

无人机在果园精准作业中的研究进展与挑战分析

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摘要: 无人机凭借其高机动性与平台扩展性,在果园遥感监测、变量施药与智能决策等方面展现出显著优势,成为推动果园植保智能化发展的关键装备。该文系统梳理了果园无人机平台的发展路径与典型应用,按照遥感型、作业型与融合型进行分类,剖析其在果树结构重建、果实识别、变量施药与喷雾调控中的关键技术与研究进展;并进一步总结了果园无人机系统从感知赋能向智能协同演化的4个阶段,揭示其背后的平台演进逻辑与集成趋势。在此基础上,深入探讨了当前果园环境下无人机应用面临的感知精度不稳定、变量控制滞后与系统闭环构建困难等关键问题,并展望未来在多模态感知、边缘智能、果园数字孪生与空-地协同作业等方向的技术突破。

关键词: 果园无人机;智能施药;遥感监测;变量作业;系统集成;植保智能化

Research progress and challenges of UAVs in precision orchard operations

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Abstract: Unmanned aerial vehicle (UAV), leveraging their high mobility and platform expansibility, have demonstrated significant advantages in orchard remote sensing monitoring, variable-rate application, and intelligent decision-making, emerging as pivotal equipment for advancing intelligent orchard plant protection. This paper systematically reviews the development trajectory and typical applications of UAV platforms in orchards and classifies them into remote-sensing, operation, and integrated types. The key technologies and research progress in fruit tree structure reconstruction, fruit recognition, variable-rate spraying, and spray control are analyzed. Furthermore, four evolutionary stages of orchard UAV systems, from perception-enabled systems to intelligent collaboration, are summarized, and the underlying platform evolution logic and integration trends are revealed. Based on this, the paper delves into the key challenges currently faced by UAV applications in orchard environments, including unstable perception accuracy, lagging variable control, and difficulties in constructing closed-loop systems, and prospects future technological breakthroughs in multi-modal perception, edge intelligence, orchard digital twins, and aerial-ground cooperative operations.

Key words: orchard UAV; intelligent spraying; remote sensing monitoring; variable-rate operation; system integration; intelligent plant protection

果园作为典型的多年生木本作物种植系统,具有植株空间结构复杂、种植周期长、作业精度要求高等特点。面对日益增长的劳动力短缺、资源利用效

率低下与绿色防控需求,传统以经验驱动为主的果园管理模式难以满足现代农业对高效、精准与智能化的作业要求(韩冷等,2022;何雄奎,2022;姜赛珂

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等,2023)。因此,以无人机为代表的高机动性、低空自主平台正日益成为果园数字化与智慧化转型的重要支撑力(何雄奎,2019;别宇辉等,2025;王鹏程等,2025)。

过去十年间,无人机技术在农业中的应用取得了显著突破,尤其在果园环境中表现出强大的环境适应性与作业灵活性(李红军等,2021;Chen et al., 2022;Chakraborty et al., 2023)。从早期用于果树定位与图像采集的感知平台,到当前融合多模态感知、人工智能分析与精准作业控制的系统化解决方案,果园无人机已从辅助工具逐步演化为核心作业单元(Chen et al., 2021; Liu et al., 2023; Chao et al., 2025)。这一演化不仅涉及平台类型与系统架构的转变,更体现了感知能力、决策逻辑与执行控制的深度集成。当前,无人机在果园中的应用场景已涵盖遥感监测、表型提取、变量施药、果实识别、智能采摘等多个环节,并逐步构建起数据获取-智能分析-精准执行的闭环控制体系(Ferro et al., 2023; Garcia-Ruiz et al., 2023; Chen et al., 2025)。然而,受限于果树冠层遮挡严重、地形多变、风扰复杂等因素,无人机在结构感知鲁棒性、变量控制精度、系统响应时效性与多源信息融合等方面仍面临诸多挑战,尚未形成可广泛推广的标准化解决方案(Grella et al., 2017;何雄奎,2018;Gavara et al., 2025)。

在此背景下,系统回顾与分析无人机在果园中的技术演化路径、平台类型、核心应用与关键挑战,对于厘清当前研究瓶颈、明确未来发展方向、推动从单一任务执行向智慧果园系统构建的转型具有重要意义。因此,本文基于近十年相关研究的系统性文献梳理与典型技术案例分析,重点围绕以下4个方面进行综述:一是果园无人机平台类型与系统集成演化路径;二是遥感与表型监测、智能施药、变量控制等核心应用技术;三是人工智能、大数据融合与闭环控制系统的集成现状;四是未来发展方向与亟待突破的关键挑战。

1 果园无人机平台类型与技术发展路径

1.1 无人机平台类型与典型应用

当前果园中应用的无人机平台可根据其功能侧重与系统集成程度划分为遥感型、作业型与融合型三类,并逐步向一体化智能作业系统演进(图1)。遥感型平台聚焦于信息获取任务,常搭载红-绿-蓝(red-green-blue, RGB)、多光谱、高光谱、热红外或激光雷达等传感器,广泛用于果树冠层结构重建、果实

识别、叶面参数估测与水分胁迫监测等场景,具备高时空分辨率和灵活部署能力,适应多种果园类型与地形条件。在实际应用中,作业型平台则以大载荷、高效率为核心优势,广泛用于农药喷洒、养分施用与投料作业。这些平台通常配备前后双雷达、多路视觉系统与实时动态差分定位(real-time kinematic, RTK)高精度导航,支持按行或按株精准喷洒与变量施药,有效提升喷雾穿透性并显著减少人工风险。与此同时,近年来兴起的融合型平台将感知与作业功能高度集成,构建了感知-决策-执行闭环系统,如集成处方图、人工智能(artificial intelligence, AI)识别与变量控制功能的大疆智能农业平台,已实现了基于实时监测数据的自动喷洒路径规划、作业参数调控和作业后反馈分析,为变量施药、病虫害预警和产量估测等精准管理任务提供了系统性支持。

1.2 技术发展路径与系统集成演进

果园无人机技术的发展经历了从单一感知平台到智能化、系统化管理工具的逐步演化,主要可划分为4个阶段(图2)。最初阶段(2015年以前)以感知赋能为核心,无人机主要作为信息采集工具,利用RGB图像进行果树定位与果实检测等基础任务,尚未与管理系统实现联动。随着多光谱、热红外与激光雷达LiDAR(light detection and ranging)等多源传感器的集成应用,在2015—2019年进入多源融合阶段,无人机在果树冠层结构重建、生理状态监测与环境因子感知方面的能力显著增强,为后续变量管理研究奠定了基础(Albetis et al., 2017; Andújar et al., 2019; Ali & Imran, 2021)。2019年以后, AI技术快速嵌入农业遥感场景,推动无人机平台向智能分析阶段发展,研究者广泛采用YOLO、U-Net、DeepLab等深度学习框架及随机森林、支持向量机等机器学习算法,拓展了果实检测、病虫害识别、果树冠层建模等智能任务的适用范围(Yadav et al., 2021; Alshammari & Shahin, 2022; Cantürk et al., 2023; Akdoğan et al., 2025)。自2022年起,果园无人机进入系统闭环与协同管理新阶段,逐步实现感知-决策-执行的智能闭环,部分平台已具备实时路径修正、喷量调节与轨迹追踪功能(Blanco et al., 2019; Arakawa & Kamio, 2023; Ariza-Sentís et al., 2024)。当前研究正进一步聚焦于无人机与地面作业装备的协同作业、多尺度数据融合及果园数字孪生构建等系统性问题,标志着果园无人机正从单一作业单元加速向智能决策载体转型(Jiang et al., 2022; Li YF et al., 2023)。

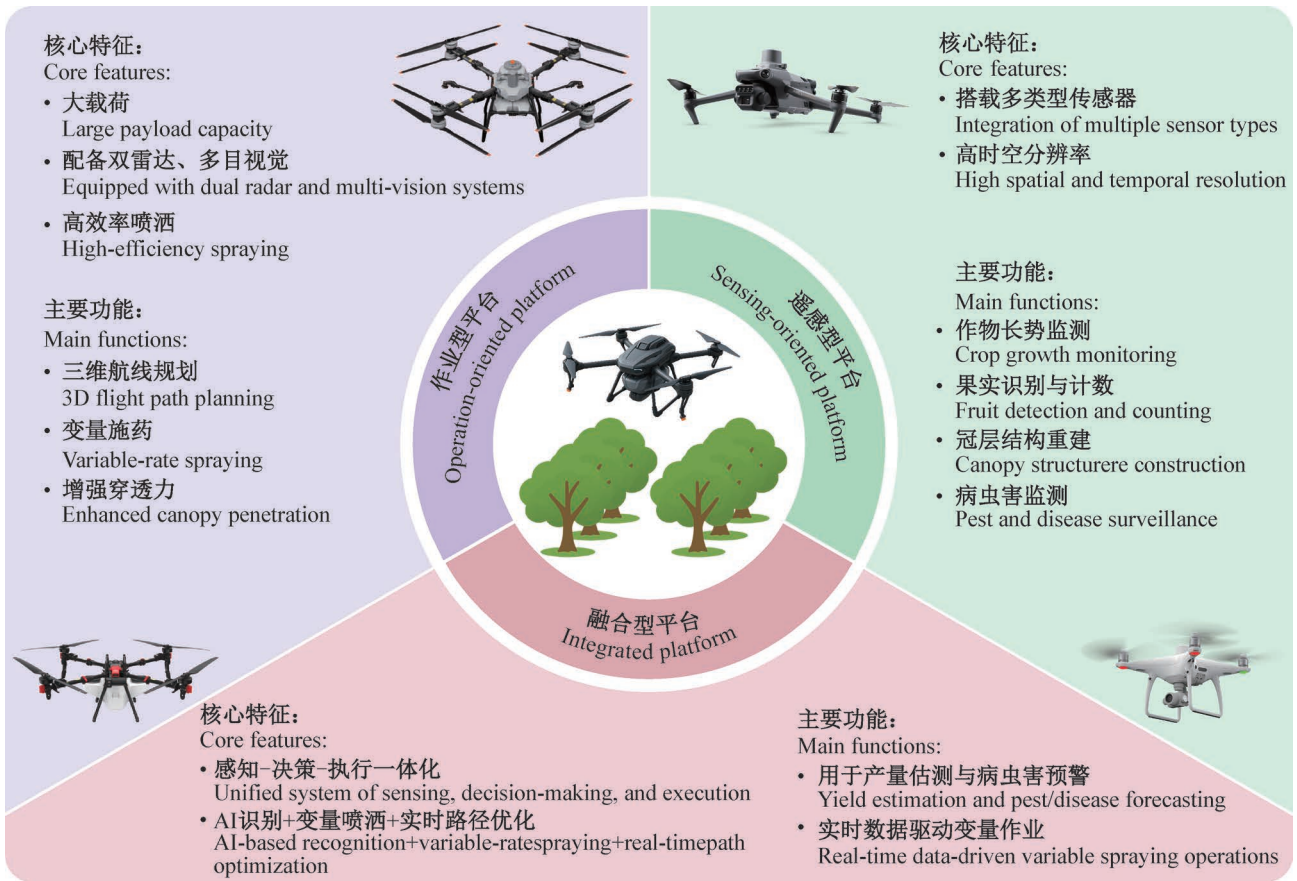


图1 果园无人机平台类型与应用功能分类图

Fig. 1 Classification of orchard UAV platform types and application functions

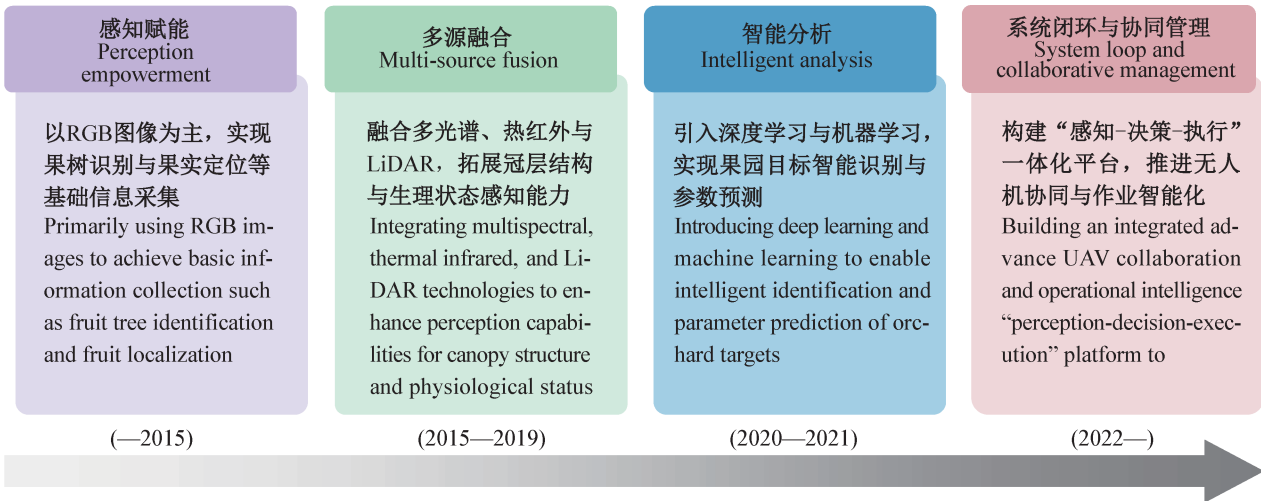


图2 果园无人机技术演化路径

Fig. 2 Evolution pathway of orchard UAV technology

2 核心应用技术与关键场景

2.1 果园遥感与表型监测

随着果园管理逐步由经验驱动向数据驱动的精细化、智能化方向演进, 高通量遥感表型技术正日益

成为果园数字化管理的重要基础(闫云才等, 2023; 潘时佳等, 2024)。在无人机平台不断成熟的推动下, 果树结构参数提取、果树冠层功能状态监测、果实负载估算及作业决策支持等方面取得了显著进展(徐伟萌等, 2022; 罗翔等, 2024), 逐步构建起从多源

遥感感知到管理行为优化的完整链条(Cheng et al., 2020; Ding et al., 2023)。

在传感器与平台方面,果园遥感体系已实现高度多模态融合,常用传感器包括可见光、多光谱、高光谱、热红外与LiDAR等类型,具备灵活组合与场景适配能力(傅隆生等, 2022; 李达岁等, 2023; 冯健等, 2024)。不同传感器类型在结构重建、功能状态监测与管理指标提取中各具优势(表1)。其中, LiDAR具备优异的空间解析度与穿透能力,广泛用于果树冠层结构建模、体积与空隙率计算等任务(Escola et al., 2017; Gené-Mola et al., 2021); 多视角RGB影像结合运动恢复结构(structure from motion, SfM)/多视图立体视觉(multi-view stereo, MVS)技

术可实现成本较低的三维树体建模与冠层密度估算(Fernández-Sarría et al., 2022; Bing et al., 2025); 多光谱和高光谱数据则适用于果树冠层营养、水分胁迫与果实成熟度的精细监测(Catania et al., 2023; Arapostathi et al., 2024); 热红外遥感则为蒸散通量估算与能量平衡分析提供了关键支持。不同传感器组合的选择应根据目标指标的类型差异进行优化, 结构类指标(如冠体积、叶面积密度)多依赖于点云与几何模型重建, 功能类指标(如光合效率、温度状态)则需结合高光谱或热红外信息提取。合理构建遥感组合方案, 有助于提升果园变量施药、智能采收与精准管理的感知基础。

表1 不同类型遥感传感器在果园中的典型应用及适配指标

Table 1 Typical applications and suitability metrics of different remote sensing sensors in orchards

传感器 Sensor	数据类型 Data type	典型应用场景 Typical application scenario	适配结构/功能指标 Representative structural/ functional indicator	优势特点 Key advantage
RGB	二维图像 2D imagery	果树定位、果实识别、树体轮廓提取 Tree localization, fruit detection, canopy contour extraction	冠幅、树高、果实数量 Canopy width, tree height, fruit number	成本低、获取简便 Low cost, easy data acquisition
多光谱 Multispectral	多波段图像 Multiband imagery	叶绿素估算、营养状态分析、水分胁迫监测 Chlorophyll estimation, nutrient status assessment, water stress monitoring	植被指数 Vegetation index	光谱信息丰富, 适用于营养及水分监测 Rich spectral information, suitable for nutrient and water status monitoring
高光谱 Hyperspectral	高分辨率连续光谱 High-resolution continuous spectra	成熟度判别、病虫害初筛、营养精细监测 Maturity assessment, early disease and pest detection, detailed nutrient monitoring	含氮指数、红边参数、叶绿素指数等 Nitrogen-related index, red-edge parameter, chlorophyll index, etc.	精度高, 波段连续性强 High accuracy, continuous spectral bands
热红外 Thermal infrared	温度图像 Temperature imagery	冠层蒸散通量、果树水分状态、能量平衡监测 Canopy evapotranspiration estimation, tree water status assessment, energy balance analysis	冠层温度、能量通量 Canopy temperature, energy flux	可反映植物水分和胁迫状态 Sensitive to plant water status and stress
激光雷达 LiDAR	空间坐标点云数据 3D spatial point clouds	冠层结构重建、体积估算、叶面积指数提取 Canopy structure reconstruction, volume estimation, leaf area index extraction	冠体积、冠层空隙率、冠层密度 Canopy volume, canopy porosity, canopy density	穿透强、结构精度高 Strong penetration capability, high structural accuracy
RGB+SfM/ MVS	多角度图像/点云 Multi-view imagery/point clouds	树体几何建模、密度估算、空间分布分析 Tree geometric modeling, canopy density estimation, spatial distribution analysis	树高、冠幅、密度估计 Tree height, canopy width, density estimation	成本低、易操作 Low cost, easy implementation

SfM: 运动恢复结构; MVS: 多视图立体视觉。SfM: Structure from motion; MVS: multi-view stereo.

树高、冠幅、冠体积、冠层密度等果树结构表型参数, 直接影响果园通风透光状况与喷雾穿透效果, 亦是果实生长空间与产量潜力的重要表征(Anifantis et al., 2019; Campos et al., 2021; Zhang et al., 2023)。近年来, 随着无人机遥感与三维重建技术的

发展, 果树结构性状的提取效率与精度显著提升。例如, Gómez-Gálvez et al. (2021) 在全球橄榄种质资源库中, 基于多视角无人机影像提取树冠冠幅与体积特征, 实现了大规模树木结构性状的自动化测定, 并与地面实测数据高度一致, 为果园资源评价与精

准管理提供了可靠支撑。此外,低成本无人机搭载单镜头传感器结合 SfM 方法进行三维建模,已被用于快速估算果树高度与冠幅等关键参数,不仅处理效率显著提升,且在多种作物和地形条件下表现出良好的适应性与较高的估算精度(Díaz-Varela et al., 2015; Kelly et al., 2025)。与此同时,越来越多的研究尝试将 LiDAR 点云用于冠层体密度重建(Han et al., 2023; Jiang et al., 2024),并结合喷雾流场模拟开展结构-功能协同建模,逐步推动果园从静态结构识别迈向动态响应建模与变量作业调控一体化的发展路径。除了结构表型,果实级表型监测在果园遥感中的作用愈发突出(Cui et al., 2024; 董一波和刘立群, 2025; 晏琳等, 2025)。Akdoğan et al. (2025) 已成功利用 YOLO 等深度学习目标检测模型基于橙园 RGB 影像进行果实识别与计数,并构建果实负载回归模型,用于整园尺度的产量估算与空间变异性分析,精度达到95%以上。果实数量与尺寸分布不仅反映产量,也可用于推断生理状态或病虫害胁迫响应。

遥感监测的最终目标在于将结构-功能-管理行为进行耦合,使表型数据能够服务于决策制订。当前研究正在从静态结构建模向准动态与动态响应建模扩展,应考虑风扰、冠层波动、季节演替等非稳态特征以提升遥感结果的现场适应性。例如,结构参数(如体积、空隙率)与风速、喷雾穿透率间的相关性被用于优化变量施药策略;果实负载分布与采摘路径设计也实现了从经验向智能路径生成的转变。多时相无人机数据结合果实、枝条与树体结构的耦合分析,将推动果园管理逐步迈入感知-判断-执行闭环控制的新阶段。

尽管在感知平台、数据获取与信息提取等方面取得了显著进展,但果园遥感应用仍面临多重挑战:如树冠遮挡严重、高大作物建模困难、多传感器数据融合缺乏标准化流程、数据处理能力与实时性不足等(Donmez et al., 2021)。尤其在多源数据融合、动态冠层建模、系统集成与决策支持模型构建方面仍需深入研究。未来发展方向应聚焦于以下3个方面:一是多模态融合平台构建,如 RGB+LiDAR+高光谱联合感知;二是实时在线建模与系统耦合,如喷雾作业与遥感反馈联动;三是面向行为优化的耦合模型开发,实现遥感监测向智能施药、变量采收与自动修剪的无缝衔接。

2.2 无人机在果园中的智能施药与变量作业控制

果园作为高结构异质性作业环境,其冠层层级

复杂、通透性差且地形多样,这一特点使得传统地面施药方式在覆盖率、穿透性及作业效率方面普遍存在局限性(李扬帆等, 2022)。植保无人机因具备低空悬停、路径灵活及喷头控制精准等优势,已成为果园精准施药研究的重要载体(Biglia et al., 2022; Carreño Ruiz et al., 2024; Butler-Ellis et al., 2025)。为进一步提升施药均匀性与冠层穿透效果,空-地协同施药技术逐渐受到关注,通过无人机与地面装备的配合实现立体化精准药剂覆盖(图3)。近年来,相关研究围绕施药参数优化、喷头结构调控与感知驱动的变量施药路径等方面持续展开,并逐步形成从物理过程理解到系统智能协同的整体发展趋势(Campos et al., 2020)。

在喷雾过程中,果树冠层结构对药液空间分布的影响尤为突出。不同树形的叶面积指数与通透性差异直接影响雾滴的沉积路径与停留区域(Cheng et al., 2022; 2024)。田间研究表明,结构规整、孔隙度高的倒三角和篱壁形冠层更易形成稳定的通风廊道,无人机在中低飞行高度下可显著提升冠层中下层的喷雾穿透性与沉积均匀性(Zhang et al., 2017; Tang et al., 2018; Hou et al., 2019);相比之下,圆头型冠层结构则加剧了内外层沉积差异。这一差异凸显了冠层结构对下洗气流传播及沉积分布间复杂耦合机制的调控作用。

飞行高度与飞行速度是决定无人机喷雾动力学特性及冠层沉积分布的核心操作参数(王昌陵等, 2017)。飞行高度直接影响下洗气流的动压衰减、雾滴在到达冠层前的能量损失及其与枝叶结构的相互作用。已有研究表明,过高的飞行高度会导致动能不足,下层冠层覆盖率显著下降,而过低的飞行高度则可能诱发近地回流、雾滴再悬浮和非靶标沉积风险(如喷雾偏移与地面损失增加)(Sarri et al., 2019; Biglia et al., 2022)。因此,合理的飞行高度一般控制在1.2~2.0 m区间,此飞行高度下动压输入与冠层空间覆盖之间可取得较好的平衡(Tang et al., 2018; 张瑞瑞等, 2020)。飞行速度主要通过调控下洗气流的牵引能力与雾滴的空气动力学响应来影响沉积靶向性与附着稳定性。飞行速度增加虽可增强穿透能力,但同时会扩大雾滴谱宽,使沉积均匀性下降。无人机在桃园的喷雾试验表明,当飞行速度由1 m/s提升至3 m/s时,雾滴中值粒径由约300 μm 增大至约500 μm ,导致沉积变异系数升至150%,表现为高穿透但低均匀性(Li et al., 2022)。Zhang et al. (2016) 对不同树形与无人机喷雾高度的系统试验进一步指

出,在约1.2 m的飞行高度下,冠层中层区域的雾滴沉积密度最高且空间变异性最低,雾滴穿透性和均匀性均表现最佳。这表明中等飞行高度能够在动能

衰减与冠层阻滞之间构建更稳定的雾滴传输路径,从而实现更高的喷雾效率。



A: 果园空-地协同立体施药示意图; B: 空中施药装备; C: 地面施药装备。A: Schematic diagram of air-ground cooperative stereo pesticide application in orchards; B: aerial pesticide application equipment; C: ground pesticide application equipment.

图3 果园空-地协同立体施药系统

Fig. 3 Air-ground cooperative stereo spraying system for orchards

喷头类型在无人机喷雾系统中发挥着核心作用,其雾化特性直接决定雾滴粒径分布、谱宽结构以及雾滴在下洗气流中的空气动力学行为,是影响雾化质量、抗飘移性能和冠层穿透能力的关键因素(何勇等,2018;Guo et al.,2022;Wang et al.,2021)。通常而言,粒径较小的雾滴更易受到环境风场扰动与蒸发作用的影响,从而增加飘移损失;而大粒径雾滴虽具有更高动能,有利于穿透冠层中下层,但因覆盖范围受限可能导致沉积均匀性下降。由此可见,喷头类型不仅影响雾滴的初始物理特性,而且通过调节雾滴与旋翼尾流的耦合效率还可调控冠层空间中的沉积结构。当前无人机果园施药中应用较广的喷头包括液压扇形喷头、离心式喷头以及空气诱导喷嘴(王昌陵等,2020;王志翀等,2020)。其中,空气诱导喷嘴因能够生成夹带气体的中等粒径雾滴,在降低飘移与提升靶标区域沉积方面具有显著优势

(Wang et al.,2021;Guo et al.,2022)。在葡萄园等复杂地形条件下,Biglia et al.(2022)的研究进一步强调了喷头结构与风场相互作用的重要性,合适的喷头类型与飞行策略匹配可显著提升冠层中下层的沉积密度,同时减少非靶标区域损失。此外,喷头的喷角设计与安装姿态亦是决定无人机喷雾动力结构的重要因素。当喷头喷角与旋翼尾流方向保持一致时能够提高动量传递效率,促进雾滴更有效地进入冠层内层(Carreño Ruiz et al.,2024)。在国内的实际应用中,诸如IDK90015等空气诱导喷嘴已广泛用于无人机果园施药,其在增强冠层外层与中层覆药的同时,有效抑制了药剂近地飘移(Tang et al.,2018;Guo et al.,2022)。相关田间试验进一步证实,中等飞行高度(约1.2~2.0 m)与适宜喷头类型的组合往往能在沉积效率与层间均匀性之间取得最佳平衡(Zhang et al.,2017;Tang et al.,2018)。总体来看,

喷头类型、喷角设计及其与下洗气流的匹配程度共同构成了无人机喷雾动力学的核心控制环节,对优化果园冠层空间的沉积分布具有决定性意义(张豪等,2019)。

变量施药技术的提出旨在突破果园全园均量喷雾的传统施药模式,通过感知系统提取果树空间结构或目标信息,动态生成喷量处方图,并驱动路径规划系统与喷头控制单元实现按需变量喷雾(图4)。该系统通常由结构感知-处方生成-变量执行三层组成。结构感知层常采用LiDAR点云或RGB/多光谱图像识别方法提取树体位置、体积、叶面积指数或叶面积密度等参数(Han et al., 2025)。处方生成层

常采用结构参数与喷量间的多项式拟合模型或经验分级规则实现喷量调节控制,也有部分研究尝试引入机器学习模型,通过结构-沉积响应样本训练预测雾滴强度,实现跨品种冠层结构的自适应变量控制。执行层采用变量喷雾控制,涉及路径精细调度、喷头开关控制与流量调节等环节,需在飞控系统中构建稳定、低延迟的数据接口。目前主流飞控平台多采用脉冲宽度调制(pulse width modulation, PWM)信号调控喷头工作状态,尚缺乏喷头级反馈机制(漆海霞等,2021)。为此,通过在无人机平台集成边缘计算模块,可构建实时感知-控制闭环,有效提升变量施药的控制精度与作业稳定性。

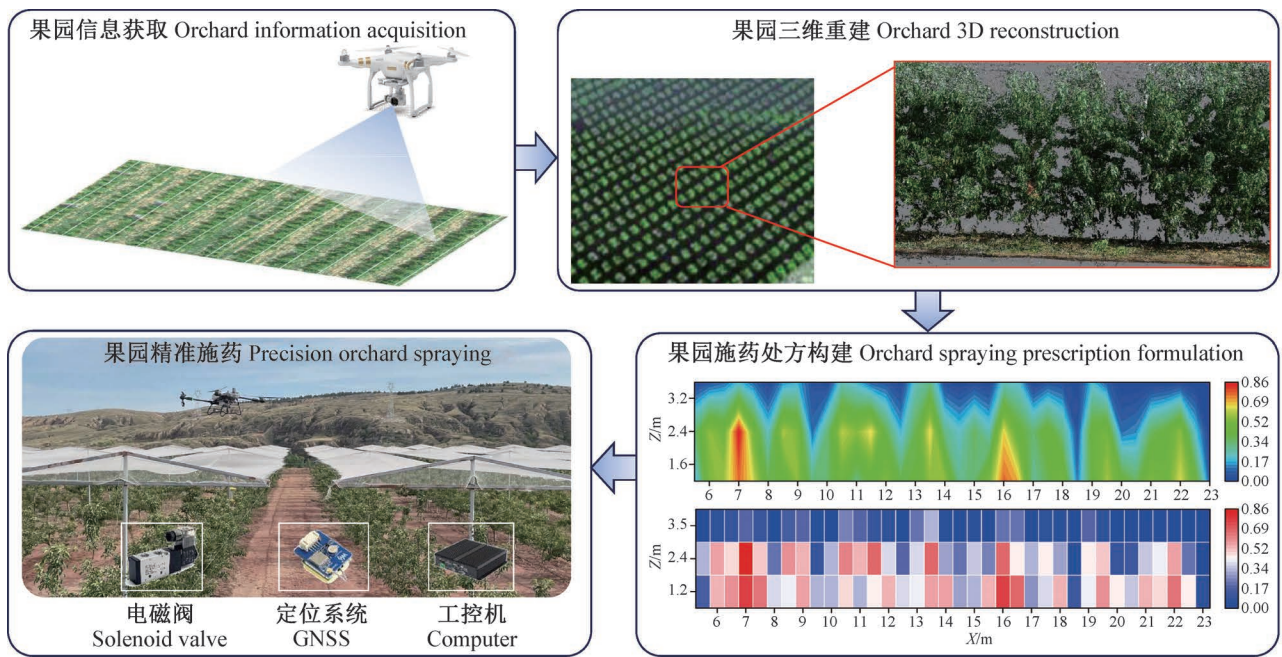


图4 果园结构感知-处方生成-变量执行施药系统

Fig. 4 Orchard spraying system for structure perception, prescription generation, and variable-rate application

尽管变量施药技术已于试验条件下在提升靶标沉积效率、降低药液使用量方面展现出显著优势,但在实际果园环境中仍存在诸多问题(Qi et al., 2023; Yan et al., 2023; Yu et al., 2025)。其一,感知数据存在遮挡干扰严重、不同光照条件下稳定性差的问题,导致处方图生成精度受限;其二,不同果树种类、冠层结构与管理模式差异较大,缺乏适用于多场景的通用结构-喷量映射模型;其三,执行系统响应时间长、通信延迟高、变量控制过程中易出现过喷或延喷等现象;其四,当前大多数变量控制系统为开放回路,缺乏雾滴在线检测与实时反馈机制,难以根据施药效果动态调节作业策略。因此,未来果园无人机变量施药系统的发展应着重于以下4个方面:一是

构建多模态融合感知模型,提升结构信息鲁棒性;二是开发高时效、高泛化性的喷量控制算法,实现不同区域、树种、风速条件下的自适应变量施药;三是构建喷头级边缘控制系统,实现毫秒级控制响应;四是同时引入雾滴实时监测技术,构建感知-决策-执行的闭环自适应变量控制体系,从而全面提升无人机在果园复杂环境下的智能施药能力。

2.3 数据智能分析与人工智能融合

随着果园无人机遥感、表型监测技术的成熟,数据量与结构日益复杂,传统人工分析效率低且难以挖掘深层次关联。因而,数据智能分析诸如机器学习、深度学习、融合算法等成为从数据获取向智能决策跃升的关键环节(Zhang et al., 2022; Zhao et al.,

2024; Yang et al., 2025)。当前研究在三大维度同步推进:高维特征提取、模型驱动决策支持、实时在线系统集成。

首先,在高维特征提取层面,无人机平台所收集的遥感图像、点云数据、果实负载计数、喷雾沉积信息等构成了果园信息的多维时空特征(Belmonte et al., 2023)。通过深度学习网络可实现果实自动识别、数量估算及质量预判。例如, Yang et al. (2024)提出了一种轻量级深度检测模型ELD (efficient light-weight object detector), 该模型可用于复杂果园环境下的果实识别, 识别准确率达87.4%, 相比传统模型, ELD模型参数减少且实时帧率达156 FPS。Li DH et al. (2023)基于无人机图像与深度学习算法构建了龙眼产量估算模型, 该模型在块级估算中的决定系数约为0.71。这些研究表明借助人工智能方法可在结构层面监测果树状态, 而且可在果实层面建立识别-计数-预估流程, 从而为变量施药、差区采摘提供数据支持。其次, 在模型驱动决策支持层面, AI已逐渐从识别任务延伸至管理决策过程。例如, Zhang et al. (2021)以果园为研究对象进行综述, 指出利用无人机进行果园管理的关键在于将传感器数据、分析模型与管理行为耦合起来。具体而言, 在变量施药场景中, 可通过将冠层结构参数、雾滴沉积特征、风速/风向数据等输入机器学习或深度网络, 产生结构-喷量映射, 从而生成处方图并驱动喷雾系统执行。然而, 要提升系统的实际应用普适性与实时性, 仍需在迁移学习、小样本学习、模型轻量化部署等关键技术取得突破。最后, 在实时在线系统集成层面, 果园管理正在向实时反应、边缘处理、闭环控制转变。无人机所获取的数据若能即时反馈至控制系统, 则可实现喷雾路径调整、喷头开关控制、变量喷量切换等闭环行为。这一趋势体现在实时检测-动态决策-执行反馈体系的构建中。例如, Zhang et al. (2021)指出未来无人机在果园中的应用应构建感知-决策-执行三位一体架构, 并解决模型泛化、系统延迟、数据融合瓶颈。

当前的深度学习研究多侧重于监测或识别环节, 而将识别结果进一步转化为可执行的管理策略仍缺乏在真实果园场景中的大规模验证。此外, 结构信息、功能参数与施药效果等多源数据的融合仍受到数据异构性、时序不同步与标注成本高等因素的制约, 限制了模型在复杂环境中的稳定性与可推广性。同时, 算法与硬件平台尚未完全实现树体尺度或果园尺度的实时闭环控制, 系统在响应时间、

可靠性与成本方面仍存在瓶颈, 难以满足精细化变量施药的快速决策需求。未来的研究方向应致力于构建可跨树种、可跨地形应用的结构-功能-行为统一映射模型, 以实现管理策略在不同果园场景中的自适应迁移。另外, 有必要推进边缘智能与云端协同架构的深度融合, 提升系统的实时处理能力与决策闭环速度, 并探索将AI模型直接嵌入无人机喷雾平台, 使其具备从感知、分析到执行的自主运行能力, 为真正意义上的智能果园奠定技术基础。

3 热点主题演变与全球研究格局

为系统梳理无人机在果园领域的研究演进路径与国际合作态势, 本文基于Web of Science核心合集(SCI-Expanded)开展文献计量分析, 聚焦“无人机在果园中的应用”主题。通过限定检索式: TS=(unmanned aerial vehicle OR UAV OR drone OR multicopter OR multi-rotor OR quadcopter OR rotary-wing UAV OR helicopter UAV) AND (orchard OR fruit tree OR fruit orchard OR vineyard OR citrus OR apple OR pear OR peach OR olive OR mango OR tree crop OR perennial crop), 从2015年1月1日至2025年11月30日间公开发表的相关SCI论文中共筛选出759篇。基于CiteSpace 6.4.R1软件对关键词、国家、机构等进行共现与聚类分析, 以揭示无人机果园研究的知识结构与发展热点。

随着果园数字化转型与无人机多传感平台的广泛部署, 研究热点呈现出明显的从感知获取向智能决策与作业控制演进的趋势(图5)。在早期阶段(2015—2018年), 关键词突现集中在canopy temperature、NDVI、chlorophyll fluorescence、deficit irrigation等术语, 反映出研究者对果树生理状态、水分调控与叶片参数提取的关注, 研究内容以遥感指标提取和作物状态监测为主。进入中期阶段(2019—2021年), 研究逐步向果园结构感知与果实检测等任务转移, 如3D reconstruction、fruit detection、RGB imagery、LiDAR、point cloud等成为高频关键词, 标志着果园结构建模与三维重建成为热点。与此同时, 深度学习模型的引入推动了识别精度的提升, deep learning、semantic segmentation、YOLO、convolutional neural network等技术关键词在此期间快速突显。在当前阶段(2022年至今), 研究重点进一步聚焦于数据智能化处理与变量作业控制, droplet deposition、spray drift、path planning、variable-rate

spraying 等关键词频繁突现,显示出无人机在果园中正从静态感知工具演变为精准作业与实时决策的关键节点。关键词聚类分析显示,deep learning、

remote sensing、droplet deposition 构成当前研究的核心主题群体,体现了从作物状态识别到施药控制的感知-决策-执行一体化技术路径。

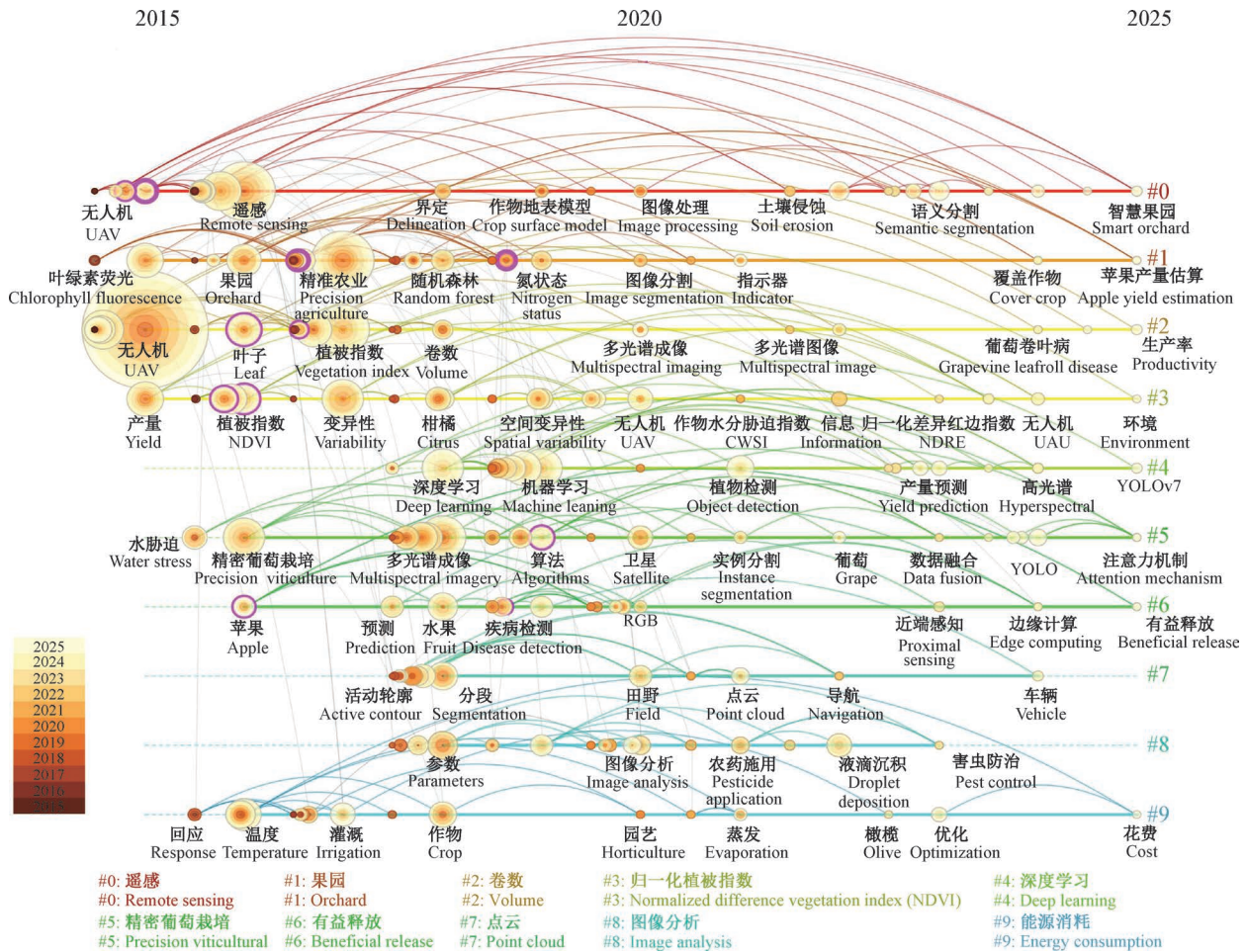


图5 无人机果园应用研究关键词时间演进与聚类图(2015—2025年)

Fig. 5 Temporal evolution and clustering of keywords in UAV orchard application research (2015—2025)

在全球研究格局方面,文献合作网络显示,中国、意大利、西班牙与美国是无人机在果园应用领域的主要研究力量(图6)。其中,中国在变量施药系统集成、三维重建算法、果实检测等方面形成明显优势,意大利、西班牙、美国紧随其后,分别在果园精准农业理论、多光谱融合分析和作业平台开发方面具有代表性成果。中国在近5年的相关研究增长最快,特别是在结合果园复杂冠层结构的深度学习方法方面产出颇丰,展现出从算法开发到系统应用的强劲动能。在研究机构层面,高影响力研究主要集中于国家级农业研究机构与农业大学。如中国农业大学与华南农业大学、西班牙高等科学研究理事会、意大利国家研究委员会、美国农业部等在无人机果园应用研究方面均有系统性成果,并与多个国家的相关研究机构构建了稳定的合作网络(图6)。合作

图谱显示,发达国家在技术算法研究上具有主导地位,而中国等国家则更多聚焦于实际场景验证与系统集成,体现出区域研究侧重的互补性。此外,研究合作日趋紧密,跨国机构联合开展的果园智能管理项目不断增多,为未来构建多尺度、可迁移的果园管理模型提供了坚实基础。

4 关键挑战与未来发展方向

尽管果园无人机技术已在感知精度、变量施药与智能控制等方面取得重要进展,但其在系统部署与大规模推广过程中仍面临多重挑战。首先,果园冠层结构复杂、遮挡严重、地形多变,导致当前感知系统在非理想条件下精度下降,鲁棒性不足,尤其在多时相与风扰环境中,结构重建与参数提取稳定性差。其次,变量施药系统核心的结构-喷量映射模

型普遍缺乏通用性和可迁移性,现有方法多依赖场景特定规则或单一训练数据,难以适应不同树种、冠层结构与气象条件下的精准控制需求。进一步来看,施药控制仍以“开放回路”为主,缺乏实时反馈与在线调节机制,喷头级控制粒度有限,系统响应滞后,难以构建快速闭环。与此同时,无人机与地面作

业装备等多平台间协同不足,接口标准不统一,任务协同与资源调度机制尚不健全,限制了果园智能系统的集成深度。此外,尽管深度学习模型在果实识别与结构提取中表现优异,但其泛化能力弱、决策逻辑不可解释等问题,制约了其在关键任务中的可靠性与实用性。

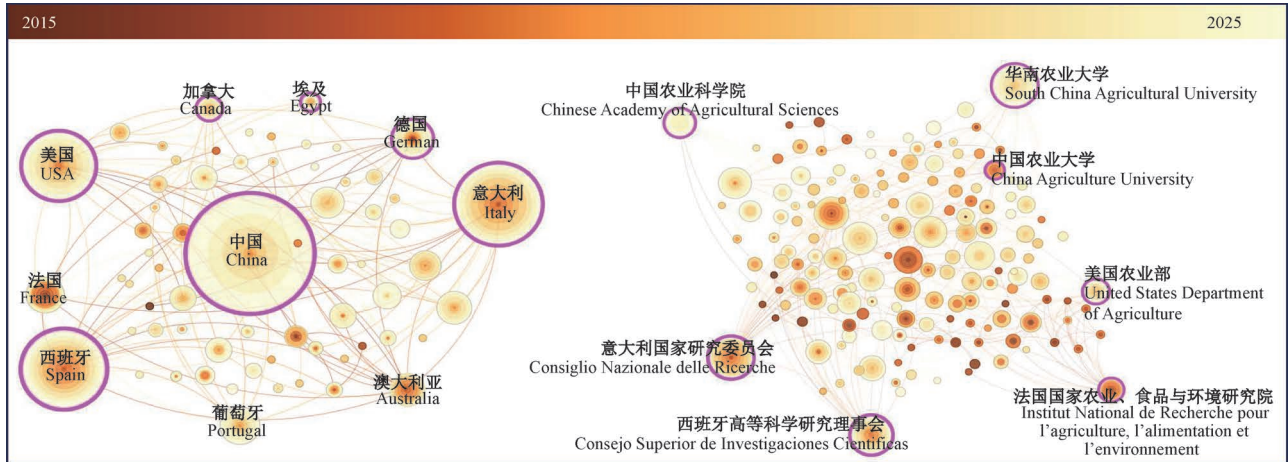


图6 无人机果园应用研究的合作网络(2015—2025年)

Fig. 6 Collaboration network of UAV orchard application research (2015—2025)

未来亟需构建高鲁棒性多模态感知系统,提升复杂环境下结构重建能力;发展融合风场与喷雾动力的多变量耦合模型,实现结构-喷量映射的跨场景通用性;部署边缘计算架构与雾滴实时监测技术,构建喷头级闭环控制体系;推动多平台间的标准化协同接口建设,实现感知-决策-执行的系统协同;同时发展具备物理约束与知识引导的可解释AI模型,以支撑无人机在果园复杂环境中的智能、安全、可靠运行。这些挑战的突破将为构建真正意义上的智能果园提供关键支撑与理论基础。

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