

生物与信息技术赋能作物有害生物绿色防控研究进展

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2026-02-07 收稿, 2026-03-23 修回, 2026-06-10 接受, 2026-06-12 网络版发表

河南省重大科技专项(241100110300)和河南省重点研发专项(261111111000)资助

摘要 传统有害生物防控依赖人力、经验及化学农药, 导致了防控不及时、抗药性加剧、用药不合理、农药利用率低等问题, 创新有害生物绿色防控体系已成为应对农药抗性、保障农产品质量安全的国际共识. 近年来, 以基因编辑为代表的生物技术和以人工智能为代表的信息技术在有害生物防控中发挥着重要作用, 本文系统阐述了生物育种技术、微生物组工程、RNA生物农药、信息素和代谢工程等生物技术助力作物有害生物绿色防控, 有效缓解了对传统化学农药的依赖; 探讨了信息技术在构建智能监测预警网络、创制绿色农药和辅助精准施药推动作物有害生物智能防控中的应用, 为有害生物科学防控提供了有力支撑. 生物技术与信息技术在有害生物防控领域的深度融合, 将进一步推动农业生产向绿色化、高效化和智能化转型, 保障全球粮食安全与农业可持续发展.

关键词 有害生物, 生物育种, 生物农药, 人工智能, 绿色防控

随着全球气候变暖、跨境贸易增加, 有害生物和入侵生物的发生和危害加剧, 加之世界人口的持续增长, 对粮食安全提出了新的挑战^[1]. 传统农业生产中作物有害生物防控长期依赖人力、经验和化学农药, 存在有害生物防治不及时、抗药性发展迅速、农药使用不合理、农药利用率低等问题, 也导致了生态环境污染、生物多样性下降^[2]. 推动植物保护向绿色、智能、高效的方向转型, 构建更具韧性的农业生态系统, 已成为全球农业科技创新的核心焦点.

近年来, 随着基因编辑、RNA干扰、转基因等生物技术以及以传感器、卫星遥感、人工智能(artificial intelligence, AI)为核心的信息技术的蓬勃发展, 植物保护在有害生物监测预警、绿色农药小分子产品开发、生物防治、精准用药等方面进行着一场深度变革, 构建了以智慧植保为核心的作物有害生物绿色防控技术体系, 形成了监测、诊断、决策、执行的闭环, 促进了

化学农药的减施增效, 提升了农产品质量安全, 推动了农业的绿色高质量发展. 本文主要从生物技术和信息技术两方面综述其在作物有害生物绿色防控体系方面应用的研究进展.

1 生物技术助力作物有害生物绿色防控

1.1 生物育种技术

挖掘作物体内抗病虫害和除草剂基因并培育抗性品种是进行有害生物防治的有效途径, 以基因编辑、转基因、碱基编辑与引导编辑等为代表的生物育种技术为这一领域带来了革命性突破^[3,4]. 该技术体系以精准的遗传调控替代传统化学干预, 推动植保模式从被动应对到主动防御、从化学依赖到遗传调控转变.

在基因编辑方面, CRISPR/Cas9系统通过在特定位点引入双链断裂实现基因敲除或替换, 成为作物绿色

引用格式: 刘润强, 柏连阳. 生物与信息技术赋能作物有害生物绿色防控研究进展. 科学通报, 2026, 71: 4799–4809

Liu R, Bai L. Recent advances in green pest management of agricultural crops via biotechnology and information technology (in Chinese). Chin Sci Bull, 2026, 71: 4799–4809, doi: [10.1360/CSB-2026-0190](https://doi.org/10.1360/CSB-2026-0190)

防控的重要工具^[5,6]。在抗病方面,通过定向编辑植物本身的感病基因,可在不影响农艺性状的前提下增强抗病性。例如,敲除水稻*Os8N3*基因可显著提升对白叶枯病的抗性^[7];编辑水稻*OsRBL1*基因可使其获得对稻瘟病的抗性^[8];敲除小麦*TaPslPKI*基因可产生对条锈病的广谱抗性^[9]。在抗虫方面,该技术通过精准编辑与害虫取食和发育相关的植物宿主基因,有效提升其抗虫能力。例如,敲除玉米中与挥发物合成相关的*TPS*基因,使植株对玉米螟(*Ostrinia nubilalis*)的引诱力下降^[10];编辑大豆中调控茉莉酸信号通路的*GmMYC3*基因,显著增强大豆对斜纹夜蛾(*Spodoptera litura*)的抗性^[11]。在抗除草剂方面,主要通过提高除草剂靶标表达量和降低靶标与除草剂的亲和力来提高作物对除草剂的耐受性。例如,通过编辑*EPSPS*、*ALS*、*HPPD*等除草剂靶标基因使作物获得抗除草剂特性,为杂草防控提供了解决方案^[12]。

转基因技术则通过外源基因的导入,实现对靶标有害生物的高效防控。抗病方面,转*Lr34*玉米显著增强了对普通锈病和大斑病的抗性^[13];转几丁质酶基因马铃薯则增强了对青枯病的抵御能力^[14]。在抗虫方面,转苏云金芽孢杆菌(*Bacillus thuringiensis*, *Bt*)基因棉花对棉铃虫(*Helicoverpa armigera*)的防治效果显著,双价抗虫棉更可兼抗棉铃虫与蚜虫,每年可减少化学农药使用量约1~1.5万吨^[15,16];在抗除草剂方面,转*EPSPS*基因增强了大豆、玉米对草甘膦、草丁膦等除草剂的耐受性^[17];转杂草来源细胞色素P450基因和谷胱甘肽-S转移酶(*glutathione S-transferase*, *GST*)基因水稻获得了对多种除草剂的显著抗性^[18~20]。

近年来,碱基编辑、引导编辑等新型精准育种技术的突破,可在不造成DNA双链断裂的情况下,实现单碱基精准替换及小片段的定点插入与缺失,进一步提升了防控的精准度与生物安全性。例如,利用碱基编辑器对水稻*OsTubA2*基因进行定向突变,可获得对氟乐灵等除草剂的稳定抗性^[21];通过引导编辑技术修复水稻*HIS1*基因片段,可恢复其对*HPPD*类除草剂的抗性,编辑效率可达11.5%~15.5%^[22]。这些技术能够在几乎不引入外源DNA的情况下实现性状改良,为绿色抗性育种提供了新途径。

1.2 微生物组工程

植物对环境胁迫的响应不仅取决于自身基因组,还在很大程度上受到其相关微生物组的调控。因此,植

物及其相关微生物共同构成的功能整体,已被认为是维持作物健康和提升抗病能力的重要基础^[23]。植物通过根系分泌物对根际微生物群落进行选择塑造,而有益微生物则通过竞争性定殖、调节养分供给以及诱导系统性抗性等多种机制抑制病原物侵染,从而增强作物对病、虫、草等多重生物胁迫的综合抗性^[24]。

在作物绿色防控体系中,根际有益菌、内生菌和生防菌是微生物组工程关注的典型功能类群。这些微生物不仅能够直接促进植物生长,还可作为生物防治因子有效降低化学农药的施用。例如,非致病性丁香假单胞菌衍生物可诱导植物产生类似“呼救”的根际响应,降低根系分泌物中肉豆蔻酸含量,进而选择性富集德沃斯氏菌(*Devosia*)等有益类群,显著增强植株对后续病原菌侵染的抵抗能力^[25]。相较而言,内生菌更多参与植物体内的防御调控过程,如核盘菌(*Sclerotinia sclerotiorum*)以内生方式定殖于小麦、水稻、大麦、玉米和燕麦等多种作物后,可明显提高宿主对赤霉病、条锈病和稻瘟病的抗性^[26]。此外,具备抗生素合成能力的生防菌在真菌和细菌中广泛存在,例如由绿针假单胞菌(*Pseudomonas chlororaphis*)与能够产生吩嗪类化合物的枯草芽孢杆菌(*Bacillus subtilis*)构建的合成亲和菌群,可显著提升对小麦茎基腐病的生物防治效果^[27]。

然而,单一有益微生物在田间环境中的防控效果往往受生态背景影响而表现不稳定,基于微生物互作关系与功能协同设计的合成菌群因此展现出更高的应用潜力。微生物组研究中逐步发展出“自下而上”和“自上而下”两种改造策略^[28]。“自下而上”策略通过从与特定植物密切相关的微生物中筛选功能菌株,并通过基因改造或功能重组构建成功能明确的合成菌群^[29]。例如,基于微生物组网络分析筛选出的关键调控菌、特异富集菌及具有拮抗功能的菌株,构建由细菌与真菌共同组成的跨界人工合成菌群,可有效抑制番茄枯萎病的发生^[30]。在此基础上,功能菌株还可通过分子设计强化生防特性并实现工程化应用。例如,武汉科诺生物科技股份有限公司联合中国农业科学院植物保护研究所创制的苏云金芽孢杆菌工程菌G033A可同时防控鳞翅目和鞘翅目害虫,已完成生物农药登记,并入选2023年农业农村领域重大新产品名单^[31]。相比之下,“自上而下”策略则通过施加特定选择压力对初始微生物群落进行定向驯化,促使群落在整体水平上向目标功能方向重组与演化^[32]。例如,有机肥施用可促进土壤中捕食性原生生物与抑病芽孢杆菌的互作,通过原生

生物对细菌群落的选择性调控,间接提升芽孢杆菌丰度及其非核糖体肽类抗菌物质的合成,从而有效抑制尖孢镰刀菌等土传病原菌,减轻香蕉枯萎病并提高作物产量^[33]。

1.3 RNA生物农药

以RNA干扰(RNA interference, RNAi)技术为原理的RNA生物农药开发被称为“农药史上的第三次革命”,其原理是通过引入与靶标基因mRNA序列互补的双链RNA(dsRNA),引发mRNA降解,从而抑制靶标基因的表达^[34]。RNAi机制广泛存在于植物、真菌、线虫、昆虫和哺乳动物等生物中,在有害生物防治领域展现出巨大的应用潜力^[35]。与传统化学农药相比, RNA生物农药具有多项优势,如高度特异性,通过靶向有害物种共有基因或融合基因而兼具广谱性,靶标基因的可替换性高,容易进行抗药性治理,不改变生物体的遗传特性,公众接受度高,对环境安全,研发成本低^[36,37]。

RNA生物农药的使用技术主要有基于喷雾诱导基因沉默(spray-induced gene silencing, SIGS)的喷洒型核酸农药和基于寄主植物诱导基因沉默(host-induced gene silencing, HIGS)的转基因植物核酸农药^[38]。以纳米材料为载体负载的dsRNA可以增强其在环境中的稳

定性和进入靶标生物体的能力,进而提升干扰效率,目前常用于递送RNA生物农药的纳米载体包括有机纳米材料脂质(脂质体等)、聚合物纳米材料(壳聚糖、SPC等)、多肽纳米材料(细胞膜穿透肽等),以及无机纳米材料碳基纳米材料(碳纳米管、碳量子点等)、层状双氢氧化物等(图1)^[39]。

建立RNAi靶标基因库是RNA生物农药开发的关键,理想的RNAi靶标基因应是有害生物生长发育的关键基因,在体内高表达,且无功能冗余^[40]。当前害虫中研究较多的靶标基因包括作用于昆虫蜕皮、变态等关键生长发育阶段的特有靶标基因,如几丁质合成酶基因*CHS*、保幼激素合成途径关键基因*JHAMT*、蜕皮激素受体基因*EcR*、海藻糖合成酶基因*Tre*、支链氨基酸转氨酶基因*ilvE*等,高效的持家基因*Snf7*、*V-ATPase*等,以及与化学农药协同使用减少用量的解毒代谢基因,如细胞色素P450基因^[41~44]。病原菌中研究较多可作为靶标基因的有生长发育关键基因麦角甾醇生物合成基因*CYP51*、微管蛋白基因 *$\beta 2$ -tubulin*,以及关键致病基因*DES*,持家基因*EF-1 α* 等^[45]。杂草中的靶标基因包括除草剂靶标和生长发育关键基因,如叶绿素a/b结合蛋白基因^[46,47]。

当前仅有针对害虫防治的商品化RNA生物农药,

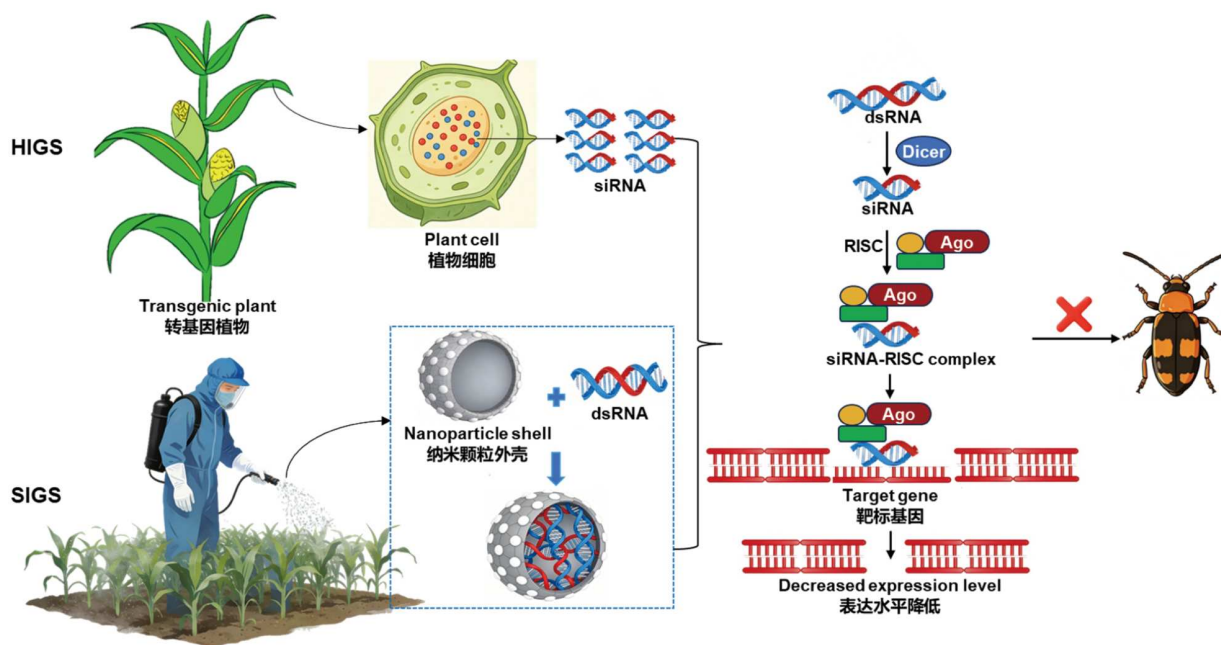


图1 RNA生物农药的施用技术及作用原理。图中药剂喷洒、植物细胞、纳米颗粒、玉米根萤叶甲在作者指导下借助人工智能工具豆包获得
Figure 1 Application technology and mechanism of RNA biopesticides. The pesticide spraying, plant cells, nanoparticles and *Diabrotica virgifera* shown in the figure were generated using artificial intelligence tool Doubao under the authors' guidance

全球首款表达dsRNA的转基因玉米(HIGS)MON87411于2017年6月获得美国环境保护署的种植许可,该品种同时表达Bt蛋白和靶向玉米根萤叶甲(*Diabrotica virgifera virgifera*)DvSnf7基因的dsRNA^[48]。2023年12月,全球首款喷雾施用型RNA生物农药(SIGS)CalanthaTM获得美国环境保护署批准上市,并于2024年开始商业销售。2025年5月,美国环境保护署宣布拟批准GreenLight Biosciences公司研发的第二款RNA生物农药Vadesca-na,用于控制蜜蜂巢穴中的瓦螨(*Varroa destructor*)。2026年1月,我国硅羿科技(上海)有限公司研发的防治烟草花叶病毒病的RNA杀菌剂的新通用名称Tomovir-cona获得国际标准化组织(ISO)临时批准,产品成分为特异性干扰烟草花叶病毒衣壳蛋白mRNA的dsRNA,这是全球首款防治病毒病的RNA杀菌剂。

1.4 信息素和代谢工程

信息素是生物体释放至体外、用于个体间通讯的化学信号物质,在作物有害生物绿色防控中应用广泛^[49]。其中,昆虫信息素的应用技术较为成熟。昆虫信息素是由昆虫分泌的化学通讯物质,主要包括性信息素、聚集信息素、报警信息素等^[50~52]。性信息素在害虫监测、诱杀和迷向防治中作用显著。迷向防治通过缓释载体持续释放高浓度信息素,干扰雄虫定位雌虫,降低交配率,具有专一性强、环境兼容性好的特点,已在多种鳞翅目害虫防治中推广。此外,信息素还可用于蚜虫、叶蝉等媒介昆虫的监测和行为调控,间接辅助病毒病的绿色防控。信息素也可与其他生物防治手段协同使用,例如与昆虫病毒联用,结合诱杀与病毒传播,进一步提升防控效果。目前国内已实现了多种信息素化合物的合成,但仍需借助合成生物学手段如微生物发酵技术实现规模化低成本生产^[53]。国外已有企业通过发酵工艺生产用于水稻螟虫防控的性信息素,并在田间取得良好防效。与此同时,微纳米胶囊、静电纺丝纳米纤维等新型缓释系统的开发,也有助于提升信息素在田间释放的稳定性和持久性^[54]。

与信息素的外源干预不同,植物次生代谢工程旨在从作物内部系统性增强其生态防御能力,涵盖抗虫、抗病和抑草等多重功能。当遭受生物胁迫时,植物通过茉莉酸、水杨酸等信号通路激活防御反应,合成酚类、萜类、生物碱等次生代谢产物^[55,56]。这些物质不仅可直接抑制或毒杀害虫和病原菌,还能激发植物系统抗性^[57]。部分化感物质还可通过根系分泌或残体分解抑

制周边杂草生长,为生态抑草提供新途径。例如,化感水稻品种“PI312777”通过根系分泌化感物质,可有效抑制抗性及敏感型稗草的生长,并通过调整根系构型及氮素利用策略增强自身竞争能力^[58]。代谢工程通过过表达关键酶基因以促进目标产物积累,借助组织特异性或诱导型启动子实现时空精准调控,并利用基因编辑或RNAi等技术抑制竞争途径,引导代谢流向目标化合物。目前,该技术已在水稻、玉米、小麦等作物中得到应用,例如通过增强萜类挥发物合成以吸引天敌、提高酚类物质含量以增强抗病性,以及调控化感物质合成以培育抑草新品种,逐步减少对化学农药的依赖^[59~61]。随着CRISPR/Cas9、RNAi等分子生物学工具的快速发展,以及代谢组学、转录组学等多组学技术的深入应用,植物次生代谢网络的解析及设计能力持续提升,将为培育兼具抗虫、抗病和抑草功能的多抗作物品种提供坚实的技术支撑。

2 信息技术推动作物有害生物智能防控

2.1 构建智能监测预警网络

病虫害监测预警是有害生物绿色防控体系的重要组成部分^[62]。“十四五”以来信息技术飞速发展,农业物联网智能传感系统、AI图像识别、无人机高光谱遥感、卫星遥感、机器学习模型等信息技术在病虫害监测预警领域深度融合,一张“空—天—地”一体化的病虫害监测预警网络已基本形成(图2)。

在作物病害监测上主要以物联网技术、遥感与光谱信息技术结合机器学习和深度学习模型来实现智能、高效监测。如利用传感器对农田温度、土壤水分、湿度与光照强度进行实时监测,采用ESP32边缘计算设备将实时数据无线上传至Firebase或ThingSpeak等云平台进行存储与分析,实现促进作物高效生产的快速、科学决策,助力农业可持续发展^[63]。通过无人机搭载高光谱遥感技术对感染细菌性条斑病水稻、叶瘟病等病害的水稻的光谱数据进行图像采集,再利用深度学习模型建立高准确率的水稻病害识别模型,实现对水稻病害的大范围无损诊断^[64,65]。在虫害监测上通常应用物联网技术、雷达监测技术、遥感与地理信息技术和人工智能与大数据技术进行监测预警。如基于物联网技术和AI图像识别技术开发的害虫种类精准识别软件和智能虫情测报灯,使农业从业者可实时监测草地贪夜蛾在田间的发生情况,确定防控最佳窗口期^[66,67]。通

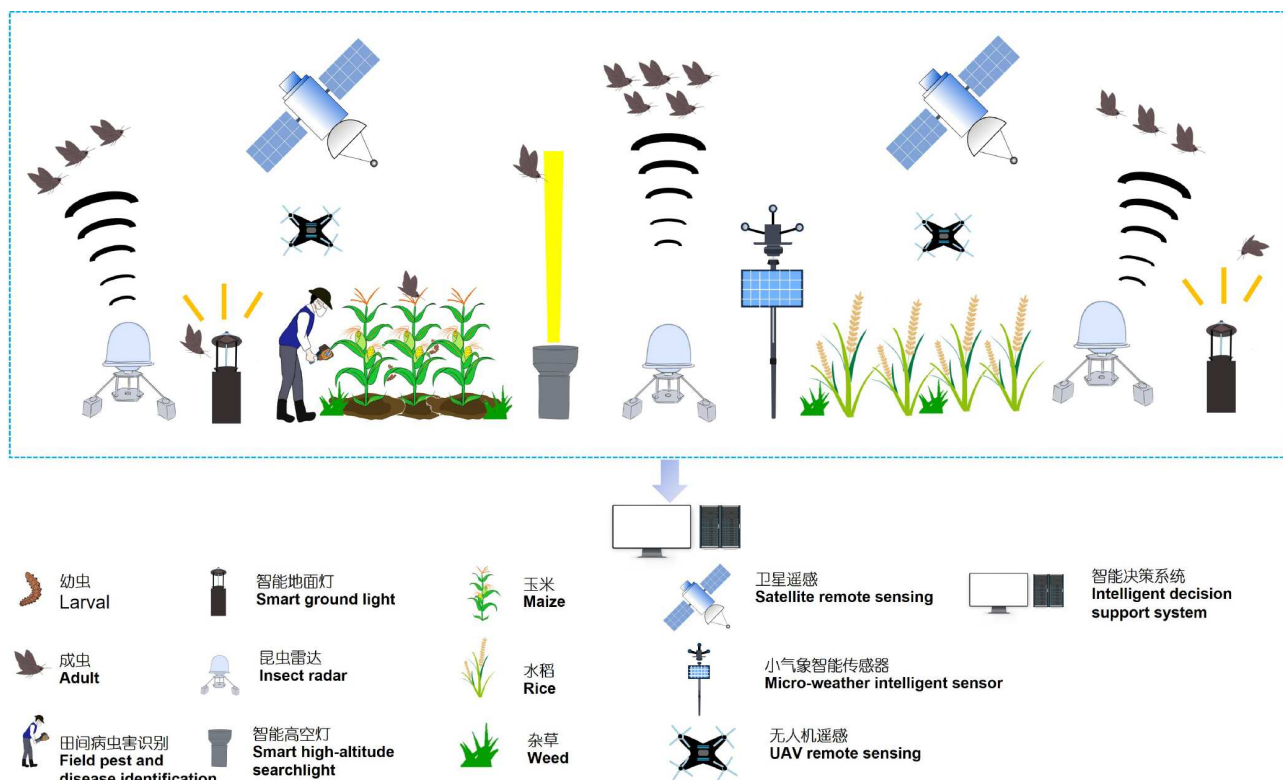


图2 “空—天—地”一体化的病虫害监测预警网络

Figure 2 An integrated “space-air-ground” monitoring and early-warning network for crop diseases, insect pests and weeds

过昆虫雷达对迁飞害虫的迁飞行为进行解析,开展多种重大迁飞害虫的长期自动化监测业务^[68,69]。利用遥感影像数据对土壤水分、温度、降雨等生境条件进行反演,分析虫卵孵化与土壤水热的关系,对飞蝗卵孵化动态进行预警^[70-72]。使用注意力的长短期记忆交互卷积神经网络ALIC模型对广东地区多年的逐日气象数据和虫情数据进行分析,建立了未来1、3、7天害虫预测模型^[73]。在草害监测上,则依赖遥感监测技术、机器视觉与AI识别技术、光谱诊断与多源数据融合技术等来实现精准监测预警。如利用无人机结合彩色红外成像系统识别杂草的种类^[74]。如以Swin Transformer深度学习和AI图像识别技术捕捉杂草与作物细微差异的判别特征,随后使用两阶段迁移学习策略精准识别了玉米幼苗及其田间伴生的7种杂草图像,识别准确率达99.18 %^[75]。

2.2 创制绿色农药

近20年来,我国科学家先后创制了毒氟磷、氰烯菌酯、四氯虫酰胺、啮草酮等绿色农药新品种50余个,

我国成为了国际上为数不多的具有新农药创制能力的国家。以AI为代表的信息技术快速发展,显著提升了行业内小分子先导化合物的发现效率和优化能力,加速了绿色农药的研发速度(图3)^[76]。

在靶标发现环节,组学技术与AI算法结合,系统识别害虫、病原或杂草的特异性候选靶点。我国开发的AIMMS、HISNAPI等蛋白可靶性分析平台,以及Plant-SPEAD等植物特异性数据库,可精准预测潜在结合位点并提供关键基因资源,显著突破了传统靶标鉴定的局限性^[77-79]。在分子设计阶段,生成式AI与计算机辅助药物设计紧密结合,能够基于SMILES序列、分子指纹等数据自主生成具有新颖结构和优良性质的分子骨架,其中PADFrag、ACFIS和AILDE等工具开发实现了高效的分子片段虚拟筛选,极大加速了先导化合物的发现与优化进程^[80-82]。在筛选与评估环节,AI虚拟筛选技术可快速从海量分子中初筛高潜力化合物,并借助Cloud 3D-QSAR、OptADMET和ChemFREE等工具对化合物构效关系和毒性进行早期评估,从而大幅缩短实验周期和降低研发成本^[83-85]。在制剂优化阶段,

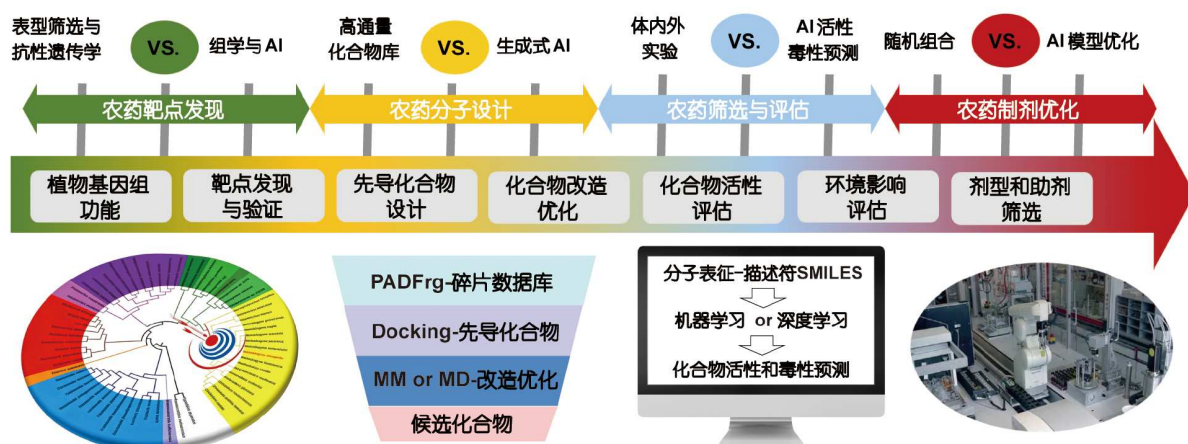


图3 创制绿色农药的流程

Figure 3 The process of developing green pesticides

自动化试验设备与AI配方优化模型结合,可针对性推荐合适剂型及助剂,提升农药稳定性和应用效果^[86]。

AI与组学、计算化学、量子力学等学科交叉渗透,构建了AI药物发现与设计技术体系。其中,贵州大学郝格非教授团队构建了国际首个系统性的农药信息学平台,为农药活性、抗性、生物利用度、毒性、代谢及生物安全性分析提供信息化工具^[87]。华中师范大学杨光富团队则开发了国际首个农药分子设计一体化平台Pesticide Discovery AI(PDAI),覆盖了农药靶标发现、虚拟筛选、结构优化、毒性与抗性预测全流程,集成了分子对接、分子动力学模拟和3D-QSAR等工具,实现农药研发的自动化与标准化^[88]。

2.3 辅助精准施药

精准施药是智慧植保的重要组成部分,指通过图像识别、传感探测等技术获取病虫害类别及在农作物上的位置等信息,利用计算决策系统根据其发生的严重程度,制定精准的喷雾策略,驱动变量执行系统采取实时、非均匀、离散化的精准作业,以实现按需施药^[89]。在有害生物防控的同时,提高农药利用率,降低农药用量和环境污染。

AI促成了施药过程人、机、药的分离,在精准施药领域的应用主要有施药器械和施药技术。施药器械包括地面施药器械和植保无人机等新型载具,AI在施药器械的自动喷雾、无人驾驶、自主导航、自动避障等领域发挥关键作用,地面施药器械搭载的多模态感知终端可实现厘米级定位施药,在设施农业和精细化

作业中发挥着重要作用;植保无人机通过多光谱导航实现复杂地形下的全域覆盖,在大面积作物的快速施药、丘陵山地等地面器械难以作业的区域发挥出极大的优势^[90]。在施药技术领域,AI通过集成作物信息获取技术、变量施药技术、雾滴飘移防控技术和在线混药技术,实现病虫害防控作业的精准化与智能化。如范道全等人^[91]依据叶面积密度参数与脉宽调制驱动技术(pulse width modulation, PWM),开发了一款变量喷雾控制系统,相较于连续恒定式喷雾和对靶开关式喷雾,可分别实现省药71.96%和29.72%。

3 总结与展望

生物技术和信息技术的深度融合,正以前所未有的方式推动作物有害生物绿色防控体系的智慧化转型。功能基因组学、转录组学、代谢组学等多组学技术的发展为抗病虫草害基因挖掘、RNA生物农药设计和开发、新颖原创性分子靶标挖掘、微生物基因改造提供了坚实的基础, RNA干扰、基因编辑、转基因等技术为有害生物防治提供了新颖的实现路径,显著提升了生物防治的效能与可持续性,有效降低了对传统化学农药的依赖,是有害生物抗药性治理的有效手段。与此同时,以AI为代表的信息技术的深度融合,为有害生物的科学防控提供了数据驱动的决策支持,有害生物的监测预警网络为适时防控和合理用药提供了精准指导,有效降低了对传统人力、经验的依赖,计算化学大大提高了绿色新农药的创制速度,精准用药提高了农药利用率,提升了防控的精准度和效率。生物技术与信息

技术在有害生物防控领域的深度融合,旨在将植保实践从依赖传统化学农药的简单模式,系统性地转型升级为基于多维度感知、智能化决策与精准化执行的农业干预体系,正在从根本上推动农业生产向资源高效、环境友好、生态可持续的方向发展。

然而,这一技术体系目前仍面临着严峻的挑战,主要可归纳为三个层面:(1)技术层面,基因编辑作物、工程功能微生物等产品的环境释放长期生态风险、基因漂移可能性及其对社会经济的影响,尚需基于长期监测数据的严谨科学评估;(2)系统层面,智慧植保本质上是一个复杂的系统,其有效运行依赖于农学、植物病理学、微生物学、计算科学、工程学等多学科的深度交叉。目前,各领域技术发展呈现割裂状态,缺乏统一的标准,导致技术堆砌难以形成协同效应。更关键的是,缺乏能够对技术组合进行全生命周期、多场景验证的大型集成模拟与试验平台,阻碍了技术从实验室到田间的应用;(3)产业层面,高昂的应用门槛与薄弱的基础设施,使其难以普惠广大中小农户,市场与政策激励机制也有待完善。

展望未来,融合生物技术和信息技术的智慧植保

的发展将是一个技术深化、系统集成与制度创新协同进化的过程。一方面,依托生物技术的低成本绿色防控技术广泛应用。随着技术水平的发展,以基因编辑为代表的新型、多样化、低成本的生物技术在有害生物防控领域广泛应用,生物防治、物理防治、化学防治并重的新形势取代当前以化学防治为主的格局,生物多样性、环境污染得到大幅度改善。另一方面,有害生物防控的智能化水平进一步提高。智慧植保体系进一步完善,从监测预警到自主决策、精准施药,从新农药研发到环境风险评估、制剂产品开发、药效测定,在一定程度上实现自动化,田间操作完全由作业机器人取代,实验室开发工作由具身智能体根据人类提出的试验目的自主完成,工作效率大幅度提高。

综上所述,生物技术和信息技术的协同创新重塑了作物有害生物防控的格局,将有害生物防控从依赖经验的传统模式,引领至一个精准化、智能化、绿色化的新模式。二者的深度融合,不仅显著提升了防控水平的智慧化进程和生态环境发展的可持续性,也推动了全球粮食安全和农业产业升级。

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Summary for “生物与信息技术赋能作物有害生物绿色防控研究进展”

Recent advances in green pest management of agricultural crops via biotechnology and information technology

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Traditional pest management has long depended on manual labor, farmer experience-based practices, and the extensive use of chemical pesticides. This approach often leads to delayed pest detection, accelerated development of pesticide resistance, irrational chemical application, and low use efficiency. Consequently, improving green pest control systems has become an urgent priority for global agriculture, both to ensure food security and to mitigate the environmental and health risks associated with conventional methods. In recent years, biotechnology, especially gene editing, and information technology, most notably artificial intelligence, have emerged as transformative tools in pest management. This review systematically summarizes the contributions of biological innovations to crop protection. These include biological breeding, for example, the development of pest-resistant crop varieties; microbiome engineering, which modulates beneficial plant-associated microbes to suppress pests; RNA-based biopesticides such as those using spray-induced gene silencing; pheromone-based pest control enabling species-specific mating disruption; and metabolic engineering to produce natural plant defense compounds. These advances have substantially reduced reliance on conventional chemical pesticides, offering more targeted, sustainable, and environmentally friendly alternatives. Furthermore, we discuss the deployment of information technologies in constructing intelligent monitoring and early-warning networks. Such systems integrate remote sensing, IoT-based field sensors, and AI-driven image recognition to enable real-time pest identification and population forecasting. These technologies also play a crucial role in developing green pesticides, for example, by accelerating the virtual screening of bioactive molecules and enabling precision application through variable-rate sprayers and autonomous decision-support systems. Together, these tools provide strong support for the scientific and rational control of pest outbreaks, reducing both economic losses and ecological damage. The deep integration of biotechnology and information technology is poised to further catalyze the transformation of agricultural production toward greater sustainability, efficiency, and intelligence. By combining the molecular precision of biotech tools with the analytical power of digital systems, next-generation pest management can achieve proactive, adaptive, and site-specific interventions. This synergy will be critical for addressing emerging challenges such as climate-driven pest migration, evolving resistance mechanisms, and the need to reduce agrochemical footprints, thereby ensuring global food security and advancing sustainable agricultural development worldwide.

pest, biological breeding, biopesticides, artificial intelligence, green management

doi: [10.1360/CSB-2026-0190](https://doi.org/10.1360/CSB-2026-0190)