



近二十年我国杀虫剂毒理学研究进展 (I) ——杀虫剂的毒性与环境安全性研究*

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摘要 本文介绍了中国昆虫学家、杀虫剂毒理学研究者与植物保护专家及害虫防治工作者最近 20 年来在杀虫剂的毒性, 尤其是杀虫剂对靶标害虫及非靶标昆虫的毒性方面的研究进展, 并就杀虫剂对害虫的防控效果、杀虫剂对天敌昆虫的影响以及杀虫剂的环境安全性方面的研究内容进行了系统性综述。

关键词 杀虫剂毒性; 非靶标毒性; 天敌昆虫; 杀虫剂残留; 杀虫剂环境安全性

Advances in insecticide toxicology in China in the last two decades (I) : Insecticide toxicity and environmental safety

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Abstract Advances in research on insecticide toxicity, especially with respect to target and non-target insects, by Chinese entomologists, insecticide toxicologists, plant protection specialists and pest control experts, in the last 20 years is introduced, and effects of insecticides on pest insects, the natural enemies of pest insects and the environment, systematically reviewed.

Key words insecticide toxicity; non-target toxicity; enemy insect; insecticide residue; insecticide environmental safety

1 杀虫剂毒性

杀虫剂的使用历史悠久, 长期以来, 它在保护植物健康、提高农作物产量、促进农业发展方面都做出了巨大的贡献。近年来, 化学杀虫剂在农业害虫与卫生害虫的防治中更是扮演极其重要的角色。但同时, 绝大多数杀虫剂也会对非靶标生物产生毒害作用, 此外, 在目前的施用技术条件下, 杀虫剂使用后大部分都散落于靶标作物以外的介质中, 且容易造成其在环境中的残留, 对生态系统平衡及环境安全乃至人类健康都构成威胁。因此, 在使用杀虫剂时除了考虑目标害

虫的针对性及对虫害的防控效果外, 还必须充分考虑农业与公共卫生系统的可持续发展以及环境健康与生态系统的安全。

根据对最近 20 年来我国在昆虫科学及杀虫剂毒理学研究领域正式发表的研究论文分析, 发现大部分的内容都是关于杀虫剂对非靶标生物毒性的研究, 且多数是关于杀虫剂对靶标生物与其天敌的选择毒性研究, 其原因很大可能是由于现在广泛使用的杀虫剂的靶标毒性及其机理已相对清楚, 而随着杀虫剂的大量使用, 人们对杀虫剂的非靶标毒性及杀虫剂生态环境安全性的担忧日益成为相关领域研究中更为关注的课题。

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1.1 杀虫剂对害虫的毒性

杀虫剂被发明研制的目的就是为了解决生产实际中害虫防治的问题。近 20 年来,我国有关杀虫剂对靶标生物毒性研究的害虫包括稻飞虱 *Nilaparvata lugens*、小菜蛾 *Plutella xylostella*、棉铃虫 *Helicoverpa armigera*、蚜虫 *Aphidoidea* 等常见的农作物害虫。多数研究从生产实际的需要出发进行杀虫剂对害虫的药效或防效研究,研究内容大多较为简单,例如:测定杀虫剂对某种(些)害虫的致死中浓度、半数致死量等基本参数或简单的田间试验测定防治效果。也有一些稍微“复杂”的研究,例如:同时测定多种杀虫剂对害虫的毒性,以比较不同的杀虫剂对所测昆虫的毒性大小,也有些研究从杀虫剂的化学结构及其性质的角度探讨杀虫剂的毒性问题,但研究大多还是限于单一的毒性比较(谌爱东等, 2003; 吕宝乾等, 2005)。以下按照杀虫剂种类分述。

1.1.1 有机磷与氨基甲酸酯类杀虫剂 有机磷与氨基甲酸酯类杀虫剂一直以来都是我国农业生产上用量较大的一类杀虫剂。这类杀虫剂对害虫的毒杀机制已经比较清楚,所以相关毒性研究报道并不多见,主要的研究集中在某些特别的害虫上。例如:有研究者用有机磷杀虫剂敌敌畏和毒死蜱以及氨基甲酸酯类杀虫剂丁硫克百威作用于嗜卷书虱 *Liposcelis bostrychophila* 和嗜虫书虱 *Liposcelis entomophila*,发现能够抑制超氧化物歧化酶(Superoxide dismutase, SOD)的活性,此外,2 种书虱的谷胱甘肽巯基转移酶(Glutathione-S-transferase, GST)活力和动力学参数都存在着显著差异,表明 GST 在书虱的药剂敏感性中起着重要作用(程伟霞等, 2006)。研究人员针对我国东亚飞蝗 *Locusta migratoria manilensis* 不同种群,研究其对有机磷和氨基甲酸酯类杀虫剂的敏感谱,分析不同种群乙酰胆碱酯酶(Acetylcholinesterase, AChE)的敏感性差异,建立分子技术用于对田间种群靶标不敏感性的筛查检测(Zheng et al., 2006; Wu et al., 2007; Yang et al., 2008)。

1.1.2 拟除虫菊酯类杀虫剂 对拟除虫菊酯类杀虫剂的毒性及防效研究较少。有报告认为氯氰

菊酯可在椰心叶甲 *Brontispa longissima* 综合治理中发挥有效作用(许春霭等, 2008)。用菊酯类杀虫剂处理蚜虫后发现,不同浓度高效氯氰菊酯和氯菊酯对枸杞蚜虫 *Aphis* sp. 的 GST 活性均有抑制作用,而不同浓度氰戊菊脂、溴氰菊酯、甲氰菊脂和氟氯氰菊酯处理的枸杞蚜虫的 GST 活性均升高(张丛等, 2015)。比较深入的研究涉及新的分析技术的应用,例如:运用蛋白质组学技术,分析德国小蠊 *Blattella germanica* 在用氯氰菊酯处理不同时间后的蛋白质水平的变化,发现杀虫剂处理时间长短对所测指标有很大的影响(Yang et al., 2019)。基因组分析发现,斑痣悬茧蜂 *Meteorus pulchricornis* 体内的 GST 基因在氯氰菊酯(Cypermethrin)的解毒过程中起重要作用(Zhang et al., 2019)。

1.1.3 烟碱类杀虫剂 有报告称亚致死量的吡虫啉对红火蚁 *Solenopsis invicta* 的摄食及挖掘行为有剂量依赖性的影响(Wang et al., 2015a)。对蝗虫的研究发现,吡虫啉的药物浓度对蝗虫中枢神经系统的影响不同:低浓度吡虫啉调节两个烟碱型乙酰胆碱受体(Nicotinic acetylcholine receptor, nAChR)亚基的基因,而高浓度吡虫啉只调节一个 nAChR 亚基基因(Wang et al., 2015b)。对棉蚜 *Aphis gossypii* 的毒性测定发现,即使给予亚致死量的环氧虫啉(Cycloxyaprid),其成虫寿命及生殖力都会降低,且子代的发育也受影响(Yuan et al., 2017)。此外,通过对褐飞虱 *Nilaparvata lugens* 的研究发现,环氧虫啉、烯啶虫胺对褐飞虱的毒性随温度升高显著增加(Mao et al., 2019a)。

1.1.4 大环内酯类杀虫剂 对于大环内酯类杀虫剂的杀虫毒性,有研究测定多杀菌素对棉铃虫 *Helicoverpa armigera* 的半数致死量,发现在亚致死浓度下的多杀菌素可使存活幼虫的发育时间及蛹期延长,并导致蛹化率、破茧率和生殖力下降及成虫寿命缩短(Wang et al., 2009a)。也有用草地贪夜蛾 *Spodoptera frugiperda* 细胞系 Sf-9 的培养细胞开展此类杀虫剂毒性的研究,发现甲氨基阿维菌素苯甲酸盐可以降低细胞的活力,且可诱导细胞单链 DNA 断裂(Wu et al., 2016)。同样用 Sf-9 细胞系开展研究发现,多

杀菌素可通过增强活性氧的产生、线粒体通透性转换孔的开放以及线粒体膜电位的失常引起细胞色素 C 的释放并最终导致程序性细胞死亡 (Yang *et al.*, 2017)。

1.1.5 酰胺类杀虫剂 采用饲料混毒法测定氯虫苯甲酰胺对甜菜夜蛾 *Spodoptera exigua* 3 龄幼虫的致死剂量 (LC₂₅ 和 LC₅₀)，发现经亚致死浓度的氯虫苯甲酰胺处理后的甜菜夜蛾幼虫历期和蛹期延长，体重和蛹重减轻，羽化率、产卵量均下降，此外，其体内的酯酶和多功能氧化酶 (Mixed function oxidase, MFO) 活性也显著降低，表明氯虫苯甲酰胺对甜菜夜蛾的种群增长和代谢酶活性都具有抑制作用 (Lai *et al.*, 2011)。

在小菜蛾 *Plutella xylostella* 上的测定也发现类似现象，氯虫苯甲酰胺在亚致死剂量下小菜蛾死亡率增高、幼虫生长受到抑制、幼虫至化蛹平均历期延长，蛹重和化蛹率均降低。表明亚致死剂量氯虫苯甲酰胺对小菜蛾种群增长有较强的抑制作用 (Wang *et al.*, 2013a)。

1.1.6 生物毒素类杀虫剂 用从苏云金芽孢杆菌菌株 BRC-HZP10 中分离出的 Cry2Ad 毒素蛋白，测定其对小菜蛾的毒性，结果显示该毒素有较好的杀虫效果，可导致小菜蛾产卵期与幼虫发育期缩短，种群繁殖力和卵孵化率均降低 (Liao *et al.*, 2015)。

对于其他植物源性杀虫剂的靶标毒性，有研究者曾测定植物提取物对舞毒蛾 *Lymantria dispar* 的毒性，认为 0.6% 氧苦内酯和 5% 桉油精这 2 种植物提取成分可作为防治舞毒蛾的植物源杀虫剂推广应用 (丁吉同等, 2013)。研究测定黑藜芦提取物对德国小蠊的毒性，认为黑藜芦生物碱可作为德国小蠊的天然潜在杀虫剂 (Cai *et al.*, 2018)。而对木酚素 (Lignan) 的杀虫活性测定发现，提取自透骨草 *P. leptostachya* 的木酚素具有较强的杀虫活性，可用于开发新植物源杀虫剂 (Li *et al.*, 2019d)。

1.1.7 其他杀虫剂 研究发现，吡啶杀虫剂 5-氨基乙酰丙酸 (ALA) 对稻蝗 *Oxya chinensis* 的作用效果与稻蝗体内原吡啶含量有关，后者能诱导激活蝗虫体内 GST、过氧化氢酶 (Catalase, CAT)、谷胱甘肽过氧化物酶 (Glutathione

peroxidase, GSH-Px) 的活性，抑制谷胱甘肽还原酶 (Glutathione reductase) 的活性，而 ALA 可使 AChE 和 GSH-Px 失活 (阴琨等, 2008)。

对新型季酮酸类杀虫剂的毒性测定发现，螺虫乙酯对棉蚜的毒性呈时间依赖性，不仅降低棉蚜的繁殖力，还可增加体内羧酸酯酶 (Carboxylesterase, CarE) 的活性 (Gong *et al.*, 2016)。

而有机氯杀虫剂目前在生产实际中已很少使用。研究发现，五氯酚可影响土壤跳虫 *Folsomia candida* 体内包括细胞色素 P450 在内的多种基因的表达，该杀虫剂对土壤跳虫的生殖毒性的主要作用是它可以导致化学物诱导的蜕皮周期延迟 (Qiao *et al.*, 2015)。

1.1.8 杀虫剂与其他化学物对害虫的联合毒性 目前针对杀虫剂与其他化学物的联合杀虫毒性的研究较少。在摇蚊 *Chironomus dilutes* 上的研究发现，苄氯菊酯与镉的联合毒性具有拮抗作用，镉加速了摇蚊对苄氯菊酯的解毒过程 (Chen *et al.*, 2015)，此外，还测定了酶活力和相关基因的表达，发现镉对苄氯菊酯的代谢动力学没有明显影响，但能增加代谢相关基因的表达量，导致摇蚊体内的苄氯菊酯向低毒代谢物的转化加速 (Chen *et al.*, 2016)。

1.1.9 手性杀虫剂对害虫的毒性作用问题 一些杀虫剂由于具有手性结构，其不同对映体和消旋体的毒性及在环境中的消解速率都可能有很大的不同。例如：联苯菊酯 (Bifenthrin) S 对映体要比其 R 对映体对靶标害虫菜青虫的毒性大 300 倍 (Liu *et al.*, 2008)。通过对广谱杀虫剂氟克迈酰胺 (Fluxametamide) 对小菜蛾等害虫的测试发现，其消旋体比对映体更具毒性，而 S 对映体比 R 对映体的急性毒性高出 30 倍 (Li *et al.*, 2019b)。有机磷杀虫剂甲基异柳磷 (Isfenphos methyl) 的 S 对映体也比 R 对映体对南方根结线虫等靶标害虫的毒性要大很多 (最多高出近 150 倍)，而 S 对映体对非靶标生物的毒性平均只比 R 对映体高出 2 倍 (Gao *et al.*, 2019)。这些研究结果为如何选择这类杀虫剂有效防控虫害而又不会对非靶标昆虫形成太大的威胁提供指导。

1.2 杀虫剂对非靶标昆虫的毒性

对于非靶标昆虫毒性的研究,呈现出相对集中的研究对象,以家蚕和蜜蜂占有最高比例;此外,寄生蜂也常被作为杀虫剂的非靶标毒性的研究对象(对天敌昆虫的毒性研究综述详见本文第2.1节)。

1.2.1 杀虫剂对家蚕的毒性 通过饲叶法测定,阿维菌素对家蚕的毒性为高毒,认为应禁止阿维菌素在桑园及附近农田使用(吴声敢等,2004)。生长调节剂与双酰胺类杀虫剂对家蚕的毒性研究比较多。例如:对昆虫生长调节剂苯甲酰尿杀虫剂氟啶脲的毒性试验显示,施药剂量为其急性毒性 LC_{50} 值的 1/800 对家蚕较为安全(池艳艳等,2014)。双酰胺类杀虫剂氯虫苯甲酰胺影响家蚕体内解毒酶活性及相关基因的表达,导致 P450 与 GST、CarE 活性升高,且氯虫苯甲酰胺可通过影响家蚕脂肪组织中 P13K 信号通路调节下游解毒酶的表达量,增强解毒能力(Mao et al., 2019b)。基因表达谱分析揭示,氯虫苯甲酰胺抑制中肠的氧化磷酸化路径及抗氧化防御系统相关基因的表达,引起中肠氧化损伤导致家蚕生长抑制(Hu et al., 2019)。对氯代烟碱类杀虫剂测定发现,啉虫脒(Acetamiprid)可致家蚕中肠损伤,引起生长发育异常(Wang et al., 2019a),而且也可以通过影响内分泌相关基因的表达导致家蚕生殖紊乱(Cheng et al., 2019)。最近的研究发现,啉虫脒可以抑制家蚕 CarE 的转录,通过 FoxO/CncC/Keap1 信号通路上调 GST 基因的转录水平及增加 GST 酶活性(Wang et al., 2020a)。

有机磷杀虫剂对非靶标昆虫毒性的研究对象主要以家蚕为主,令人惊奇的是,研究者几乎只选择辛硫磷(Phoxim)研究其对家蚕的毒性。研究发现,辛硫磷可导致氧化应激(Yu et al., 2011)、丝腺细胞凋亡(Ma et al., 2013)、GST 和酯酶的基因转录水平增加(Gu et al., 2013; Wang et al., 2013c),家蚕可通过过氧化物酶基因的表达调节改变氧化还原平衡状态以减少辛硫磷引起的氧化损伤(Shi et al., 2014)。接触辛硫磷后家蚕中肠组织线粒体肿胀、细胞色素 C 释放到胞质中, Toll 及免疫信号被抑制(Gu et al.,

2014)。通过基因分析发现,辛硫磷可诱导多个 P450 基因的表达及线粒体电子转移链平衡改变(Li et al., 2015, 2016)。此外,辛硫磷可在家蚕丝腺中累积引起丝腺损伤(Cheng et al., 2018),并引起免疫应答抑制,导致家蚕肠道中微生物群落及结构改变,影响包括免疫功能在内的肠道正常功能,最终导致对病原微生物感染的敏感性增加及蚕体的损伤(Gu et al., 2017; Li et al., 2020a, 2020b)。

通过比较 5 种 Bt 蛋白对家蚕的毒性发现, Cry2Fa 和 Cry1Aa 对家蚕幼虫毒性较大,而对靶标害虫二化螟的活性较低,不适合水稻鳞翅目害虫的防治(Jiao et al., 2016)。

1.2.2 杀虫剂对蜜蜂的毒性 有研究者测定苯基吡唑类杀虫剂氟虫腈(Fipronil)对蜜蜂的经口毒性,发现其对蜜蜂工蜂属剧毒(杨艳霞等, 2008),研究发现,手性氟虫腈对意大利蜂 *Apis mellifera ligustica* 的毒性无对映体选择差异(Li et al., 2010)。有机磷与氨基甲酸酯类杀虫剂对蜜蜂毒性的研究比较少,有报道马拉硫磷 R 对映体对蜜蜂毒性最大,其次是消旋体,再其次是 S 对映体(R 型比 S 型有更高的毒性)(Sun et al., 2012)。

摄入亚致死剂量的吡虫啉可诱导成年意大利蜂脑神经细胞出现 caspase 依赖性细胞凋亡(吴艳艳等, 2014; Wu et al., 2015)。亚致死浓度噻虫嗪可明显降低工蜂的平均寿命(岳孟等, 2017),在防治棉蚜时使用吡虫啉和噻虫嗪会增加对意大利蜂的毒性风险(Jiang et al., 2018),而低浓度噻虫嗪对中华蜜蜂 *Apis cerana cerana* 的回巢时间、飞行能力等都有不利影响(Ma et al., 2019)。此外,噻虫啉可引起蜜蜂肠道微生物紊乱,导致存活率降低(Liu et al., 2020)。在半野外和实验室条件下测试,杀虫剂助剂也可加剧啉虫脒对蜜蜂的毒性(Chen et al., 2019a)。研究发现,呋虫胺(Dinotefuran)对意大利蜜蜂的毒性具有对映体选择性,其 S 对映体比 R 对映体的毒性平均高出 85 倍,而 R 对映体对棉蚜和绿盲蝽 *Lygus lucorum* 的毒性比消旋体的毒性平均只高出 2 倍(Chen et al., 2019b)。通过高通量测序发现, R 对映体比 S 对映体引起

更大的基因调控变化 (Liu *et al.*, 2019a), 对其分子机理研究显示, S 对映体结合到蜜蜂的 nAChR 的 $\alpha 8$ 亚单位上产生更大的毒性, 施用 R 对映体对蜜蜂的危害最小。故防治棉蚜和绿盲蝽时推荐施用纯的呋虫胺 (R 对映体) 以获得良好防效的同时降低对蜜蜂种群的威胁 (Chen *et al.*, 2019b)。

研究发现, 亚致死剂量的联苯菊酯可降低蜜蜂的生殖力、减少成蜂量 (Dai *et al.*, 2010)。氟氯苯菊酯 (Flumethrin) 对蜜蜂的 LD_{50} 值高于大部分拟除虫菊酯类杀虫剂, 可影响中华蜜蜂的嗅觉及学习记忆 (Tan *et al.*, 2013)。在体外培养条件下, 溴氰菊酯可以作用于蜜蜂成年工蜂脑细胞的 T 型电压门控钙离子通道, 导致其学习、信息获取的行为异常 (Wang *et al.*, 2017a)。高效氯氟氰菊酯 (λ -cyhalothrin) 和溴氰菊酯都对蜜蜂的记忆产生影响, 亚致死剂量即可缩短其生命周期、影响学习记忆行为及相关基因表达或导致认知功能紊乱 (Liao *et al.*, 2018; Zhang *et al.*, 2020a)。体外试验发现, 氟氯苯菊酯通过改变 SOD 和 CAT 活性、脂质过氧化物 (如: MDA) 的量和解毒酶 (如: GST) 活性而对蜜蜂幼虫产生毒性 (Qi *et al.*, 2020)。

田间测试发现, 含 Bt 蛋白 Cry1Ah 的转基因玉米对蜜蜂生存、发育及行为无影响 (Dai *et al.*, 2012)。通过毒理学、生物化学与组织学分析证明 Bt 晶体蛋白 Cry1C 与 Cry2A 对蜜蜂幼虫无毒 (Wang *et al.*, 2015c)。含 Bt 蛋白 Cry1Ba3 转基因甘蓝对蜜蜂的存活、解毒酶活性等都没有明显影响 (Yi *et al.*, 2018)。上述结果表明 Bt 蛋白类杀虫剂对蜜蜂较为安全。

1.2.3 杀虫剂联合使用及施用方式对非靶标昆虫毒性的影响 有机磷和菊酯类杀虫剂联合使用对家蚕的急性毒性主要表现为加成效应 (Zhang *et al.*, 2008)。测试多种杀虫剂联合使用对家蚕的毒性, 发现毒死蜱和溴氰菊酯联合产生拮抗作用, 而其他两两结合则产生加成毒性效应 (Yu *et al.*, 2016)。

有研究通过改变施药方式来降低对非靶标昆虫益虫的风险, 在新疆棉区的大面积试验发

现, 滴灌 (Drip irrigation) 施用氟啶虫胺腈可以有效控制棉蚜并将该药剂对蜜蜂的风险降到最低 (Jiang *et al.*, 2020)。

2 杀虫剂的生态环境安全性

近 20 年来, 国内有关杀虫剂环境安全性的研究工作进展较快, 且大部分研究与杀虫剂毒性、抗性研究方向重合。所做工作与生产实际结合较为紧密, 大部分为单纯测定靶标生物毒性与非靶标生物 (如: 害虫天敌) 的抗药性, 为农业生产、疾病防控工作提供科学施药用药指导。此外, 关于杀虫剂在环境中的残留以及对环境生态安全与人类健康威胁的研究也有大量报道。

2.1 杀虫剂对害虫天敌的影响

杀虫剂对非靶标昆虫的影响详见第 1.3 节的描述。植物保护工作者更为关注的是杀虫剂对害虫天敌的安全性问题。但到目前为止, 杀虫剂对天敌昆虫的研究多数还是以一般的毒性测定为主或是与靶标害虫与其天敌昆虫的毒性的选择性比较研究为主。例如: 测定啉虫脒对椰心叶甲与椰心叶甲啉小蜂 *Tetrastichus brontispae*、橡副珠蜡蚧 *Parasaissetia nigra* 与班翅食蚜蚧小蜂 *Coccophagus ceroplastae* 的选择毒性, 发现选择效应不明显, 不推荐在农业生产中使用 (许春霁等, 2008; 张方平等, 2008)。除此之外, 有测定赤眼蜂对常见的烟碱类杀虫剂的急性毒性的反应, 结果发现, 噻虫嗪对拟澳洲赤眼蜂 *Trichogramma confusum* 和稻螟赤眼蜂 *Trichogramma japonicum* 的急性毒性最高; 其次为烯啶虫胺; 而吡虫啉对亚洲玉米螟赤眼蜂 *Trichogramma ostrinae* 和拟澳洲赤眼蜂的毒性最低 (王彦华等, 2012)。测定阿维菌素类、拟除虫菊酯类、新烟碱类、昆虫生长调节剂和吡唑类杀虫剂对上述 4 种赤眼蜂的安全性, 发现除有机磷和氨基甲酸酯具有中等至高毒性风险外, 其他杀虫剂大多 (个别例外) 都比较安全 (Zhao *et al.*, 2012; Wang *et al.*, 2012, 2013b, 2014)。研究发现, 防治小菜蛾的常用杀虫剂高效氯氟氰菊酯、多杀菌素、阿维菌素、溴虫腈和杀螟丹对拟

澳洲赤眼蜂成蜂有明显的触杀毒性(王德森等, 2012), 多杀菌素对小菜蛾天敌寄生蜂 *Diadegma insulare* 及捕食瓢虫 *Coleomegilla maculate* 无明显毒性, 有利于小菜蛾的防控, 但氯氟氰菊酯对这 2 个天敌都有较强毒性(Liu *et al.*, 2012)。新烟碱杀虫剂中啉虫脒和噻虫啉对赤眼蜂的毒性较小(Jiang *et al.*, 2019)。最近的研究发现, 用于防控稻纵卷叶螟 *Cnaphalocrocis medinalis* 的 4 种常用杀虫剂中氯虫苯甲酰胺对寄生蜂的毒性最低(Yang *et al.*, 2020)。

为明确吡蚜酮(Pymetrozine)等杀虫剂对水稻田天敌蜘蛛的安全性, 有学者采用浸渍法测定了杀虫剂对水稻田优势蜘蛛草间钻头蛛 *Hylyphantes graminicola* 和八斑鞘腹蛛 *Theridion octomacutatum* 的毒性, 结果显示吡蚜酮等 5 种杀虫剂对这两种蜘蛛都是低风险性, 而阿维菌素则为高或极高风险性杀虫剂(王玺等, 2013), 此外, 阿维菌素对烟芽茧蜂也具有很强的毒性作用, 在寄生蜂卵期与幼虫期用药, 可显著降低当代成蜂羽化率, 但蛹期用药无影响(陈德锐等, 2014), 这为避免伤及寄生蜂对阿维菌素的用药时间提供了重要的指导。类似的研究也显示生长调节剂类杀虫剂对丽蚜小蜂 *Encarsia formosa* 的不同发育阶段的毒性不同, 对幼虫有轻中度毒性, 但对蛹无毒性作用(Wang and Liu, 2016)。研究发现, 环氧虫啉具有较好的毒性选择性, 对棉蚜天敌异色瓢虫 *Harmonia axyridis* 和中华草蛉 *Chrysoperla sinica* 毒性较低, 但对棉蚜的毒性较高, 可用于抗药性棉蚜的防控(Cui *et al.*, 2016)。亚致死量的吡虫啉可导致七星瓢虫 *Coccinella septempunctata* 生殖率降低(Xiao *et al.*, 2016)。有研究测定联苯菊酯与氟氯氰菊酯对七星瓢虫的毒性, 发现这两种杀虫剂都对七星瓢虫表现为高毒(Liu *et al.*, 2019b)。高效氯氟菊酯和多杀菌素即使在很低的浓度下对螟黄赤眼蜂 *Trichogramma chilonis* 的产卵和寄主识别以及雄性交配选择都会产生不利影响(Wang *et al.*, 2016; 2017b)。关于杀虫剂对天敌昆虫的手性选择性毒性研究较少, 有文献报道, 丁烯氟虫腈(Flufiprole)R 对映体要比 S 对映体对稻纵卷叶螟赤眼蜂的急性毒性高出 5 倍左右(Tian *et al.*,

2016)。

生物杀虫剂 Bt 蛋白的残效期较短, 对广赤眼蜂 *Trichogramma evanescens* 雌蜂的存活能力和寄生能力影响较小(朱九生等, 2009)。研究显示, 转基因玉米对非靶标天敌瓢虫无生态风险(Chang *et al.*, 2017), 转基因水稻及其中的 Bt 蛋白 Cry1C 和 Cry2A 对稻虱缨小蜂 *Anagrus nilaparvatae* 无毒性风险(Gao *et al.*, 2010; Tian *et al.*, 2018)。2 种 Bt 蛋白 Cry1Ah 和 Cry2Ab 对棉蚜及瓢虫无明显毒性(Zhao *et al.*, 2016), 更为详细的研究则是通过毒理学、组织病理学、生化与分子生物学的分析, 表明 Bt 蛋白 Vip3Aa 对瓢虫无毒性作用(Zhao *et al.*, 2020)。上述结果提示, 生物杀虫剂 Bt 对天敌昆虫比较安全。

2.2 杀虫剂在环境中的残留

关于杀虫剂在施用对象、农作物植株、籽实、叶片以及环境介质(包括土壤、水体等)中的残留有大量的研究报道。本文只选择其中几例做简单介绍。研究发现, 在水稻和甘蓝上按规定使用推荐剂量的毒死蜱不会造成残留超标(Chen *et al.*, 2012)。在甘蔗田中施用毒死蜱在植株和土壤中的半寿期只有 6 d 左右, 间隔 60 d 采收, 无论以标准剂量或高剂量施用毒死蜱在甘蔗中的残留量都难以检出, 对人类健康不构成威胁(Wang *et al.*, 2019b)。由于蔬菜和水果在目前膳食结构中占有较高比例, 而有关蔬果中农药残留超标引发的事件屡有发生(Wu *et al.*, 2017), 农药残留已成为农产品质量安全的重要问题。以丁硫克百威为对象, 研究在不同施药条件及不同种植模式下在喷施对象作物中的残留行为, 并对该杀虫剂进行膳食风险评估(He *et al.*, 2016; Yu *et al.*, 2017)。根据施用后的消解动态变化, 提出在大棚种植的黄瓜上施用丁硫克百威至少要有 27 d 的采收间隔期(Geng *et al.*, 2018)。也有研究者就如何提高膳食样品中新烟碱类化合物检测的敏感性进行分析并提出有效的清除策略(Li *et al.*, 2019c)。

在检测技术方面, 有不断改进的报道, 包括样品中的单一杀虫剂残留的测定以及多个杀虫剂残留的同时测定等。从应用单克隆抗体技术检

测多种菊酯类杀虫剂残留 (Wang *et al.*, 2011) 和间接免疫荧光法测定氯虫苯甲酰胺 (Cui *et al.*, 2014) 到 ELISA 法检测和筛查农产品中的氟啶虫酰胺残留 (Liu *et al.*, 2016) 和用碳糊电极检测环境中的甲基对硫磷残留 (Li *et al.*, 2018) 以及采用 QuEChERS-气相色谱-串联质谱法检测黄瓜中 10 种杀虫剂的残留 (白国涛等, 2019)。越来越多更加新颖的方法用于多种杀虫剂残留的检测, 例如: 表面等离子共振技术检测环境中毒死蜱的残留 (Li *et al.*, 2019a); 表面增强拉曼散射传感器快速检测果蔬等农产品中的甲基对硫磷的残留 (Wu *et al.*, 2019); 用结合纳米技术的电化学感受器监测食品样品中的 DDT 残留 (Miao *et al.*, 2020) 等。

2.3 杀虫剂对生态环境及人类健康的威胁

越来越多的研究关注手性杀虫剂对环境生态系统的影响。早期通过体外细胞系和整体实验发现, 联苯菊脂 S 对映体比 R 对映体对细胞增殖的影响高出 10 倍, 而对卵黄蛋白诱导能力也相差 100 倍以上 (Wang *et al.*, 2007), 用人羊膜上皮细胞测定也显示联苯菊脂 S 对映体比 R 对映体的毒性更大 (Liu *et al.*, 2008)。调查发现, 氟虫腈在蜜蜂采蜜的植物上的降解并没有对映体选择性 (Li *et al.*, 2010)。马拉硫磷在大白菜和油菜上的降解其 S 对映体比 R 对映体更快, 相反, R 对映体在甜菜上优先降解, 而在水稻和小麦上的降解则无这种对映体选择性 (Sun *et al.*, 2012)。研究发现, 丁烯氟虫腈 S 对映体在大白菜和菠菜上的分解更快, 而 R 对映体则在黄瓜和番茄上优先分解。这些结果提示在考察手性杀虫剂的环境毒性时应该考虑到其对映体的立体选择性 (Tian *et al.*, 2016)。水胺硫磷 (Isocarbophos) S 对映体在同等效果下用量要比其消旋体用量减少 35%, 实际使用可减少对环境的污染 (Di *et al.*, 2019)。

在杀虫剂残留所导致的环境生态风险方面, 对江苏农村地区一千多名孕妇尿液分析发现, 菊酯类杀虫剂代谢物的水平较高, 提示胎儿可能曾接触此类杀虫剂 (Qi *et al.*, 2012)。2007 年的一项全国性调查显示, 居民日常食品样品中可不同

比例检出多种有机氯杀虫剂 (Zhou *et al.*, 2012), 而在长江流域附近的城市海鲜中检测出六氯环己烷 (HCH) 和 DDT (Jin *et al.*, 2015)。另一项调查显示, 在 75% 的日常膳食样品中检出至少一种新烟碱类杀虫剂 (Li *et al.*, 2019b)。上述这些都反映出环境中杀虫剂残留的普遍性, 且对我们日常生活和身体健康构成威胁。

通过生态风险评价分析, 发现在我国东海岸某些地区, 烟碱类杀虫剂的使用已从旧类型转变为新类型 (如: 呋虫胺和烯啶虫胺); 估计每年释放到邻近海域的新烟碱类总量超过千吨, 其中大部分进入东海 (Chen *et al.*, 2019c)。调查发现, 广州珠江开发地区地表水和底泥中都有新烟碱类杀虫剂的污染 (Yi *et al.*, 2019; Zhang *et al.*, 2020b)。虽然蜂蜜中也能检出新烟碱类杀虫剂, 但其残留水平对人类健康尚不构成风险 (Wang *et al.*, 2020b)。然而, 也有研究认为, 尽管吡虫啉的日常接触量比较低, 但人群的日常接触风险不应被忽视 (Chen *et al.*, 2020)。

杀虫剂的副作用给人类的生活带来很大的负面影响。一项小样本流行病学调查显示, 婴儿出生体重降低可能与其出生前接触 DDT、灭蚁灵等杀虫剂有关 (Guo *et al.*, 2014)。研究发现, 长期接触有机磷杀虫剂氧乐果的工人其外周淋巴细胞端粒长度明显高于对照组, 且 p53、p21 表达水平明显降低, 该发现为氧乐果中毒诱发癌变的机制提供有力证据 (Duan *et al.*, 2017)。孕妇或胎儿出生前接触克百威将会对胎儿发育产生不利影响 (Zhang *et al.*, 2018)。最近的研究揭示, DDT 代谢物 DDE 影响人类健康, 导致体重和脂肪含量增加、肠道营养不良且改变血浆脂质代谢组谱, 引起脂质代谢平衡紊乱 (Han *et al.*, 2020; Liang *et al.*, 2020)。

有研究者将与多种有机磷杀虫剂累积接触后的受害特征与膳食摄入量相结合, 探讨通过膳食累积接触有机磷的风险评估方法。该研究对提升我国食品安全风险评估水平具有现实意义 (何贤松等, 2013; 赵敏娴等, 2013)。研究者通过依托于早期建立的“出生队列”研究计划, 探索孕期不同阶段接触农药的特征及其影响因素 (Ding *et al.*, 2015a; 2017), 并采用婴儿发育

量表评价宫内接触杀虫剂对儿童神经发育的影响,发现儿童的低发育商数与出生前接触多溴联苯醚有关 (Ding *et al.*, 2015b)。最近的研究显示,神经系统发育不良与儿童早期接触环境中的毒死蜱有关,但与产前接触此种杀虫剂无关 (Guo *et al.*, 2019)。此外,还有大量关于杀虫剂对健康影响的实验研究和流行病学调查的研究报道,限于篇幅,恕不详细综述。

3 总结与展望

本综述介绍了国内近 20 年在杀虫剂对靶标害虫及非靶标昆虫 (尤其是天敌昆虫) 的毒性研究以及杀虫剂的环境安全性方面的研究及进展。因篇幅限制,只介绍了一些代表性工作。总体上,近 20 年来,中国杀虫剂毒理学研究有了长足的进展,研究水平也有了相应的提高,但是,距离国际前沿尚有一定的差距,例如,很多关于杀虫剂毒性机理的研究还只是限于对表达水平发生改变的基因的筛选以及基因组分析的研究,较少涉及真正的功能基因调节在杀虫剂毒性中的机制的深入分析和探索。此外,近年来流行低剂量毒性作用研究,部分研究者感兴趣于杀虫剂的“亚致死剂量”和“亚致死效应”,但是,究竟什么是“亚致死剂量”和“亚致死效应”? 文献中并没有确切的答案。今后杀虫剂毒理学应进一步加强基础研究,深入揭示杀虫剂毒性的分子机制,为害虫防控提供科学依据。

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