棉叶螨的抗药性现状与治理策略

甄丛爱[1]　买合吐木古力·艾孜不拉[2]　张　帅[3]　李大鹏[4]　张　雷[1*]
程沈航[1]　高希武[1*]

（1. 中国农业大学植物保护学院昆虫学系，北京 100193；2. 新疆维吾尔自治区植物保护站，乌鲁木齐 830006；
3. 全国农业技术推广服务中心，北京 100026；4. 中国园林博物馆，北京 100072）

摘要：棉叶螨也称为棉红蜘蛛，属蛛形纲叶螨科，其种类繁多，分布范围广，世代周期短，是为害棉花的一类重要害螨。目前，用于防治棉叶螨的化学药剂主要是神经毒剂及呼吸抑制剂2大类，且棉叶螨对多数药剂产生了不同程度的抗性，以二斑叶螨 *Tetranychus urticae* 为首的植食性害螨已成为世界上抗药性最严重的节肢动物之一。美国路易斯安那州棉田二斑叶螨种群对阿维菌素产生了1 415倍抗性，而国内棉花上棉叶螨主要对有机磷类药剂产生了较强抗性，最高为467倍。棉叶螨产生抗药性的机制主要涉及靶标突变及解毒代谢增强，其中靶标突变主要涉及乙酰胆碱酯酶、电压门控钠离子通道和谷氨酸门控氯离子通道等；细胞色素P450单加氧酶、羧酸酯酶和谷胱甘肽 *S*-转移酶等一种或多种解毒酶共同参与害螨对化学药剂的解毒代谢。该文主要从棉叶螨的种类及分布、用于防治棉叶螨的化学药剂、棉叶螨的抗药性现状、抗药性机制解析和抗药性治理策略5个方面进行阐述，提出因地制宜的抗药性治理策略，旨在为棉叶螨的田间防治提供指导。

关键词：棉叶螨；种类；分布；化学防治；抗药性；抗药性机制；抗性治理

Current status of insecticide resistance in cotton spider mites and resistance management strategies

Zhen Congai[1]　Mahtumgul Hezbulla[2]　Zhang Shuai[3]　Li Dapeng[4]　Zhang Lei[1*]
Cheng Shenhang[1]　Gao Xiwu[1*]

（1. Department of Entomology, College of Plant Protection, China Agricultural University, Beijing 100193, China;
2. Plant Protection Station of Xinjiang Uygur Autonomous Region, Urumqi 830006, Xinjiang Uygur Autonomous Region, China; 3. National Agro-Tech Extension and Service Center, Beijing 100026, China;
4. The Museum of Chinese Garden and Landscape Architecture, Beijing 100072, China）

Abstract: The cotton spider mites, commenly called cotton red spider mites, belonging to Arachnida, Tetranychidae, are the crucial mite pests for cotton crops, with multiple species, wide distribution, and short lifecycle. Chemicals for controling the cotton spider mites mainly contained abamectin and mitochondrial electron transport inhibitors (METI). Moreover, the cotton spider mites have developed different degrees of resistance to the most commonly used insecticides. Taking the two-spotted spider mite *Tetranychus urticae* as an example, it has been one of the most devastating insecticide-resistant arthropods worldwide. The *T. urticae* population from cotton crops in Louisiana, USA developed high resistance to abamectin with the resistance ratio of 1 415, while the resistance was mainly focused on organophosphorus in China, with the highest resistance ratio of 467. The underlying mechanisms of pesticide

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* 通信作者（Authors for correspondence），E-mail：zhanglei860@sina.com，gaoxiwu@263.net.cn
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resistance in the cotton spider mites are complicated, which usually comprised of the target mutation and enhanced detoxification. The target mutation mainly existed in acetylcholinesterase (AChE), voltage-gate sodium channel (VGSC), glutamate gated chloride channel (Glucl), etc; the enhanced detoxification was caused by one or more detoxification enzyme genes, such as cytochrome P450 monooxygenases, carboxylesterases, and glutathione *S*-transferases, etc. In this paper, the species and distribution of the cotton spider mites, the insecticides used for controlling cotton spider mites, the status of resistance development, the resistance mechanisms and management strategies were reviewed. The purpose of this review is to propose some strategies for managing the pesticide resistance in the cotton spider mites.

Key words: cotton spider mites; species; distribution; chemical control; pesticide resistance; resistance mechanism; resistance management

棉叶螨又称棉红蜘蛛，属蛛形纲蜱螨目叶螨科，是为害棉花的一类重要害螨。棉叶螨种类繁多，包括朱砂叶螨 *Tetranychus cinnabarinus*、二斑叶螨 *T. urticae*、截形叶螨 *T. truncates*、神泽氏叶螨 *T. kanzawai*、土耳其斯坦叶螨 *T. turkestani* 和敦煌叶螨 *T. dunhuangensis* 等。棉叶螨食性杂，除取食棉花外，还对菜豆、玉米、大豆、苹果、向日葵和枣等作物造成损害。Wilson（1993）研究发现二斑叶螨对澳大利亚棉花造成的产量损失达20%~40%。Williams（2017）指出棉叶螨在2016年已成为美国棉花生产中的第5大害虫，对80.94万 hm^2 棉田造成的籽棉产量损失高达8 897.234 t。金德锐等（1987）研究发现单株棉叶螨数量超过20头时会对棉花产量造成显著影响。棉叶螨具有个体小、世代周期短和繁殖速度快等特点，属于易产生抗药性的害螨。但是化学防治目前依然是防治棉叶螨的主要手段（刘波和桂连友，2007；Adesanya et al.，2021）。本文将主要从棉叶螨的种类及分布、用于防治棉叶螨的化学药剂、棉叶螨的抗药性现状、抗药性机制解析和抗药性治理策略5个方面进行阐述，提出因地制宜的抗药性治理策略，旨在为棉叶螨的田间防治提供指导。

1 棉叶螨的种类及地理分布

在棉叶螨的主要种类中，二斑叶螨在世界各地棉区均有发生，而其他棉叶螨仅在某一个或几个国家或地区发生。不同地区发生的棉叶螨种类不同，同一地区发生的棉叶螨优势种也会随着外界环境的变化而变化（表1）。

表1 棉叶螨的种类及其地理分布

Table 1 The species and distribution of the cotton spider mites

种名 Species	地理分布 Distribution	参考文献 Reference
朱砂叶螨 *T. cinnabarinus*	中国：新疆维吾尔自治区（简称新疆）奎屯市、昌吉市和玛河流域，安徽省萧县和宿松县，江苏省南京市和盐城市，山东省德州市和聊城市，河北省邱县和邯郸市，四川省阆中市 China: Kuytun, Changji cities, and Manasi Revier region in Xinjiang Uygur Autonomous Region (Xinjiang); Xiao and Susong counties in Anhui Province; Nanjing and Yancheng cities in Jiangsu Province; Dezhou and Liaocheng cities in Shandong Province; Qiu County and Handan City in Hebei Province; Langzhong City in Sichuan Province	鲁素玲和丁胜利，1989；赵瑞升和任成保，2001；束春娥等，2002；陈建军，2004；李泽善等，2004；马晓牧等，2005；张明辉，2006；张新才，2006；哈尼马提等，2010；马广民等，2010；姚彦如，2016 Lu & Ding, 1989; Zhao & Ren, 2001; Shu et al., 2002; Chen, 2004; Li et al., 2004; Ma et al., 2005; Zhang MH, 2006; Zhang XC, 2006; Hanimati et al., 2010; Ma et al., 2010; Yao, 2016
二斑叶螨 *T. urticae*	中国：新疆昌吉市、安徽省宿松县、湖北省荆州市、山东省德州市和四川省阆中市 China: Changji City in Xinjiang, Susong County in Anhui Province, Jingzhou City in Hubei Province, Dezhou City in Shandong Province, Langzhong City in Sichuan Province	魏岑等，1985；李泽善等，2004；张明辉，2006；哈尼马提等，2010；姚彦如，2016 Wei et al., 1985; Li et al., 2004; Zhang MH, 2006; Hanimati et al., 2010; Yao, 2016
	美国：中南部和加利福尼亚州 USA: mid-southern and California	Grafton-Cardwell et al., 1991; Keena et al., 1991; Scott et al., 2013; Martin & Latheef, 2018
	澳大利亚：新南威尔士州、昆士兰州中部南至新南威尔士州与维多利亚州边界线 Australia: New South Wales, Central Queensland south to the New South Wales/Victorian border	Wilson, 1993; Wilson & Morton, 1993; Herron et al., 1998; 2021; Wilson et al., 2018

续表1 Continued

种名 Species	地理分布 Distribution	参考文献 Reference
	土耳其：阿达纳、安塔利亚、伊兹密尔、马尼萨及乌尔法 Turkey: Adana, Antalya, Izmir, Manisa and Urfa	Ay & Gürkan, 2005
	巴西：东南部地区 Brazil: southeast region	Mendonça et al., 2011
敦煌叶螨 *T. dunhuangensis*	中国：新疆南部、甘肃省河西走廊 China: southern Xinjiang, Hexi Corridor of Gansu Province	庄生仁等，2009；Li et al.，2018 Zhuang et al., 2009; Li et al., 2018
截形叶螨 *T. truncates*	中国：新疆南部、奎屯市和昌吉市，甘肃省河西走廊，山东省德州市，河北省邯郸市 China: southern region, Kuytun and Changji cities in Xinjiang; Hexi Corridor of Gansu Province; Dezhou City in Shandong Province; Handan City in Hebei Province	陈建军，2004；马晓牧等，2005；张明辉，2006；庄生仁等，2009；哈尼马提等，2010；Li et al.，2018 Chen, 2004; Ma et al., 2005; Zhang MH, 2006; Zhuang et al., 2009; Hanimati et al., 2010; Li et al., 2018
土耳其斯坦叶螨 *T. turkestani*	中国：新疆奎屯市、昌吉市和玛河流域 China: Kuytun, Changji cities and Manasi revier region	鲁素玲和丁胜利，1989；陈建军，2004；哈尼马提等，2010 Lu & Ding, 1989; Chen, 2004; Hanimati et al., 2010
	美国：加利福尼亚州圣华金河谷 USA: San Joaquin Valley of California	Grafton-Cardwell et al., 1991
	塔吉克斯坦：首都附属区、哈特隆州和索格特州 Tajikistan: Capital affiliated area, Khanlon and Sogd States	王明全，2016 Wang, 2016
太平洋叶螨 *T. pacificus*	美国：加利福尼亚州 USA: California	Grafton-Cardwell et al., 1991; Keena et al., 1991
卢氏叶螨 *T. ludeni*	澳大利亚：悉尼 Australia: Sydney	Herron et al., 1998
	巴西：东南部地区 Brazil: southeast region	Mendonça et al., 2011
兰姆叶螨 *T. lambi*	澳大利亚：新南威尔士州、昆士兰州 Australia: New South Wales, Queensland	Herron et al., 2021
墨西哥叶螨 *T. mexicanus*	巴西：东南部地区 Brazil: southeast region	Mendonça et al., 2011
单爪螨 *M. planki*	巴西：东南部地区 Brazil: southeast region	Mendonça et al., 2011
巴士托叶螨 *T. bastosi*	巴西：东南部地区 Brazil: southeast region	Mendonça et al., 2011

1.1 国外棉叶螨的种类及地理分布

Herron et al.（1998）指出20世纪70年代，二斑叶螨和卢氏叶螨 *T. ludeni* 在澳大利亚棉田普遍发生，到80年代二斑叶螨取代卢氏叶螨成为优势种。Herron et al.（2021）于2016—2018年调查发现兰姆叶螨 *T. lambi* 已经成为澳大利亚棉田的优势叶螨种。Wilson et al.（2018）指出为害澳大利亚棉花的螨类包括二斑叶螨、卢氏叶螨、兰姆叶螨、麦圆叶爪螨 *Penthaleus major*、红足海蠊螯螨 *Halotydeus destructor* 和麦岩螨 *Petrobia lateens*，其中二斑叶螨是最主要的害螨。顾世民等（2015）调查发现塔吉克斯坦棉田发生的叶螨是二斑叶螨复合种；而王明全（2016）则报道塔吉克斯坦棉田发生的叶螨以土耳其斯坦叶螨为主。土耳其棉花生产区分为地中海棉区、爱琴海棉区及安纳托利亚东南部棉区，朱砂叶螨是地中海棉区的优势种；而二斑叶螨是爱琴海棉区及安纳托利亚东南部棉区的优势种（Yarpuz-Bozdogan，2016）。二斑叶螨在土耳其的阿达纳、安塔利亚、伊兹密尔、马尼萨及乌尔法棉区均有发生（Ay & Gürkan，2005）。巴西棉田中常见的害螨包括二斑叶螨、卢氏叶螨、墨西哥叶螨 *T. mexicanus*、单爪螨 *Mononychellus planki* 和巴士托叶螨 *T. bastosi*（Mendonça et al.，2011）。

1.2 国内棉叶螨的种类及地理分布

我国棉区主要分为长江流域棉区、黄河流域棉区及以新疆维吾尔自治区（简称新疆）为主的西北内陆棉区，并且近年来西北内陆棉区规模呈扩大趋势（陆宴辉，2021）。王慧芙（1979）通过鉴定雄成螨的外生殖器发现朱砂叶螨主要分布于江西、湖南、湖北、安徽、上海和四川6个省市，在北京市及黄河流域如河南省新野县和陕西省大荔县也有分布；截形叶螨主要分布在北京、河北、河南及江苏等省市；土

耳其斯坦叶螨仅在新疆玛纳斯棉田被发现。曹煜(1988)于1986—1987年调查发现河南省新乡县棉区棉叶螨主要为朱砂叶螨和截形叶螨,且不同年份或月份发生的优势种也会有所变化。鲁素玲和丁胜利(1989)于1986—1988年对新疆玛河流域棉田叶螨进行调查,发现该棉区有土耳其斯坦叶螨和朱砂叶螨2种害螨,前者为优势种。程立生(1998)在1998年通过田间调查发现土耳其斯坦叶螨和敦煌叶螨仅分布于西北内陆棉区;二斑叶螨在北京市和甘肃省天水市等局部地区为害花卉和果树作物,但在棉田尚未发现;在黄河流域棉区和长江流域棉区则以神泽氏叶螨和截形叶螨与朱砂叶螨混合发生为主。Li et al.(2018)研究发现新疆阿克苏等地区由于农林作物种植模式的改变(果棉间作等模式代替单一棉田种植)导致截形叶螨近年来的发生呈加重趋势。Jin et al.(2019)根据2013—2017年的野外调查结果发现我国目前为害棉花的叶螨主要包括神泽氏叶螨、截形叶螨、二斑叶螨、卢氏叶螨、皮氏叶螨 *T. piercei* 和红叶螨 *T. pueraricola*;且叶螨在我国的发生格局基本是北方地区以截形叶螨为主,而长江中下游地区以神泽氏叶螨为主,红叶螨则是西南地区的重要种。

2 用于防治棉叶螨的化学药剂

根据2013年全球农药市场销售额,杀螨剂销售额占杀虫剂总销售额的7%(van Leeuwen et al.,2015),而实际用于防治螨类的药剂占比远高于此,因为许多广谱杀虫剂也可用于防治害螨。杀螨剂销售额中用于防治叶螨 *Tetranychus* spp.(二斑叶螨为主)的比例高达62%;按作物分类的话,用于果树及蔬菜的杀螨剂销售额占杀螨剂总销售额的74.0%,其次是用于玉米和棉花的杀螨剂,占比分别是7.6%及6.7%(van Leeuwen et al.,2015)。Sparks et al.(2020)根据Agranova(http://www.a2os.com/)提供的2018年杀螨剂销售额数据,分析发现全球杀螨剂市场主要由6类杀螨剂主导,分别是谷氨酸门控氯离子通道(glutamate gated chloride channel,GluCl)变构调节剂(如阿维菌素)、乙酰辅酶A羧化酶抑制剂(如螺螨酯)、线粒体三磷酸腺苷合成酶抑制剂(如炔螨特)、线粒体电子传递复合体I(mitochondrial electron transport complex I,MET I)抑制剂(如哒螨灵)、线粒体电子传递复合体III(MET III)抑制剂(如联苯肼酯)和线粒体电子传递复合体II(MET II)抑制剂(如丁氟螨酯),占比分别为40.6%、19.9%、13.8%、10.0%、9.5%和6.0%。目前,化学药剂仍然是防治棉叶螨的有效手段。Attia et al.(2013)总结了杀螨剂的类型、作用方式、次级化学结构及害螨对杀螨剂产生的抗药性现状。

国际组织农药抗药性行动委员会(Insecticide Resistance Action Committee,IRAC)在2021年根据作用方式将杀螨剂分为4大类,分别是针对神经和肌肉靶标、呼吸系统靶标、生长和发育靶标及作用机理未知的杀螨剂。针对神经和肌肉靶标的杀螨剂涵盖9大类10小类,如氨基甲酸酯类、有机磷类、环戊二烯类、有机氯类、除虫菊素、拟除虫菊酯类、多杀菌素、阿维菌素、弥拜菌素、双甲脒、谷氨酰胺合成酶-omega/kappa HXTX-HV1a肽、异噁唑啉类以及Acynonapyr。针对呼吸系统靶标的杀螨剂囊括6大类11小类,如丁醚脲、杀螨隆、有机锡杀螨剂、丙炔螨特(克螨特)、虫螨腈、灭螨醌、嘧螨酯、联苯肼酯、腈吡螨酯、丁氟螨酯及吡唑酰苯胺。针对生长和发育靶标的杀螨剂分为3大类4小类,如四螨嗪、氟螨嗪、噻螨酮、乙螨唑、苯甲酰脲类、季酮酸及其衍生物(螺螨酯和螺甲螨酯)。作用机理未知的杀螨剂包括苯螨特、灭螨猛和三氯杀螨醇(http://www.irac-online.org)。除上述化学杀螨剂外,矿物油也可用于防治害螨,主要机理是阻塞害螨气孔使其缺氧窒息死亡。Urbaneja et al.(2008)发现2种矿物油可用于西班牙橘园中二斑叶螨的防治,效果与吡螨胺、四螨嗪和喹螨醚相当。Chueca et al.(2010)证实4种矿物油产品均可用于防治西班牙沙柑果园中的二斑叶螨,尤以Texaco D-C-Tron Plus效果最好。本文在中国农药信息网查询了登记用于防治棉田叶螨的化学药剂,对处于登记有效期内的主要化学药剂进行总结(表2)。

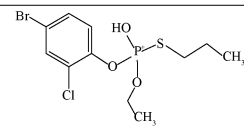
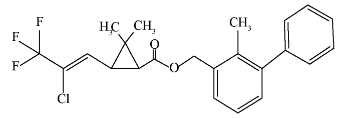
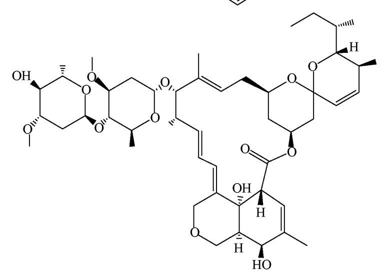
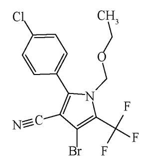
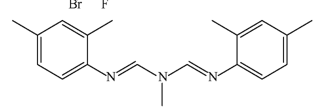
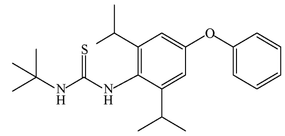
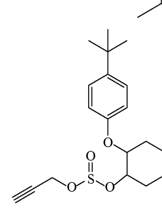
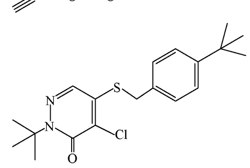
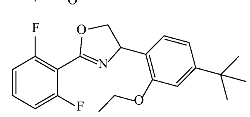
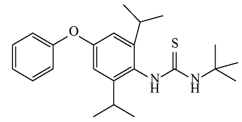
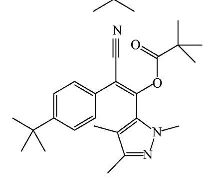
3 棉叶螨的抗药性现状

棉叶螨世代周期短,繁殖力极强,且拥有单双倍体生殖方式,这些特点使其易对化学药剂快速产生抗性。二斑叶螨已对96种杀虫/螨剂产生了抗性(van Leeuwen et al.,2010;Sparks & Nauen,2015;Adesanya et al.,2020;Sparks et al.,2020)。van Leeuwen et al.(2009)在综述中曾对二斑叶螨抗药性进行总结,报道了40个国家的二斑叶螨种群已对超过30种有机磷类及氨基甲酸酯类药剂产生抗性;并且根据抗药性数据得出二斑叶螨种群中对乙酰胆碱酯酶抑制剂、线粒体电子传递抑制剂、阿维菌素、拟除虫菊酯类及其他类药剂产生抗性的比例分别为

31%、25%、12%、7%及24%。基于此，本文对棉花上 棉叶螨的抗药性现状进行了整理和总结(表3)。

表2 防治棉叶螨的主要化学药剂

Table 2 A list of major chemicals for the cotton spider mites control

作用方式 Mode of action	类型 Chemical family	杀螨剂名称 Chemical name	结构式 Structure
乙酰胆碱酯酶抑制剂 AChE inhibitor	有机磷类 Organophosphate	丙溴磷 Profenofos	
钠离子通道调节剂 Sodium channel modulator	拟除虫菊酯类 Pyrethroids	联苯菊酯 Bifenthrin	
谷氨酸门控氯离子通道变构调节剂 Glutamate gated chloride channel allosteric modulator	阿维菌素类 Avermectins	阿维菌素 Abamectin	
干扰质子梯度影响氧化磷酸化的解偶联剂 Uncouplers of oxidative phosphorylation via disruption of the proton gradient	吡咯类 Pyrrole	虫螨腈(溴虫腈) Chlorfenapyr	
章鱼胺受体激动剂 Octopamine receptor agonist	三氮杂戊二烯 Triazapentadiene	双甲脒 Amitraz	
线粒体三磷酸腺苷合成酶抑制剂 Inhibitor of mitochondrial ATP synthase	硫脲类 Thiourea	丁醚脲 Diafenthiuron	
	亚硫酸酯类 Sulfite ester	炔螨特 Propargite	
线粒体电子传递复合体I抑制剂 Mitochondrial electron transport complex I inhibitor	哒嗪酮类 Pyridazinone	哒螨灵 Pyridaben	
线粒体电子传递复合体II抑制剂 Mitochondrial electron transport complex II inhibitor	吡唑基丙烯腈类衍生物 Pyrazolyl acrylonitrile derivatives	乙唑螨腈 Cyetpyrafen	
	苯甲酰乙腈类 Benzoylacetonitile	丁氟螨酯 Cyflumetofen	
	丙烯腈类 Acrylonitrile	腈吡螨酯 Cyenopyrafen	

续表2 Continued

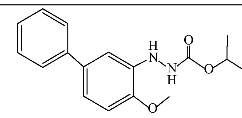
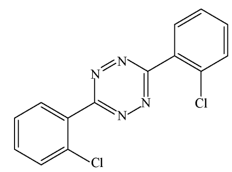
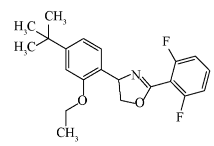
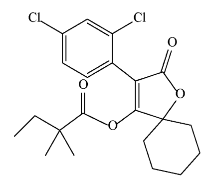
作用方式 Mode of action	类型 Chemical family	杀螨剂名称 Chemical name	结构式 Structure
线粒体电子传递复合体III抑制剂Qo位点 Mitochondrial electron transport complex III inhibitor Qo site	联苯肼类 Bifenazate	联苯肼酯 Bifenazate	
影响几丁质合成酶1的螨虫生长抑制剂 Mite growth inhibitor affecting chitin synthase 1	四嗪类 Tetrazine	四螨嗪 Clofentezine	
	二苯基噁唑衍生物 Diphenyloxazole	乙螨唑 Etoxazole	
乙酰辅酶A羧化酶抑制剂 Inhibitors of acetyl CoA carboxylase	季酮酸及其衍生物 Tetronic and tetramic acid derivatives	螺螨酯 Spirodiclofen	
作用机理未知或未确定 Unkown compounds	多硫化钙 Sulfurs	石硫合剂 Lime sulfur	S, CaS_X

表3 棉花上棉叶螨对化学药剂的抗性水平

Table 3 The chemical resistance level of the cotton spider mites on cotton

年份 Year	药剂 Chemical	地区 Location	物种 Species	抗性水平 Resistance level	参考文献 Reference
1962	内吸磷 Demeton	中国湖北省仙桃市(沔阳县) Xiantao City (Mianyang County), Hubei Province, China	突叶螨 *T. tumidus*	中等 Medium	张泽溥和王少成,1964 Zhang & Wang, 1964
1976—1995	砜吸磷、乐果、对硫磷、丙溴磷、久效磷 Demeton-*S*-methyl sulfone, dimethoate, parathion, profenofos, monocrotophos	澳大利亚坎珀当、沃尔维奇 Camperdown, Woolwich, Australia	二斑叶螨 *T. urticae* 卢氏叶螨 *T. ludeni*	中等至高等 Medium to high 低等至高等 Low to high	Herron et al., 1998
1987	三氯杀螨醇 Dicofol	中国河南省新乡县、虞城县、南阳县、太康县 Xinxiang, Yucheng, Nanyang, Taikang counties in Henan Province, China	朱砂叶螨 *T. cinnabarinus*	敏感至低等 Sensitive to low	吴孔明等,1989;1990 Wu et al., 1989; 1990
	氧化乐果 Omethoate	中国河南省虞城县 Yucheng County, Henan Province, China	朱砂叶螨 *T. cinnabarinus*	敏感 Sensitive	吴孔明等,1989;1990 Wu et al., 1989; 1990
	对硫磷 Parathion	中国河南省新乡县 Xinxiang County, Henan Province, China	朱砂叶螨 *T. cinnabarinus*	高等 High	吴孔明等,1989;1990 Wu et al., 1989; 1990
	氧化乐果 Omethoate	中国河南省新乡县 Xinxiang County, Henan Province, China	突叶螨 *T. tumidus*	敏感性降低 Sensitive reduced	吕印谱,1990 Lü, 1990
	甲氰菊酯 Fenpropathrin	中国河南省新乡县 Xinxiang County, Henan Province, China	突叶螨 *T. tumidus*	中等 Medium	吕印谱,1990 Lü, 1990
	久效磷、磷胺、1605 Monocrotophos, phosphamidon, 1605	中国河南省新乡县 Xinxiang County, Henan Province, China	突叶螨 *T. tumidus*	中等至高等 Medium to high	吕印谱,1990 Lü, 1990

续表3 Continued

年份 Year	药剂 Chemical	地区 Location	物种 Species	抗性水平 Resistance level	参考文献 Reference
1989	三氯杀螨醇、克螨特 Dicofol, propargite	澳大利亚新南威尔士州 New South Wales, Australia	二斑叶螨 *T. urticae*	敏感 Sensitive	Wilson et al., 1995
1992	三氯杀螨醇、久效磷 Dicofol, monocrotophos	中国河北省正定县、武安市 Zhengding County, Wu'an City, Hebei Province, China	突叶螨 *T. tumidus*	敏感至敏感性降低 Sensitive to sensitive reduced	曹煜和刘明丽，1993 Cao & Liu, 1993
1994	乐果 Dimethoate	澳大利亚新南威尔士州 New South Wales, Australia	二斑叶螨 *T. urticae*	高等 High	Wilson et al., 1999
	硫丹 Endosulfan	澳大利亚新南威尔士州 New South Wales, Australia	二斑叶螨 *T. urticae*	敏感 Sensitive	Wilson et al., 1999
1996	三氯杀螨醇 Dicofol	土耳其安塔利亚 Antalya, Turkey	朱砂叶螨 *T. cinnabarinus*	敏感至中等 Sensitive to medium	Dagli & Tunc, 2001
1998	联苯菊酯 Bifenthrin	土耳其阿达纳 Adana, Turkey	二斑叶螨 *T. urticae*	敏感性降低至高等 Sensitive reduced to high	Ay & Gürkan, 2005
1999	联苯菊酯 Bifenthrin	土耳其乌尔法 Urfa, Turkey	二斑叶螨 *T. urticae*	高等 High	Ay & Gürkan, 2005
1999—2000	联苯菊酯 Bifenthrin	澳大利亚新南威尔士州的麦夸里、纳莫伊、克莱尔谷 Macquarie, Namoi and Gwydir Valleys of New South Wales, Australia	二斑叶螨 *T. urticae*	敏感至高等 Sensitive to high	Herron et al., 2001
1997—2003	溴虫腈 Chlorfenapyr	澳大利亚新南威尔士州、昆士兰州 New South Wales, Queensland, Australia	二斑叶螨 *T. urticae*	敏感至中等 Sensitive to medium	Herron et al., 2004
2010—2014	螺螨酯 Spirodiclofen	巴西戈亚斯、玛多克罗索省 States of Goias, Mato Grosso, Brazil	二斑叶螨 *T. urticae*	敏感 Sensitive	Sato et al., 2016
2010—2012	哒螨灵、阿维菌素、甲胺基阿维菌素、炔螨特、螺螨酯 Pyridaben, abamectin, emamectin benzoate, propargite, spirodiclofen	中国湖北省荆州市、襄阳市、嘉鱼市 Jingzhou, Xiangyang, Jiayu cities, Hubei Province, China	朱砂叶螨 *T. cinnabarinus*	敏感至敏感性降低 Sensitive to sensitive reduced	朱秀等，2015 Zhu et al., 2015
2013—2015	阿维菌素 Abamectin	美国路易斯安那州、密西西比州、阿肯色州、田纳西州 Louisiana, Mississippi, Arkansas, Tennessee, USA	二斑叶螨 *T. urticae*	中等至高等 Medium to high	Brown et al., 2017

抗性水平分级依据NY/T2058—2014分级标准划分，抗性倍数≤3为敏感；3<抗性倍数≤5为敏感性降低；5<抗性倍数≤10为低等水平抗性；10<抗性倍数≤100为中等水平抗性；抗性倍数>100为高等水平抗性。Resistance level grade is divided by NY/T2058—2014 based on resistance ratio (R). $R \leq 3$ indicates sensitive; $3<R\leq 5$ indicates sensitive reduced; $5<R\leq 10$ indicates low resistance; $10<R\leq 100$ indicates medium resistance; $R>100$ indicates high resistance.

3.1 国外棉叶螨的抗药性现状

Andres & Prout（1960）对1956年采自美国加利福尼亚州圣华金谷棉田的太平洋叶螨 *T. pacificus* 种群进行测定，发现该种群已对对硫磷产生抗性。1969年，埃及棉田中红色型和绿色型二斑叶螨复合种群对三氯杀螨醇产生了抗性，其中红色型产生的抗性属于区域发生，绿色型产生的抗性则属于点发生（Ghobrial et al.，1969）。1988年，来自美国加利福尼亚州同一棉田的太平洋叶螨种群及二斑叶螨种群，噻螨酮对前者的毒力明显低于对后者的毒力；来自加利福尼亚州不同棉田的5个二斑叶螨种群对噻螨酮的敏感性相差不大，而来自3个不同棉田的太平洋叶螨种群对噻螨酮的敏感性相差10倍以上（Keena et at.，1991）。2013—2015年采自美国中南部棉区路易斯安那州、密西西比州、阿肯色州和田纳西州棉田的12个二斑叶螨种群均对阿维菌素产生不同水平的抗性，抗性倍数为11~1 415倍，其中路易斯安那州种群对阿维菌素的抗性最强（Brown et al.，2017）。

Herron et al.（1998）对1976—1995年近20年的

监测数据进行分析，发现澳大利亚棉田二斑叶螨和卢氏叶螨对所有测试的有机磷杀虫剂（砜吸磷、乐果、对硫磷、丙溴磷、久效磷）均产生了抗性，其中二斑叶螨的抗性倍数在15~750倍之间，卢氏叶螨的抗性倍数高达375倍。Wilson et al.（1995）在1989年对新南威尔士州若干棉田二斑叶螨种群进行三氯杀螨醇及克螨特的抗性监测，结果表明该地区棉田种群对这2种药剂尚未产生抗性。Wilson et al.（1999）研究结果显示，于1994年采自新南威尔士州棉田的二斑叶螨混合种群对乐果产生了1 364倍的抗性，而对硫丹则尚未产生抗性。1993—1994年联苯菊酯在澳大利亚登记用于防治棉田鳞翅目夜蛾科害虫及二斑叶螨，1996—1997年二斑叶螨对联苯菊酯开始产生抗性，到1999—2000年在35个棉田二斑叶螨种群中对联苯菊酯产生抗性的个体比例介于20%~90%之间，抗性倍数最高达109倍（Herron et al.，2001）。Herron et al.（2004）监测结果显示1997—2003年采自澳大利亚棉田的二斑叶螨种群对溴虫腈（虫螨腈）的抗性倍数为9倍。Herron et al.（2021）通过诊断计量法发现澳大利亚棉田二斑叶螨种群在2007年之前对阿维菌素未产生抗性，2007—2008年仅有1个种群对该药剂产生抗性，且抗性个体的比例为6%，2010—2019年对阿维菌素的抗性每年都在持续增加，且2018—2019年有高达80%的田间种群产生抗性，但尚未发现该害螨对丁醚脲产生抗性；2015—2016年对克螨特产生抗性的种群比例为33%；兰姆叶螨尚未对阿维菌素、丁醚脲和克螨特产生抗性。

Dagli & Tunc（2001）于1996年采用不同的生测方法测定了土耳其安塔利亚朱砂叶螨种群对三氯杀螨醇的抗性水平，不同生测方法的测定结果有所不同，其中经浸渍法测定的抗性倍数最高为26倍，经叶片残留法测定的抗性倍数最大为58倍，且朱砂叶螨温室蔬菜种群的抗药性高于棉田种群。1998年采自土耳其阿达纳和1999年采自乌尔法棉田的二斑叶螨种群对联苯菊酯的抗性最高分别为564倍和669倍（Ay & Gürkan，2005）。

Sato et al.（2016）采用诊断计量法对采自巴西戈亚斯、玛多克罗索及圣保罗的棉花、豆类、草莓、菊花及玫瑰作物上23个二斑叶螨田间种群进行抗药性监测，发现采自圣保罗地区草莓、菊花及玫瑰上的种群的抗性频率较高。

Xue et al.（2020）对2017—2018年采自欧洲9个国家30个地区的32个二斑叶螨种群进行抗药性监测，发现有10个种群（4个种群来自意大利，3个种群来自英国，2个种群来自西班牙，1个种群来自比利时）对阿维菌素产生了30~1 600倍的抗性；有9个种群对弥拜菌素产生了12~204倍的抗性。Xue et al.（2021a）发现只含I321T突变位点的4个二斑叶螨种群对阿维菌素的抗性倍数在47~104倍之间；含I321T、V327G和L329F这3个点突变位点的种群对阿维菌素的抗性倍数则高达328倍。Xue et al.（2021b）证实2016—2018年采自欧洲且只含细胞色素b点突变G126S的9个二斑叶螨种群对联苯肼酯处于敏感水平。

3.2 国内棉叶螨的抗药性现状

张泽溥和王少成（1964）于1962年检测出湖北省沔阳县（现为仙桃市）棉叶螨对内吸磷的抗性倍数为62倍。吴孔明等（1989；1990）在1987年发现河南省新乡县棉区朱砂叶螨种群对对硫磷的抗性倍数为467倍。吕印谱（1990）于1987年监测到河南省新乡县棉叶螨种群对久效磷、磷胺、1605的抗性倍数分别为20倍、42倍和467倍；新乡县大块乡和获嘉县中和乡种群对甲氰菊酯的抗性倍数分别为10倍和20倍。曹煜等（1993）监测发现河南省新乡县七里营乡朱砂叶螨和截形叶螨种群对三氯杀螨醇和久效磷表现出抗性，抗性倍数为2~9倍，对氧化乐果仍处于敏感水平；而宁夏回族自治区的朱砂叶螨和截形叶螨种群对3种药剂均处于敏感水平。曹煜和刘明丽（1993）在1992年发现河北省正定县棉叶螨种群对三氯杀螨醇和久效磷的抗性倍数为3倍，而武安市种群对这2种药剂的抗性倍数分别是5倍和6倍，此外，这2个种群对氧化乐果仍处于敏感阶段。刘庆娟等（2012）利用玻片浸渍法测定了二斑叶螨对甲氰菊酯和哒螨灵的敏感性，结果表明由中国农业科学院郑州果树研究所提供的二斑叶螨种群对甲氰菊酯和哒螨灵的抗性倍数分别为5倍和105倍。朱秀等（2015）于2010—2012年连续3年对湖北省荆州市、襄阳市及嘉鱼市棉区的朱砂叶螨种群进行抗药性监测，发现与2010年的毒力测定结果相比，这3个种群在2011—2012年对哒螨灵、甲氨基阿维菌素苯甲酸盐、炔螨特及螺螨酯的敏感性降低。

3.3 棉叶螨对杀螨剂的交互抗性

吴孔明等（1989）发现河南省新乡县朱砂叶螨种群为对硫磷高抗品系，对复方水胺硫磷、久效磷和马拉硫磷均产生一定的交互抗性，抗性倍数为16~42倍。Rauch & Nauen（2002）通过交互抗性试验发现抗毒死蜱、哒螨灵、唑螨酯、吡螨胺、噻螨酮、四螨嗪和三

氯杀螨醇的二斑叶螨种群均对螺螨酯表现为敏感，阿维菌素抗性种群对螺螨酯的交互抗性仅为3倍左右，说明螺螨酯不易与其他药剂产生交互抗性。van Leeuwen et al.（2009）总结了1989—2009年近20年二斑叶螨对不同类型杀螨剂产生交互抗性的事例，证实联苯肼酯抗性种群对灭螨醌产生了交互抗性；螺螨酯抗性种群对螺甲螨酯产生了交互抗性。高新菊等（2010）发现抗甲氰菊酯二斑叶螨种群（抗性倍数为247倍）对三氯氟氰菊酯、苦皮藤生物碱、三唑锡及四螨嗪的交互抗性分别为20倍、19倍、9倍和5倍。张志刚等（2011）通过交互抗性测定发现对螺螨酯抗性倍数为59倍的二斑叶螨品系对甲氰菊酯产生了12倍的交互抗性。Khalighi et al.（2014）发现二斑叶螨田间种群对丁氟螨酯和腈吡螨酯存在交互抗性。Khalighi et al.（2016）证实二斑叶螨抗腈吡螨酯品系对丁氟螨酯及哒螨灵产生了交互抗性。Monteiro et al.（2015）报道尚未发现阿维菌素与联苯菊酯产生交互抗性。Ferreira et al.（2015）发现来自巴西博尼图及布雷让2个地区的高抗阿维菌素二斑叶螨种群对杀螨隆、弥拜菌素、唑螨酯、虫螨腈、螺螨酯、苯丁锡及克螨特产生了明显的交互抗性。Feng et al.（2018）发现朱砂叶螨抗丁氟螨酯品系对哒螨灵产生了64倍的交互抗性，但与阿维菌素、甲氰菊酯、克螨特和联苯肼酯尚未产生交互抗性。Adesanya et al.（2018）发现抗四螨嗪二斑叶螨种群（抗性倍数为133倍）对噻螨酮产生了272倍的交互抗性；抗乙螨唑二斑叶螨种群（抗性倍数为13倍）对四螨嗪产生了82倍的交互抗性；抗噻螨酮二斑叶螨种群（抗性倍数为268倍）对四螨嗪产生了65倍的交互抗性。Chen et al.（2019）发现腈吡螨酯与乙唑螨腈两者之间存在明显的交互抗性。Sugimoto et al.（2020）发现对丁氟螨酯抗性倍数为8 528倍的二斑叶螨品系对腈吡螨酯产生了5 882倍以上的交互抗性；对腈吡螨酯抗性倍数大于5 882倍的二斑叶螨品系对丁氟螨酯产生了5 435倍以上的交互抗性。

4 棉叶螨的抗药性机制

棉叶螨对杀虫（螨）剂产生抗性的机理包括4个方面，一是靶标突变导致的靶标抗性；二是解毒酶如羧酸酯酶（carboxylesterase，CarE）、细胞色素P450单加氧酶（cytochrome P450 monooxygenase，P450）和谷胱甘肽*S*-转移酶（glutathione S-transferase，GST）等介导的代谢抗性；三是害螨的生理改变，如表皮渗透性下降或增加农药的隔离；四是行为变化。棉叶螨种群对某种药剂产生抗性的过程有时是由一种机制起主要作用，但大部分是2种机制共同发挥作用。本文主要就前2种抗性机制进行综述。

4.1 靶标抗性

杀螨剂的作用类型主要分为3类，一是神经毒剂，如有机磷类和氨基甲酸酯类的靶标是乙酰胆碱酯酶（acetylcholinesterase，AChE）；拟除虫菊酯类和DDT的靶标是电压门控钠离子通道（voltage-gate sodium channel，VGSC）；阿维菌素类的靶标是GluCl；二是线粒体电子传递抑制剂，如哒螨灵、丁氟螨酯和联苯肼酯；三是螨生长抑制剂，如乙螨唑和四螨嗪，其靶标是几丁质合成酶1（chitin synthase 1，CHS1）。靶标抗性是指靶标位点突变致使靶标敏感度降低，与杀虫剂的结合能力下降。Adesanya et al.（2021）对二斑叶螨产生的靶标抗性种类、抗性及基因突变发生的时间轴及点突变在全球的分布情况进行了系统总结。本文在此基础上将棉叶螨发生的靶标抗性机制进行梳理分析（表4）。

Xu et al.（2021）证实朱砂叶螨的*γ*-氨基丁酸（*γ*-aminobutyric acid，GABA）受体的一个亚基RDL2是阿维菌素的作用靶标，且GABA积聚是其对阿维菌素产生抗性的原因。关于靶标突变对抗药性的贡献也有例外，如Xue et al.（2021b）通过点突变检测及毒力测定发现只含有G126S点突变的二斑叶螨种群未对联苯肼酯产生抗性，表明G126S点突变与二斑叶螨对联苯肼酯的抗性无关。

4.2 代谢抗性

除靶标抗性外，代谢抗性机制在抗药性发生发展中也发挥着相当重要的作用。害虫/螨抗药性是否与解毒酶代谢有关通常是通过酶活性及增效剂试验进行初步确定。外源物质在生物体内的解毒代谢可由I相、II相甚至III相代谢酶来参与，I相主要是由P450和CarE介导的有毒物质的直接分解，II相是GST等介导的外源有毒物质的溶解增强，III相是由ABC转运蛋白等催化外源有毒物质排出体外（Feyereisen et al.，2015）。棉叶螨对各类杀螨剂产生抗性的代谢机制主要是一种或多种解毒酶活性升高。作为基因组已知的二斑叶螨，其解毒代谢相关基因家族存在特异扩张，如P450家族中CYP2分支，CarE家族的2个新分支J’和J’’，GST家族中delta-class和mu-class分支及数量庞大的ABC转运蛋白基因（杨静等，2022）。解毒代谢抗性的研究主要集中在传统意义上的3大解毒酶，即P450、CarE和GST。近年来随着研究的不断深入，尿苷二磷酸–葡

葡糖醛酸转移酶、ABC转运蛋白和内环裂解双加氧酶等解毒酶也被证实与叶螨的抗药性有关。

表4 棉叶螨对各种类型杀螨剂的靶标抗性机制

Table 4 Target mutations associated with acaricide resistance in the cotton spider mites

分子靶标 Target gene	种名 Species	药剂 Chemical	突变 Mutation	参考文献 Reference
乙酰胆碱酯酶 Acetylcholinesterase	二斑叶螨 *T. urticae*	久效磷 Monocrotophos	F439W和G228S(主要作用) F439W and G228S (main role)	Kwon et al., 2010a
		毒死蜱、灭多威、乐果 Chlorpyrifos, methomyl, dimethoate	F331W/Y, T280A, G328A, A201S	Khajehali et al., 2010; İnak, 2022
	神泽氏叶螨 *T. kanzawai*	杀扑磷 Methidathion	F331W	Aiki et al., 2005
电压门控钠离子通道 Voltage-gate sodium channel	二斑叶螨 *T. urticae*	联苯菊酯、甲氰菊酯、三氯杀螨醇、fluvinate、DDT Bifenthrin, fenpropathrin, dicofol, fluvinate, DDT	M918T, T929I, L932F, L1024V, A1215D, F1528L, F1538I, L1595P, L1024V	Tsagkarakou et al., 2009; Piraneo et al., 2015; van Leeuwen et al., 2015; Riga et al., 2017; Xu et al., 2018
	朱砂叶螨 *T. cinnabarinus*	甲氰菊酯 Fenpropathrin	F1538I	Feng et al., 2011a; Xu et al., 2013
谷氨酸门控氯离子通道 Glutamate gated chloride channel (GluCl)	二斑叶螨 *T. urticae*	阿维菌素 Abamectin	位于GluCl1上的G314D和位于GluCl3上的G326E G314D in GluCl1 and G326E in GluCl3	Kwon et al., 2010b; Mermans et al., 2017
		阿维菌素、弥拜菌素 Abamectin, milbemycin	G314D, G326E, I321T, L329F	Xu et al., 2018
几丁质合成酶1 Chitin synthase 1	二斑叶螨 *T. urticae*	乙螨唑、四螨嗪、噻螨酮 Etoxazole, clofentezine, hexythiazox	I1017F	Osakabe et al., 2017; Herron et al., 2018; İnak et al., 2019; Adesanya et al., 2021
乙酰辅酶A羧化酶 Acetyl-CoA carboxylase	二斑叶螨 *T. urticae*	螺螨酯 Spirodiclofen	A1079T	Adesanya et al., 2021
线粒体电子传递复合体I Mitochondrial electron transport complex I	二斑叶螨 *T. urticae*	哒螨灵、唑螨酯、吡螨胺 Pyridaben, fenpyroximate, tebufenpyrad	H92R	Bajda et al., 2017; Itoh et al., 2022
线粒体电子传递复合体II Mitochondrial electron transport complex II	二斑叶螨 *T. urticae*	丁氟螨酯 Cyflumetofen	I260T	Sugimoto et al., 2020
		腈吡螨酯、吡唑酰苯胺 Cyenopyrafen, pyflubumide	I260V, S56L, H258Y	Maeoka & Osakade, 2021; Njiru et al., 2022
线粒体电子传递复合体III Mitochondrial electron transport complex III	二斑叶螨 *T. urticae*	联苯肼酯 Bifenazate	G126S, I136T, S141F, P262T, G132A, A269V, I144T	van Leeuwen et al., 2008; Piraneo et al., 2015; Shi et al., 2019; Fotoukkiaii et al., 2020a, b
		灭螨醌 Acequinocyl	I256V, N321S	Kim et al., 2019
		联苯肼酯、灭螨醌 Bifenazate, acequinocyl	G126S+A133T	Fotoukkiaii et al., 2020a

4.2.1 二斑叶螨的代谢抗性

Çağatay et al.(2018)研究发现采自土耳其安塔利亚及穆拉2个地区的3个抗阿维菌素二斑叶螨田间种群(抗性倍数为223~404倍)产生抗性的原因是酯酶、P450和GST活性共同增强;酯酶和P450活性增强被证实与二斑叶螨对螺螨酯的抗性有关(Rauch & Nauen,2002);P450活性增强与二斑叶螨对灭螨醌(Sugimoto & Osakabe,2019;Liu ZX et al.,2020)和联苯菊酯(Xu et al.,2020)的抗性有关;总酯酶及特异性酯酶Est-4活性增强与二斑叶螨对联苯菊酯的抗性有关(Ay & Gürkan,2005);GST活性增强与二斑叶螨对阿维菌素的抗性有关(Konanz & Nauen,2004)。

在二斑叶螨中,通过表达代谢试验证明CYP392E10可代谢螺螨酯(Demaeght et al.,2013);CYP392A11通过羟基化腈吡螨酯和唑螨酯来降解其毒性(Riga et al.,2015);CYP392A16可代谢阿维菌素及吡唑酰苯胺(Adesanya et al.,2020);TuG-

STd14（Pavlidi et al.，2015）和TuGSTd05（Pavlidi et al.，2017）分别可代谢阿维菌素与丁氟螨酯；UGT204B和UGT202A能糖基化阿维菌素降低其毒性（Snoeck et al.，2019）。

在二斑叶螨中，荧光定量PCR检测结果表明，*CYP389C10*、*CYP392D8*、*CYP392A11*和*CYP392A12*过表达与其对阿维菌素的抗性有关（Xu et al.，2021）；P450活性升高及*CYP392A11*和*CYP392A12*过表达与其对腈吡螨酯的抗性有关（Khalighi et al.，2016）；*CYP392A16*和*CYP392E8*过表达与其对Pyflubumide的抗性有关（Fotoukkiaii et al.，2021）；细胞色素P450还原酶基因*CPR*过表达与其对阿维菌素、联苯菊酯及唑螨酯的抗性有关（Adesanya et al.，2020）；*CCE04*$^{SR\text{-}VP}$过表达与其对螺螨酯的抗性有关（Wei et al.，2020）；*UGT204B*（Snoeck et al.，2019）、*UGT69*、*UGT55*和*UGT79*（Papapostolou et al.，2021）过表达与其对阿维菌素的抗性有关；*tetur05g05060*和*tetur02g09830*过表达仅与其对阿维菌素的抗性有关，而*tetur02g09850*过表达则与其对阿维菌素和弥拜菌素的抗性有关（Xue et al.，2020）；*TuABCC-02*和*pABC-23*过表达与其对乙螨唑、四螨嗪及丁氟螨酯的抗性有关（Papapostolou et al.，2021）。Hu et al.（2019）发现亚致死浓度LC_{30}的阿维菌素、甲氰菊酯和吡螨胺处理后可使二斑叶螨*CYP392D3*和*CYP392D7*的表达量显著升高，且P8核受体通过改变P450活性进而影响二斑叶螨对这3种杀螨剂的敏感性。

4.2.2 朱砂叶螨的代谢抗性

利用酶活性测定方法证实朱砂叶螨体内P450活性升高与其对甲氰菊酯的抗性有关（Shi et al.，2015a）；而GST活性增强与其对丁氟螨酯的抗性有关（Wang et al.，2014）。

在朱砂叶螨中，CYP389C16可代谢丁氟螨酯和哒螨灵（Feng et al.，2020a）；酯酶TCE2可分解甲氰菊酯和丁氟螨酯（Shi et al.，2016a）；CarE6能分解甲氰菊酯（Wei et al.，2019a）；TcCCE12（Wei et al.，2019b）、TCGSTM4（Zhang et al.，2018）和TcGSTm02（Feng et al.，2019）均能分解丁氟螨酯；UGT201D3可代谢阿维菌素（Wang et al.，2020）；酰胺酶TcAmidase01可水解丁氟螨酯（Liu JL et al.，2020）。

在朱砂叶螨中，通过荧光定量PCR技术证实*CYP389B1*、*CYP392A26*、*CYP391A1*、*CYP384A1*、*CYP392D1*和*CYP392A28*过表达与其对甲氰菊酯的抗性有关（Shi et al.，2016b）；*CYP392A1*过表达与其对丁氟螨酯的抗性有关（Liu et al.，2021）；*CPR*过表达与其对甲氰菊酯（Shi et al.，2015b）和哒螨灵（Wei et al.，2021）的抗性有关；*TCE2*过表达与其对阿维菌素、氧化乐果和甲氰菊酯的抗性有关（Feng et al.，2011b）；*CarE3*、*CarE6*、*CarE7*、*CarE9*、*CarE10*、*CarE13*、*CarE15*和*CarE18*过表达与其对甲氰菊酯的抗性有关，而*CarE4*、*CarE5*、*CarE14*和*CarE19*过表达则与其对丁氟螨酯的抗性有关（Wei et al.，2016）；*TcCCE23*下调与其对丁氟螨酯的抗性有关（Wei et al.，2019b）；*TcGSTd1*、*TcGSTd2*和*TcGSTm2*过表达与其对哒螨灵的抗性有关（Luo et al.，2014）；*TCGSTM2*、*TCGSTM3*和*TCGSTM8*过表达与其对甲氰菊酯的抗性有关（Shen et al.，2014）；*TcGSTm02*（Feng et al.，2020b）和*TcGSTm04*（Feng et al.，2022）过表达与其对丁氟螨酯的抗性有关；*TcPgp1*和*TcPgp2*过表达与其对阿维菌素的抗性有关（Xu et al.，2016）。Xu et al.（2019）通过荧光定量PCR检测、酶活性测定及RNA干扰技术得出朱砂叶螨内环裂解双加氧酶基因*TcID-RCD1*与其对阿维菌素的抗性有关。

5 棉叶螨抗药性治理策略

目前棉叶螨的防治主要依靠化学药剂，因此棉叶螨的抗药性问题是一个亟需解决的难题。抗药性治理主要是针对抗药性问题提出合理的解决方案，最终目的是有效控制害虫。参考相关害虫抗药性治理方法，本文综合分析认为可从以下3个方面治理棉叶螨的抗药性。

5.1 杀螨剂品种轮换与合理混用

马康生等（2021）指出杀虫剂轮用的依据是在产生抗药性的害虫种群中许多抗性个体的生存适合度降低，当面临多种药剂的选择压下这类个体必然会被逐渐淘汰，进而整个种群又恢复为敏感种群。在实际田间生产中，可根据前3年药剂的使用情况及作用方式，选择与前期作用方式不同的药剂，同一作用方式的杀螨剂避免混用及连续使用。如田间喷施噻螨酮时应避免与四螨嗪及乙螨唑连续使用（Jeschke，2021）。值得注意的是，联苯肼酯虽与有机磷类、氨基甲酸酯类不是同一类型药剂，但田间应避免与这2类药剂同时使用。另外，混用的话还需注意药剂之间是否会产生拮抗作用。López-Manzanares et al.（2022）发现球孢白僵菌*Beauveria bassiana*与螺螨酯、螺虫乙酯混配具有协同增效作用，而与乙螨唑具有明显的拮抗作用。

5.2 使用选择性杀螨剂

目前,新作用方式的杀螨剂从发现到投入市场的研发成本越来越大,耗时也更长。新农药品种的频繁使用会导致害虫对新药剂快速产生抗性,因此引入新型杀螨剂也只能暂时缓解抗药性问题。在实际生产中应更加注重选择性杀螨剂的使用,既能有效防治叶螨,又能很好地保护天敌。如黄庆超等(2021)通过毒力测定发现阿维菌素不仅对新疆棉田截形叶螨的毒力强,而且对当地优势天敌多异瓢虫 *Hippodamia variegata* 的安全性高。

5.3 抗药性综合治理

有害生物综合治理是抗药性治理策略最理想的措施。在农业防治方面,可以通过加大抗叶螨作物品种的选育力度(Azadi Dana et al.,2018)和合理利用田间作种植模式来进行抗药性治理。如王玲等(2016)发现田间茄子间作大蒜可抑制截形叶螨种群的发生量。在生物防治方面,应选择捕食性天敌优势种,如优化捕食螨的释放比例(Schmidt-Jeffris & Beers 2018),加大生物制剂的使用,尤其是植物提取物及植物产品,这种方式在害螨的防治中越来越受到重视(Marrone, 2019; Sparks et al. 2020)。Jakubowska et al.(2022)对用于防治二斑叶螨的生物防治措施进行了系统总结,生物防治资源包括植物提取物、细菌、真菌、捕食螨及昆虫。其中,提取的植物精油有较好的应用效果,如薄荷 *Mentha pulegium* 精油(Topuz et al.,2012)、迷迭香 *Rosmarinus officinalis* 精油(程作慧等,2016)、藿香 *Agastache rugosa* 精油(Cheng et al.,2020)及香茅 *Herba cymbopogonis* 精油微乳液(程作慧等,2021)均对朱砂叶螨有良好的熏蒸作用。Durofil et al.(2021)综述了树胡椒 *Piper aduncum* 精油对二斑叶螨的致死中浓度范围在5.83~7.17 μg/mL之间。张宣等(2021)在甘肃省河西走廊棉区开展棉叶螨防治试验,发现植物源杀虫剂藜芦碱、苦参碱和松油,生物源药剂阿维菌素及矿物源药剂矿物油、软皂水剂和硅藻土+有机硅助剂均可用于防控棉叶螨,药后10 d防效仍能达到72.39%~92.81%。Kungu et al.(2019)采用三氯杀螨醇处理后的网笼笼罩木龙葵 *Solanum scabrum* 植株,同时释放捕食螨长足小植绥螨 *Phytoseiulus longipes*,可明显控制二斑叶螨的种群数量。

6 展望

近年来,棉叶螨的发生呈现加重趋势,推测原因有3个,一是全球气候变暖加剧干旱问题,这种环境更加适宜叶螨为害;二是农业种植结构的调整,叶螨从其他作物或果蔬转移到棉田的概率增大;三是棉田中经常使用吡虫啉等新烟碱类杀虫剂防治刺吸式害虫,如棉蚜、蓟马和粉虱,而直接或系统接触吡虫啉可显著提高二斑叶螨的生殖力(James & Price,2002)。要想对棉叶螨这类害螨进行有效防治,首先需明确防治对象具体是哪个种,叶螨可以根据雄性外生殖器进行形态学鉴定,鉴于叶螨个体小,有时形态学鉴定困难,则需借助分子生物学手段进行准确鉴定,如Chen et al.(2020)通过 *Taq*Man特异探针对二斑叶螨、卢氏叶螨及兰姆叶螨的ITS1序列进行扩增,可从分子水平对三者进行有效鉴别。其次需掌握棉叶螨的种群动态规律,为防治时机的选择提供参考依据。郭伟等(2021)构建了基于无人机成像高光谱的棉叶螨为害等级估测模型,可快速准确获取棉叶螨为害情况,为其田间种群动态调查提供有效的工具。新疆地区果棉间作的种植模式值得密切关注,需定期监测果树上的叶螨种群,防止果树上的害螨向棉田迁移。最后需针对棉叶螨的抗药性制定合理的治理策略。第一,需加强棉叶螨抗性遗传、风险评估和交互抗性等基础研究,为田间用药提供参考依据。在大田防治中,顺序使用、轮换使用或混合使用不同作用方式的化学农药是害螨抗药性治理中一个非常重要的环节。第二,施药方式的改变,比如将喷雾改成滴灌,如He et al.(2018)在棉田中用滴灌的方式将乐果运输于棉花植物内,发现其能有效防治二斑叶螨,且棉花种子中无农药残留。棉叶螨喜在叶背部为害,针对其为害特点,未来应尝试更多有效的施药方式,达到精准减量的要求。第三,充分利用综合防治策略,如加强棉花抗叶螨品种的选育和增大生物防治的比例等。

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