次生代谢物介导的植物与烟粉虱互作分子机制及其绿色防控

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摘要：在植物与植食性昆虫长期协同进化过程中，植物进化出了复杂的化学防御体系，而昆虫也进化出了相应的反防御机制。烟粉虱*Bemisia tabaci*作为一种重大农业害虫，通过直接取食韧皮部汁液、分泌蜜露诱发煤污病以及传播植物病毒等方式对农作物造成严重的影响。植物次生代谢物作为植物重要的化学防御物质在防御烟粉虱时发挥着关键作用，烟粉虱也通过其精细的化学感受与解毒代谢系统来应对防御物质。该文系统总结萜类、酚类、含氮化合物及酰基糖等主要防御次生代谢物在植物防御烟粉虱中的功能及相关作用机制，并阐述烟粉虱对寄主植物次生代谢物的化学感受以及代谢解毒等适应机制。同时，从多环境条件验证、多技术整合、非靶标效应评估及新兴技术应用等方面探讨基于植物化学防御机制介导的烟粉虱综合防控技术的未来研究方向。旨在深入理解次生代谢物介导的植物−烟粉虱互作的生态与分子机制，为培育作物抗虫品种以及开发可持续害虫综合治理策略提供理论依据。

关键词：烟粉虱；植物次生代谢物；化学感受；解毒；害虫综合治理

Secondary metabolites-mediated interaction between plants and whiteflies: molecular mechanisms and eco-friendly management

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Abstract: During the long co-evolution arms race between plants and herbivorous insects, plants have evolved sophisticated chemical-based defense mechanisms, while herbivores also developed intricate counter-defense mechanisms. The tobacco whitefly *Bemisia tabaci*, a major agricultural pest, causes severe economic losses through ingesting phloem sap, excreting honeydew that promotes sooty mold growth, and transmitting numerous plant viruses. Plant secondary metabolites constitute a central chemical defense against whiteflies; in response, tobacco whiteflies have evolved advanced chemosensory and metabolic detoxification systems to circumvent plant defensive defensive compounds. This review

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systematically summarized the functions and mechanisms of major defensive secondary metabolites, including terpenes, phenolics, nitrogen-containing compounds, and acylsugars, in plant defense against tobacco whiteflies. This review also further examines the chemosensory and metabolic detoxification mechanisms that whiteflies deploy against these compounds. Meanwhile, we discuss further research directions for integrated management strategies based on plant chemical defenses, including validation under multiple environments, integration of multiple technologies, assessment of non-target effects, and application of novel approaches. This review aims to provide a theoretical foundation for advancing the understanding of secondary metabolites-mediated plant-whitefly interaction, guiding direction for breeding insect-resistant crop varieties, and developing sustainable pest management strategies.

Key words: *Bemisia tabaci*; plant secondary metabolite; chemosensation; detoxification; integrated pest management

在植物生长发育过程中,多种生物与非生物胁迫持续为害其生存(Wilkinson et al.,2019)。在生物胁迫中,植食性昆虫由于其高度的多样性与丰富度,是植物生产与繁衍的重大限制因子(Savary et al.,2019;Wilkinson et al.,2019)。近十年来,大量研究聚焦于植食性昆虫与植物之间互作的化学与分子机制方面,阐明了植物对植食性昆虫的多层级防御相应机制(Erb & Reymond,2019;Snoeck et al.,2022)。昆虫也同样进化出了相应的化学感受与代谢解毒机制以应对植物防御(Morin et al.,2024)。这种长期共存介导的防御与反防御"军备竞赛"显著影响了二者在自然生态系统中的进化轨迹(Erb & Reymond,2019),同时也给全球农业生产带来了巨大挑战(Savary et al.,2019)。因此,深入理解植物与植食性昆虫相互作用的机制,具有重要的科学意义与经济价值。

烟粉虱 *Bemisia tabaci* 是农业生产中为害最为严重的刺吸式害虫之一,通过直接取食韧皮部汁液造成植物生理紊乱,分泌蜜露诱发煤污病,严重影响作物的产量与品质(Morin et al.,2024)。更严重的是,烟粉虱能够以持久循环的方式传播多种菜豆金色花叶病毒属 *Begomovirus* 病毒,导致番茄黄化曲叶病毒(tomato yellow leaf curl virus,TYLCV)病等毁灭性病毒病害大规模流行(蔡朝晖等,2020;Wang & Blanc,2021)。当前,烟粉虱的防控主要依赖化学杀虫剂。然而,长期大量使用杀虫剂已导致烟粉虱对多种杀虫剂产生抗性,严重削弱了化学防治的可持续性(Schlaeger et al.,2018;Horowitz et al.,2020;胡明鑫等,2023)。因此,在害虫综合治理框架下,亟需开发化学防治替代或补充策略,其中寄主植物抗性的挖掘与利用备受关注。

植物在与植食性昆虫长期进化过程中,演化出了多样化的化学防御体系(Mithöfer & Boland,2012;Wari et al.,2022)。次生代谢物作为植物防御反应的关键物质,具有结构多样、功能特异的特点,能够在直接防御(如毒杀、驱避)和间接防御(如吸引天敌)等多个层面发挥作用。根据生物合成时序,次生代谢物可分为组成型与诱导型两大类;根据化学结构,次生代谢物主要涵盖萜类、酚类、含氮化合物及酰基糖等物质(Mithöfer & Boland,2012)。近年来,大量研究致力于挖掘不同作物基因型中具有抗烟粉虱活性的次生代谢物,并探索其在可持续害虫治理中的应用潜力(Maldonado Machado da Cruz et al.,2026)。

尽管已有研究在次生代谢物鉴定与功能解析方面取得了重要进展(Mithöfer & Boland,2012;Wari et al.,2022),但目前对植物–烟粉虱互作中次生代谢物的作用机制仍缺乏系统性梳理。基于上述背景,本综述系统归纳植物抗烟粉虱的萜类、酚类、含氮化合物及酰基糖等主要次生代谢物,阐述其化学结构、合成途径及对烟粉虱的趋避性与抗生性效应;从化学感受和代谢解毒两个层面总结烟粉虱对植物次生代谢物的感知与适应机制;从多环境验证、多技术整合、非靶标效应及生物技术应用等角度展望基于次生代谢物的绿色防控策略。

1 植物防御烟粉虱的关键次生代谢物的种类、合成与功能

根据生物合成时序,普遍将植物内源性防御化合物划分为组成型与诱导型次生代谢物两类(Mithöfer & Boland,2012)。组成型次生代谢物在易受植食性昆虫取食的组织中持续合成并储存,构成植物应对生物胁迫的即时防线;诱导型次生代谢物则是在植食性昆虫取食过程中,植物感知到特定

分子模式后启动合成的(Böttger et al.,2018)。植物次生代谢物的多样性源于其典型结构在合成途径中所经历的多步衍生化修饰,如酰基化、糖基化、甲基化、羟基化和异戊烯基化等(Wang et al.,2019)。根据化学结构,植物次生代谢物通常分为萜类、酚类及含氮化合物三大类群(War et al.,2020,图1)。值得注意的是,茄科植物体内若干关键的防御相关代谢物并未包含在上述类别中,其中最具代表性的是酰基糖(Moghe et al.,2023)。此外,十字花科植物中的硫代葡萄糖苷等也是重要的防御代谢物,但相关研究表明,只有极端高含量的硫代葡萄糖苷才对烟粉虱等刺吸式口器害虫产生显著影响,因此该类物质不在本文的关注范围内(Li et al.,2021)。

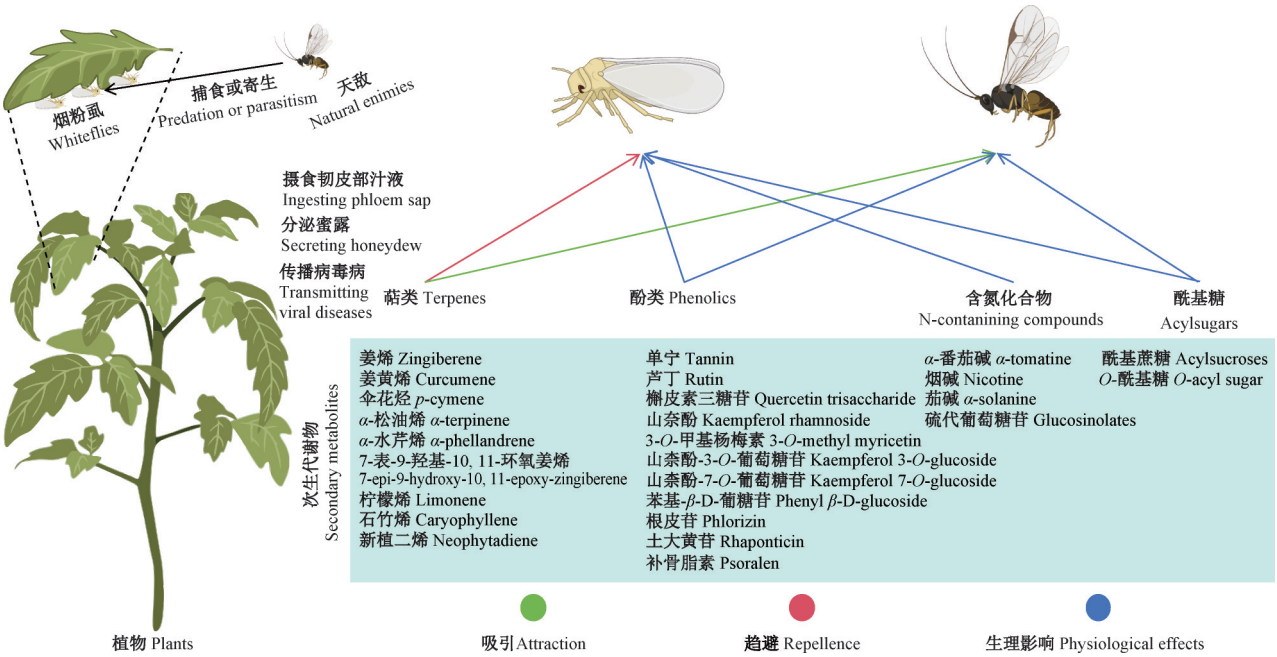


图1 次级代谢物在植物与烟粉虱互作中的作用模式

Fig. 1 Mode of action of secondary metabolites in the interaction between plants and whiteflies

1.1 萜类化合物

萜类化合物由异戊二烯单元聚合形成的烃类化合物构成,根据异戊二烯单元数量可划分为单萜、倍半萜、二萜、三萜、四萜及多萜(War et al.,2020)。萜类骨架可在甲基转移酶和酰基转移酶等催化下衍生化修饰形成萜类化合物(Pichersky & Raguso,2018)。萜类化合物在植物抗烟粉虱过程中发挥着关键作用,主要通过以下几种机制。

萜类化合物主要作为植物挥发物干扰烟粉虱行为,抑制其寄主选择与产卵行为(Razzaq et al.,2023)。研究表明,倍半萜类化合物姜烯和莪术烯可作为驱避剂影响烟粉虱的寄主选择行为(Bleeker et al.,2009)。单萜类如对伞花烃、α-松油烯和α-水芹烯亦对烟粉虱具有驱避作用(Bleeker et al.,2009;2011;Conboy et al.,2019;2020)。特定立体异构体姜烯类化合物7-表姜烯及其脱氢衍生物R-姜黄烯也对烟粉虱表现出显著的驱避活性(Bleeker et al.,2011)。

其次,部分单萜类代谢物可通过使蛋白质变性降低植物营养价值(Park et al.,2010;Afroz et al.,2021)。从烟粉虱高抗番茄 *Solanum lycopersicum* 品系叶片渗出物鉴定出7-表-9-羟基姜烯和7-表-9-羟基-10,11-环氧姜烯两种姜烯类衍生物,其含量与烟粉虱存活率呈显著负相关,表明其具有潜在杀虫活性(Zabel et al.,2021),但其详细作用机制仍有待深入研究。

此外,萜类化合物还可靶向乙酰胆碱酯酶、γ-氨基丁酸受体、电控钠离子通道等分子靶点,对昆虫产生神经毒性效应(Abdelgaleil et al.,2024)。目前相关研究主要集中于咀嚼式口器害虫(Wari et al.,2022),萜类物质是否同样作用于刺吸式口器害虫烟粉虱的这些分子靶标,还需进一步的功能解析。

最后,在害虫综合治理应用方面,番茄与万寿菊 *Tagetes erecta* 间作可显著降低烟粉虱种群数量,万寿菊的主要挥发物柠檬烯可作为化学杀虫剂替代品,显著提高作物产量(Conboy et al.,2019;2020)。

此外，除与万寿菊间作外，单一萜类化合物的应用也对烟粉虱表现出防控潜力。石竹烯可作为防御激发子诱导植物挥发物合成，激活抗虫防御反应（Xu et al.，2024）。同时，利用生物胁迫诱导产生的萜类化合物处理植物，可增强其间接抗虫防御能力，这一策略也已展现出应用前景（Ayelo et al.，2021）。

1.2 酚类化合物

酚类化合物的特征在于分子结构中至少含有一个酚羟基，经莽草酸与苯丙烷途径或乙酸–丙二酸途径生物合成（Cheynier et al.，2013；Marchiosi et al.，2020）。根据酚羟基数量、碳骨架结构及取代基性质，可划分为单酚和多酚化合物（Kabera et al.，2014；Silva et al.，2023）。多酚类化合物（包括类黄酮与非类黄酮）是植物界分布最广的化感物质之一（War et al.，2020）。酚类化合物在植物防御中发挥着重要作用，既可表现为直接接触毒性，亦可通过氧化生成活性氧干扰昆虫生长发育。单宁等部分酚类化合物能与昆虫肠道蛋白共价结合，干扰其消化过程（Wink，2003；Razzaq et al.，2023）。

多项研究表明，植株对烟粉虱的抗性水平与总酚及单宁含量显著正相关（Anu et al.，2021；Pal et al.，2021；衡森等，2023）。烟粉虱取食可改变叶片的类黄酮组成，显著降低芦丁、山奈酚、鼠李糖苷、槲皮素三糖苷及3-*O*-甲基杨梅素等化合物含量，进而影响烟粉虱寄主选择行为，而回补芦丁或槲皮素可抑制烟粉虱取食行为及病毒传播（Su et al.，2018；2020）。利用类黄酮含量差异显著的番茄近等基因品系研究发现，高类黄酮品系番茄对烟粉虱吸引力显著低于低类黄酮品系番茄，且高类黄酮品系番茄可有效抑制烟粉虱传播TYLCV（Yao et al.，2019）。进一步研究发现，高类黄酮品系番茄对烟粉虱的抗性与其能够抑制烟粉虱效应蛋白BtE3表达有密切关系，其中槲皮素与芦丁可显著抑制*BtE3*基因表达（Su et al.，2025）。烟粉虱取食高类黄酮品系番茄可诱导活性氧积累，上调胼胝质合成酶表达并诱导筛管中胼胝质沉积，显著降低烟粉虱对韧皮部的取食效率（Yang et al.，2023a；Li et al.，2025）。经芦丁处理的番茄种子还能够促进植株茉莉酸–异亮氨酸积累进而激活茉莉酸防御信号通路，显著增强植株对烟粉虱的抗性（Tang et al.，2023；Zhang et al.，2026）。此外，在辣椒*Capsicum annuum*中，补骨脂素也被证实通过抑制烟粉虱解毒酶活性来降低其存活率与产卵量（Han et al.，2026）。

1.3 含氮化合物

含氮化合物主要包括生物碱与氰苷两大类（War et al.，2020；Yactayo-Chang et al.，2020）。根据化学结构及氮原子来源，生物碱可分为真生物碱、原生物碱和伪生物碱（Abegaz & Kinfe，2019；Lichman，2021）。植物生物碱对昆虫有神经毒性、繁殖力抑制等多效性作用，糖苷生物碱可干扰昆虫蜕皮和变态等生理过程（Oberdörster et al.，2001；Chowański et al.，2016；Züst & Agrawal，2016）。

番茄富含甾体生物碱及其糖苷化衍生物，其中最重要的*α*-番茄碱由番茄碱苷元与四糖基团连接而成（Fiesel et al.，2022；Wang et al.，2024）。茄属*Solanum*生物碱中的烟碱作用于昆虫中枢神经系统的乙酰胆碱受体（Kliot et al.，2014）。尽管生物碱在植物抗虫中作用显著，但其与烟粉虱抗性相关的研究比较有限。已有研究发现番茄抗性品系中生物碱含量显著高于敏感品系，但尚未建立直接因果关系（Mrosso et al.，2022）。烟碱因与新烟碱类杀虫剂作用靶标相同，已被证实对烟粉虱有直接毒性（Kliot et al.，2014；Pym et al.，2024 ）。

1.4 酰基糖

酰基糖由糖核心与多条脂肪酸链通过酯化反应连接而成，因糖核心类型、酰基链长度及取代位置等差异表现出显著的结构多样性（Fan et al.，2019；Fiesel et al.，2022；Moghe et al.，2023）。该类化合物既可通过粘附昆虫发挥直接防御作用，亦可通过影响三营养级互作发挥间接防御作用（Weinhold et al.，2011；Fan et al.，2019；Moghe et al.，2023）。

研究表明，番茄抗性品系ABL 14-8的抗性主要源于高密度IV型腺毛及其分泌的高含量酰基糖（Rodrıguez-Lopez et al.，2012）。番茄野生品系LA716对烟粉虱表现出较高致死率与取食抑制，其抗性同样与IV型腺毛及其分泌的酰基糖密切相关（Narita et al.，2023）。抗敏品系杂交试验结果证实，腺毛密度和酰基糖含量与烟粉虱抗性呈显著正相关（Silva et al.，2014；Dias et al.，2016）。大田试验结果也表明，番茄野生品系LA716上烟粉虱种群数量显著下降，捕食性天敌定殖能力增强（Pandey et al.，2023；Smeda et al.，2023）。酰基糖对植食性昆虫的防控效果受糖骨架、脂肪酸链组成、含量及其互作关系等共同影响（Mutschler et al.，2023）。不同组分酰基糖的抑制效果存在显著差异（Leckie et al.，2016），其中富含中链酰基基团的*O*-酰基糖在高抗烟草*Nicotiana benthamiana*中的大量积累是导致烟粉虱

致死效应的重要因素（Wang JX et al.，2025）。

2 烟粉虱对植物次生代谢物的感知与适应机制

面对植物多样化的化学防御体系，烟粉虱在与寄主植物长期协同进化过程中，演化出了高效的化学感受与代谢解毒系统，使其能够精准定位寄主，评估寄主质量，并有效应对植物产生的防御性次生代谢物（Morin et al.，2024）。本文将从化学感受和生理代谢解毒两个层面系统阐述烟粉虱对植物次生代谢物的感知机制与反防御适应策略。

2.1 化学感受机制

化学感受物质在昆虫定位寄主植物过程中发挥着关键作用，其中植物释放的挥发性有机化合物构成了重要的化学感受物质（Simon et al.，2015）。研究表明，绿叶挥发物中的（*E*）-2-己烯醛和3-己烯-1-醇对烟粉虱有吸引作用，而*D*-柠檬烯、*β*-月桂烯及（*E*）-*β*-罗勒烯等萜类化合物则表现出驱避效应（Li et al.，2014；Du et al.，2016；Tu & Qin，2017）。

参与化学感受机制的基因家族主要包括气味结合蛋白（odorant-binding protein，OBP）、化学感受蛋白（chemosensory protein，CSP）、嗅觉受体（olfactory receptor，OR）及味觉受体（gustatory receptor，GR）（Sánchez-Gracia et al.，2009）。在烟粉虱基因组中，共注释获得8个OBP基因和19个CSP基因（Wang et al.，2017；Zeng et al.，2019）。烟粉虱OBP与CSP基因总数与其他韧皮部取食的半翅目昆虫相当，但显著低于其他目昆虫（Wang et al.，2017；Zeng et al.，2019）。烟粉虱OR基因数量为9~20个，明显少于胸喙亚目中其他近缘类群（Tian et al.，2022）。

近年来，OBP、CSP及OR蛋白在烟粉虱感知植物源代谢物过程中的具体作用陆续被报道。例如，*CSP1*的表达可被新烟碱类杀虫剂噻虫嗪显著诱导，且该蛋白能够结合亚油酸，但其相关功能尚不明确（Liu et al.，2016）。此外，化学感受系统目前普遍被证实能够被病毒劫持进而影响烟粉虱与植物互作。比如，番茄褪绿病毒（tomato chlorosis virus，ToCV）侵染番茄后释放的萜类挥发物新植二烯可被烟粉虱气味结合蛋白BtOBP2结合，同时该挥发物对烟粉虱具有显著吸引作用（Shi et al.，2025）；该病毒侵染烟粉虱会导致数个OBP与CSP基因表达量发生显著改变，对其中差异表达的基因进行功能验证后发现BtOBP17与BtCSP1能够结合对烟粉虱具有吸引作用的挥发物乙基苯乙酮（Wang JC et al.，2025）。甜瓜褪绿黄化病毒（cucurbit chlorotic yellows virus，CCYV）侵染可诱导烟粉虱*BtOBP5*的表达，进而影响其寄主选择行为，然而其与植物挥发物的结合能力尚不清楚（He et al.，2023）。同时，近年来的研究也发现OR基因也可被病毒劫持，比如TYLCV侵染一方面影响番茄月桂烯的释放，另一方面抑制烟粉虱体内可结合月桂烯的*BtOR6*基因表达，从而改变其寄主选择行为，促进病毒传播（Liang et al.，2025）。这些研究表明，植物病毒普遍存在劫持烟粉虱化学感受系统，进而操纵其相关的选择性行为，最终促进植物病毒病的传播与暴发。此外，味觉受体GR基因也参与了寄主对寄主植物营养物质的识别。例如，GR基因*BtabGR1*在异源表达中表现出显著的蔗糖特异性响应，沉默该基因可干扰烟粉虱对蔗糖浓度的辨别（Li FQ et al.，2022；Aidlin et al.，2023）。

2.2 代谢解毒机制

为应对植物产生的大量防御性次生代谢物，烟粉虱除了通过其化学感受系统选择适宜的寄主外，也可通过高效的代谢解毒系统降低其毒性（Malka et al.，2018；Pym et al.，2019）。昆虫解毒过程主要涉及5个关键蛋白家族，分别为细胞色素P450单加氧酶（简称P450）、尿苷二磷酸（uridine diphosphate，UDP）-糖基转移酶、谷胱甘肽*S*-转移酶、羧酸酯酶以及腺嘌呤核苷三磷酸结合盒转运蛋白（adenosine triphosphate-binding cassette transporter，ABC）（Malka et al.，2018；Pym et al.，2019）。

早期大量关于寄主转换的研究都发现，烟粉虱在转换寄主植物后其体内的相关解毒酶基因的表达模式都会出现显著变化，暗示解毒酶介导的代谢机制是其寄主范围广泛的主要原因（Wang et al.，2013；Xu et al.，2015；Tian et al.，2022）。沉默相关解毒基因的试验结果表明，这些基因在烟粉虱应对植物代谢物的过程中发挥着关键作用。迄今为止，数项研究将特定解毒蛋白的活性与烟粉虱对植物代谢物的修饰（解毒）产物直接关联起来。例如，谷胱甘肽*S*-转移酶BtGSTs5催化硫代葡萄糖苷与谷胱甘肽结合从而使其失活（Eakteiman et al.，2018）；糖苷水解酶BtSUC2和BtSUC5将氰苷和硫代葡萄糖苷转化为无活性的衍生物（Malka et al.，2020；Easson et al.，2021）；硫代葡萄糖苷硫酸酯酶家族的BtGSS通过脱硫作用降低硫代葡萄糖苷的毒性（Manivannan et al.，2021）；酚糖丙二酰基转移酶家族的BtPMaT1对酚糖苷进行代谢修饰以实现解毒（Xia et al.，2021）；

P450解毒酶也参与了对烟碱的解毒代谢(Kliot et al.,2014;Pym et al.,2024)。此外,超氧化物歧化酶和芳基硫酸酯酶这两个蛋白家族也可能分别参与烟粉虱对植物防御化合物活性氧和硫代葡萄糖苷的解毒过程(Gao et al.,2015;Malka et al.,2016;宋天雪等,2019)。

烟粉虱生物学与基因组学研究的一项重要进展是发现其基因组中存在多个水平基因转移(horizontal gene transfers,HGT)事件。Li Y et al.(2022)通过对218个高质量昆虫基因组进行系统分析发现,烟粉虱基因组中获得的HGT基因数量有170个,远超其他昆虫。此外,Gilbert & Maumus(2022)亦在烟粉虱中鉴定出24个HGT事件,剔除数据重叠部分后,烟粉虱基因组共携带184个HGT基因。Xia et al.(2021)前期一项突破性研究发现,烟粉虱获得的植物源酚糖苷丙二酰转移酶基因可中和寄主番茄中的酚糖苷类防御物质,从而显著提升烟粉虱在番茄植株上的存活能力。相关研究为解释HGT事件如何为昆虫提供获得新功能的进化捷径、进而促进其对寄主植物的适应性提供了有力的试验证据(Xia et al.,2021;Kirsch et al.,2022)。

综上所述,烟粉虱通过化学感受系统与解毒酶系统的协同作用,形成了对植物次生代谢物的精准识别与解毒能力。这一双重适应机制,加上水平基因转移带来的新功能基因的获取,共同构成了烟粉虱应对寄主植物化学防御的强大反防御体系,为其广泛的寄主适应性奠定了分子基础。

3 结论与展望

近年来,定向育种的目标主要提升作物产量与品质,在驯化过程中丢失了大量抗性相关性状(Gaspariniet al.,2021;Du et al.,2025)。近期研究发现,通过引入野生型抗性基因以增强作物抗性,是抑制害虫为害的潜在防控策略(Jaganathan et al.,2026)。尽管目前在农作物生产中烟粉虱的防控面临较大的挑战,越来越多的研究也证实了基于植物次生代谢物的化学防御极具前景式(Maldonado Machado da Cruz et al.,2026)。本综述系统梳理了主要次生代谢物在防御烟粉虱中的作用,并总结了烟粉虱为适应植物化学防御所演化出的感知、代谢等策略。

植物次生代谢物在防御烟粉虱中发挥多层次、多靶点作用(Mithöfer & Boland,2012)。萜类化合物主要作为挥发物干扰烟粉虱的寄主定位与产卵行为,部分萜类化合物具有神经毒性。酚类化合物(尤其是类黄酮)既可抑制烟粉虱取食,又可激活茉莉酸防御信号通路并抑制烟粉虱效应蛋白表达(Yao et al.,2019;Yang et al.,2023a;Su et al.,2025)。酰基糖作为茄科植物特有的防御代谢物,通过腺毛分泌并粘附昆虫,表现出直接致死效应(Rodrıguez-Lopez et al.,2012)。

烟粉虱演化出了高效的化学感受与代谢解毒系统(Morin et al.,2024)。化学感受蛋白构成了识别植物挥发物的分子基础,植物病毒可通过调控这些基因的表达操纵烟粉虱的寄主选择行为。五大解毒酶家族在适应不同寄主过程中表现出显著的表达可塑性,而水平基因转移则为烟粉虱提供了快速获取新功能基因的进化捷径,如植物源酚糖苷丙二酰转移酶的获得,使其能够有效中和番茄的酚类防御物质(Xia et al.,2021)。

植物与烟粉虱之间基于次生代谢物的相互作用,构成了一场持续的“化学军备竞赛”,植物不断演化出多样化的防御代谢物,烟粉虱则通过化学感受系统快速识别,通过解毒酶系统高效代谢,甚至通过水平基因转移获取新的解毒功能基因。这种博弈决定了二者在农业生态系统中的种群消长动态,更是给农业安全生产提出了巨大的挑战。

现有研究多局限于实验室可控环境,而在开放大田及温室大棚条件下,温度、湿度、土壤肥力、作物生育期及烟粉虱隐种等因素均可能影响次生代谢物防控策略的成效(Pandey et al.,2023)。目前虽有基于高含量次生代谢物抗性番茄品系的试验结果表明,该策略可抑制烟粉虱的种群增长及其对TYLCV的传播(Yao et al.,2019),但不同栽培环境下不同植物品系对烟粉虱抗性的差异表明有必要开展多环境条件下的系统研究,以准确揭示环境因素对烟粉虱寄主选择偏好与直接抗性的影响,为将实验室成果向田间应用转化提供理论依据(Smeda et al.,2023)。

由于烟粉虱快速进化的适应机制,对烟粉虱的防控亟需多层次与动态化的手段。害虫防控策略若仅依靠单一次生代谢物,烟粉虱可快速进化出相应的适应手段。基于此,未来的综合治理手段必须考虑多层次的防控手段协同利用,构建多层次的防御体系,比如对烟粉虱具有直接防御效果的次生代谢物与能够吸引天敌的挥发物协同利用。此外,基于间作的生态防治策略(Conboy et al.,2019),也可与诱导抗性相结合,为更有效地防控烟粉虱提供新思路。

植物次生代谢物在农业生态系统中的影响具有

广泛性，目前研究也应深入评估基于次生代谢物的害虫防控策略对系统中尤其是天敌在内的非靶标生物的影响。比如，高类黄酮番茄品系可对烟粉虱捕食性天敌东亚小花蝽*Orius sauteri*的生长发育产生负面影响（Yang et al.，2023b），而高酰基糖番茄品系也同样显著抑制了斯氏钝绥螨*Amblyseius swirskii*的生长与捕食（Pandey et al.，2023）。这些研究都说明基于次生代谢物的防控策略在害虫综合治理中与其他技术兼容的重要性。未来研究也应系统评估抗性种质资源对非靶标生物的影响，筛选在抗性品系上也能高效防控的天敌昆虫，实现害虫防控与生态安全的协同发展。

当前，前沿生物技术可通过精细调控代谢合成，打破传统育种中品质与抗性之间的权衡效应。通过成簇规律间隔短回文重复序列（clustered regularly interspaced short palindromic repeats，CRISPR）等基因编辑工具精细调控相关因子，可为不牺牲产量与品质的情况下增强害虫抗性提供潜在的可能（Huang et al.，2022；Bai et al.，2024）。未来研究应聚焦与关键调控因子的功能解析，为精准编辑提供理论基础，进而创制高品质且高抗性的番茄品系。

综上所述，次生代谢物介导的植物与烟粉虱互作的研究已从抗虫品系筛选到抗虫代谢物的鉴定以及目前的复杂互作机制的解析，同时室内的机理研究也逐渐走向了田间应用验证。深化该领域的相关研究，不仅可以揭示植物与昆虫互作的化学与分子机制，加深对植物与昆虫协同进化的理解，也为培育作物抗虫品种、发展害虫综合治理策略提供了关键的理论依据与实践价值。

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