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## 采后番茄灰霉病早期检测与品质评价的多模态传感研究进展

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**摘要:** 番茄灰霉病主要由灰葡萄孢菌 *Botrytis cinerea* 侵染引起。现有研究多侧重于番茄 *Solanum lycopersicum* 叶片尺度灰葡萄孢菌的田间检测或采用单一传感模态, 尚缺乏以采后果实为核心, 系统整合多检测模态并衔接病理机制的文献梳理。多模态传感技术可从多维信号捕捉病害早期微弱变化, 已成为重要的早期预警手段。以“采后番茄灰霉”“光谱”“机器视觉”“电子鼻”“多模态融合”等为关键词组合, 以近 10 a 研究为主, 围绕病理机制、光谱、机器视觉、电子鼻及多模态融合梳理研究进展。成熟诱导易感, 细胞壁降解及挥发性有机化合物变化为早期检测提供生物学基础。光谱可表征内部组织与生化变化, 机器视觉适于表面筛查, 电子鼻可感知气味变化。番茄成熟度评价中的多模态融合优势为灰霉病检测提供了方法参考。未来需构建覆盖不同果型、品种、成熟度与储藏条件的果实时序数据集, 发展可解释融合模型并验证跨设备泛化能力, 推进便携式装备与在线预警应用。表 3 参 81

**关键词:** 番茄; 灰霉病; 光谱成像; 机器视觉; 电子鼻; 多模态融合

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## Research progress on multimodal sensing for early detection of gray mold and quality assessment in postharvest tomatoes

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**Abstract:** Existing studies primarily focus on field detection of gray mold caused by *Botrytis cinerea* at the leaf scale in tomatoes (*Solanum lycopersicum*) or employ a single sensing modality, lacking a systematic review that centers on postharvest fruit integrating multiple sensing modalities and linking them to pathological mechanisms. Multimodal sensing technology can capture subtle changes in early-stage disease from multidimensional signals and is an important means for early warning. Using keywords including “postharvest tomato gray mold”, “spectral imaging”, “machine vision”, “electronic nose” and “multimodal fusion” as combinations, this review summarizes research progress in pathological mechanisms, spectroscopy, machine vision, electronic noses, and multimodal fusion in the past 10 years. Mature-induced susceptibility, cell wall degradation, and changes in volatile organic compounds provide the biological basis for early detection. Spectroscopy characterizes internal tissues and biochemical changes. Machine vision supports surface screening, and electronic noses detect odor changes. The multimodal fusion benefits in tomato maturity

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assessment provide a methodological reference for gray mold detection. Future research should establish a real-time data set covering different fruit types, varieties, maturity stages, and storage conditions, develop interpretable fusion models and verify cross-device generalization ability, and promote portable sensing equipment and online early-warning applications. [Ch, 3 tab. 81 ref.]

**Key words:** tomato (*Solanum lycopersicum*); gray mold; spectral imaging; machine vision; electronic nose; multimodal fusion

灰葡萄孢菌 *Botrytis cinerea* 是引起番茄灰霉病的主要病原真菌<sup>[1]</sup>, 造成采后番茄 *Solanum lycopersicum* 果实软腐<sup>[2]</sup>、霉层形成<sup>[3]</sup> 及风味劣变<sup>[4]</sup>。侵染早期可见症状不明显<sup>[5]</sup>, 而色素、水分、细胞壁及代谢已发生变化<sup>[6-7]</sup>, 使人工巡检难以及时识别, 需发展快速、无损的早期检测方法<sup>[8-10]</sup>。

近年来, 围绕果蔬采后品质与病害无损检测, 已有若干相关综述发表: JELALI<sup>[11]</sup> 和 DAS 等<sup>[12]</sup> 分别综述了番茄病害深度学习检测, 但主要聚焦于叶片尺度的田间场景。ALI 等<sup>[13]</sup> 综述了电子鼻在采后果蔬病害早期检测中的应用, 但未涉及与其他传感模态的融合。OLADIPO 等<sup>[14]</sup> 综述了番茄采后保鲜技术, 但未系统讨论无损检测技术体系。与上述工作不同, 本研究以采后番茄灰霉病为主线, 系统整合病理机制与多模态无损检测研究, 重点探讨灰霉病早期可感知信号的生物学基础, 不同检测模态的适用边界, 及每种独立模态在多模态融合框架中的协同作用, 并明确识别当前研究从叶片向果实、从实验室向产线迁移中的关键瓶颈与未来方向。

## 1 番茄灰霉病的生理与病理机制

### 1.1 潜伏侵染与病程启动

番茄灰霉病具有明显的潜伏侵染特征, 病原可在田间初始侵染后以静止状态存在, 也可在采后经机械损伤或果面裂口再次侵入<sup>[15]</sup>。当果实进入后熟、衰老或高湿储运环境时, 潜伏病菌会迅速转入活动病斑阶段并持续扩展<sup>[16]</sup>。从病理过程看, 病原早期侵染依赖伤口、角质层薄弱区及细胞壁降解过程, 这也是其由潜伏态转入活动病斑阶段的重要基础。ROMANAZZI 等<sup>[17]</sup> 进一步指出, 灰葡萄孢菌在低温储藏条件下仍可维持缓慢的菌丝扩展和组织侵染活性, 低温储藏仅能延缓病程进展而无法彻底阻断侵染链条。因此, 番茄灰霉病的发生实质上是从田间到储运期间的连续过程, 这也是早期难以凭外观识别的主要原因<sup>[18]</sup>。

### 1.2 番茄果实成熟诱导易感与异常促熟

灰葡萄孢菌能够主动促进番茄后熟进程, 从而增强致病能力。SILVA 等<sup>[7]</sup> 通过信使核糖核酸 (mRNA) 测序证实, 灰葡萄孢菌侵染可上调番茄乙烯生物合成基因表达, 加速果实转色和质地软化; 基于酶联免疫吸附测定 (ELISA) 的糖组学技术揭示, 侵染果实的细胞壁多糖变化与自然成熟果实高度相似。在未熟果实接种实验中, 果胶酶基因 (*Bcpg1/Bcpg2*) 的双基因敲除突变体后, 即使果实随后成熟, 也仍不能由潜伏态转为活跃侵染, 说明果胶降解是灰葡萄孢菌启动侵染和诱导宿主成熟的必要条件。因此, “诱导宿主成熟—促进细胞壁解聚—增强病原扩展” 构成了采后灰霉病发展的正反馈机制。

### 1.3 品质响应及其可传感基础

在采后番茄灰霉病的病程发展过程中, 番茄果实已出现色泽、硬度、呼吸代谢和挥发性代谢等多维变化。这些变化构成了不同检测模态的生物学靶点: 色素衰减与组织结构变化为光谱检测提供了反射或吸收特征响应基础; 表面褪色、水渍化为机器视觉检测提供了可见表面特征; 挥发性有机化合物组成与丰度的代谢重编程为电子鼻检测提供了气味指纹信号来源。上述多维信号的异步性和互补性为不同模态间互补提供依据。

## 2 光谱技术在番茄灰霉病检测领域研究进展

### 2.1 灰葡萄孢菌侵染与正常成熟果实的光谱区分

正常成熟与灰葡萄孢菌侵染均会改变果实色素、组织结构及含水状态, 光谱判别需结合正常成熟基

线、局部空间异常和多波段特征。MA 等<sup>[19]</sup>利用时间分辨叶绿素荧光寿命，监测果实成熟与早期衰败，为时序基线建模提供参照。JAVIDAN 等<sup>[20]</sup>结合图像与高光谱识别番茄叶片真菌病害；KAPETAS 等<sup>[21]</sup>结合五波段图像、自注意力模型和实时荧光定量聚合酶链式反应，实现番茄叶片灰霉病早期检测。

现有研究仍以番茄叶片为主，采后果实应用需进一步控制成熟度差异。对草莓 *Fragaria × ananassa* 叶片和果实的研究也支持光谱识别早期真菌侵染<sup>[22–26]</sup>，但相应波段和判别阈值仍需在番茄果实上验证。

2.2 灰葡萄孢菌侵染相关敏感波段及应用

XIE 等<sup>[8]</sup>利用高光谱区分健康番茄叶片与不同感染程度，FAHRENTTRAPP 等<sup>[9]</sup>采用五波段传感器监测番茄叶片，在受控条件下最早于接种后 9 h 识别感染区域，720 nm 红边和 840 nm 近红外通道判别力较高。这些结果提供了病程分级及少波段早期检测的依据，但仍需在采后果实中验证。

番茄品质研究已覆盖成熟度、硬度、糖酸和色素预测<sup>[27–30]</sup>，并延伸至采前监测、便携式和手持检测<sup>[31–34]</sup>。低温胁迫番茄幼苗研究展示了由高光谱筛选波段、再简化为多光谱的路线<sup>[35]</sup>；苹果 *Malus domestica* 霉心病<sup>[36]</sup>和表面缺陷<sup>[37]</sup>、马铃薯 *Solanum tuberosum* 黑心病<sup>[38]</sup>的光谱检测也提供了方法参照。代表性工作见表 1。

表 1 光谱技术在番茄相关研究中的代表性工作

| Table 1 Representative works on the application of spectroscopic techniques in the study of tomato |                           |         |  |
|----------------------------------------------------------------------------------------------------|---------------------------|---------|--|
| 研究对象和任务                                                                                            | 结论                        | 参考文献    |  |
| 番茄品质、成熟度、硬度等品质指标                                                                                   | 支持品质指数、番茄红素及可溶性固形物含量/硬度建模 | [28–30] |  |
| 便携式光谱与多品种评价                                                                                        | 可估测色泽、干物质、硬度、色素等；酸度预测较弱   | [32–34] |  |
| 低温胁迫番茄幼苗多酚估测                                                                                       | 由高光谱筛选波段，简化为多光谱传感器        | [35]    |  |
| 番茄叶片灰葡萄孢菌感染                                                                                        | 高光谱可用于预测过氧化物酶活性           | [39]    |  |
| 番茄病毒感染叶片分级                                                                                         | 高光谱可用于病害程度分级              | [40]    |  |

3 机器视觉和深度学习在番茄灰霉病检测领域研究进展

机器视觉通过颜色、形状和纹理进行番茄成熟度、缺陷及病害识别，成本低，易于在线部署，但对采后灰霉病症前检测研究仍有限<sup>[41–42]</sup>。传统阈值与几何方法易受光照、遮挡和个体差异影响；单阶段目标检测模型 (YOLO) 及轻量化网络改善了成熟度与外观检测，并向实时部署发展<sup>[43–46]</sup>。

现有高精度结果多来自受控场景，储运中的反光、冷凝水和遮挡仍影响泛化<sup>[11–12,47]</sup>。常规彩色视觉适合症状出现后的在线筛查，潜伏侵染的内部生理变化则需结合光谱等信息。代表性工作见表 2。

表 2 机器视觉在番茄灰霉病及相关任务中的代表性研究

| Table 2 Representative studies of machine vision in tomato gray mold and related tasks research |                                 |                                 |         |
|-------------------------------------------------------------------------------------------------|---------------------------------|---------------------------------|---------|
| 研究对象和任务                                                                                         | 方法类型                            | 主要结果或结论                         | 参考文献    |
| 番茄成熟度及外观品质识别                                                                                    | YOLOv5s、改进 YOLOv4/YOLOv5s-lite/ | 相较传统方法，深度学习在环境适应性和检测精度上更具优势     | [43–44] |
|                                                                                                 | YOLOv7，兼顾识别、轻量化与实时性             |                                 | [45–46] |
| 番茄外观缺陷检测                                                                                        | 深度学习：残差网络(ResNet)迁移学习           | 可较有效地区分健康果与缺陷果，减少人工特征工程依赖       | [47]    |
| 番茄植株病害诊断                                                                                        | 深度学习：显式控制隐藏类别策略                 | 强调跨场景泛化问题，提示高精度结果未必可直接迁移到复杂实际环境 | [48]    |
| 棚室番茄果实识别                                                                                        | 深度学习：融合注意力机制的识别模型               | 提高了棚室环境下果实识别模型的可靠性              | [49]    |
| 灰霉病早期症状多光谱分割                                                                                    | 语义分割网络U-Net++ 与MobileViT-S 编码器  | 接种后第2天可定位病斑，总体准确率90.1%          | [50]    |
| 番茄灰霉病图像数据集构建                                                                                    | 温室实拍标注数据集                       | 含82张灰霉病图像，支持分类与目标检测任务           | [51]    |

此外，GIAKOUMOGLOU 等<sup>[50]</sup>结合多光谱和深度学习分割灰霉病感染区域，在黄瓜 *Cucumis sativus* 植株接种后第 2 天获得 0.375 的交并比 (intersection over union, IoU)，总体准确率为 90.1%，为病程定位提供了方法参照。LIU 等<sup>[51]</sup>发布包含番茄灰霉病的温室病害标注图像集，为模型训练提供了数据基础。

## 4 电子鼻在番茄灰霉病检测领域研究进展

番茄在采后成熟、衰老及病原侵染过程中会持续发生挥发性有机化合物组成及丰度变化,使气味指纹成为连接品质响应与病害发生的前置信号。与侧重单体化合物解析的气相色谱-质谱联用技术 (GC-MS) 不同,电子鼻更擅长对整体气味模式进行无损、快速和低成本识别。

### 4.1 成熟度混杂因素与气味漂移

电子鼻最早主要用于表征番茄成熟相关的挥发性有机化合物变化。相关研究表明:电子鼻能够较清晰地区分不同成熟阶段的番茄样品<sup>[52]</sup>。这一结果提示了成熟过程会显著改变气味形式,因此成熟度是番茄病害电子鼻识别中必须控制的重要混杂因素。若不区分正常成熟程度导致的挥发性有机化合物漂移,就难以准确区分病原侵染引起的异常气味变化与自然后熟引起的正常气味变化。

电子鼻研究进一步由成熟度分级拓展到采后品质预测。已有研究利用电子鼻对硬度、可溶性固形物含量和 pH 等品质指标进行无损建模<sup>[53]</sup>。这说明挥发性特征还可用于果实品质指标的间接预测。

### 4.2 品质响应表征与模态互补

已有研究将电子鼻与机器视觉结合用于番茄成熟等级识别和硬度预测,并证明融合系统优于单一检测技术<sup>[54]</sup>。这说明气味信息与颜色、外观等视觉特征具有明显互补性。因为病害早期往往首先表现为代谢异常和气味偏移,而并非清晰可见的霉层或组织腐烂,因此电子鼻更适合承担前端预警角色,而视觉信息更适合后期症状确认与分级。

### 4.3 灰霉病直接证据与应用边界

近年的工作开始直接面向与番茄灰霉病相关的挥发性有机物及其便携式检测。代表性研究开发了面向番茄成熟度、健康状态及灰葡萄孢菌感染状态识别的便携式多传感器系统,并证明其能够区分不同成熟度与感染状态<sup>[55]</sup>。更直接的证据来自针对番茄灰霉病抑制与气味监测的研究。该类研究揭示了电子鼻不仅能够区分与感染相关的异常气味,还可跟踪灰霉病导致的霉味缺陷与风味下降过程<sup>[56]</sup>。可见,电子鼻能够进一步刻画灰霉病造成的品质下降程度,是连接病害进程、风味响应和货架期变化的检测手段。

目前,该方向仍主要依赖理想实验条件和人工处理试验。抑菌处理研究显示,喜树碱对灰葡萄孢菌的菌丝生长及番茄离体叶片接种病斑具有抑制作用<sup>[1]</sup>。现有研究对自然潜伏侵染样本的识别能力及模型跨设备稳定性的验证仍不足。其他果蔬病害中的电子鼻与数据融合研究则为番茄灰霉病模型设计和后续多模态融合提供了方法参考。相关研究的代表性工作见表 3。

表 3 番茄电子鼻检测的代表性研究

Table 3 Representative studies of electronic nose applications in tomatoes

| 研究对象和任务      | 方法/系统                  | 主要结论                          | 参考文献 |
|--------------|------------------------|-------------------------------|------|
| 番茄成熟度识别      | PEN2 电子鼻+主成分分析/线性判别分析  | 可区分不同果实成熟阶段样品                 | [52] |
| 樱桃番茄采后品质预测   | 电子鼻+偏最小二乘回归/极限学习机      | 可用于鲜度分级以及硬度、可溶性固形物含量、pH 等品质建模 | [53] |
| 番茄成熟/健康/感染识别 | 便携式多传感器 TOMATO-NOSE 系统 | 可区分不同成熟与感染状态                  | [55] |
| 灰霉病抑制与香气缺陷监测 | 电子鼻结合处理试验              | 可跟踪感染相关异常气味与霉味缺陷变化            | [56] |

电子鼻也已被用于马铃薯真菌性腐烂早检<sup>[57]</sup>、苹果霉心病识别<sup>[58]</sup>和梨腐败分级<sup>[59]</sup>。近年来关于番茄灰霉病相关挥发性有机化合物的生物学研究也为电子鼻检测提供了重要的机制支撑。SHI 等<sup>[60]</sup>研究发现:出芽短梗霉菌 *Aureobasidium pullulans* S2 在抑制番茄灰霉病过程中可产生 2-苯乙醇、2-庚醇等具有抑菌活性的挥发性有机化合物,说明灰霉病发生与防御过程中的挥发性有机化合物组分变化具有明确的生物学基础。ZHANG 等<sup>[61]</sup>进一步证实,伯克霍尔德氏菌 *Burkholderia* sp. BV6 产生的挥发性有机化合物 (尤其是 2-壬醇) 对樱桃番茄灰霉病具有显著抑制效果,且挥发性有机化合物的抑菌活性具有广谱性。YUN 等<sup>[62]</sup>则从代谢通路层面揭示了暹罗芽孢杆菌 *Bacillus siamensis* 产生的挥发性有机化合物可通过改变灰葡萄孢菌的代谢途径和致病性来抑制樱桃番茄采后灰霉病,这为理解电子鼻信号的生物学可解释性提供了参考。

上述研究表明:番茄灰霉病的发生、发展和拮抗过程均伴随着特征性挥发性有机化合物组分的变

化。这些研究为挥发性有机化合物相关检测提供了机制线索，其诊断价值仍需在受感染果实中验证。可见，电子鼻作为挥发性有机化合物模式识别工具，在灰霉病早期预警中的应用具有明确的生物学依据。

## 5 多模态融合与可迁移借鉴

### 5.1 番茄相关多模态融合研究

现有番茄灰霉病检测融合研究主要涉及叶片病害与果实品质 2 个层面<sup>[63]</sup>。多光谱荧光-反射融合用于叶片灰霉病检测，早期识别精度与病程分类精度分别为 97.21% 和 97.56%<sup>[41]</sup>；多维数据融合亦可用于番茄病叶分级<sup>[64]</sup>。果实研究中，图像、可见光-近红外光谱与触觉融合的成熟度识别准确率为 99.4%，内外成熟不一致样品为 94.4%，总体准确率较最优单模态提高 5.2 个百分点<sup>[63]</sup>；视觉与电子鼻融合的硬度预测决定系数 ( $R^2$ ) 为 0.94<sup>[54]</sup>。上述结果分别支持病害检测和品质评价，尚不能直接等同于采后果实灰霉病早期检测性能。

### 5.2 迁移案例与方法启示

其他果实研究中，可见光与高光谱融合用于番木瓜 *Carica papaya* 成熟度估计<sup>[65]</sup>；光谱与电子鼻结合已用于猕猴桃 *Actinidia deliciosa* 后熟品质跟踪<sup>[66]</sup> 及苹果霉心病检测<sup>[67]</sup>，为番茄多模态检测提供了方法参考。融合增益取决于模态互补性、数据对齐和策略选择<sup>[68]</sup>；向灰霉病迁移时，仍需区分正常成熟与感染信号。

其他对象的研究包括柚 *Citrus maxima* 果实外观与内部品质关联分析<sup>[69]</sup>，相关综述分别涉及食品电子鼻与电子舌应用，如苹果<sup>[70]</sup>、荔枝 *Litchi chinensis*<sup>[71]</sup>、鸡蛋<sup>[72]</sup> 和水稻 *Oryza sativa* 籽粒的无损品质检测<sup>[73]</sup>，以及蔬菜种子病害识别<sup>[74]</sup>；果蔬高光谱检测综述<sup>[75]</sup> 提供了技术背景。肉类腐败的电子鼻-多光谱融合检测<sup>[76]</sup>，玉米 *Zea mays* 种子活力的交叉注意力融合研究<sup>[77]</sup> 和番茄早疫病叶片色素高光谱估测<sup>[78]</sup>，分别为融合结构设计与病害生化特征表征提供参考。

### 5.3 面向采后番茄灰霉病的融合框架

基于现有研究，采后番茄灰霉病病程预测的最有潜力融合路线是构建以表型特征+高光谱内部组织特征+电子鼻特征为核心的三模态框架。该框架可以在以下 4 个层面协同设计：①数据层。以果实个体为单位进行时序对齐，同一果实在相同时间节点同步采集机器视觉图像、光谱数据和电子鼻响应信号，确保按果实个体和采集时点对应各模态数据，并使图像与光谱采样区域一致。②模型层。根据模态特性选择融合策略。对于常规彩色机器视觉图像与光谱等同源光学信号可采用特征级融合，将卷积神经网络提取的图像特征与光谱特征在隐层空间拼接或交叉注意力对齐；对于电子鼻等异源信号，可采用决策级融合，各模态独立建模后通过加权投票集成输出最终判别结果；近期提出的跨模态<sup>[77]</sup> 注意力机制也为异源多模态端到端融合提供了新思路。③训练层。针对采后灰霉病样本获取困难的现实，引入数据增强、迁移学习和域自适应方法缓解小样本与跨设备漂移问题<sup>[79]</sup>。④应用层。以覆盖不同果型与品种、跨成熟度（绿熟至红熟）和跨储藏条件（常温与冷链）的稳健泛化为目标，逐步从实验室离线分析向冷链节点和分选线在线部署推进<sup>[80-81]</sup>。通过上述 4 个层面协同推进，就可能真正实现从“实验室验证”到“产业化应用”的跨越。

## 6 结论

采后番茄灰霉病早期识别需要综合利用病原侵染、果实成熟和品质劣变产生的信号。

灰霉病的果实潜伏期侵染、成熟诱导易感和异常促熟共同决定了可见症状出现之前就已存在可利用的生物学信号，包括色素衰减、组织结构重塑和挥发性有机化合物代谢重编程。这是开展症前预警的理论基础。光谱、机器视觉和电子鼻分别对应内部组织与生化变化、表面表型信息以及挥发性代谢异常，但单一模态均难以独立覆盖灰霉病早期“外观滞后、内部先变、气味先漂移”的全过程。本综述的核心发现之一是当前研究在“采后果实尺度”和“灰霉病”2 个关键词的交叉领域仍存在显著空白，多数光谱和视觉研究来源于叶片尺度或成熟度等邻近任务，直接面向番茄果实灰霉病早期检测的核心文献极为有限。多模态融合的真正价值在于重构从病理响应到检测模态识别之间的对应关系。已有证据表明，多光谱荧光-反射融合可实现灰霉病接种后早期分类，图像、光谱与触觉融合可改善番茄成熟度识别，电

子鼻与视觉融合可用于番茄果实成熟等级识别和硬度预测。但当前融合研究普遍缺乏标准化的番茄果实时序数据集和跨场景验证。

未来研究应考虑推进以下方向：①数据集建设。构建标准化的番茄果实灰霉病时序数据集，涵盖不同品种、不同果实成熟阶段(绿熟期、转色期、粉红期、红熟期)和不同储藏条件(常温与冷链)，纳入接种后不同时间节点(如0、12、24、48、72 h)的多模态同步采集数据。②模型开发。发展病理机制约束的特征工程与可解释深度学习模型，使模型输出能够与灰霉病的生物学进程建立对应关系。③泛化能力提升。借助迁移学习、域自适应和数据增强技术，强化小样本、跨设备和跨品种条件下的模型泛化能力，缩小实验室与产线之间的性能差距。④工程化部署。推动便携式多传感融合装备开发，面向冷链节点和分选线场景，实现从离线分析向在线预警的转化。

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