2-phenylethanol	—	Teulon <i>et al.</i> , 2007
大茴香醛 <i>p</i> -anisaldehyde	Teulon <i>et al.</i> , 1993	Teulon <i>et al.</i> , 1993, 2007
苯甲酸甲酯 Methyl benzoate	—	Teulon <i>et al.</i> , 2007
(S)-(-)-马鞭草烯酮 (S)-(-)-verbenone	Abdullah <i>et al.</i> , 2015	—
γ -癸酸内脂 γ -decalactone	Teulon <i>et al.</i> , 2014	—
δ -癸酸内脂 δ -decalactone	Teulon <i>et al.</i> , 2014	—
异烟酸甲酯 Methyl isonicotinate	Davidson <i>et al.</i> , 2007; Teulon <i>et al.</i> , 2014, 2017	Davidson <i>et al.</i> , 2009; Teulon <i>et al.</i> , 2014, 2017
异烟酸乙酯 Ethyl isonicotinate	Davidson <i>et al.</i> , 2007	Teulon <i>et al.</i> , 2007; Davidson <i>et al.</i> , 2009
烟酸乙酯 Ethyl nicotinate	Teulon <i>et al.</i> , 1993; Davidson <i>et al.</i> , 2007	Teulon <i>et al.</i> , 1993, 2007; Davidson <i>et al.</i> , 2009
4-乙酰基吡啶 Methyl 4-pyridyl ketone	Davidson <i>et al.</i> , 2007	—
Isopropyl isonicotinate	—	Teulon <i>et al.</i> , 2007
n-propyl isonicotinate	—	Teulon <i>et al.</i> , 2007

化合物的释放方式 (Nielsen *et al.*, 2019)。目前, 蓟马信息素化合物载体材料有开口玻璃瓶 (Opened glass vials) (Teulon *et al.*, 1993, 2007; Davidson *et al.*, 2009)、浸渍棉卷 (Impregnated cotton rolls) (Teulon *et al.*, 1993)、半渗透聚乙烯袋 (Semi-permeable polyethylene bags) (Nielsen *et al.*, 2019) 及 Lurem-TR 商品化诱剂使用的载体材料 (Semi-permeable barriers covering a reservoir containing the compound) (Broughton and Harrison, 2012; Broughton *et al.*, 2015), 以及昆虫源信息素常用的橡胶载体等, 如蓟马诱芯 ThripLine ams (Broughton *et al.*, 2015)。研究发现, 以棉卷为载体时, 异烟酸甲酯的释放速率最快, 以半渗透聚乙烯袋为载体时, 异烟酸甲酯的释放速率较慢, 持效期更长。此外, 直接将信息化合物喷涂至色板 (Spraying or painting onto traps) (Davidson *et al.*, 2007; van Tol *et al.*, 2007)、或将化合物融合在色板黏着胶内制作高效诱虫色板 (任小云等, 2019) 也是一种常用的方法, 有利于化合物挥发、释放, 可用于评估信息化合物对蓟马的诱捕效果 (Nielsen *et al.*, 2019)。载

体材料的选择应综合考虑田间生产的技术需求 (如作物的栽培系统、诱捕器的选择)、化合物的初始剂量、实验持续时间等, 以确定合适的载体材料。

4 展望

随着我国种植业产业结构调整和设施园艺面积不断增加, 为蓟马的发生和为害提供了有利条件, 严重威胁着保护地蔬菜、花卉等相关产业的可持续发展。同时, 随着我国对农药使用减量、农业生产增效等相关政策的提出和落地, 以及大众对食品安全要求的提高, 对害虫的防控技术和方法提出了新的要求。因此, 成熟、有效的蓟马早期监测和防控技术的研发对蓟马的综合治理非常重要。蓟马行为调控研究应与农业生产紧密结合, 提高对蓟马的诱控效果。作者认为, 未来研究应从以下方面开展:

1) 蓟马诱剂配方优化评估。评估和优化诱剂配方是昆虫诱剂研发的重要组成部分。蓟马引诱物质的筛选常常为某一种化合物, 缺乏对不同组分混配的效果评估。在对寄主植物进行定位过

程中,植食性昆虫凭借植物释放的特定物质组成的比例实现 (Bruce *et al.*, 2005, Gregg *et al.*, 2016),对于寄主植物种类单一的昆虫而言,通过模拟植物释放出化合物的比例开发诱剂较为容易实现,但是对于寄主植物种类较多的多食性、杂食性昆虫来讲,这种方式存在局限性 (Gregg *et al.*, 2016)。因此,可以通过将多种对昆虫具有引诱作用的化合物混合,以期筛选出引诱效果更好的诱剂配方(超融合 Superblending) (Gregg *et al.*, 2018)。这种超融合的化合物可能来自于不同的寄主植物,通过这种方式筛选出的诱剂不等同于任何一种植物挥发物的组分 (Gregg *et al.*, 2016, 2018),有利于诱剂在不同的作物、不同的生境中起作用。通常来讲,这种多种化合物的组合对昆虫的引诱作用优于单一化合物的引诱效果 (Landolt *et al.*, 2006; Molnár *et al.*, 2019),因此,可以通过这种方式进一步筛选出对蓟马更加有效的诱剂。

2) 室内研究与田间应用相结合。在室内,研究人员通过嗅觉仪、风洞实验,可以初步筛选出用于昆虫引诱或驱避物质的成分,但是由于昆虫对化合物的反应与昆虫的营养状态、虫龄 (Davidson *et al.*, 2006)、交配状态 (Gadenne *et al.*, 2016) 等相关,因此在室内进行行为反应测定时,应将上述因素考虑在内。且田间环境条件(如温湿度、光周期等)与室内差异较大,因此室内的行为反应结果不能作为筛选昆虫引诱物质的决定性指标 (Gregg *et al.*, 2018)。此外,在室内条件下,气流经过滤后进入气味源再由昆虫感知,导致昆虫所感知的气味刺激是单一的,不同于田间复杂的背景气味条件。背景气味对信息化化合物的影响有 3 种:无影响、干扰或增效 (Shröder and Hilker, 2008),因而需要在温室、田间对室内结果做进一步验证,提高对诱剂研发评估的准确度。

3) 多种措施协调应用。综合利用蓟马行为调控的措施,提高农田生态系统中蓟马的生态调控能力,减少化学农药的投入。在农业生产中,应充分利用蓟马对颜色、信息素、寄主植物的行为反应特点,使用对蓟马引诱和驱避作用显著的

植物,在田间将驱避植物与作物间作、外围种植引诱植物或增设诱虫色板、引诱剂等装置,组成蓟马的“推-拉”治理体系 (Cook *et al.*, 2007) 或“引诱-杀死”治理策略,降低主要作物上蓟马种群数量、减少对作物的危害。

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