

五种昆虫病原线虫对番茄潜叶蛾的致死作用*

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摘要 【目的】探讨昆虫病原线虫对番茄潜叶蛾 *Tuta absoluta* 的侵染致死效果。【方法】采用生物测定法分别评估 5 种昆虫病原线虫 *Steinernema carpocapsae* All、*S. longicaudum* X-7、*S. feltiae* SN、*Heterorhabditis bacteriophora* H06 和 *H. indica* LN2 在培养皿中对番茄潜叶蛾 2 龄幼虫、4 龄老熟幼虫及蛹的毒力效果, 并进一步测定了高毒力线虫在模拟生境条件(寄主植物叶片和土壤中)下对以上虫态的致死作用。【结果】在培养皿中, 剂量为 10 IJs/虫测定条件下, 5 种昆虫病原线虫对番茄潜叶蛾 2 龄幼虫和 4 龄老熟幼虫表现出高毒力, 处理 72 h, 2 龄幼虫和 4 龄老熟幼虫的校正死亡率分别为 $\geq 88.33\%$ 和 100.00% ; 斯氏线虫对蛹的敏感性优于异小杆线虫, 其中 *S. carpocapsae* All 和 *S. longicaudum* X-7 对蛹的校正死亡率分别为 81.25% 和 70.73% , 显著高于 *H. bacteriophora* H06 (62.50%) 和 *H. indica* LN2 (52.08%) ($F = 6.702$, $df = 4, 20$, $P < 0.001$)。在模拟生境中, 剂量为 10 IJs/cm² 测定条件下, 5 种昆虫病原线虫对叶片中 2 龄幼虫 72 h 的校正死亡率为 100% ; 剂量为 15 IJs/cm² 时, 5 种线虫对土壤中 4 龄老熟幼虫 72 h 的校正死亡率为 100% , 且 *S. carpocapsae* All 对土壤中蛹的防治效果最好, 侵染致死率达 79.17% , 显著优于 *S. longicaudum* X-7 (64.58%) 和 *S. feltiae* SN (62.50%) ($F = 10.176$, $df = 2, 12$, $P = 0.003$)。【结论】*S. carpocapsae* All、*S. longicaudum* X-7、*S. feltiae* SN、*H. bacteriophora* H06 和 *H. indica* LN2 对叶片中番茄潜叶蛾幼虫高度敏感, 可进一步研究其田间防控效果, 并可通过研发和利用叶面保护剂稳定或增强线虫叶面防效; *S. carpocapsae* All 针对土壤中 4 龄老熟幼虫和蛹的侵染致病效果最好, 可有效防控番茄潜叶蛾土壤隐蔽虫态。

关键词 番茄潜叶蛾; 昆虫病原线虫; 幼虫; 蛹; 致死作用; 生物防治

Pathogenicity of five entomopathogenic nematodes to *Tuta absoluta*

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Abstract [Aim] To examine the effect of infection of the 2nd and 4th instar larvae and pupae of *Tuta absoluta* by entomopathogenic nematodes (EPNs). [Methods] The pathogenicity of five EPNs, *Steinernema carpocapsae* All, *S. longicaudum* X-7, *S. feltiae* SN, *Heterorhabditis bacteriophora* H06 and *H. indica* LN2, to 2nd and 4th instar mature larvae and pupae were determined using bioassays. [Results] In a petri dish bioassay, infection with the five EPNs (10 IJs/insect) resulted in $\geq 88.33\%$ and 100.00% corrected mortalities of the 2nd and 4th instar larvae after 72 h. Infection with *Steinernema* spp. was relatively virulent to pupae compared to *Heterorhabditis* spp. Significantly higher corrected mortalities of pupae (81.25% and 70.73%) were caused by *S. carpocapsae* All and *S. longicaudum* X-7 at a dosage of 10 IJs/insect compared to the same dosage of *H. bacteriophora* H06 (62.50%) and *H. indica* LN2 (52.08%) ($F = 6.702$; $df = 4, 20$; $P < 0.001$). Under simulated conditions, 100% corrected mortality of the 2nd instar larvae on leaves were caused by infection with the five EPNs

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at a dosage of 15 IJs/cm² after 72 h. Infection with the five EPNs at a dosage of 15 IJs/cm² also resulted in 100% corrected mortality of 4th instar larvae in soil were after 72 h. Infection with *S. carpocapsae* All at a dosage of 20 IJs/cm² caused significantly higher corrected mortalities (79.17%) of pupae in soil than infection by *S. longicaudum* X-7 (64.58%) and *S. feltiae* SN (62.50%) ($F = 10.176$; $df = 2, 12$; $P = 0.003$). **[Conclusion]** *Steinernema carpocapsae* All, *S. longicaudum* X-7, *S. feltiae* SN, *H. bacteriophora* H06, *H. indica* LN2 are highly virulent to *T. absoluta* larvae on leaves, which could be used to evaluate their efficacy as biological controls for this pest in the field. Leaf surface protectants can be developed to stabilize or enhance the efficacy of EPNs applied to leaves. Infection with *S. carpocapsae* All resulted in higher corrected mortalities of 4th instar larvae and pupae in soil than infection by *S. longicaudum* X-7 and *S. feltiae* SN, which suggests that *S. carpocapsae* All has the potential to control *T. absoluta* in soil.

Key words *Tuta absoluta*; entomopathogenic nematode; larva; pupa; pathogenicity; biological control

番茄潜叶蛾 *Tuta absoluta* 属鳞翅目 Lepidoptera 麦蛾科 Gelechiidae, 原产于南美洲秘鲁, 是一种极具破坏性的潜叶类害虫。自 2017 年首次在我国新疆地区被发现以来, 该虫迅速扩散至西南、西北、华东、华北和华中 20 多个省 (自治区、直辖市), 进一步扩张趋势明显 (Zhang *et al.*, 2021)。番茄潜叶蛾寄主广泛, 包括茄科、豆科、十字花科及禾本科等 9 科 40 余种植物, 最嗜番茄, 在番茄植株整个生育期内均可发生为害 (Desneux *et al.*, 2010), 主要以幼虫潜入叶片取食叶肉, 形成细小的潜道, 也可蛀食果实形成孔洞, 导致植株早衰、果实腐烂, 一般可造成番茄减产 20%-30%, 严重发生时可导致减产 80%-100%, 是番茄产业极具毁灭性的害虫之一 (Desneux *et al.*, 2010; 张桂芬等, 2018)。我国番茄种植面积位居世界第一, 是全球番茄第三大种植国和加工番茄制品第一大出口国 (Food and Agriculture Organization, 2017)。番茄潜叶蛾的入侵定殖对我国番茄产业的安全生产构成了巨大威胁 (冼晓青等, 2019)。

番茄潜叶蛾的发生和为害具有隐蔽性, 成虫通常将卵产于植株顶梢叶片背面、正面或嫩茎上, 幼虫孵化后即潜入叶片或果实取食为害, 大部分幼虫发育至老熟后吐丝下垂在土壤中 (深度 1-2 cm) 化蛹 (Uchoa-Fernandes 1995; Biondi *et al.*, 2018)。目前, 番茄潜叶蛾的防治主要依赖化学药剂, 然而由于其隐蔽发生和隐匿为害, 导致化学药剂防控不彻底, 需频繁用药 (Picanço *et al.*, 1998; Guedes and Picanço, 2012)。化学药剂的长期不合理使用不仅会导致番茄潜叶蛾抗药性增

加 (Silva *et al.*, 2016; Guedes *et al.*, 2019; Oke *et al.*, 2020; 李晓维等, 2022), 还会对授粉昆虫和天敌产生不利影响, 污染环境, 从而引发种植业风险、消费者风险及环境风险 (Zappalà *et al.*, 2012; Zlof and Suffert, 2012) 等问题。因此, 亟需研发安全高效的生物防控技术以保障番茄安全生产。

昆虫病原斯氏属 *Steinernema* 与异小杆属 *Heterorhabditis* 线虫是一类杀虫能力强、杀虫谱广且可规模化培养的生物天敌资源。该类线虫具有主动搜索能力, 对地下和钻蛀性等隐蔽发生害虫防治效果良好 (Georgis *et al.*, 2006), 已广泛应用于农林、牧草、花卉和卫生等领域害虫的防治 (Ehlers, 2001; Gaugler *et al.*, 2002; Labaude and Griffin, 2018), 对隐蔽发生的番茄潜叶蛾也表现出一定的生物防治潜力。针对番茄潜叶蛾幼虫, 国外科研人员已开展了大量研究, 筛选出多种对幼虫高毒力的线虫种类 (Batalla-Carrera *et al.*, 2010; Van Damme *et al.*, 2016; Dlamini *et al.*, 2020), 但对土壤中隐蔽虫态蛹的高毒力线虫种类和致死效果尚不清楚。鉴于不同昆虫病原线虫对不同靶标害虫的敏感性不同 (Lacey *et al.*, 2015), 且靶标害虫不同虫态的敏感性也存在差异 (Grewal *et al.*, 2004; Ma *et al.*, 2013), 本研究在室内条件下测定了 5 种已经商业化生产的昆虫病原线虫对番茄潜叶蛾 2 龄和 4 龄老熟幼虫及蛹的致死作用, 以期筛选出高效的昆虫病原线虫品系, 明确昆虫病原线虫对番茄潜叶蛾的控制效果, 为田间应用昆虫病原线虫防治番茄潜叶蛾提供数据支撑。

1 材料与方法

1.1 试验用虫

番茄潜叶蛾: 2 龄幼虫、4 龄老熟幼虫和蛹均由山东省农业科学院植物保护研究所农业昆虫监测与防控创新团队在养虫室内用“凯萨”番茄植株幼苗饲养。种群饲养和试验开展均在条件为温度 $(26 \pm 1)^\circ\text{C}$, 相对湿度 $65\% \pm 5\%$, 光周期 16 L : 8 D 的 RXZ-430D 智能人工气候箱中进行。

昆虫病原线虫: 斯氏线虫 *Steinernema carpocapsae* All、*S. longicaudum* X-7、*S. feltiae* SN 与异小杆线虫 *Heterorhabditis bacteriophora* H06 和 *H. indica* LN2 侵染期线虫 (Infective juveniles, IJs) 均由山东省农业科学院植物保护研究所采用海绵培养基培养法培养, 经自来水清洗后置于 IS-RDV1 立式恒温振荡器 (15°C , 120 r/min) 上备用。试验所用线虫保存时间不超过 15 d, 存活率在 95% 以上。

1.2 5 种昆虫病原线虫对番茄潜叶蛾裸虫的致死作用

采用培养皿滤纸测定法, 将 5 种昆虫病原线虫分别配制为 100 IJs/mL 的线虫悬浮液。在垫有两层中性滤纸的一次性培养皿 ($d = 9\text{ cm}$) 中均匀滴加 1 mL 线虫处理液, 对照组滴加等量清水, 用无菌毛刷轻轻刷入 10 头番茄潜叶蛾 2 龄幼虫、4 龄老熟幼虫或蛹, 处理剂量为 10 IJs/虫。在幼虫试验中, 每一培养皿内添加 $1\text{ cm} \times 1\text{ cm}$ 的新鲜番茄叶片作为饲料。用封口膜将培养皿密封后置于培养箱中。每个处理和对照设 5 个重复, 每皿 10 头虫为 1 个重复。每 12 h 观察并统计幼虫存活情况, 连续观察 3 d; 7 d 后统计蛹的羽化情况。

1.3 5 种昆虫病原线虫对叶片中番茄潜叶蛾 2 龄幼虫的致死作用

采用塑料盒滤纸测定法, 所用线虫为 1.2 中筛选出的高毒力线虫种类。挑选带有 2-3 龄幼虫的番茄叶片, 剪取 10 片, 平面排布于底部直径

为 14 cm (约 150 cm^2) 的圆盒底部。将昆虫病原线虫分别配制为 300 IJs/mL 线虫悬浮液, 用喷壶均匀喷施 5 mL 线虫悬浮液 (10 IJs/cm^2), 对照组喷施等量清水。用带有圆孔 ($d = 2\text{ mm}$) 的盖子密封后, 将盒子置于培养箱中。每个处理和对照设 5 个重复, 每盒 10 片叶 (10 头幼虫) 为一个重复。每 24 h 观察并统计幼虫存活情况, 连续观察 3 d。

1.4 高毒力昆虫病原线虫对土壤中番茄潜叶蛾 4 龄老熟幼虫和蛹的致死作用

采用塑料盒沙土测定法, 所用线虫为 1.2 中筛选出的高毒力线虫种类。将底部直径为 14 cm (约 150 cm^2) 的圆盒中装入沙土 400 g (含水量为 10%), 沙土厚度约为 3 cm, 用毛笔挑取 10 头 4 龄老熟幼虫或蛹置于每盒土壤中。配制线虫悬浮液 450 IJs/mL, 每盒喷施线虫悬浮液 5 mL, 则为 15 IJs/cm^2 , 对照组喷施等量清水, 将盒子置于培养箱中。每个处理和对照设 5 个重复, 每盒 10 头虫为一个重复。每 12 h 观察并统计老熟幼虫存活情况, 连续观察 3 d; 7 d 后统计蛹的羽化情况。

1.5 数据分析

数据统计分析使用 SPSS 软件 (SPSS 16.0 for Windows)。番茄潜叶蛾死亡率按照 Abbott (1925) 公式校正, 计算其校正死亡率。所有百分数值均经反正弦 Arcsin 转换后进行单因素方差分析 (One-way ANOVA), 并采用 Tukey 检验分析差异显著性 ($P < 0.05$)。

死亡率 (%) = (死虫数/供试总虫数) $\times 100$,

校正死亡率 (%) = (处理组死亡率 - 对照组死亡率) / (1 - 对照组死亡率) $\times 100$ 。

2 结果与分析

2.1 5 种昆虫病原线虫对番茄潜叶蛾裸虫的致死作用

2.1.1 5 种昆虫病原线虫对培养皿中番茄潜叶蛾 2 龄幼虫的致死作用

昆虫病原线虫处理 12 h,

培养皿中番茄潜叶蛾 2 龄幼虫开始陆续死亡, 其中 *H. indica* LN2 处理的幼虫校正死亡率最低 ($3.33\% \pm 3.33\%$), 显著低于 *S. carpocapsae* All ($23.33\% \pm 1.93\%$)、*S. longicaudum* X-7 ($23.33\% \pm 4.30\%$) 和 *S. feltiae* SN ($30.00\% \pm 4.30\%$) 处理 ($F = 7.414$, $df = 4, 15$, $P = 0.002$); 随着处理时间延长, 各处理幼虫死亡率逐渐上升, 但处理间差异不显著 ($F \leq 2.630$, $df = 4, 15$, $P \geq 0.076$); 处理 36 h, 幼虫死亡率均达 60.00% 以上; 处理 72 h, 幼虫死亡率均达 88.33% 以上, 其中 *S. carpocapsae* All、*S. longicaudum* X-7 和 *H. indica* LN2 线虫处理的幼虫校正死亡率高达 95.00% 以上 (图 1)。

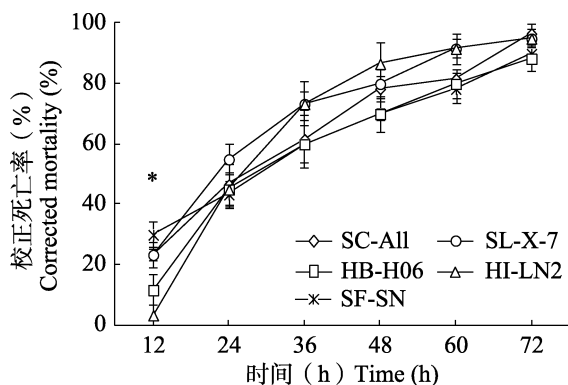


图 1 5 种昆虫病原线虫对培养皿中番茄潜叶蛾 2 龄幼虫的校正死亡率

Fig. 1 Corrected mortalities of the 2nd instar larvae of *Tuta absoluta* treated by five entomopathogenic nematodes in the petri dishes

星号 (*) 表示不同处理间显著差异 ($P < 0.05$, Tukey 检验)。图 2 同。

Asterisk (*) indicates statistical significance ($P < 0.05$, Tukey test). The same for Fig. 2.

SC-All: *Steinernema carpocapsae* All; SL-X-7: *S. longicaudum* X-7; SF-SN: *S. feltiae* SN; HB-H06: *Heterorhabditis bacteriophora* H06; HI-LN2: *H. indica* LN2. 下图同。The same below.

2.1.2 5 种昆虫病原线虫对培养皿中番茄潜叶蛾 4 龄老熟幼虫的致死作用 5 种昆虫病原线虫对培养皿中番茄潜叶蛾 4 龄老熟幼虫处理 12 h 的校正死亡率均低于 10%, 各处理间无显著差异 ($F = 0.446$, $df = 4, 15$, $P = 0.773$); 处理 24 h, *S. longicaudum* X-7 对 4 龄老熟幼虫的校正死亡率达 $57.50\% \pm 4.79\%$, 显著高于 *S. carpocapsae* All

和 *H. bacteriophora* H06 ($F = 4.265$, $df = 4, 15$, $P = 0.017$); 处理 36 h, 5 种线虫对 4 龄老熟幼虫的校正死亡率均达 70.00% 以上, 处理间差异不显著 ($F \leq 2.718$, $df = 4, 15$, $P \geq 0.070$); 处理 72 h, 所有线虫对 4 龄老熟幼虫的校正死亡率均达 100.00% (图 2)。

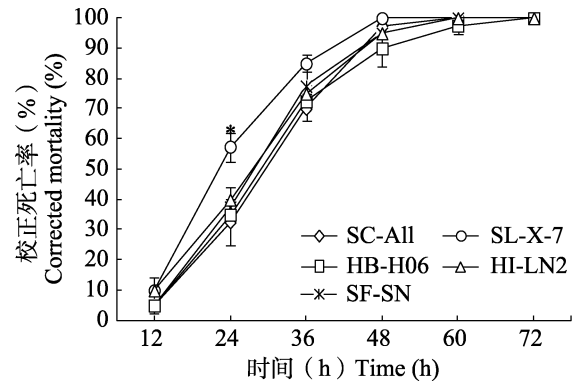


图 2 5 种昆虫病原线虫对培养皿中番茄潜叶蛾 4 龄老熟幼虫不同处理时间的校正死亡率

Fig. 2 Corrected mortalities of the 4th instar larvae of *Tuta absoluta* at different time treated by five entomopathogenic nematodes in the petri dishes

2.1.3 5 种昆虫病原线虫对培养皿中番茄潜叶蛾 蛹的致死作用 5 种昆虫病原线虫对培养皿中番茄潜叶蛾 蛹的校正死亡率不同 (图 3)。 *S. carpocapsae* All 处理的蛹校正死亡率达 $81.25\% \pm 3.90\%$, 显著高于 *H. bacteriophora* H06 和 *H. indica* LN2 处理 ($62.50\% \pm 5.31\%$ 和 $52.08\% \pm 4.17\%$) ($F = 6.702$, $df = 4, 20$, $P < 0.001$), 与 *S. longicaudum* X-7 ($70.83\% \pm 3.90\%$) 和 *S. feltiae* SN ($68.75\% \pm 3.29\%$) 处理没有显著差异 ($P > 0.05$)。

2.2 5 种昆虫病原线虫对叶片中番茄潜叶蛾 2 龄幼虫的致死作用

5 种昆虫病原线虫对叶片中番茄潜叶蛾 2 龄幼虫的校正死亡率随处理时间延长而升高, 同一处理时间所有线虫间无显著差异 ($F \leq 3.143$, $df = 4, 15$, $P \geq 0.046$) (图 4)。处理 12 h, 5 种线虫对 2 龄幼虫的校正死亡率均小于 23.33%; 处理 24 h, 5 种线虫对 2 龄幼虫的校正死亡率均上升至 53.33% 以上; 处理 72 h, 各处理组 2 龄幼虫的校正死亡率均达 100.00%。

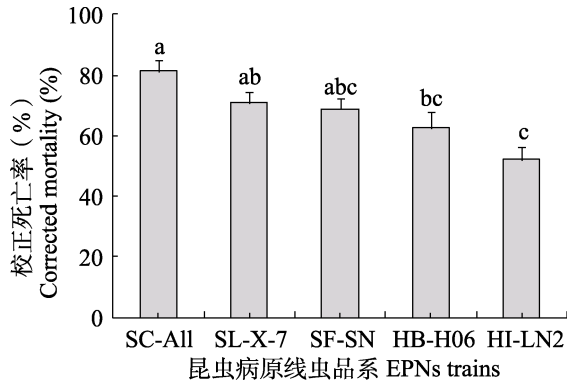


图 3 5 种昆虫病原线虫对培养皿中番茄潜叶蛾蛹的校正死亡率

Fig. 3 Corrected mortalities of the pupae of *Tuta absoluta* treated by five entomopathogenic nematodes in the petri dishes

EPN: 昆虫病原线虫; 柱上不同字母代表各处理间显著差异 ($P < 0.05$, Tukey 检验)。图 6 同。

EPN: Entomopathogenic nematodes. Histograms with different letters indicate significant difference ($P < 0.05$, Tukey test). The same for Fig. 6.

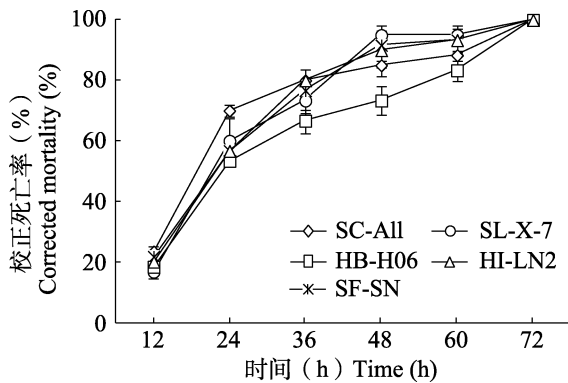


图 4 5 种昆虫病原线虫对叶片中番茄潜叶蛾 2 龄幼虫不同处理时间的校正死亡率

Fig. 4 Corrected mortalities of the 2nd instar larvae of *Tuta absoluta* in the leaf at different time treated by five entomopathogenic nematodes

2.3 高毒力昆虫病原线虫对土壤中番茄潜叶蛾 4 龄老熟幼虫和蛹的致死作用

2.3.1 5 种昆虫病原线虫对土壤中番茄潜叶蛾 4 龄老熟幼虫的致死作用 5 种昆虫病原线虫对土壤中番茄潜叶蛾 4 龄老熟幼虫的校正死亡率随处理时间延长而逐渐上升, 同一处理时间不同线虫间无显著差异 ($F \leq 2.324$, $df = 4, 15$, $P \geq 0.104$) (图 5)。处理 12 h, 5 种线虫对土壤中 4 龄老熟

幼虫的致死率为 12.50%-25.00%; 处理 36 h, 各处理组 4 龄老熟幼虫的校正死亡率达 75.00%以上; 处理 48 h, 4 龄老熟幼虫的校正死亡率均高于 95.00%。

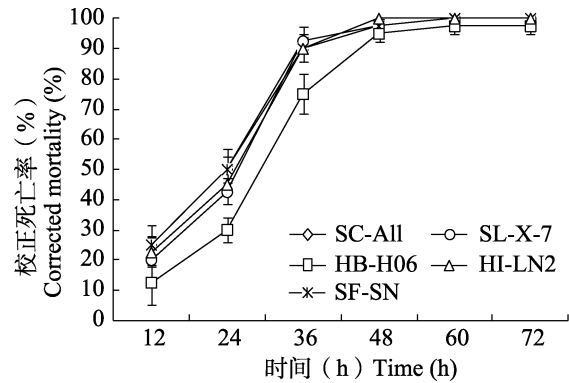


图 5 5 种昆虫病原线虫对土壤中番茄潜叶蛾 4 龄老熟幼虫不同处理时间的校正死亡率

Fig. 5 Corrected mortalities of the mature larvae of *Tuta absoluta* in the soil at different time treated by five entomopathogenic nematodes

2.3.2 高毒力昆虫病原线虫对土壤中番茄潜叶蛾蛹的致死作用 3 种斯氏线虫对土壤中番茄潜叶蛾蛹的校正死亡率不同 (图 6)。*S. carpocapsae* All 处理的蛹校正死亡率最高, 达 $79.17\% \pm 3.29\%$, 显著高于 *S. longicaudum* X-7 ($64.58\% \pm 2.55\%$) 和 *S. feltiae* SN ($62.50\% \pm 2.55\%$) 处理; *S. longicaudum* X-7 与 *S. feltiae* SN 对土壤中蛹的校正死亡率无显著差异 ($F = 10.176$, $df = 2, 12$, $P = 0.003$)。

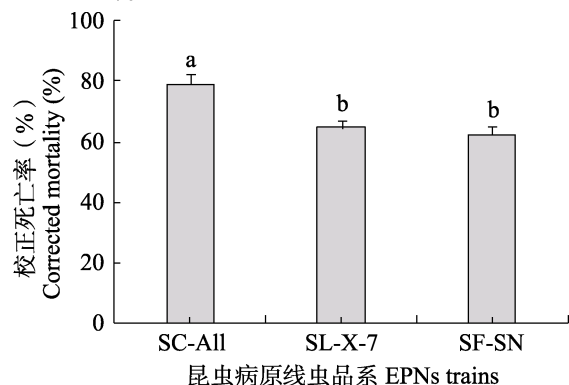


图 6 高毒力昆虫病原线虫对土壤中番茄潜叶蛾蛹的校正死亡率

Fig. 6 Corrected mortalities of the pupae of *Tuta absoluta* in the soil treated by entomopathogenic nematodes with high pathogenicity

3 讨论

不同害虫对不同昆虫病原线虫的敏感性存在差异,针对靶标害虫筛选高毒力的线虫种类是利用昆虫病原线虫成功防治害虫的首要前提 (Lacey and Georgis, 2012; Shapiro-Ilan and Dolinski, 2015)。本研究测定的 5 种昆虫病原线虫 *S. carpocapsae* All、*S. longicaudum* X-7、*S. feltiae* SN、*H. bacteriophora* H06 和 *H. indica* LN2 对番茄潜叶蛾幼虫均具高毒力。在培养皿中 10 IJs/虫条件下处理 72 h, 2 龄幼虫和 4 龄老熟幼虫的死亡率均高达 88.33% 以上。多种鳞翅目害虫如草地贪夜蛾 *Spodoptera frugiperda* (梁铭荣等, 2020; Guo *et al.*, 2023)、地老虎 *Agrotis ipsilon* (Yan *et al.*, 2014; 张安邦等, 2015) 和草地螟 *Loxostege sticticalis* (李朔涵, 2023) 的幼虫对昆虫病原线虫均具高敏感性, 大蜡螟幼虫更是作为土壤中昆虫病原线虫资源普查的诱饵 (谷黎娜, 2008) 及线虫毒力检测的靶标害虫 (马娟等, 2022)。同样, 国外对番茄潜叶蛾幼虫已筛选出多种高毒力的线虫种类或品系, 如 *S. carpocapsae*、*S. feltiae* 和 *H. bacteriophora* 在 3 h 内可致死 63%-86% 的幼虫 (Batalla-Carrera *et al.*, 2010), *S. yirgalemense* 和 *S. jeffreyense* 在 60 IJs/虫条件下对幼虫的致死率高达 98.3%-100% (Van Damme *et al.*, 2016; Dlamini *et al.*, 2020)。这些结果表明番茄潜叶蛾幼虫对昆虫病原线虫极为敏感。

番茄潜叶蛾幼虫在番茄叶片内取食叶肉, 形成半透明、形状各异的潜道或潜斑 (张桂芬等, 2022), 对幼虫而言形成了一层特殊的保护结构。昆虫病原线虫钻入潜道或潜斑内是成功防控番茄潜叶蛾的关键。研究结果表明, 在模拟生境条件下, 5 种线虫均能够钻入叶片潜道或潜斑内寄生番茄潜叶蛾幼虫, 剂量为 10 IJs/cm² 时, 5 种线虫对叶片中幼虫的致死率达 100%, 这与国外学者的研究结果基本一致, *S. carpocapsae* 和 *S. feltiae* 能够钻入叶片寄生幼虫, 在一定剂量范围内 (6.8-25 IJs/cm²) 对幼虫产生较高致死效果 (85.7% 以上) (Batalla-Carrera *et al.*, 2010; Van

Damme *et al.*, 2016)。由此可见, 昆虫病原线虫具有叶面喷施防控番茄潜叶蛾幼虫的应用潜力。但在实际应用中, 昆虫病原线虫易受叶面环境 (温度、湿度和光照等) 影响, 其田间应用技术及防控效果还需进一步研究。同时, 选择抗逆性强的线虫种类, 并研发利用高效、低成本的叶面保护剂如抗蒸发剂、保水剂、粘合剂和紫外保护剂等来保护线虫, 对昆虫病原线虫在叶面上的成功应用也极为必要。

昆虫病原线虫对同一靶标害虫不同虫态的毒力效果不同, 对蛹的敏感性往往要低于幼虫 (Wakil *et al.*, 2022; Guo *et al.*, 2023)。本研究中, 5 种昆虫病原线虫对番茄潜叶蛾蛹的致死效果均低于幼虫。昆虫病原线虫以携带的肠道共生细菌致病害虫, 主要通过靶标害虫的自然开口 (口、肛门和气孔)、伤口或节间膜进入宿主血腔, 而蛹敏感性较差可能主要是因为幼虫化蛹时角质层硬化和增厚, 以及自然孔口关闭形成的较为封闭的外表皮 (Grewal *et al.*, 2005)。斯氏线虫对番茄潜叶蛾蛹的毒力效果优于异小杆线虫, 其中 *S. carpocapsae* All 对土壤中蛹的毒杀效果最好, 侵染致死率达 79.17%。番茄潜叶蛾以 4 龄老熟幼虫钻入土中, 通常在 72 h 内化蛹, *S. carpocapsae* All 对土壤中老熟幼虫的侵染致死率达 100%, 表明无论番茄潜叶蛾在土壤中是以老熟幼虫、蛹单独或共同存在, *S. carpocapsae* All 均具有高效防控番茄潜叶蛾的潜力。但落地化蛹这一习性往往导致番茄潜叶蛾防治不彻底, 残留的虫源羽化后会成为新一代害虫 (郭文秀等, 2023)。本研究首次筛选到对番茄潜叶蛾蛹的高毒力线虫 *S. carpocapsae* All, 因线虫源于土壤, 其在土壤中应用具有天然优势, 因此, 施用 *S. carpocapsae* All 防控番茄潜叶蛾土壤隐蔽虫态的田间效果值得进一步探究, 有望成为解决番茄潜叶蛾防控不彻底问题的重要技术支撑。

综上所述, 5 种昆虫病原线虫 *S. carpocapsae* All、*S. longicaudum* X-7、*S. feltiae* SN、*H. bacteriophora* H06 和 *H. indica* LN2 对叶面番茄潜叶蛾幼虫均具很好的致死作用, 可进一步研究其田间防控效果, 并通过研发和利用叶面保护剂

稳定或增强线虫叶面防效; *S. carpocapsae* All 对土壤中老熟幼虫及蛹表现出高毒力, 具有防控番茄潜叶蛾土壤隐蔽虫态的潜质。

参考文献 (References)

- Abbott WS, 1925. A method of computing the effectiveness of an insecticide. *Journal of Economic Entomology*, 18(2): 265–267.
- Batalla-Carrera L, Morton A, García-del-Pino F, 2010. Efficacy of entomopathogenic nematodes against the tomato leafminer *Tuta absoluta* in laboratory and greenhouse conditions. *BioControl*, 55(4): 523–530.
- Biondi A, Guedes RNC, Wan FH, Desneux N, 2018. Ecology, worldwide spread, and management of the invasive South American tomato pinworm, *Tuta absoluta*: Past, present, and future. *Annual Review of Entomology*, 63: 239–258.
- Desneux N, Wajnberg E, Wyckhuys KAG, Burgio G, Arpaia S, Narváez-Vasquez CA, González-Cabrera J, Catalán Ruescas D, Tabone E, Frandon J, Pizzol J, Poncet C, Cabello T, Urbaneja A, 2010. Biological invasion of European tomato crops by *Tuta absoluta*: Ecology, geographic expansion and prospects for biological control. *Journal of Pest Science*, 83(3): 197–215.
- Dlamini BE, Dlamini N, Masarirambi MT, Nxumalo KA, 2020. Control of the tomato leaf miner, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) larvae in laboratory using entomopathogenic nematodes from subtropical environment. *Journal of Nematology*, 52(13): 1–8.
- Ehlers RU, 2001. Mass production of entomopathogenic nematodes for plant protection. *Applied Microbiology and Biotechnology*, 56(5): 623–633.
- Food and Agriculture Organization, 2017. Online statistical database: Food and agriculture data. 2022-09-23, <http://www.fao.org/faostat>.
- Gaugler R, Brown I, Shapiro-Ilan DI, Atwa A, 2002. Automated technology for in vivo mass production of entomopathogenic nematodes. *Biological Control*, 24(2): 199–206.
- Georgis R, Koppenhöfer AM, Lacey LA, Bélair G, Duncan LW, Grewal PS, Samish M, Tan L, Torr P, van Tol RWHM, 2006. Successes and failures in the use of parasitic nematodes for pest control. *Biological Control*, 38(1): 103–123.
- Grewal PS, Power KT, Grewal SK, Suggars A, Haupricht S, 2004. Enhanced consistency in biological control of white grubs (Coleoptera: Scarabaeidae) with new strains of entomopathogenic nematodes. *Biological Control*, 30(1): 73–82.
- Grewal PS, Koppenhöfer AM, Choo HY, 2005. Lawn, turfgrass and pasture applications//Grewal PS, Ehlers RU, Shapiro-Ilan DI (eds.). *Nematodes as Biocontrol Agents*. Wallingford: CABI Publishing. 115–146.
- Gu LN, 2008. Fauna of entomopathogenic nematodes and biology of its fine strains in Gansu province. Master dissertation. Lanzhou: Gansu Agricultural University. [谷黎娜, 2008. 甘肃省昆虫病原线虫区系及优良品系生物学特性研究. 硕士学位论文. 兰州: 甘肃农业大学.]
- Guedes RNC, Picanço MC, 2012. The tomato borer *Tuta absoluta* in South America: Pest status, management and insecticide resistance. *EPPO Bulletin*, 42(2): 211–216.
- Guedes RNC, Roditakis E, Campos MR, Haddi K, Bielza P, Siqueira HAA, Tsagkarakou A, Vontas J, Nauen R, 2019. Insecticide resistance in the tomato pinworm *Tuta absoluta*: Patterns, spread, mechanisms, management and outlook. *Journal of Pest Science*, 92(4): 1329–1342.
- Guo WX, Li LL, Jiang WF, Cheng YZ, Song YY, Cui HY, Lv SH, Yu Y, Men XY, 2023. Research progress on the harm risk of tomato leaf miner to tomato industry in Shandong Province and its monitoring, prevention and control. *Shandong Agricultural Sciences*, 55(11): 1–11. [郭文秀, 李丽莉, 姜文凤, 程亚增, 宋莹莹, 崔洪莹, 吕素洪, 于毅, 门兴元, 2023. 番茄潜叶蛾对山东省番茄产业的危害风险及其监测、防控研究进展. 山东农业科学, 55(11): 1–11.]
- Guo WX, Wang XY, Men XY, Wang CL, Pan HK, Song YY, Cui HY, Lv SH, Yu Y, Li LL, 2023. Field efficacy of *Steinernema carpocapsae* (Rhabditida: Steinernematidae) strain all in the control of fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in maize. *Biological Control*, 180: 105202.
- Labaude S, Griffin CT, 2018. Transmission success of entomopathogenic nematodes used in pest control. *Insects*, 9(2): 72.
- Lacey LA, Georgis R, 2012. Entomopathogenic nematodes for control of insect pests above and below ground with comments on commercial production. *Journal of Nematology*, 44(2): 218–225.
- Lacey LA, Grzywacz D, Shapiro-Ilan DI, Frutos R, Brownbridge M, Goettel MS, 2015. Insect pathogens as biological control agents: Back to the future. *Journal of Invertebrate Pathology*, 132: 1–41.
- Li SH, 2023. Screening and application conditions of highly pathogenic entomopathogenic nematodes in *Loxostege stictica*. Master dissertation. Harbin: Northeast Agricultural University. [李朔涵, 2023. 草地螟高致病力昆虫病原线虫品系筛选及施用条件研究. 硕士学位论文. 哈尔滨: 东北农业大学.]
- Li XW, Ma L, Lü YB, 2022. Susceptibility of Xinjiang and Yunnan populations of *Tuta absoluta* (Lepidoptera: Gelechiidae) to six insecticides and its relationship with detoxification enzyme activities. *Acta Entomologica Sinica*, 65(8): 1010–1017. [李晓维, 马琳, 吕要斌, 2022. 新疆和云南番茄潜叶蛾种群对六种杀虫

- 剂的敏感性及其与解毒酶活性的关系. 昆虫学报, 65(8): 1010–1017.]
- Liang MR, Li ZY, Dai QX, Lu YY, Chen KW, 2020. Virulence of four entomopathogenic nematodes on fall armyworm, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae). *Journal of Biosafety*, 29(2): 82–89. [梁铭荣, 李子园, 戴钊萱, 陆永跃, 陈科伟, 王磊, 2020. 4 种昆虫病原线虫对草地贪夜蛾的致死作用. 生物安全学报, 29(2): 82–89.]
- Ma J, Chen SL, Moens M, Han RC, De Clercq P, 2013. Efficacy of entomopathogenic nematodes (Rhabditida: Steinernematidae and Heterorhabditidae) against the chive gnat, *Bradysia odoriphaga*. *Journal of Pest Science*, 86(3): 551–561.
- Ma J, Guo XX, Li XH, Wang RY, Gao B, Chen SL, 2022. Tolerance of different entomopathogenic nematodes to environmental stresses. *Chinese Journal of Biological Control*, 38(1): 188–195. [马娟, 郭笑笑, 李秀花, 王容燕, 高波, 陈书龙, 2022. 不同品系昆虫病原线虫抗逆性分析. 中国生物防治学报, 38(1): 188–195.]
- Oke OA, Oladigbolu AA, Hamisu HS, 2020. Evaluation of resistance and toxicity of different insecticides on *Tuta absoluta* (Meyrick) populations in major tomato growing states of Nigeria// Niassy S, Ekesi S, Migiro L, Otieno W (eds.). Sustainable Management of Invasive Pests in Africa. Berlin: Springer Link. 45–55.
- Picanço M, Leite GLD, Guedes RNC, Silva EA, 1998. Yield loss in trellised tomato affected by insecticidal sprays and plant spacing. *Crop Protection*, 17(5): 447–452.
- Shapiro-Ilan DI, Dolinski C, 2015. Entomopathogenic nematode application technology// Campos-Herrera R (ed.). Nematode Pathogenesis of Insects and Other Pests, Sustainability in Plant and Crop Protection. BerlinCham: Springer Link. 231–254.
- Silva TBM, Silva WM, Campos MR, Silva JE, Ribeiro LMS, Siqueira HAA, 2016. Susceptibility levels of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) to minor classes of insecticides in Brazil. *Crop Protection*, 79: 80–86.
- Uchoa-Fernandes MA, Della Lucia TMC, Vilela EF, 1995. Mating, oviposition and pupation of *Scrobipalpuloides absoluta* (Meyr.) (Lepidoptera: Gelechiidae). *Anais da Sociedade Entomológica do Brasil*, 24(1): 159–164.
- Van Damme VM, Beck BK, Berckmoes E, Moerkens R, Wittemans L, De Vis R, Nuytens D, Casteels HF, Maes M, Tirry L, De Clercq P, 2016. Efficacy of entomopathogenic nematodes against larvae of *Tuta absoluta* in the laboratory. *Pest Management Science*, 72(9): 1702–1709.
- Wakil W, Usman M, Piñero JC, Wu SH, Toews MD, Shapiro-Ilan DI, 2022. Combined application of entomopathogenic nematodes and fungi against fruit flies, *Bactrocera zonata* and *B. dorsalis* (Diptera: Tephritidae): laboratory cups to field study. *Pest Management Science*, 78(7): 2779–2791.
- Xian XQ, Zhang GF, Liu WX, Wan FH, 2019. Risk assessment of the invasion of the tomato leafminer *Tuta absoluta* (Meyrick) into China. *Journal of Plant Protection*, 46(1): 49–55. [洗晓青, 张桂芬, 刘万学, 万方浩, 2019. 世界性害虫番茄潜麦蛾入侵我国的风险分析. 植物保护学报, 46(1): 49–55.]
- Yan X, Wang XD, Han RC, Qiu XH, 2014. Utilisation of entomopathogenic nematodes, *Heterorhabditis* spp. and *Steinernema* spp. for the control of *Agrotis ipsilon* (Lepidoptera, Noctuidae) in China. *Nematology*, 16 (1): 31–40.
- Zappalà L, Bernardo U, Biondi A, Cocco A, Siscaro G, 2012. Recruitment of native parasitoids by the exotic pest *Tuta absoluta* in southern Italy. *Bulletin of Insectology*, 65(1): 51–61.
- Zhang AB, NanGong ZY, Song P, Wang QY, 2015. Efficacy of entomopathogenic nematodes against *Agrotis segetum* larvae. *Journal of Environmental Entomology*, 37(3): 591–597. [张安邦, 南宫自艳, 宋萍, 王勤英. 昆虫病原线虫对黄地老虎致病力的研究. 环境昆虫学报, 37(3): 591–597.]
- Zhang GF, Liu WX, Wan FH, Xian XQ, Zhang YB, Guo JY, 2018. Bioecology, damage and management of the tomato leafminer *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), a worldwide quarantine pest. *Journal of Biosafety*, 27(3): 155–163. [张桂芬, 刘万学, 万方浩, 洗晓青, 张毅波, 郭建洋, 2018. 世界毁灭性检疫害虫番茄潜叶蛾的生物生态学及危害与控制. 生物安全学报, 27(3): 155–163.]
- Zhang GF, Xian XQ, Zhang YB, Liu WX, Liu H, Feng XD, Ma DY, Wang YS, Gao YH, Zhang R, Li QH, Wan FH, Fu WJ, Wang J, Kuang M, Yang WJ, Rao X, Gao Y, Dai AM, 2021. Outbreak of the South American tomato leafminer, *Tuta absoluta*, in the Chinese mainland: Geographic and potential host range expansion. *Pest Management Science*, 77(12): 5475–5488.
- Zhang GF, Zhang YB, Xian XQ, Liu WX, Li P, Liu WC, Li H, Feng XD, Lv ZC, Wang YS, Huang C, Guo JY, Wan FH, Ma DY, Zhang XM, Gui FR, Li YH, Lu R, Wang HQ, Wang J, 2022. Damage of an important and newly invaded agricultural pest, *Phthorimaea absoluta*, and its prevention and management measures. *Plant Protection*, 48(4): 51–58. [张桂芬, 张毅波, 洗晓青, 刘万学, 李萍, 刘万才, 刘慧, 冯晓东, 吕志创, 王玉生, 黄聪, 郭建洋, 万方浩, 马德英, 张晓明, 桂富荣, 李亚红, 罗荣, 王慧卿, 王俊, 2022. 新发重大农业入侵害虫番茄潜叶蛾的发生为害与防控对策. 植物保护, 48(4): 51–58.]
- Zlof V, Suffert M, 2012. Report of the EPPO/FAO/IOBC/NEPPO joint international symposium on management of *Tuta absoluta* (tomato borer). *EPPO Bulletin*, 42(2): 203–204.